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Groundwater resources of the internal areas of Campania region: advanced monitoring techniques and hydrogeological analysis

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Contents

<i>Abstract</i>	pag. 1
<i>Introduction</i>	pag. 2
Chapter 1: Geological, Climatic and Hydrogeological setting of the study areas	pag. 7
1.1.Regional Geological framework	pag. 7
<i>1.1.1.Paleogeography and evolution</i>	pag. 10
<i>1.1.2.Stratigraphy</i>	pag. 13
1.2.Hydrogeological setting	pag. 15
<i>1.2.1.Karst aquifers</i>	pag. 16
1.2.2.Alluvial aquifers	pag. 33
Chapter 2: Numerical simulations in groundwater flow modeling	pag. 38
2.1.MODFLOW Code	pag. 39
2.2.Finite difference method and grid discretization	pag. 42
2.3.Packages	pag. 47
<i>2.3.1.River Package</i>	pag. 49
<i>2.3.2.Recharge Package</i>	pag. 51
<i>2.3.3.Well Package</i>	pag. 52
2.4.MODPATH software	pag. 52
2.5.Graphical User Interface: Processing MODFLOW	pag. 55
Chapter 3: Numerical modeling of Benevento alluvial plain using Time Series Analysis and MODFLOW code	pag. 59
3.1.Time series analysis	pag. 60
3.2.Hydraulic characteristics of the alluvial aquifer	pag. 63

3.2.1. <i>Water table drawdown-recovery</i>	pag. 63
3.2.2. <i>Hydraulic conductivity by Dupuit's method</i>	pag. 64
3.3. Numerical modeling of the aquifer	pag. 65
3.3.1. <i>Model calibration</i>	pag. 67
3.3.2. <i>Groundwater circulation</i>	pag. 69
Chapter 4: Groundwater monitoring system, meteorological, hydrological, and historical data	pag. 72
4.1. Continuous monitoring system with TD Diver	pag. 72
4.1.1. <i>Water level measurement</i>	pag. 74
4.1.2. <i>Temperature measurement</i>	pag. 74
4.1.3. <i>Diver Office user-interface</i>	pag. 74
4.1.4. <i>Installation in study areas</i>	pag. 75
4.2. Meteorological and hydrological data	pag. 76
4.3. GIS software and Satellite data	pag. 77
4.4. Historical data	pag. 82
Chapter 5: Continuous monitoring system and time series analysis for the comprehension of karst polje dynamics	pag. 81
5.1. Description of monitoring time series	pag. 83
5.1.1. <i>Precipitation, lake storage, groundwater level and spring discharges</i>	pag. 83
5.1.2. <i>Time series analysis</i>	pag. 85
5.2. Analysis of monitoring time series	pag. 86
5.2.1. <i>November 2020-May 2021</i>	pag. 86
5.2.2. <i>November 2021-May 2022</i>	pag. 88
5.2.3. <i>November 2022-May 2023</i>	pag. 88
5.2.4. <i>November 2023-May 2024</i>	pag. 89

5.2.5. <i>Correlation between water level and Cassano and Serino spring discharges</i>	pag. 90
5.3. Relationships between karst lake level and groundwater dynamics	pag. 91
Chapter 6: Mapping and Hydrological methods for the evaluation of groundwater recharge	pag. 94
6.1. Dolines and endorheic areas mapping	pag. 95
6.1.1. <i>Types of karst closed depressions</i>	pag. 96
6.1.2. <i>Closed depression mapping</i>	pag. 99
6.1.3. <i>Morphometric parameters</i>	pag. 104
6.2. Groundwater recharge estimation	pag. 105
6.2.1. <i>Modified APLIS method</i>	pag. 105
6.2.2. <i>APLIS with endorheic areas method</i>	pag. 110
6.2.3. <i>Daily Scale Recharge model</i>	pag. 111
6.3. Lumped models for recharge evaluation: KarstMod	pag. 112
6.3.1. <i>Workflow</i>	pag. 113
6.3.2. <i>Meteorological modules</i>	pag. 114
6.3.3. <i>Structure of the model</i>	pag. 115
6.3.4. <i>Model calibration</i>	pag. 117
6.3.5. <i>Model outputs</i>	pag. 117
Chapter 7: GIS tools for closed depressions, endorheic areas mapping and statistical analysis in karst aquifers	pag. 120
7.1. Closed depressions and Endorheic areas mapping of Alburni karst massif	pag. 121
7.1.1. <i>Dolines and endorheic areas mapping</i>	pag. 121
7.1.2. <i>Morphometric and statistical analysis</i>	pag. 121

7.2. Endorheic areas mapping of Morcone karst reliefs	pag. 128
<i>7.2.1. Dolines and endorheic areas mapping</i>	pag. 128
<i>7.2.2. Morphometric analysis</i>	pag. 132
<i>7.2.3. Groundwater flow path through tracer tests performing</i>	pag. 133
Chapter 8: Groundwater recharge evaluation and modeling of karst massifs using hydrological methods and lumped model	pag. 136
8.1. Recharge evaluation using Modified APLIS Method	pag. 137
<i>8.1.1. Recharge Rate Map</i>	pag. 138
<i>8.1.2. Specific recharge map</i>	pag. 139
<i>8.2. Recharge evaluation using Modified APLIS Method with Endorheic areas</i>	pag. 143
<i>8.2.1. Recharge Rate map</i>	pag. 143
<i>8.2.2. Specific Recharge map</i>	pag. 144
<i>8.3. Daily Scale Recharge Model</i>	pag. 148
<i>8.4. Recharge models comparison</i>	pag. 151
<i>8.5. Lumped model of recharge-discharge processes of Caposele karst spring</i>	pag. 153
<i>8.5.1. Model structure</i>	pag. 153
<i>8.5.2. Model calibration and validation</i>	pag. 155
<i>8.5.3. Snow routine calibration</i>	pag. 155
<i>8.5.4. Recharge and discharge processes modeling</i>	pag. 156
Chapter 9: Some hydrogeological insights about the historical water supply in Campania region	pag. 159
9.1. Hydrogeological framework of Ancient Campania Felix region	pag. 161
<i>9.1.1. Karst Aquifers</i>	pag. 162
<i>9.1.2. Porous Aquifers</i>	pag. 162

9.1.3. Volcanic Aquifers	pag. 165
9.2. Historical insights on Augusta and Sannitico aqueducts	pag. 166
9.2.1. Augustan Aqueduct layout	pag. 168
9.2.2. Sannitico Aqueduct layout	pag. 175
9.3. The Serino springs (Caput Aquae)	pag. 178
9.3.1. Caput Aquae choice	pag. 180
9.4. Augustan Aqueduct and water supply	pag. 184
9.5. Historical evolution of the water supply of Benevento city	pag. 186
9.5.1. Historical framework	pag. 186
9.5.2. Roman Times	pag. 187
9.5.3. Lombard Times	pag. 188
9.5.4. Papal Times and Unification of Italy	pag. 189
9.6. Nowadays water supply	pag. 193
9.6.1. Serino Aqueduct	pag. 193
9.6.2. Benevento water supply	pag. 196
Conclusions	pag. 199
References	pag. 204
Appendix	
Scientific production	pag. 239
Introduction to Processing MODFLOW X theoretical and practical user Guide	pag. 243
Acknowledgments	

Abstract

This work of thesis is framed in the context of the PhD courses founded by PNRR, DM 351/2022 – “*Dottorati Innovativi per la pubblica amministrazione e il patrimonio culturale*” – “*Didattica e competenze universitarie avanzate*”. The main topic of the course was the *Quantitative and qualitative assessment of groundwater resources of the internal areas of Campania region in monitored basins*. These objectives were pursued using modern and sophisticated continuous monitoring instruments, coupled with methods related to numerical modeling and time series and GIS analysis. New and from literature methodologies have been applied to perform an improved study of karst massifs representing the main water sources of the study area. The course encompassed also a six months foreign research period in University of Malaga (Spain), at CEHIUMA Laboratory, with the research team coordinated by Professor Bartolomeo Andreo Navarro. During this period, the research activity was mainly focused on the study and application to a karst aquifer located in the project area of the recharge estimation method APLIS. Also, several field trips to the alluvial and karst aquifers studied by the research team have been carried out. This activity improved the knowledge about the management and safeguard of groundwater resources in dry areas, facing the problems of overexploitation, pollution, drought, and water supply management. Simultaneously, research works concerning activities carried out both in Italian and in Spanish countries were published or presented in congresses. Some oral contributions were presented to the International Eurokarst conference held in Rome in June 2024 and organized by Unisannio, Sapienza and Bari Universities. During the conference I was the part of the staff for the Unisannio University. National congresses like that organized by AIGAA (years 2023 and 2024), SGI (years 2023 and 2024), and IAH-Italian Chapter (year 2025) have been attended with oral or poster presentation. This work of thesis represents a summary of knowledges and experiences acquired during the three-year PhD course. Four topics have been addressed. The first one regards the numerical modeling of the Benevento Plain, an area strongly exploited by pumping wells, showing the strong control exerted by river dynamics on groundwater flow path. The second topic deals with the hydraulic dynamic of a Dragone Plain karst polje related to recharge processes of Terminio-Tuoro karst massif. The results show a strong influence of the recharge provided by the karst lake on the spring discharge of the main basal springs of Cassano Irpino. The third topic addresses the endorheic areas delineation and related statistical analysis of Alburni and Morcone karst massifs. In the first case more than 1000 closed depression and related endorheic, affecting the summit karst plateau and the recharge processes, areas have been mapped. In Morcone karst massif no more than 100 closed areas and related endorheic areas have been mapped; however, performing of tracer tests demonstrated how the two main ponors feed the principal basal springs. After a recharge evaluation was carried out using Modified APLIS and Daily Scale Recharge methods. Also, the new methodology, born by the combination of APLIS and Groundwater Recharge methods have been used. The results show the good agreement between the first two methodologies, and highlights the overestimated results provided by the new methodology. Then KarstMod software was used to define the recharge-discharge processes featuring Cervialto karst massif, highlighting how the snow cover influences the recharge processes and, thus, the spring hydrographs. At the end, historical insights on the water supply in Campania region have been studied. The Aqua Augusta and Sannitico Roman Aqueducts and the hydrogeological features affecting their construction were examined. The study highlights how the hydrological characteristics of Serino springs played a key role in water supply hypothesizing also an interconnection between the two aqueducts. Then the historical evolution of Benevento water supply, analyzing also the future scenarios, were treated. The evolution of the water supply indicates a progressively water quality drop, in the period spanning from Roman to currently time.

Introduction

This thesis deals with groundwater for drinking purpose from a hydrogeological perspective, in Campania region. The internal areas of this region have a strategic role in the framework of southern Italy water supply. As an example, Caposele, Cassano Irpino, and Serino springs represent the most important water sources of two of the most important aqueducts systems of southern Italy (Pugliese and Serino aqueducts).

Based on the currently regional aqueduct system, the groundwater resources of internal area of Campania region represent one of the most important water supplies for drinking, industrial and agricultural use of the whole region. However, the lack of hydrogeological knowledge, the disregard about risks and anthropic activities, and a dis-organized resource planning make difficult the good management and usage of these resources.

During the last decades, following the urbanistic expansion, the increasing of industries, and of specialized agricultural companies the good-quality water resources demand increased. The combined effect of both the effective precipitation drops and the increasing of pumping from aqueduct and private companies, has a negative effect on the equilibrium of water-related ecosystems. Furthermore, the qualitative decay of water resources from deep wells and springs provoked the abandonment of those resources with a consequent damage for communities.

The effect of the climate change, also, contribute to the above water supply framework. The increasing of hydrogeological drought periods, including the latter 2024 and 2025 dry periods, caused several disruptions in water management by aqueduct companies.

This thesis work fits into this water supply framework. In the following work particularly attention was given to karst aquifer (Alburni, Morcone, and North Picentini, among others), characterized by a high yield and by the possibility to have a flexible management of groundwater resources. Also, a focus on alluvial plain dynamic (Benevento alluvial plain) was carried out, since their good yield and the relatively shallow water table allowed the exploitation of groundwater resources hosted in quaternary sediments.

Four main topics have been focused: (i) numerical modeling of groundwater flow path; (ii) continuous monitoring systems in groundwater management; (iii) endorheic areas delimitation and groundwater recharge estimation in GIS environment; (iv) insights about historical water supply in Campania region.

All these topics are generally linked by the same methods and data acquisition, as the continuous groundwater level monitoring, karst landform mapping (endorheic areas), and recharge estimation. All these aspects have allowed to investigate on some further hydrogeological details and provide new insights on the ancient Roman aqueducts which were fed by karst springs.

The first topic of thesis is aimed to characterize the groundwater flow path of the Benevento Alluvial plain, affected by river-aquifer interactions and by anthropogenic stresses caused by pumping wells. Several methods to maximize the information achievable from hydrological monitoring, involving time series analysis and analytical methods were combined. To assess if river flow variability can explain that of water table, cross-correlation and time series processing were used. After, using MODFLOW code and MODPATH software, numerical simulations were performed to investigate the specific contribution on groundwater circulation of: (i) aquifer-river interactions, (ii) effective meteoric recharge, and (iii) pumping. The simulations showed that pumping groundwater comes partially from the river and that the latter represents an imposed hydrological boundary, which limits the groundwater variability and circulation in the alluvial aquifer, while meteoric recharge has a negligible role.

The second topic deals with the endorheic areas mapping and recharge evaluation carried out for Alburni karst massif and Morcone karst reliefs. Karst environments are characterized by a deep interaction between groundwater and surface landforms. These settings feature closed depressions, whose hydrological role varies depending on whether they have genetic and hydraulic relationships with overland-subsurface flow (epigenic) or deep groundwater circulation (hypogenic). Dolines and poljes are among diagnostic landforms of karst terrains. In this work of thesis, a hydrological criterion was applied to map the closed depressions and the endorheic areas featuring Alburni karst massif and Morcone karst reliefs. For this purpose, a GIS-based semi-automatic approach was used, combining the sink-filling method (applied to a 5 m-DEM) with the visual interpretation of various informative layers. This procedure produced a map showing the location and depth of closed depressions and their related endorheic area. The resulting maps highlight the presence of thousand dolines and hundreds endorheic areas, in the case of Alburni karst massif, and less than hundred dolines and related endorheic areas, in the case of Morcone karst reliefs. The main morphometric features of the dolines and endorheic areas were statistically analyzed and compared with the structural features of the massifs. Also, for Morcone karst reliefs, to reconstruct the groundwater flow

model of the aquifer and to highlight the linking between the endorheic areas and the main springs draining the massif, tracer tests were performed.

The complexities of surface morphological features of karst aquifers make these aquifers unique. Under such assumption, the recharge of Morcone karst reliefs was evaluated. This evaluation encompasses the mapping of endorheic areas with the Modified APLIS (A=Altitude, P=Slope, L=Lithology, I=Infiltration landforms, and S =Soil type) and DSR (Daily Recharge Scale Model) methods. These methods relate aquifer recharge with the surface features of karst aquifers. A modification applied to these methods allowed to consider the role of endorheic areas in recharge processes. These features cover about the 12% of the whole karst outcrop area. The recharge evaluation carried out by Modified APLIS and DSR shows, for both methods, an average infiltration rate of about 50 million of meter cubic per years. The discrepancy between input and output volume is justified by internal aquifer structure, characterized by an alternation of karstified and low-permeability layers. This condition causes the diffusion of flow path, with the formation of several interconnected water tables. Moreover, groundwater transfers would occur from the karst aquifer to the alluvial aquifers. Part of the water would supply Telese spring group through a deep flow causing the high mineralization of springs.

A further recharge-discharge processes evaluation was carried out using the lumped model platform KarstMod. This platform was employed to transform the daily affluxes into spring discharge of the Cervialto karst massif drained by Caposele spring. The aim of this modeling was the investigation of the ability of the lumped model to predict the daily discharge of a diffusive-flow karst system. Also, it shows a simple approach to calibrate snow routine parameters based on the analysis of multi-temporal satellite images. The hydrological model accurately replicates the main hydrological features of the Caposele spring, providing a valuable tool for evaluating the impacts of climate change on spring discharge.

The third topic of this thesis is related to the groundwater monitoring activities carried out in a karst polje for the comprehension of its recharge processes. For analyzing the recharge discharge processes of Dragone Plain polje, part of the wider Terminio Tuoro karst massif, a monitoring activity was carried out for the period 2022-2024 using continuous monitoring sensors installed in deep wells. The temporal evolution of the lake forming in the polje was reconstructed using satellite images, allowing to investigate the condition leading to polje flooding. The hydraulic head of the deep borehole and spring discharge were considered, representing the intermediate and final responses signals to precipitation, respectively. The lake reservoir controls groundwater fluctuations and can significantly prolong its high-stand,

influencing spring discharge. While, time series analysis revealed the different responses of the karst system to precipitation in meteorologically wet and dry years.

The insights about the ancient and historical water supply in Campania region is the focus of the fourth topic of this thesis work. Firstly, a critical analysis about the choice of Serino springs as Caput Aquae of Augustan and Sannitico Roman Aqueducts was carried out. The Augustan Aqueduct, built between 33 and 12 BC at the command of Augustus and designed by Marcus Vipsanio Agrippa, stands as one of the most remarkable hydraulic engineering feats of the Roman era. The main route of the aqueduct extends over 100 km, starting from the caput aquae, represented by the Acquaro-Pelosi springs located at the foot of the Terminio karst massif, near the village of Serino (Campania region) and ending at Castellum Aquae, which corresponds to the Piscina Mirabilis in Bacoli, near Naples. Hydrogeological and hydrological features have been analyzed to reconstruct the rationale behind the selection of the aqueduct's water sources: flow rate, ground level, and quality of the karst waters of the Serino springs best met the supply requirements. These characteristics, and others of historical and archaeological nature, suggest that the Augustan Aqueduct had a hydraulic connection with Sannitico Aqueduct, also fed by Serino springs. The Sannitico Aqueduct fed the town of Benevento towards North, and it is believed to have been built in the first century AD. As shown by this study, both aqueduct systems could be part of a unique and great hydraulic system, built in the 1st century BC to supply areas of great residential (cities and patrician villas) or military (Miseno harbor and Benevento) importance.

Secondly, an analysis about the historical evolution of the water supply systems of the city of Benevento (southern Italy) during centuries was carried out. This research focuses on three main historical periods, namely the Roman, Lombard and Papal times, and the recent-present times. During this long historical time, the water supply amount and quality have changed many times, and this has probably affected the well-being and growth of the city. The best water quality characterized the Roman times, when large karst springs were tapped, feeding the town for centuries. In this period, the town experienced the largest population expansion. On the other hand, the most depressed period was the Papal times, coinciding with the isolation of the city, as it was an enclave of the Pontifical State. During this period, the water supply from external sources was not guaranteed and therefore it primarily derived from the local, low-quality water resources. Only after the unification of Italy, and also after the Second World War, the water supply systems have been improved, and new aqueducts have brought again high-quality waters to Benevento coming from karst aquifers. Nowadays, the drinking water

management of Benevento is still a matter of debate. In the near future, the water from a dam-reservoir (Campolattaro dam, Tammaro River) will be exploited to guarantee the water needs of the city, and water-supply systems will undergo further changes.

Chapter 1: Geological, Climatic and Hydrogeological

setting of the study areas

Study area of this thesis encompasses the internal areas of Campania Region, Southern Italy (Fig. 1.1). The research is focused on the study of the hydrogeological features of three karst massifs: Alburni, Northern Picentini and Morcone Mountains, located in the north-eastern, central, and southern part of Campania Region, respectively. Also, the strategic alluvial aquifer of Benevento Plain, located in the center part of Campania region and the area where the homonymous city is located, was studied (red squares in Fig. 1.1).



Figure 1.1. Satellite image with location of study areas in Campania region. The grey line shows the borders of the regions in southern Italy (source: Google Earth; <https://www.google.it/intl/it/earth/index.html>).

1.1.Regional Geological framework

The Campanian Apennine, located inside the homonymous region of southern Italy, is a part of the wider orogenic system of southern Apennines (Vitale and Ciarcia, 2018). The orogenic structure of these reliefs (Fig. 1.2) is defined as a fold-and-thrust belt constituted by the tectonic superposition of several thrust sheets made up of Meso-Cenozoic deep basin to shallow-water successions. They are dissected by several Quaternary structural depressions, especially along the Tyrrhenian sea side (Vitale and Ciarcia, 2013).

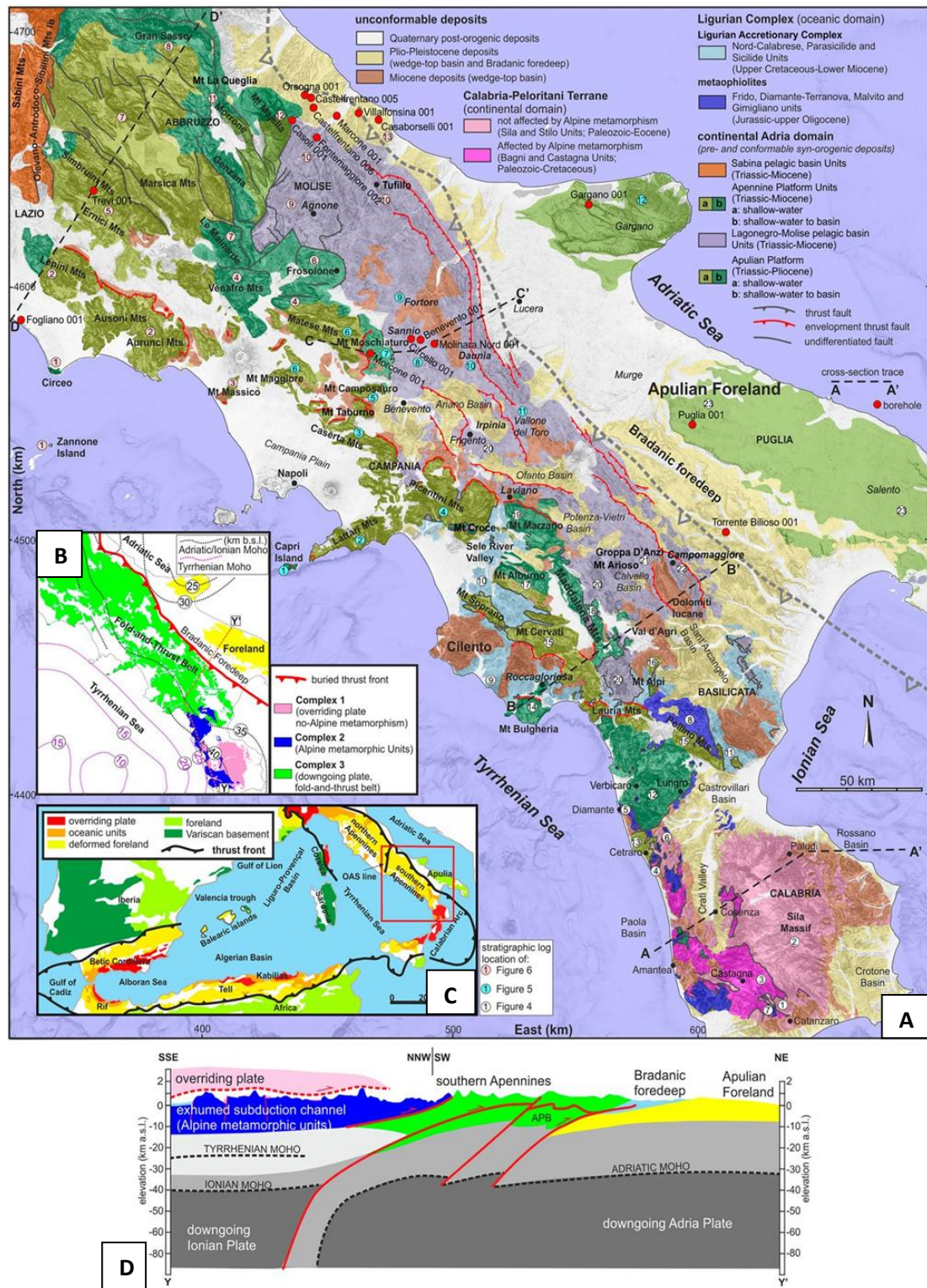


Figure 1.2. Geological framework of northern Calabria-southern Apennines system (from Ciarcia and Vitale, 2024): (A) Geological map of the northern Calabria-southern Apennines system (modified after Vitale and Ciarcia, 2022); (B) Tectonic sketch of western-central Mediterranean alpine belts (modified after Vitale et al., 2015); (C) Map of the orogenic complexes; (D) Schematic lithospheric cross-sections through northern Calabria, Southern Apennines and Apulian Foreland (trace Y-Y' is shown in Fig. 1C).

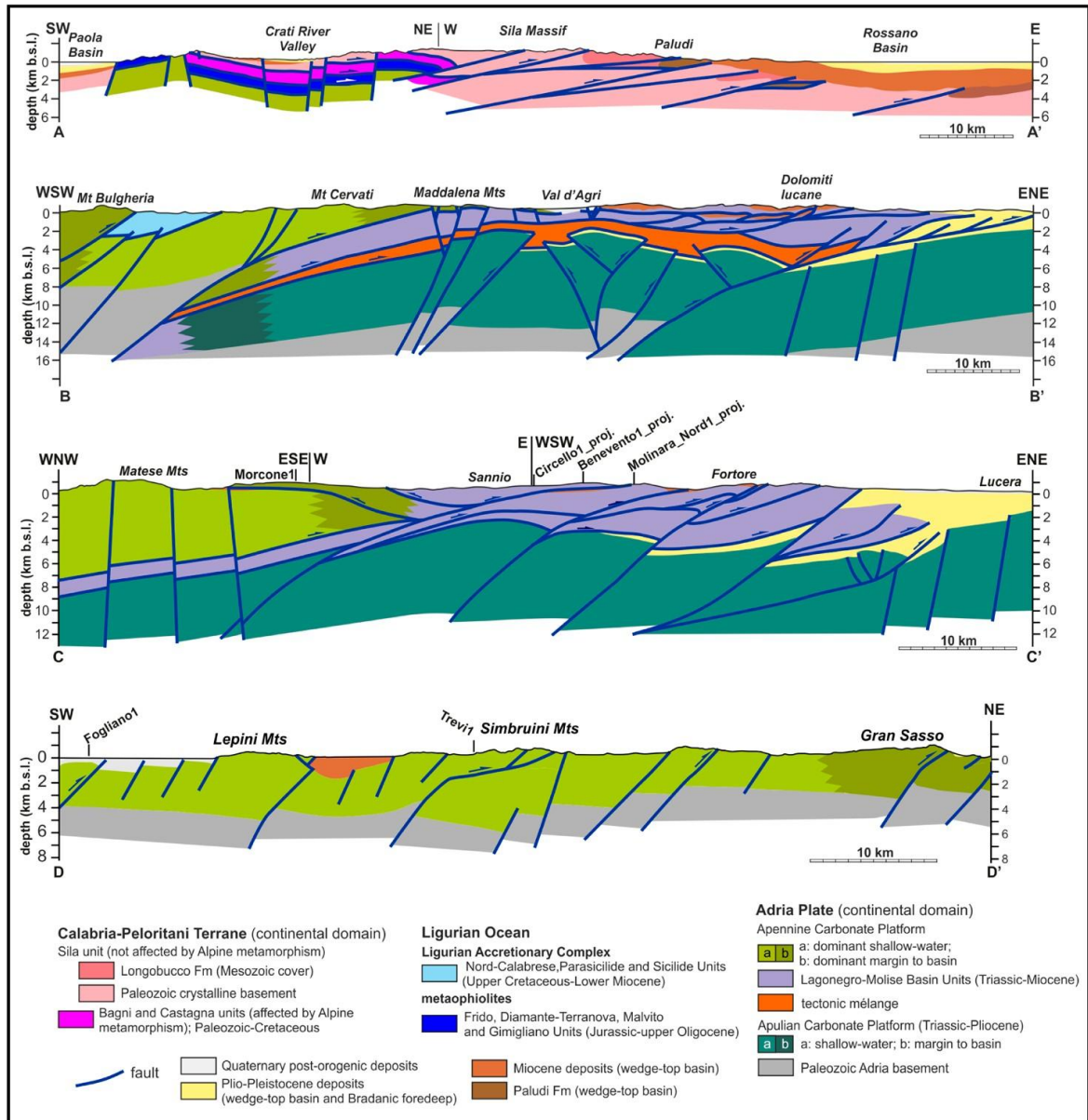


Figure 1.3. Geologic cross-sections A–A' (modified after Vitale et al., 2019), B–B' (slightly modified after Mazzoli et al., 2013), C–C' (slightly modified after Vitale and Ciarcia, 2018), and D–D' (modified after Tozer et al., 2002).

The shallow crustal structure (Fig. 1.3; cross sections B–B' and C–C') is dominated by low-angle thrusts between three main tectonic complexes represented by (Ciarcia and Vitale, 2024): (i) Ligurian Accretionary Complex (Fig. 1.2A); (ii) Apennine Carbonate Platform/slope successions; (iii) Thrust sheets of the pelagic Lagonegro-Molise Basin successions (Mostardini and Merlini, 1986). In the study area, the tectonic pile is unconformably covered by Mio-Pliocene wedge-top basin deposits and Quaternary post-orogenic and volcanics sediments. The Ligurian Accretionary Complex occupies the highest tectonic positions, covering the Apennine Carbonate Platform Units, in turn overthrusting the Lagonegro-Molise Basin units. In depth, the crustal structure is characterized by high-angle faults affecting the buried Apulian Platform

and the allochthonous wedge (Fig. 1.3.; cross sections B-B' and C-C'; [Ciarcia and Vitale, 2024](#)). Also, the Apulian Platform represents the foreland outcropping in Apulia region, outside the borders of Campania region ([Vitale and Ciarcia, 2018](#)).

1.1.1. Paleogeography and evolution

The pre-orogenic paleogeography of the western-central Mediterranean area (latest Cretaceous-Paleogene; Fig. 1.4A) shows the Ligurian Ocean separating the continental sector of the European plate, which includes the Calabria-Peloritani terrane and the Sardinia-Corsica block, from the Africa-Adria plate. During this period, the Alps were forming from the subduction of the oceanic part of the European plate (Piemont Ocean) beneath the continental part of the Adria plate ([Handy et al., 2010](#)). In contrast, the southern part of the continental Adria plate and the northern sector of the Africa plate were undergoing crustal stretching, interpreted as the result of a rifting stage ([Vitale and Ciarcia, 2022](#)) or a far-field stress state associated with the orogenic processes that involved the northern edge of Adria plate ([Agosta et al., 2021](#)).

The Ligurian and Ionian Oceans were separated by a strip joining the continental part of the Adria and Africa plates (Fig. 1.4A). During Cretaceous, the continental bridge joining the two plates allowed dinosaurs to migrate between the two sectors ([Zarcone et al., 2010](#)). Later, in the latest Cretaceous, the emerged/shallow-water area partially drowned, resulting in the complete separation of the Apennine (Adria domain) and Panormide (Africa domains) Platforms ([Vitale and Ciarcia, 2022](#)).

Focusing on the Apennine Platform/Lagonegro-Molise Basin/Apulian Platform area, the Apennine-Apulian Platform system was isolated, surrounded by pelagic basins, including the Lagonegro-Molise Basin to the south, the Ligurian Ocean to west, the Umbria-Marche Basin to the north, and, finally, the Adriatic basin to East (Fig. 1.4B; [Ciarcia and Vitale, 2024](#)). The Apulian Platform hosts a NW-SE-elongated basin where pelagic sediments were deposited as shown in borehole reconstructions ([Patacca and Scandone, 2014](#)).

Southern Apennines are the results of the subduction of the Neo-Tethys oceanic lithosphere beneath the Europa/AlKaPeCa plates (Fig. 1.5; [Vitale and Ciarcia, 2013](#)) with the E-migration of the thrust front, as consequence of the down-going slab-retreat ([Malinverno and Ryan, 1986](#)).

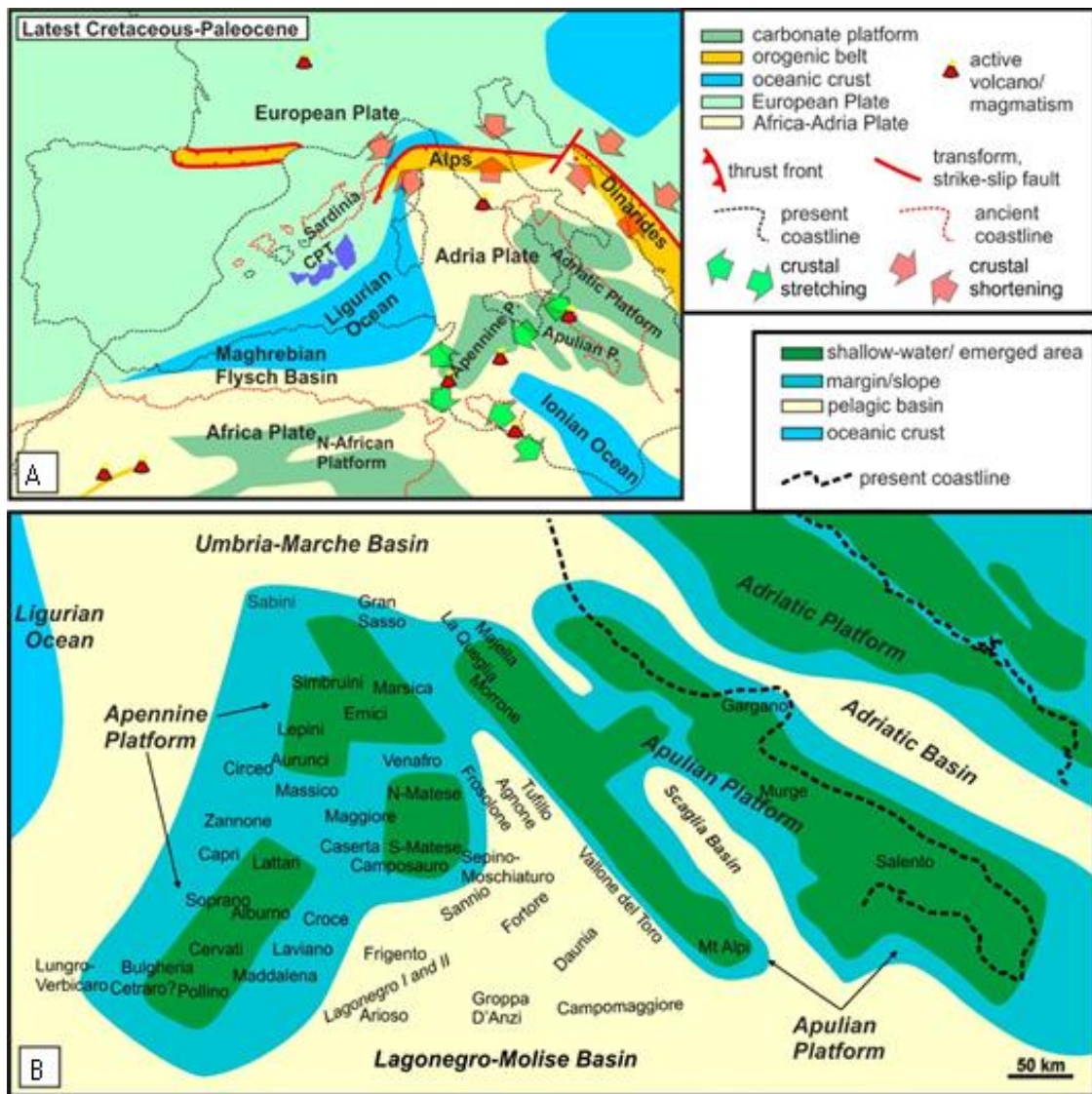


Figure 1.4. Latest Cretaceous–Paleocene paleogeographic maps (Ciarcia and Vitale, 2024): (A) western-central Mediterranean area (modified after Vitale and Ciarcia, 2013) and (B) close-up of the Apennine Platform/Lagonegro-Molise Basin/Apulian Platform area (modified after Vitale and Ciarcia, 2022).

During Paleocene/Eocene the subduction started (Rossetti et al., 2001) with different paroxysmal tectonic stages caused the opening of Ligurian-Provençal and Tyrrhenian back-arc basins (Milia et al., 2017). In the Aquitanian-Burdigalian interval, the orogenic pulses formed an incipient orogenic prism made up of oceanic to transitional successions. Subsequently, the thrust front eastward migrated, involving younger and younger foredeep basin deposits covering the margin of the Adria plate. The Mio-Pliocene orogenic evolution was marked by the sedimentation of thick sequences of turbiditic calci- and siliciclastic deposits both in foredeep and wedge-top basins (Ascione et al., 2012). Their ages constraint and define the temporal sequence of tectonic pulses, including several envelopments thrust faults that presently are the best-preserved compressional structures of the region (Vitale et al., 2017).

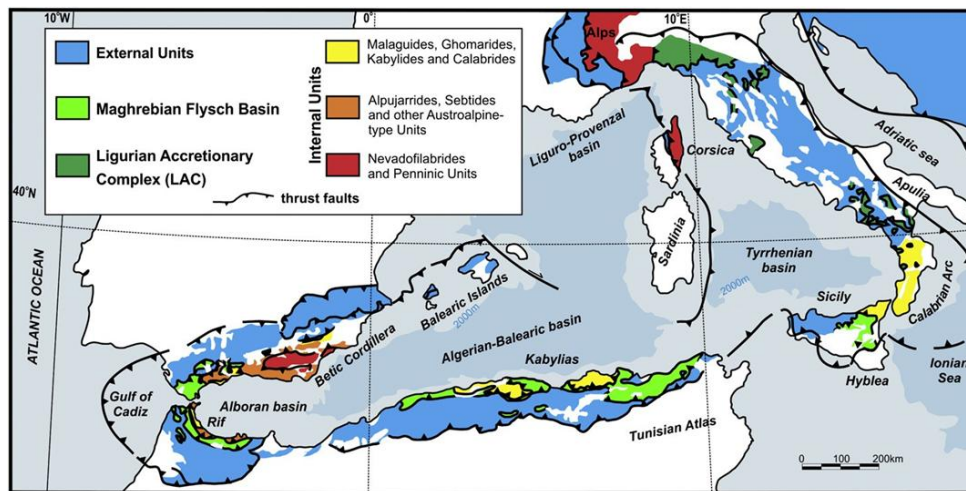


Figure 1.5. Tectonic sketch of western-central Mediterranean orogenic belts (from Vitale and Ciarcia, 2013).

During Pleistocene, extensional tectonics affected the Campanian margin and the western flank of the southern Apennines constituting several basins (Campania Plain, Sele River Plain, Salerno Gulf, Naples Gulf, Vallo di Diano and Auletta Valley; Fig. 1.6) mainly controlled by NW-SE and NE-SW normal faults (Ippolito et al., 1973). Here several intramontane depressions were the location of thick lacustrine-marine deposits, often alternating and covered by volcanic rocks, especially in the Late Pleistocene-Holocene.

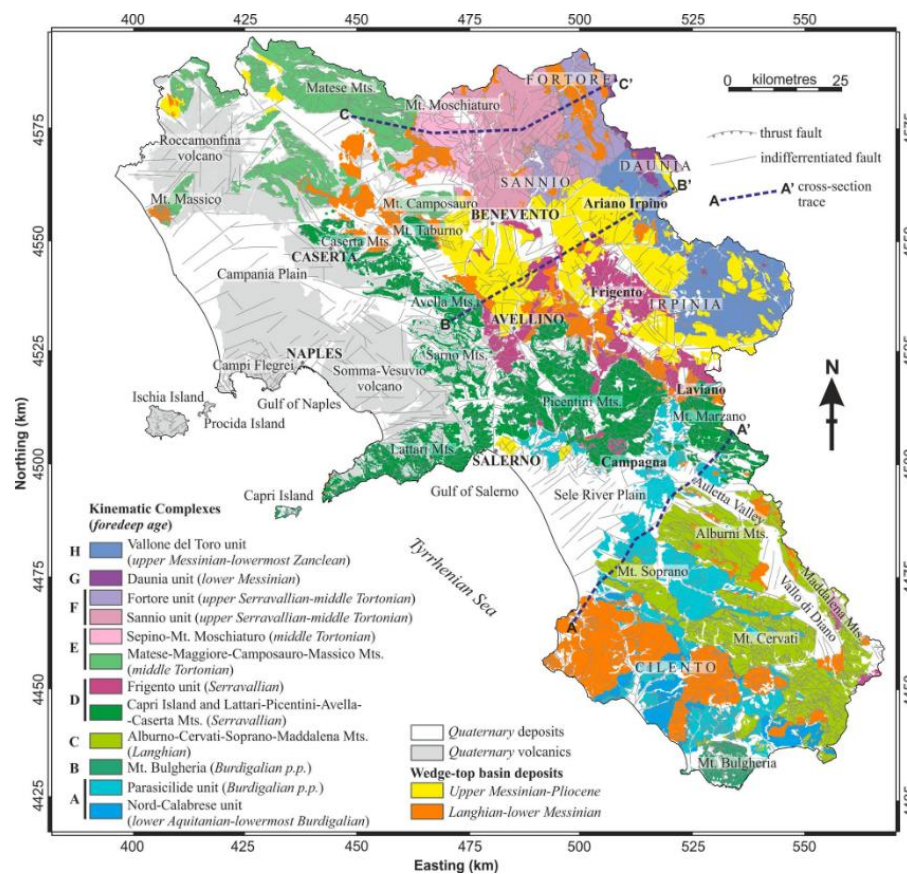


Figure 1.6. Kinematic complexes map of Campania Region (from Vitale and Ciarcia, 2018).

1.1.2.Stratigraphy

In southern Apennines several stratigraphic-structural units were recognized (D'Argenio et al., 1973). These are limited, at the bottom, by regional thrusts. Sometimes, they are cut by further tectonic surfaces separating in several other tectonic units. On these, in angular discordance, sedimentary successions due to the filling of Neogene tectonic intra-chain basins, developed. The stratigraphy of the tectonic units outcropping in Campania region are shown in figure 1.7 from Vitale and Ciarcia (2018).

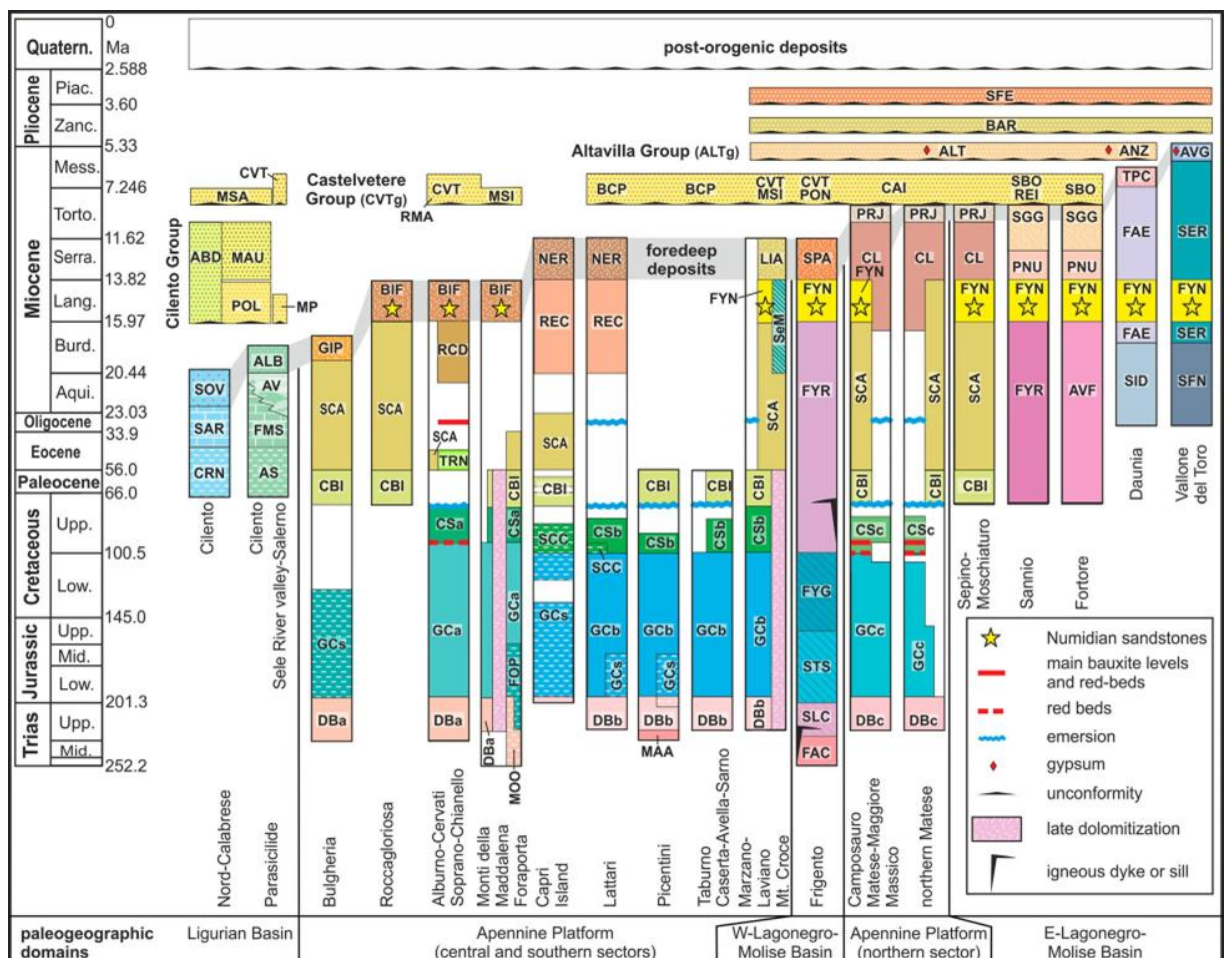


Figure 1.7. Stratigraphic chart showing the sedimentary successions exposed in the Campania region (from Vitale and Ciarcia, 2018). The acronyms in the figure are listed in the text.

Ligurian Accretionary Complex domain

The Internal units are represented by pelitic and arenitic dominant component silici-clastic and calci-clastic deposits, constituting Ligurian Accretionary Complex. During the lower Miocene, these unites were the first involved in the orogenic transport. In Campania region, the internal units include the deep basin successions of *Nord-Calabrese* and *Parasicilide* Units, cropping out extensively in the southern sector of the Campania region (Fig. 1.6).

Materials and methods

Nord Calabrese Unit, at least 1200 meters thick, is constituted by three formations: (i) *Crete Nere Formation* (uppermost Cretaceous-Middle Eocene); (ii) *Saraceno Formation* (upper Eocene-lowermost Aquitanian); (iii) *Sovereto Formation* (lower Aquitanian-lowermost Burdigalian).

Apennine Platform domain

In Campanian Apennine, Mesozoic Carbonatic successions are mainly represented by basal dolomitic terms evolving, changing, to mainly calcareous. The lower part of series, dolomitic member of Triassic age, is followed by Jurassic age limestone members showing several intervals with biostratigraphic markers (mollusks, algae, and foraminifers). The Apennine platform domain is divided in three sectors: (i) Southern comprising Mt. Bulgheria and Roccagloriosa, Alburno, Cervati and Soprano Mts., Maddalena-Foraporta Mts successions; (ii) Central comprising Capri island, Lattari, Picentini, Marzano, Sarno-Avella, and Caserta Mts., Laviano and Mt. Croce successions; (iii) Northern comprising Camposauro, Matese, Maggiore and Massico Mts successions.

Lagonegro-Molise Basin domain

Pre-orogenic successions of Mesozoic-Tertiary age developed on Apulian continental rim belong to Lagonegro-Molise Basin domain and its borders. In Campanian Apennine, Lagonegro Basin terrains discontinuously outcropping (Vallo di Diano, Picentini Mts., Irpinia, Sannio, etc.; Fig. 1.6) of distal proximal environment. They are constituted by a sedimentary succession, spanning from Triassic to middle Miocene, evolving from epicontinental/rifting basin to a batial setting, subsequently highlighting proximal depositional basin and slope base features. The main units outcropping in Campania region are: Frigento, Sepino-Moschiatturo Mt., Sannio, Fortore, Daunia, Vallone del Toro units.

Wedge-top deposits

Several unconformable sedimentary cycles of Miocene-Pliocene deposits occur above the allochthonous prism (wedge-top or piggy back basins), frequently sealing the tectonic contacts between the different thrust sheets (Bonardi et al., 2009). Generally, these calciclastic deposits show sharp lateral and vertical facies variations including olistoliths and olistostromes. Five main cycles are defined: (i) Cilento Group; (ii) Castelvetero Group; (iii) Altavilla Group; (iv) Baronina Formation; (v) Sferracavallo Formation.

Pleistocene-Recent deposits

Several Pleistocene intramontane and coastal structural depressions were formed as following the complex tectonic evolution of the eastern Tyrrhenian Sea side and Campania region (Santangelo et al., 2017 and references therein). These basins were filled by marine, lacustrine, fluvial and volcanic sediments. In Campanian and Garigliano River Plain, sediments alternate with volcanic rocks produced by Roccamonfina, before, and Campi Flegrei (Sbrana et al., 2021) and Somma-Vesuvio (Sbrana et al., 2020), after. The Pleistocene-Recent volcanic activity formed thick piles of pyroclastic and fallout deposits as well as volcanic edifices and calderas. The oldest exposed post-orogenic volcanic rocks are related to the activity of Roccamonfina volcano (630-50 ka; De Rita and Giordano, 1996). The subsequent volcanic activity was characterized by different localizations of the eruptive vents: Ischia Island (150 ka – 1302 AD; Melluso et al., 2014 and references therein), Campi Flegrei and Procida Island (80 ka – 1538 AD; Sbrana et al., 2021) and finally Somma-Vesuvio volcano which activity started ca. 39 ka up to the last eruption of the 1944 AD (Sbrana et al., 2020).

1.2. Hydrogeological setting

The central-southern Apennines are characterized by wide carbonate ridges (Fig. 1.8) representing the main aquifers (Celico, 1978; Celico, 1983). These aquifers are drained at their borders where low-permeability deposits outcrop by large flow spring with steady regime (Fiorillo et al., 2015a). These latter are constituted by synorogenic siliclastic sediments or by Plio-Quaternary deposits (alluvial, lacustrine, detrital origin) which constitute the filling of the intra-montane plains or river valleys. The siliclastic sediments (identified as no-flow boundaries) act as real aquicludes. Continental deposits correspond to multilayer aquifer/aquitard systems which can allow the spring flow or the seepage through the more permeable layers (e.g. gravel, sand, and travertines). Downthrown the carbonates can host deeper groundwater flow in confined aquifers causing locally artesian conditions (Fiorillo et al., 2018).

In Campania region also, karst aquifers represent the main water sources with a maximum spring discharge value of about 8.5 m³/s (Sarno Spring Group; Fig. 1.8), alternating with the huge water resources withdrawal from alluvial plains (Campanian, Sele, Benevento, etc..) and with the volcanic aquifers of Somma-Vesuvio, Phlegrean Fields, and Roccamonfina structures (De Vita et al., 2018).

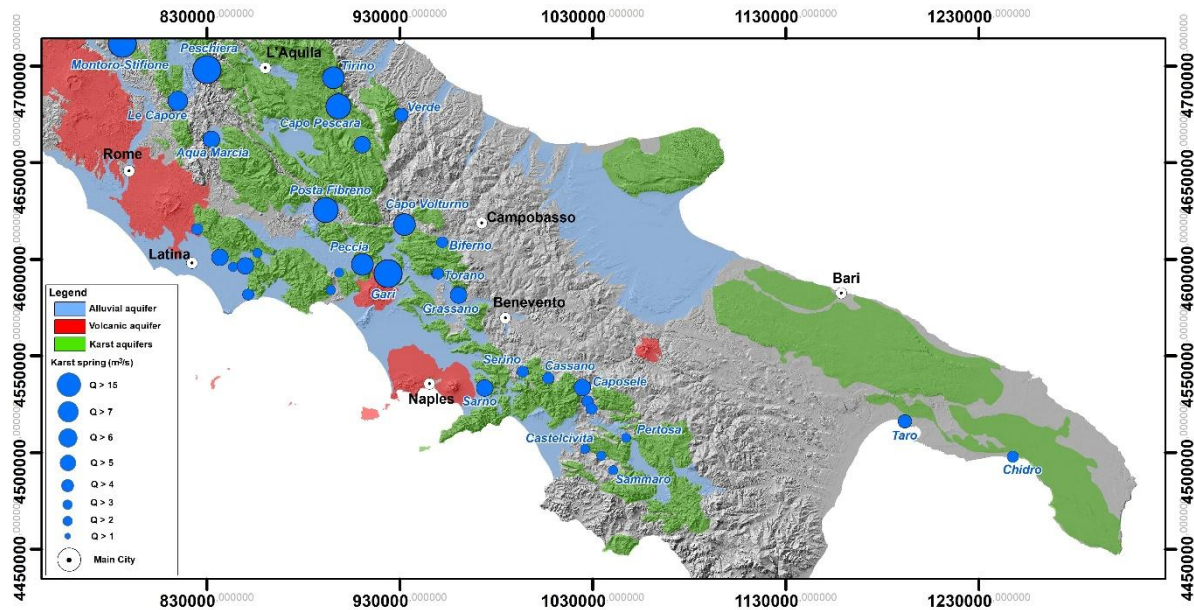


Figure 1.8. Hydrogeological scheme of central-southern Apennine (modified from Fiorillo et al., 2024).

1.2.1. Karst aquifers

Karst aquifers can be considered as very large reservoirs in which the basal groundwater flow is driven and controlled both by geometrical relationships with the adjacent geological units, and by the main inner structural discontinuities. Based on lithology (limestone, alternating of limestone, limestone with chert, marly limestone and subordinately marls, dolomite) the groundwater yield can vary from $3.700 \times 10^6 \text{ m}^3/\text{year}$ (limestone karst aquifers) to $300 \times 10^6 \text{ m}^3/\text{year}$ (dolomitic karst aquifers) (Celico, 1983; Allocca et al., 2007). The main karst aquifers studied (Alburni, Morcone, and northern Picentini Mountain karst massifs) will be described in the following sections.

Alburni karst massif

The Alburni karst massif (Fig. 1.9) is located in Cilento and Vallo di Diano National Park (southern part of Campania region), and occupies an area of 270 km^2 . The mean elevation is of 940 m a.s.l. and maximum is 1742 m a.s.l. The massif is made by a thick Mesozoic carbonate sequence of Jurassic-Cretaceous age, stratigraphically covered by a Miocene flysch sequence consisting of clays and sandstones. Flysch extensively crops out in areas surrounding the massif (Patacca and Scandone, 2007), forming aquicludes bounding karst aquifer. The alluvial deposits, slope breccias, and conglomeratic deposits are exposed in river valleys and at the foot of slopes.

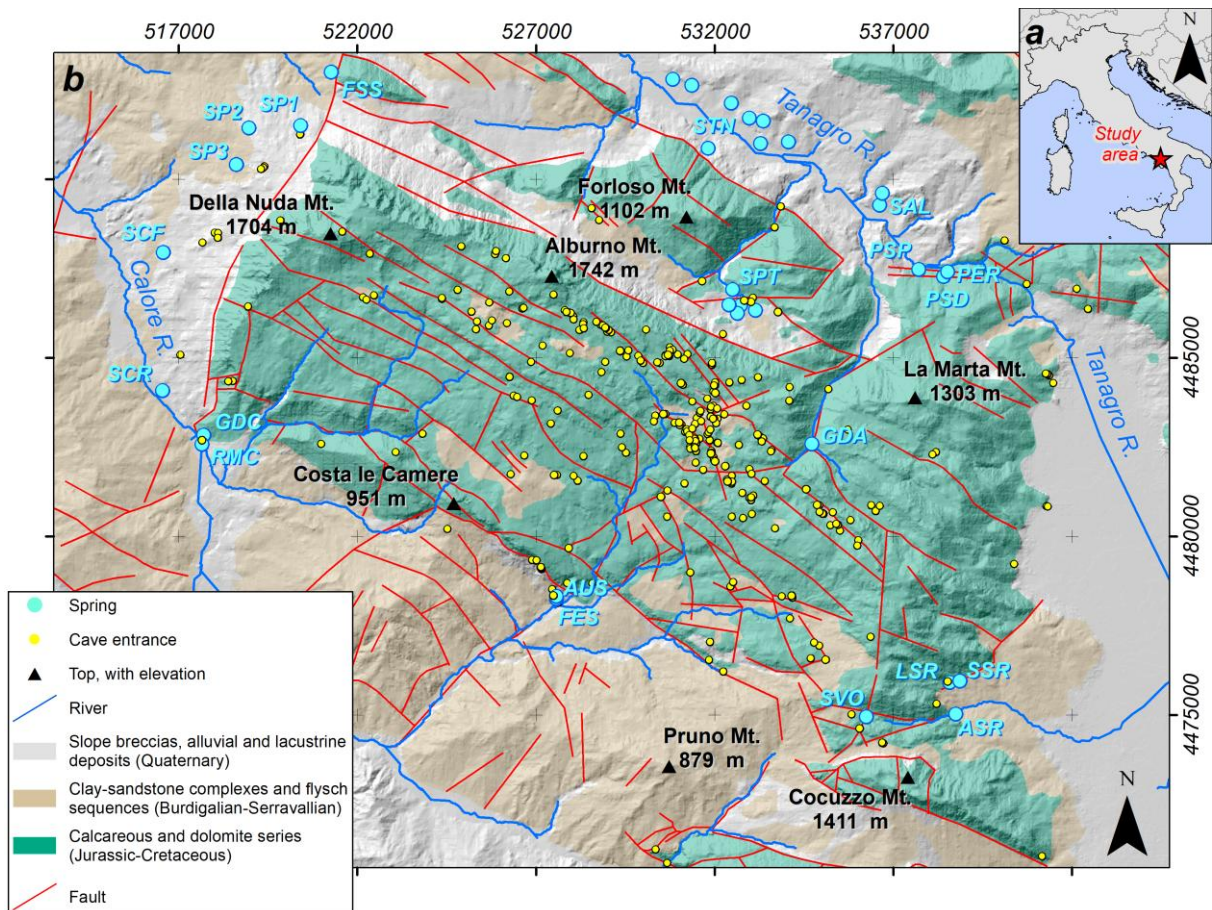


Figure 1.9. (a) Map of the Italian Peninsula and (b) hydrogeological sketch of the Alburni karst massif (from [Esposito et al., 2025a](#)).

The karst massif is well delimited by normal faults located at its boundaries. Faults caused the uplift of the Mesozoic carbonate platform in this Apennine sector, inside the deformed terrain of the chain. The karst massif represents a southwest gently dipping monoclinical structure spilt into several blocks ([Brancaccio et al., 1973](#)), bounded by Calore Lucano River (to the southwest) and Tanagro river (to the northeast). This structure has created a vast karst plateau limited by steep slopes, occupying the summit sector. The broad summit plateau makes the Alburni massif unique compared to other karst massif of central-southern Apennine area.

The climate is Mediterranean. For this area, mean annual precipitation was estimated to be 1470 mm/year ([Pagnozzi et al., 2019](#); [Fiorillo et al., 2022](#)). The maximum monthly precipitation occurs in November and the minimum in July. The temperature regime is almost opposite to that of precipitation: the higher temperature is between July and August while the minimum is in January (Fig. 1.10). Actual evapotranspiration is about one third of the annual precipitation. Because precipitation verifies during the non-hot season, its distribution allows for the highest possible recharge ([Fiorillo, 2009](#)).

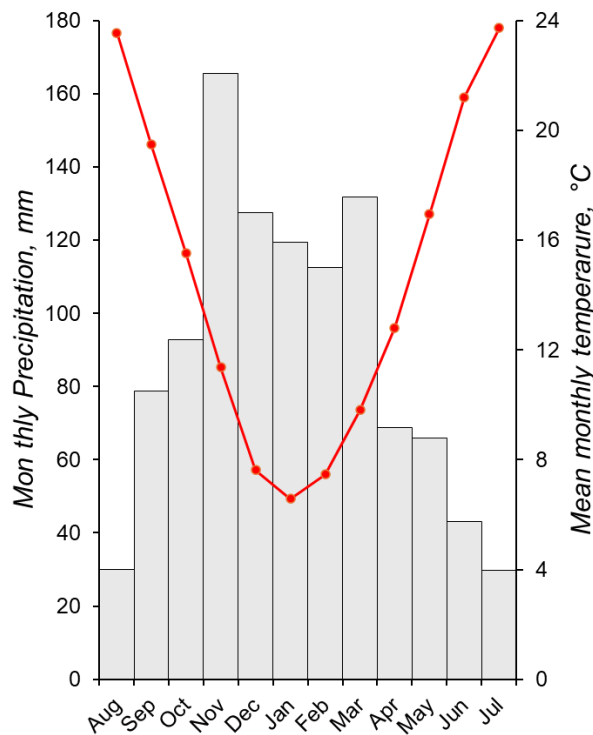


Figure 1.10. Climate features of the Auletta meteorological station located in the study area (2000-2024 period).

The Alburni plateau has been affected by karst dissolution phenomena, forming many dolines, which have transformed this surface into an extended internal runoff area. Ponors and shafts rapidly transfer the surface runoff in the complex network of caves and conduits and, then, to saturated zone (Fig. 1.11). This plateau area, extended about 90 km², provides the 45% of the total mean spring discharge, representing the 34% of the total catchment of the whole karst massif (Fiorillo et al., 2022). About 400 caves, most of them located in the northern-central sector, characterize the massif, with several reaching a depth of around 450 m and developing for some kilometers (Bellucci et al., 1991, 1995). This remarkable karst is essentially related to the presence of the wide, high plateau, bounded by fault systems, and with a variety of infiltration sites, mainly corresponding to blind valleys and small catchments on the flysch deposits, which surface hydrology feeds the many swallets at the contact with the limestone (Santangelo and Santo, 1997).

Alburni karst massif is drained by four groups of springs: (i) Pertosa, (ii) Auso, (iii) Castelvita, and (iv) Tanagro groups. Also, other minor springs represents further discharge of water table (Fig. 1.9). Spring discharges are listed in table 1.1; systematic discharge registrations are lacking and can be found only in spot measurements in literature and technical reports (Celico et al., 1994; Ducci et al., 2008).

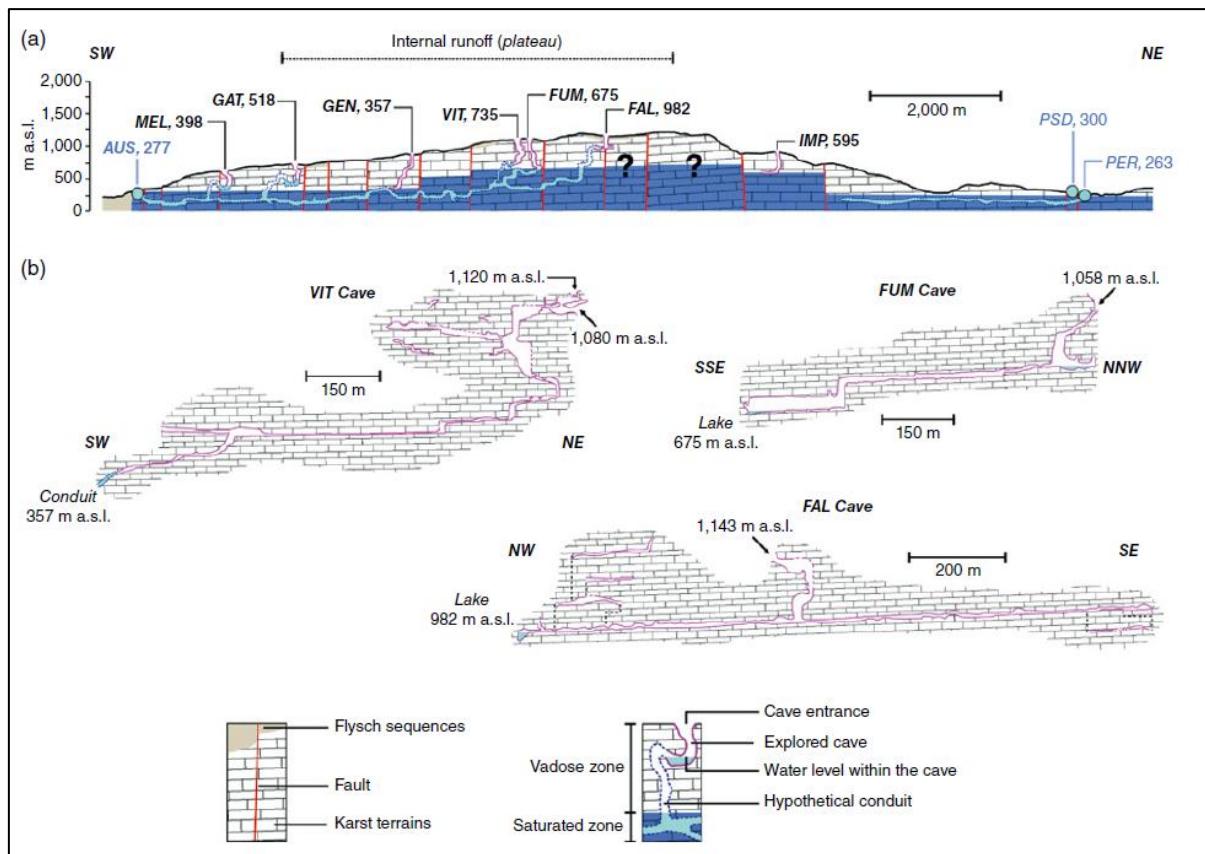


Figure 1.11. Hydrogeological schematic cross section across the Alburni Massif, based upon speleological data from the Regional Inventory of Caves of Campania (Campanian Speleological Federation). Some profiles of selected caves are also shown, after the surveys from Campanian Speleological Federation (modified from <http://www.fscampania.it/catasto-2/catasto/>), with addition of the strata attitude (from Fiorillo et al., 2022).

The Pertosa group (220-260 m a.s.l.) is located in the north-eastern sector and shows a mean discharge of $2.3 \text{ m}^3/\text{s}$. It includes the cave of the same name (Pertosa caves), Polla Santa Domenica spring, and other spring placed along the riverbed (Celico et al., 1994a).

The Auso group (280 m a.s.l.) is located in the southern sector, with a variable discharge from a few L/s to several thousand of L/s (Bellucci et al., 1991; Celico et al., 1994a). A tracer test carried out showed the direct connection among the plateau area with the main spring discharge through a karst conduit. Also, Festola spring, directly linked with Auso spring group, activates when heavy precipitation affects the area reaching maximum discharge values of about $1\text{-}2 \text{ m}^3/\text{s}$ (Bellucci et al., 1991).

The Castelvita group (65-94 m a.s.l.) rises along the Calore riverbed and in the homonymous caves (Grotte di Castelvita), with a discharge between $1 \text{ m}^3/\text{s}$ and $4 \text{ m}^3/\text{s}$ (Santo, 1993). These springs are divided into a southern group, the Mulino springs (63-65 m a.s.l.), and in a northern group, the Castelvita springs (61-65 m a.s.l.; Celico et al., 1994a; Santo, 1993).

Label	Spring name	Spring group	Elevation (m a.s.l.)	Mean discharge (m ³ /s)
PSP	Pertosa		195	1.1
SPT	Petina	Pertosa	647	0.1
PSD	Santa Domenica		243	nd
PER	Pertosa Caves		263	1.1
AUS	Auso Resurgence	Auso	280	1
FES	Festola		280	nd
RMC	Mulino di Castelcivita			
	Resurgence	Castelcivita	65	nd
GDC	Castelcivita Caves		94	1 to 4
STN	Tanagro	Lower Tanagro	204	> 8.5
SCR	Controne		100	0.1
SP1	Postiglione 1		570	0.1
SP2	Postiglione 2		570	0.1
SP3	Postiglione 3		570	0.1
SCF	Cafaro		180	nd
FSS	Fontana Scorzo	Other springs		
	Sicignano		363	0.01
SAL	Auletta		235	nd
LSR	Lavatoio San Rufo		669	0.01
SSR	San Rufo		636	nd
ASR	Abbotituro San Rufo		672	0.01
SVO	Valetorno		848	nd
GDA	Dell'Acqua Caves		875	nd

Table 1.1. Springs of the Alburni karst massif, and related discharge values if available (nd, no data; from [Esposito et al., 2025a](#)); spring location is shown in Figure 1.9.

Materials and methods

The Low Tanagro group represents a preferential drainage belt. Its discharge can exceed 8.5 m³/s (Bellucci et al., 1995). Water comes from the surrounding limestones and directly feeds Tanagro River (Celico et al., 1994a). In particular, Ognà and Marzano karst massif contributes to feed the aquifer with a discharge of 5 m³/s, transferring water through River Bianco alluvial aquifer, and the remain 3.5 m³/s come from the direct supply of Albuni karst massif (Bolognini et al., 1994).

North Picentini Mt. karst massif

The Terminio-Tuoro and Cervialto karst massifs represent the main limestone karst aquifers constituting the northern sector of Picentini Mountain Group, located in the central part of Campania region (Fig. 1.12). These two massifs, divided from the Calore River Valley, are characterized by large ground space between mountain peaks (up to 1806 m a.s.l. and to 1809 m a.s.l. for the Terminio-Tuoro and Cervialto massif, respectively) and by surrounding river valleys (Fiorillo et al., 2015b). The morphology is characterized by high slope angles connected to Quaternary tectonic uplift, which has caused several fault-scarps in the carbonate rocks, actually showing a slope angle around 35-45° (Leone et al., 2020).

These karst massifs are constituted by a series of limestone and limestone-dolomitic rocks of Late Triassic – Miocenic age, showing a thickness varying between 2500 and 3000 m. These series are extremely faulted and crashed and, in the case of Terminio-Tuoro karst massif, Calcaterra et al. (1992) detected more than 500 faults dissecting the massif. Along the northern and eastern sectors, these mountains are tectonically overlapped on terrigenous and impervious deposits, constituting of argillaceous complexes (Paleocene age) and flysch sequences (Miocene age). The Quaternary deposits covering Picentini Mountains are represented by pyroclastic deposits derived from the Somma-Vesuvio activity, constituted by several irregular, ashy pomaceous layers, intercalated with weathered ash deposits, lying on a karst substratum (Fiorillo et al., 2015b). Their thickness is variable: its minimum along steep slopes (few decimeters) and higher in the flat areas. All these deposits have high retention values and play an important role in the process of infiltration of the water into the karst substratum (Fiorillo and Wilson, 2004).

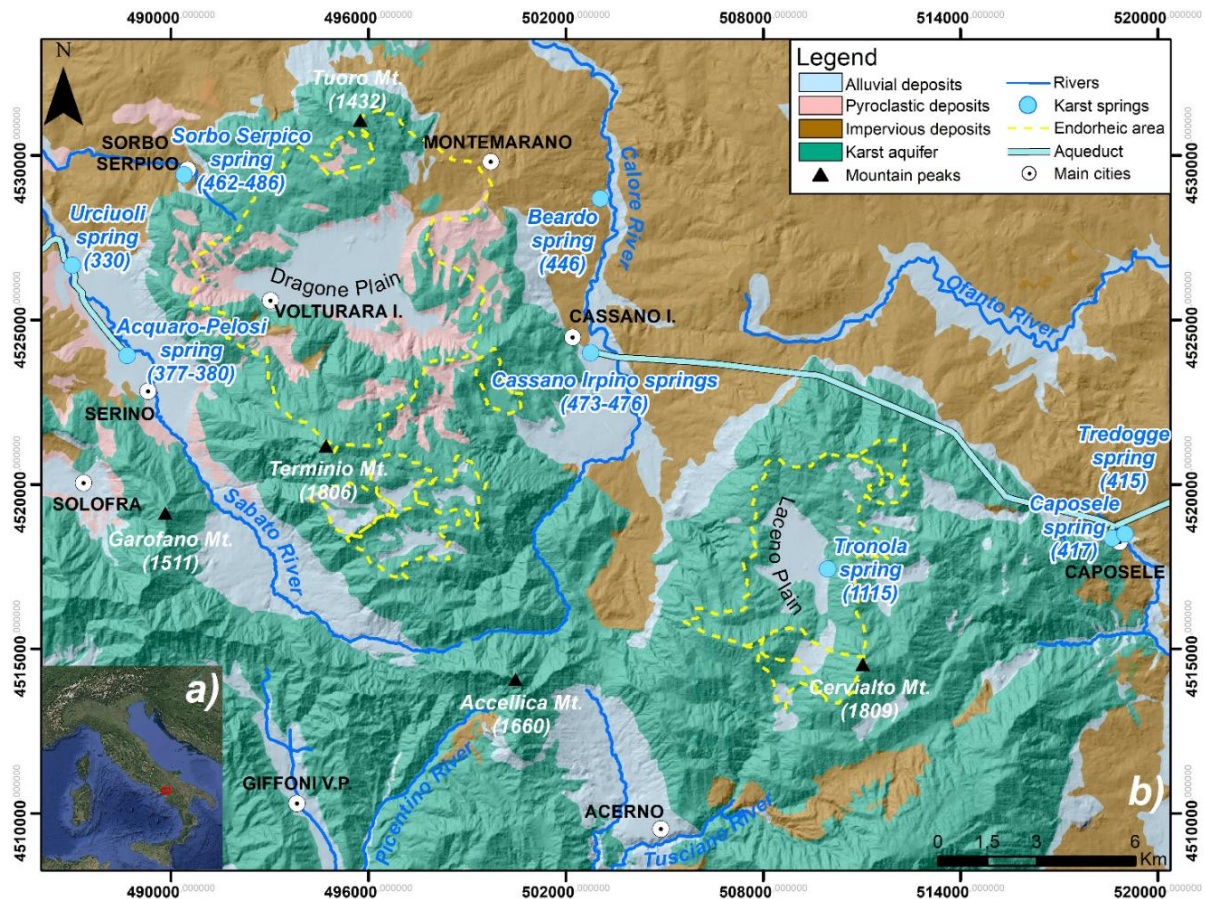


Figure 1.12. (a) Location in Italy of the studied area; (b) Hydrogeological sketch map of the North Picentini Mt. karst massif (modified from [Fiorillo et al., 2021](#)).

The climate is of Mediterranean type, characterized by a dry and warm season and a wet period, spanning from autumn to spring. The monthly precipitation reaches the maximum value during November-December and the minimum in July (Fig. 1.13). A further precipitation peak may occur in March. The temperature and potential evapotranspiration patterns are complete opposite to that of rainfall, showing a maximum in July-August and a minimum in December-February. Because rainfall primarily occurs during the no-warm season, its distribution allows a higher infiltration into the aquifer. Snowfall mainly occurs in December-March, and, subordinately, in April at high altitudes (Fig. 1.13). Generally, the snow mantle lasts from January to March and can be considered completely melted between the end of March and the beginning of April.

Hydrogeologically, limestone and limestone-dolomitic rocks forming these massifs are characterized by very high permeability, due to karst and fracturing. Tectonic framework has a pivotal role in groundwater flow. In Terminio-Tuoro karst massif, groundwater flow is through karst conduit and fissures ([Civita, 1969](#)) controlled by faults. Some Authors ([Celico, 1978](#);

(Aquino et al., 2006), based on faults trends, distinguished four different sectors feeding the main basal spring groups (Tab. 1.3). In Cervialto massif, also, the high density of faults and the heavy fractured rock allow the presence of a diffuse flow path, allowing to define a porous-equivalent karst aquifer (Pagnozzi et al., 2020).

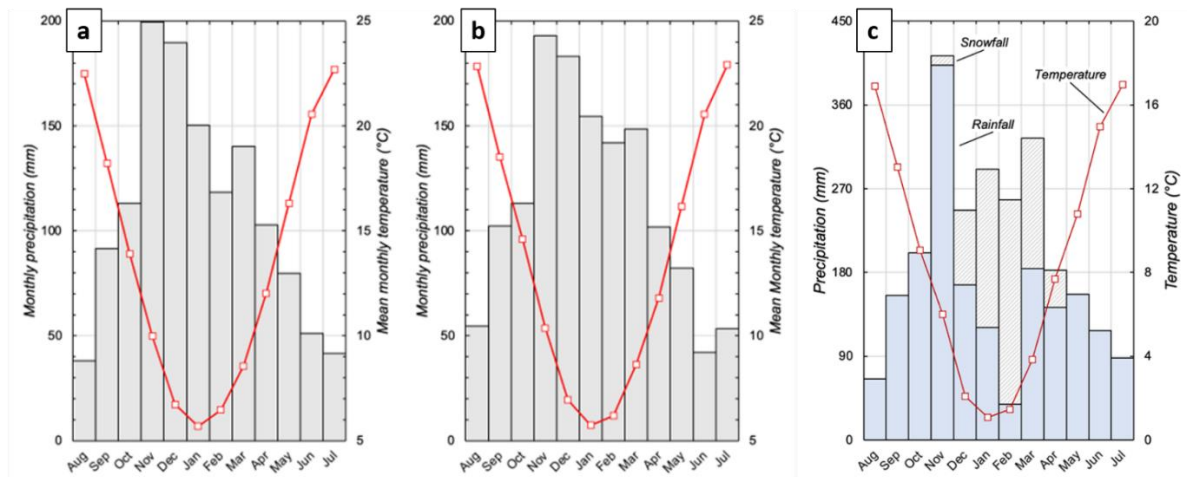


Figure 1.13. Monthly precipitation and mean monthly air temperature at (a) Serino (327 m a.s.l.), (b) Caposele (428 m a.s.l.) (period 1993-2022), and (c) Piano Laceno (period 2008-2020) meteorological stations. Precipitation data for Piano Laceno stations were provided by Acquedotto Pugliese Company. Monthly snowfall amounts are provided by snow-forecast.com (modified from Fiorillo et al., 2021).

The main springs draining Terminio-Tuoro karst massif are (Fig. 1.12; Tab. 1.2): (i) Serino spring Group; (ii) Cassano Irpino spring Group; (iii) Sorbo Serpico Spring Group; (iv) Beardo spring. The main hydrogeochemical facies of the water can be classified as bicarbonate-calcic facies. The water quality is classified as very good (Aquino et al., 2006).

The Serino spring Group, located on the north-western side of the massif, in the alluvial plain of Sabato River is constituted by two springs Acquaro-Pelosi (or high springs, 377-380 m a.s.l.) and Urciuoli (or lower springs, 330 m a.s.l.) springs. Despite a first hypothesis that concerned about a feeding mechanism through the detrital deposits between the karst massif and the alluvial plain (Civita, 1969), these springs are clearly fed by an upwelling water flux (Fig. 1.14; Fiorillo et al., 2018). In detail, the main water supply of these springs is provided by an upwelling flux coming from the limestone bedrock located under the younger quaternary alluvial deposits. This mechanism is confirmed by hydraulic head measurements carried out in ten piezometers located in Acquaro-Pelosi spring area showing an increasing value as the depth increases. Other studies demonstrated that this condition was found in other karst aquifers springs of Campania region (Fiorillo et al., 2019). The spring hydrograph (Fig. 1.15) is

Materials and methods

smoothed, showing the prevalence of a base flow. Also, the presence of some peaks in the hydrographs, especially in Urciuoli spring hydrograph, highlights a component of quick flow (Fiorillo et al., 2007).

Karst massif	Springs	Spring group	Elevation (m a.s.l.)	Discharge (m ³ /s)	Temperature (°C)	pH	EC (μS/cm)	Dh (°F)
Terminio-Tuoro	Acquaro and Pelosi	Serino	377-380	2.2	11	7.3	370	21.2
	Urciuoli		330		n.a.	n.a.	n.a.	n.a.
					11	7.2	370	19.8
	Bagno della Regina	Cassano	473-476	2.65	10	7.6	335	14.8
	Peschiera				n.a.	n.a.	n.a.	n.a.
	Pollentina				10	7.7	351	17.6
	Prete				n.a.	n.a.	n.a.	n.a.
	Lagno	Sorbo Serpico	486	0.43	n.a.	n.a.	n.a.	n.a.
	Sauceto-Titomanlio		462		11	7.2	390	18.3
	Beardo		446		13	7.4	386	17.5
Cervialto	Caposele		420	3.96	9	7.9	300	19
	Tredogge		415	0.07	n.a.	n.a.	n.a.	n.a.
	Tronola		1115	0.02	n.a.	n.a.	n.a.	n.a.

Table 1.2. Main springs of northern Picentini Mountains karst aquifers (data from Fiorillo et al., 2021; Leone et al., 2020; Fiorillo, 2009; Aquino et al., 2006). n.a. means not available.

These springs were tapped since Roman Times for the water supply of Benevento city (Esposito et al., 2024) and Neapolitan area (Esposito et al., 2025b). Currently, the springs, re-tapped by Acqua Bene Comune Aqueduct Company in 1888 (Urciuoli) and in 1937 (Acquaro-Pelosi), together with Matese massif karst springs (Torano, Mareto, and Biferno), feed the Neapolitan area (Celico, 1982; Leone et al., 2023).

The Cassano Irpino spring Group, located along the eastern border of the massif, inside the Calore River basin, is constituted by Bagno della Regina, Pollentina, Prete and Peschiera springs (Fig. 1.12). The spring hydrograph (Fig. 1.16) has mainly a base flow component (smoothed shape), with a few or absent quick flow component (presence of peaks) (Fiorillo, 2009). These springs were tapped in 1965 by Acquedotto Pugliese Aqueduct Company for the water supply of Apulia region.

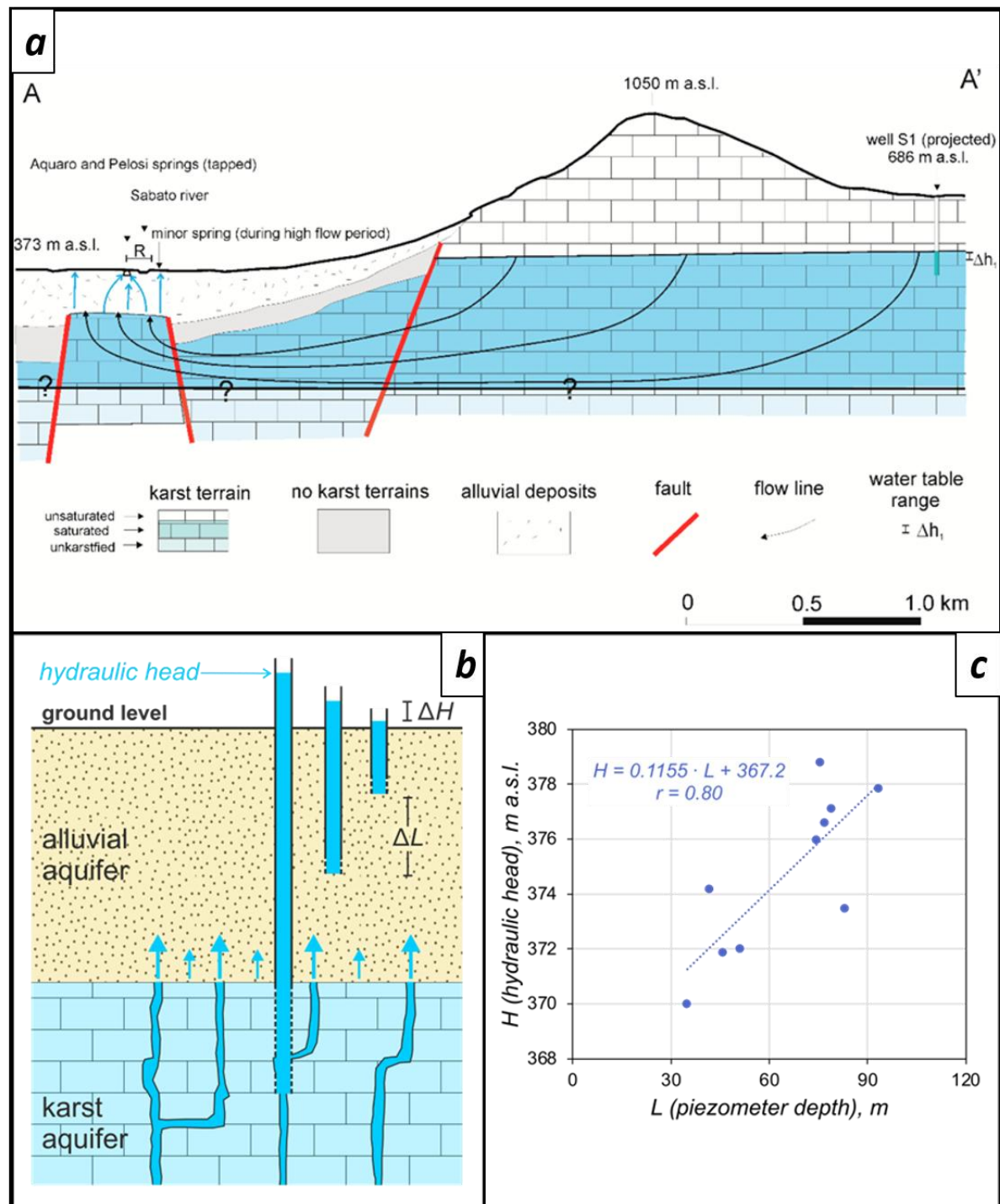


Figure 1.14. Upwelling water flux feeding Serino springs. (a) Cross section; (b) Ascendant flux connected to artesian conditions of karst aquifer covered by alluvial deposits. Measured hydraulic head is higher into the deeper piezometers. (c) Correlation between measured hydraulic head (mean values, period 1963-2004) and depth of piezometers (Fiorillo et al., 2018-modified).

Other minor outlets of massif are Sorbo Serpico Group (Nicotera, 1959), constituted by Sauceto and Titomanlio springs, and Beardo spring (Tab. 1.2). This latter is a particular spring, emerged during the drilling of a tunnel for electric purposes (Nicotera and Aquino, 1995). Both these springs are tapped by Alto Calore Aqueduct Company for the water supply of the Avellino Province municipalities (Aquino et al., 2006).

The main discharge of Cervialto karst massif is represented by Caposele spring, locally known as Sanità di Caposele, situated in the village of Caposele at the head of Sele River (Fig. 1.12 and Tab. 1.2; Celico and Civita, 1976). Like the springs of Serino group, also Caposele spring is fed by an upwelling flux coming from the buried karst bedrock. This feature was highlighted by a numerical model simulation performed by Pagnozzi et al. (2020). The hydrograph shape is smooth, with absence of peaks (quick flow), indicating that the groundwater flow is controlled by small karst fissures and occurs in a laminar regime (*diffuse flow*; Fiorillo et al., 2021; Leone et al., 2020). The period of high flow occurs in spring or summer season, after a time lag with regard to the rainy season, and is connected to a long period of antecedent cumulative rainfall.

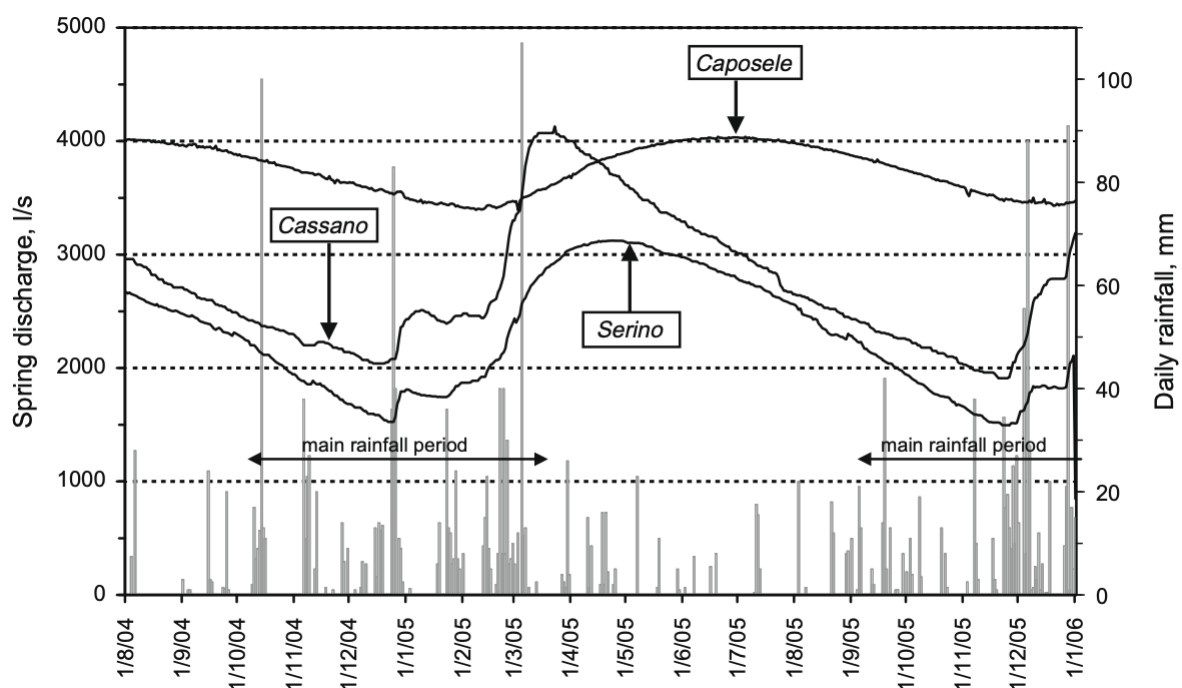


Figure 1.15 Daily rainfall (Serino rain gauge) and daily discharge of Terminio-Tuoro and Cervialto springs for 1 August 2004 to 1 January 2006 (from Fiorillo 2009).

All spring discharges (Serino, Cassano Irpino Groups, and Caposele) reached their maximum value following the Irpinian earthquake of 23th November 1980 ($M_s = 6.9$). This event caused

an anomalous increase of spring discharge (Celico, 1981) with maximum values of 7.32 m³/s (19th January 1981), 5.5 m³/s (18 January 1981) and 3.6 m³/s (18 January 1981), observed for Caposele, Cassano Irpino, and Serino springs respectively (Cotecchia and Salvemini, 1981). The spring was tapped in 1906 by Acquedotto Pugliese Company, one of the main Italian aqueduct systems, which passes the Sele-Ofanto watershed via a tunnel (Pavoncelli tunnel; Fig. 1.12) and supplies the Apulia region. The gravity tunnel has a total length of about 400 Km joining Cassano Irpino and Caposele springs with the village of Santa Maria di Leuca. Other minor outlets of the spring are represented by Tredogge and Tronola springs (Tab. 1.2; Aquino et al., 2006).

Wide endorheic areas characterize these mountains (Fig. 1.12) having an important role in recharge processes (Fiorillo et al., 2015b; Pagnozzi et al., 2019). These areas developed after the Plio-Pleistocene tectonic activity due to the rising of Apennine chain and its following evolution to continental environment (Pleistocene-Holocene), when karst processes transformed depressed areas in endorheic ones (Leone et al., 2023).

The Cervialto massif is characterized by several endorheic areas, the largest is Piano Laceno endorheic area (20.5 km²). Here, a sinking small lake exists, which increases in size during the winter-spring period. As the Caposele spring can be considered the only spring draining the Cervialto massifs, this endoreic area constitutes the entire recharge area of this spring. Because of local cave system (*Grotta del Caliendo*), located in the western side of Piano Laceno, a limited amount of groundwater is drained outside of the endorheic area and runs off in the Calore River. The endorheic area recharge is estimated in 32.9 m³/year, equal to the 34.3% of the recharge of the overall karst massif (Fiorillo et al., 2015b).

The main endorheic area of Terminio-Tuoro karst massif is the Dragone Plain polje (55.1 km²), located in the northern part of the massif (Fig. 1.12 and 1.16; Aquino and Giulivo, 2002). The Dragone Plain, with an area of 12 km² (Fig. 1.17), represents the main discharge of the river flows of the streams that drains the reliefs bordering the plain (Pasquale, 1916). The internal runoff waters are drained in a ponor, named *Bocca del Dragone* (Dragone Mouth, 674 m a.s.l.), located in the southern part of the plain at the foot of Costa Mountain, 1.3 km far from Volturara city center (Di Meo, 1932). The ponor, originally constituted by three shafts, was originated after the 1456 earthquake with the drainage of water forming the lake in the endorheic area until that time (Celico and Russo, 1981). Different measurements carried out on the ponor allow to estimate a drainage capacity equal to 0.54 m³/s (Aquino and Giulivo, 2002). Following the

several floods of the 19th and 20th centuries, several remediation measurements were proposed with the realization of the current existing hydraulic works. The main focus of the works was the opening and stabilization of ponor walls and the regimentation of the rivers that cut through the plain (Aquino et al., 2019). Following the 23th November 1980 earthquake, there was a new absorption of water that constituted the seasonally lake in the plain. From that moment, water accumulates in the plain only following plentiful rainfall.

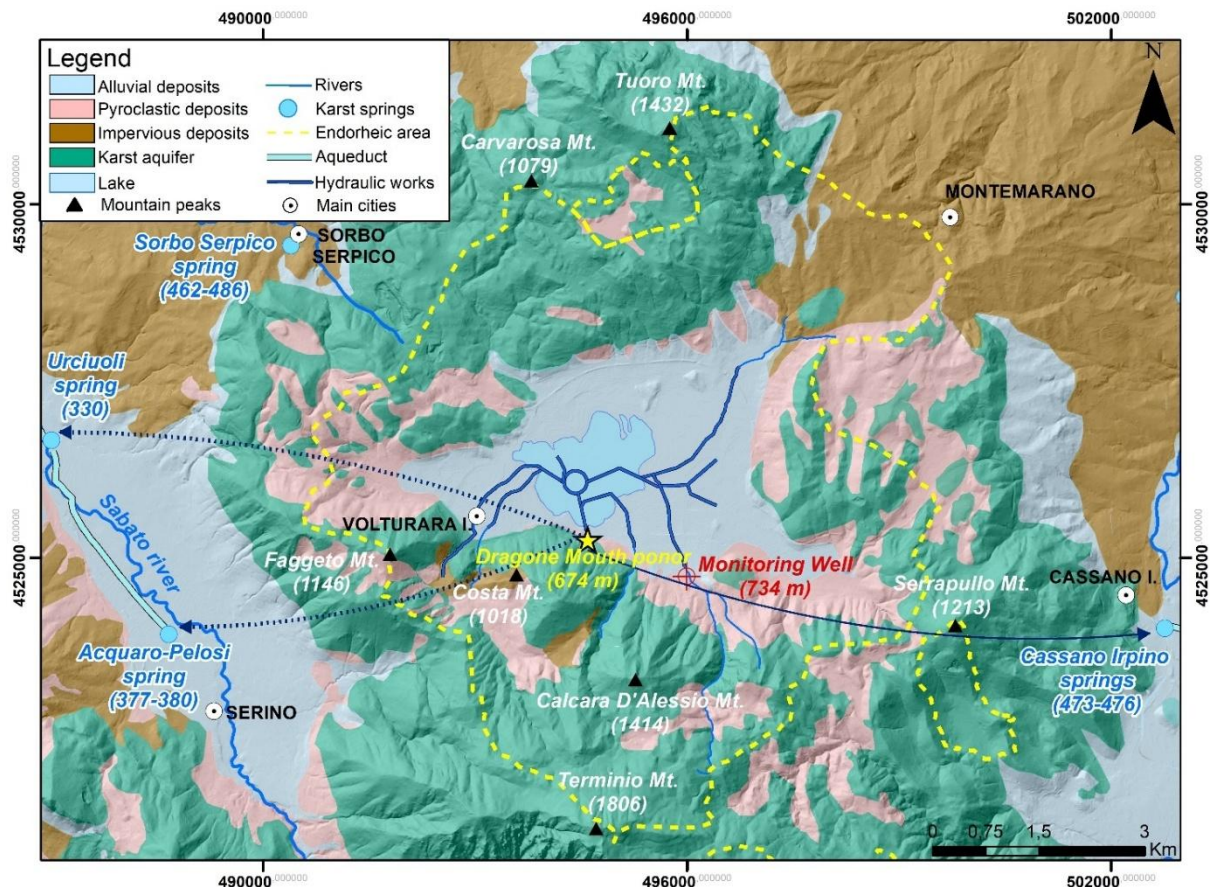


Figure 1.16. Hydrogeological sketch map of Dragone Plain. The dark blue arrows represent the results of tracer tests carried out by Celico et al. (1982). The lake surface is referred to the maximum value reached during February 2022.

The whole Dragone Plain has a pivotal role in aquifer recharge estimated in $71.6 \times 10^6 \text{ m}^3/\text{year}$ (50.9% of the recharge amount of the entire karst massif), equal to an average flow of approximately 2300 l/s (Fiorillo et al., 2015b). Dragone Mouth ponor is directly linked to the basal water table of Terminio-Tuoro karst massif. In particular, through the performance of tracer tests it was demonstrated that water adsorbed by the ponor contributes to the supply of Cassano Irpino spring Group (Fig. 1.16; Celico et al., 1982). However, no evidence has been found of a connection among the ponor and the Serino spring Group.

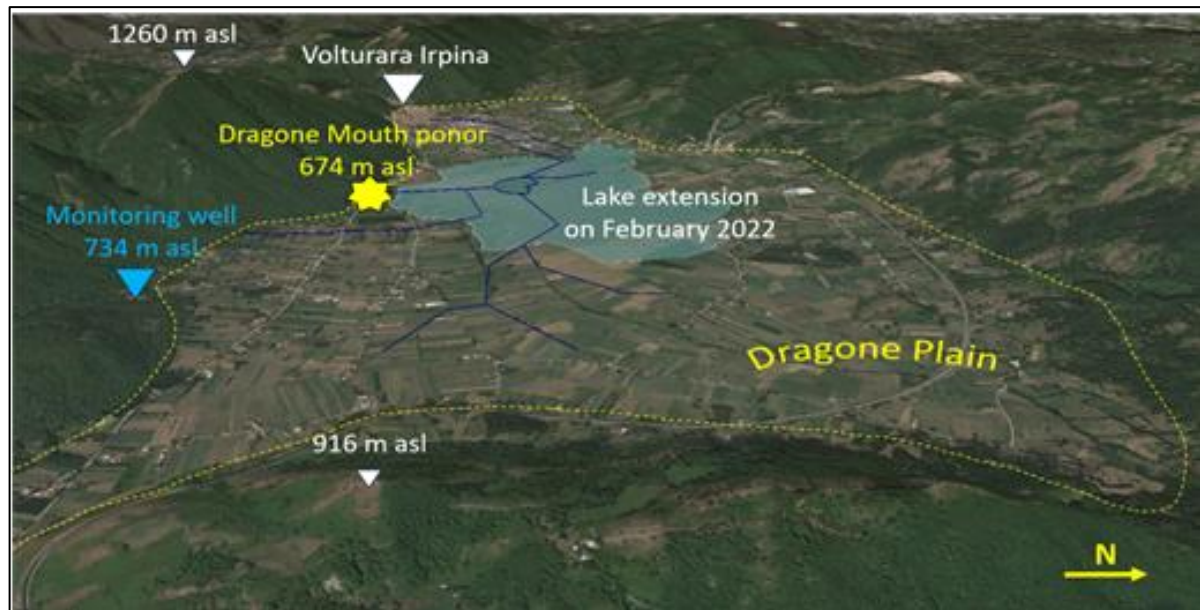


Figure 1.17. 3D view of the Dragone Plain (Google Earth Image); dashed yellow line is the limit of the flat area of the plain and white dashed line is the limit of the temporary lake on February 2022. Blu lines represent the hydraulic works carried out in the plain.

Morcone karst reliefs

Morcone karst reliefs are located in the eastern part of the greater Matese karst massif at the boundary between Campania and Molise regions (Fig. 1.18). The total extension of the aquifer is around 83.4 km² and the elevation ranges from 1200 m a.s.l., in the north-western part, to 400 m a.s.l., along the southern boundary, with a mean elevation of 761 m a.s.l. The massif is made, mainly, by continental platform to shallow-water to basin domain crystalline limestones of the *Calcarei Cristallini* Formation, bounded by marly and clay terrains of Miocenian age (*Scaglia* and *Pietraroja* Formations; Vitale and Ciarcia, 2024). These deposits are covered by Quaternary age sediments constituted by alluvial, slope-breccias, and pyroclastic deposits, these latter attributed to Ignimbrite Campana eruption (39,000 years b.p.; De Vivo et al., 2001). The above deposits represent the heterogeneous porous aquifers, widespread in the north-eastern part of the study area.

The climate is of Mediterranean type with dry and hot summers and wet periods during autumn, winter and spring seasons. The maximum value of precipitation is during November and the minimum in July. At contrary, the temperature, and thus the evapotranspiration value, shows the maximum value in August and the minimum in February (Fig. 1.19).

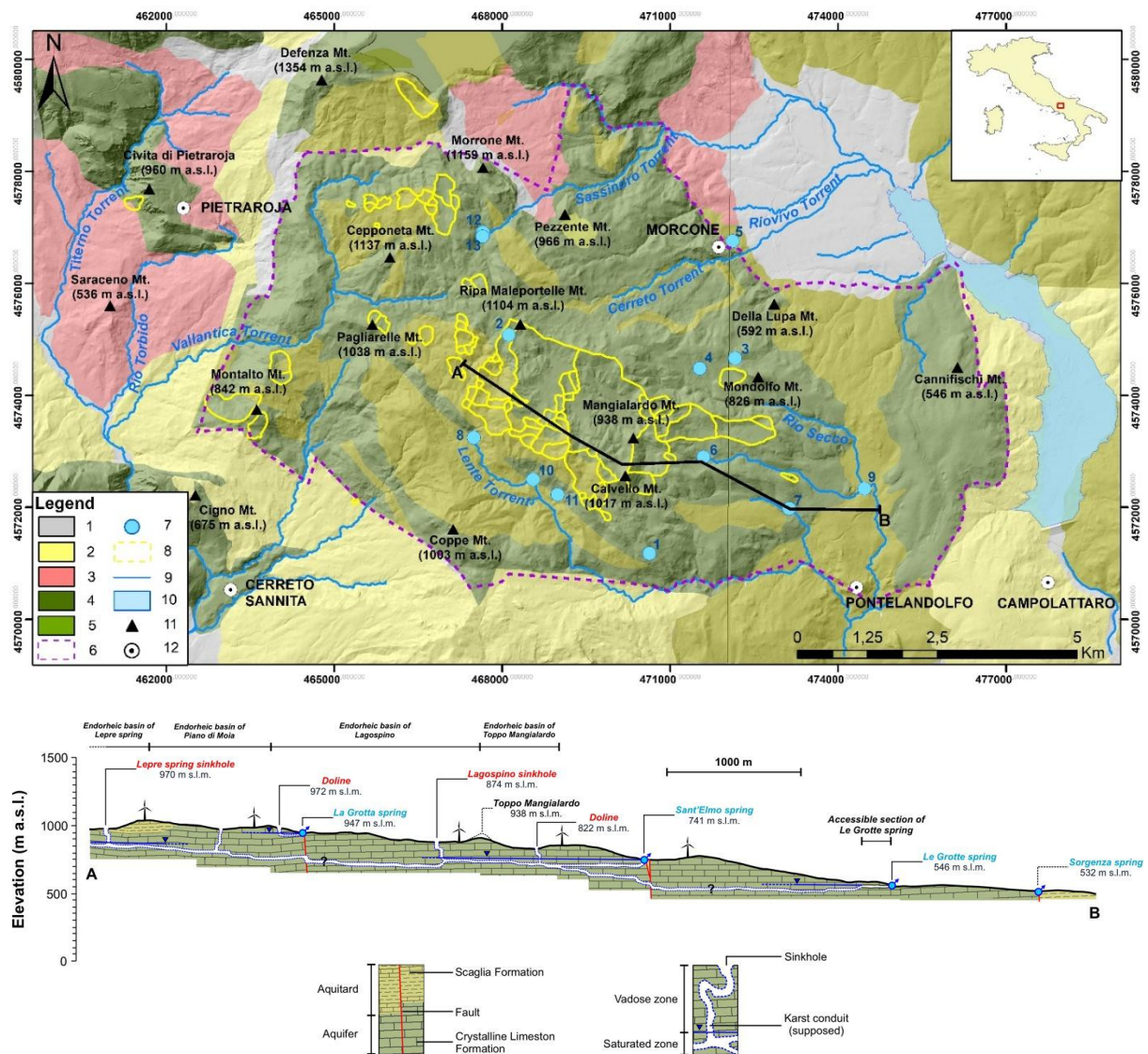


Figure 1.18. Hydrogeological map of Morcone Mountain karst massif and cross section (modified from [Valente et al., 2022](#)). Legend: 1) Alluvial aquifer (Quaternary); 2) Low permeability complex (aquitard) of Miocene – Pliocene formations (Baronia, San Giorgio, Numidian Flysch); 3) Impervious terrains (aquiclude) of Miocene (Pietraroja Formation); 4) Karst aquifer of Mesozoic-Miocene carbonate formations (Cusano, *Calcarei Cristallini*, Pre-orogenic carbonates); 5) Low permeability complex (aquitard) of Cretaceous-Miocene of *Scaglia* Formation; 6) Hydrogeological study area; 7) Karst spring; 8) Endorheic area; 9) Rivers; 10) Campolattaro dam reservoir; 11) Mountain peak; 12) Villages. The black line represents the cross-section trace.

The hydrogeological setting is a direct consequence of the geological features of the area. Morcone Mountain karst massif is a sub-structure of the greatest Moschiatturo Mountain aquifer, divided from Matese Mountain aquifer by a tectonic thrust between flysch and karst terrains ([Celico, 1978](#)). In the northern border, some faults mark the contact with the Sassinoro Mountain aquifer ([Esposito et al., 2005a](#); [De Vita et al., 2018](#)). Based on the geological data, and karst features (dolines, endorheic areas, sinkholes, and karst springs) spatial distribution, the main aquifer in the area is constituted by the formation of “*Calcarei Cristallini*”. It is

characterized by high permeability with complex geological contacts (both laterally and vertically) with less permeable terrains, such as *Scaglia* Formation, that act as aquitard (Petrella and Celico, 2009). On the borders of the karst massif the impervious terrains limit the groundwater flow towards Tammaro River to east, Calore River to south, and Titerno River to north (Aquino et al., 2015). The upper Pliocene-Pleistocene tectonic activity, that caused a general uplift of the area by normal faults and graben, and the following weathering of the karst terrains lead to the formation of several karst landforms in the highest part of the massif (Castracani et al., 1993; Valente et al., 2022). These landforms, sometimes characterized by a seasonal lake at their bottom, affects the groundwater recharge conveying runoff waters in ponors (*concentrate recharge*; Pagnozzi et al., 2019).

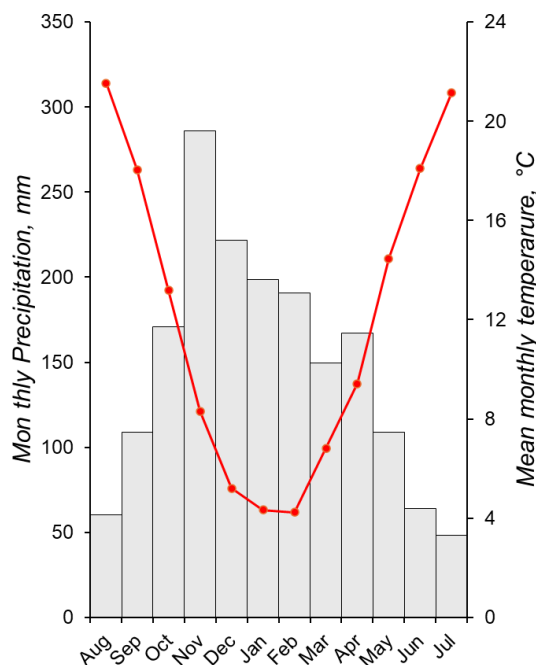


Figure 1.19. Climate features of the Roccamandolfi meteorological station located near the study area (1970-1999 period).

The main groundwater discharges are represented by several widespread springs with limited discharge (Fig. 1.18). Main springs are listed in table 1.3. Also, for this karst massif, systematic discharge registrations are lacking and can be found only in spot measurements in the literature and technical reports (Castracani et al., 1993; Esposito et al., 2005a). The main hydrogeochemical facies of the water circulating in the examined area can be classified as alkaline earthy bicarbonate facies. No mixed facies are present. The genesis of water is mainly in the nature of reservoir rocks of calcareous origin (Valente et al., 2022).

Item	Spring name	Elevation (m a.s.l.)	Mean discharge (l/s)	Temperature (°C)	pH	EC (μS/cm)	TDS (g/l)	Turbidity (NTU)
1	Acqua del Campo	774	15.0	11.5	7.1	0.365	0.237	0
2	Acqua della Lepre	1041	1.5	11.2	7.2	0.355	0.231	2.2
3	Ammeri	774	5.0	12.9	7.6	0.477	0.290	0
4	Coccimonti	809	2.5	11.2	7.1	0.436	0.284	0
5	Fontana Piedi	487	3.0	11.6	7.1	0.427	0.279	4.3
6	Fontana S. Elmo	750	80.0	10.6	7.0	0.369	0.240	4.8
7	Le Grotte	540	50.0	12.5	7.2	0.386	0.251	2.5
8	Macioccio	862	4.0	11.6	7.4	0.318	0.207	2.4
9	Sorgenza	505	50.0	12.8	7.2	0.418	0.272	4.2
10	Tofi	795	3.0	11.9	7.3	0.321	0.214	2.3
11	Tre Fontane	818	11.0	11.7	7.3	0.327	0.213	1.4
12	Tre Fontane I	1023	2.0	9.8	7.1	0.330	0.230	0.1
13	Tre Fontane II	1023	2.0	9.7	7.2	0.342	0.222	0

Table 1.3. Main features of the spring of Morcone karst massif (data from [Valente et al., 2022](#)); spring location is showed in figure 1.18.

To fill some of these gaps, a continuous monitoring activity was performed using a TD diver sensor in Sant’Elmo spring for the period November 2021-February 2023. This activity allowed to record the piezometric level feeding the spring and to draw the spring hydrograph. This plot (Fig. 1.20) highlights the recharge and recession periods of water table level. In particular, the water table fluctuation is strongly correlated with rainfall intensity and frequency, with the major influence of the rainfall of the autumn-spring period on water table level. Furthermore, there is a quick response to rainfall event on daily scale. The recession of the spring is during the period between May and October months (summer and early autumn seasons); even though little recharge episodes following heavy rainfalls are still present during this time (Fig. 1.20).

Considering the different elevation of spring and their discharges, the karst system would be characterized by several water tables. This hydrogeological framework is related to permeability variations in the faulted sedimentary sequence, which allow for the formation of several water tables located at different heights ([Celico, 1978](#); [Esposito et al., 2005a](#); [Valente et al., 2022](#)). These features can be certainly defined for the most powerful springs in terms of average flow rate (e.g., S. Elmo and Le Grotte springs; Tab. 1.3). However, the groundwater

flow path, characterized by a dispersive flow (Bonacci, 1993), doesn't allow the formation of a few powerful basal springs (Celico, 1983). The mean annual discharge of all springs draining karst massif was estimated in 17.6 hm³/year (Tab. 1.3; Valente et al., 2022). The main karst springs are all tapped from regional aqueducts companies for the drinking supply of the nearby municipalities.

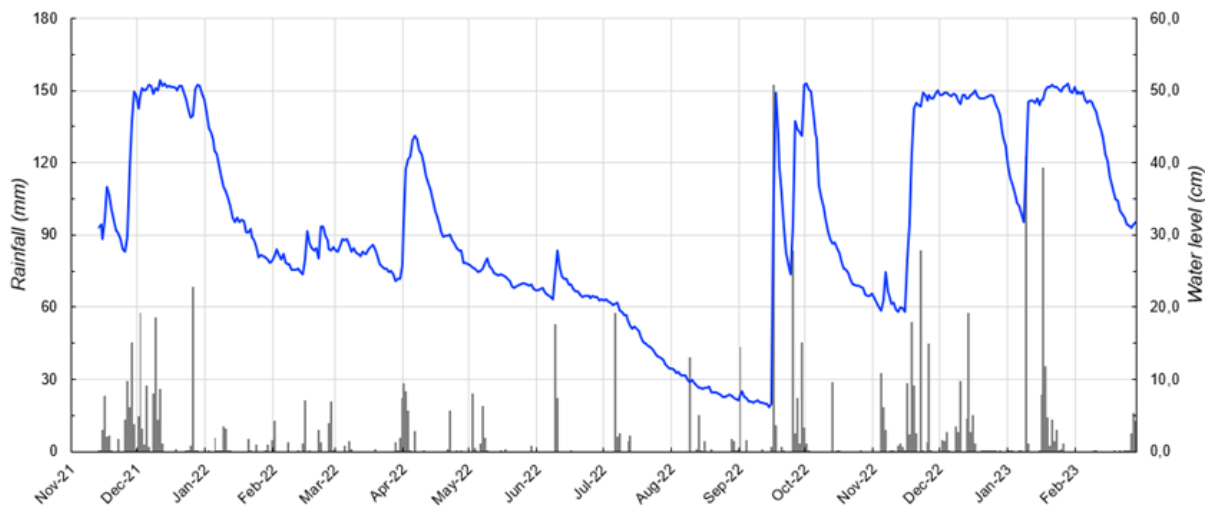


Figure 1.20. Hydrograph of water table level of Sant'Elmo spring recorded by TD diver monitoring sensor and precipitation values recorded from Morcone rain-gauge station.

1.2.2. Alluvial aquifers

The alluvial deposits constitute very heterogeneous and anisotropic aquifers whose permeability is for porosity. Depending on the existence of low permeabilities layers interbedded with alluvial deposits, on local scale, the groundwater path is often made up by a multilayered system. Within these systems both confined and unconfined aquifers can exist. Transmissivity values found for these aquifers vary from $1 \times 10^{-2} \text{ m}^2/\text{s}$ to $1 \times 10^{-5} \text{ m}^2/\text{s}$, while effective porosity varies from 5-6% to 30% (De Vita et al., 2018). In the following the main hydrogeological features of the alluvial aquifer studied (Benevento alluvial plain) will be described.

Benevento alluvial plain

The alluvial aquifer of Benevento plain (Fig. 1.21) is constituted by Quaternary deposits covering a low-permeability/impermeable bedrock consisting of Pliocene wedge-top basins clays and sands and Meso-Cenozoic deep-sea clay marls and limestones (ISPRA, 2009; Ciarcia and Vitale, 2013; Amato et al., 2017). The lowest part of Quaternary succession consists of

ancient alluvial deposits linked to Calore and Sabato Rivers (lower-middle Pleistocene; [Senatore et al., 2019](#)).

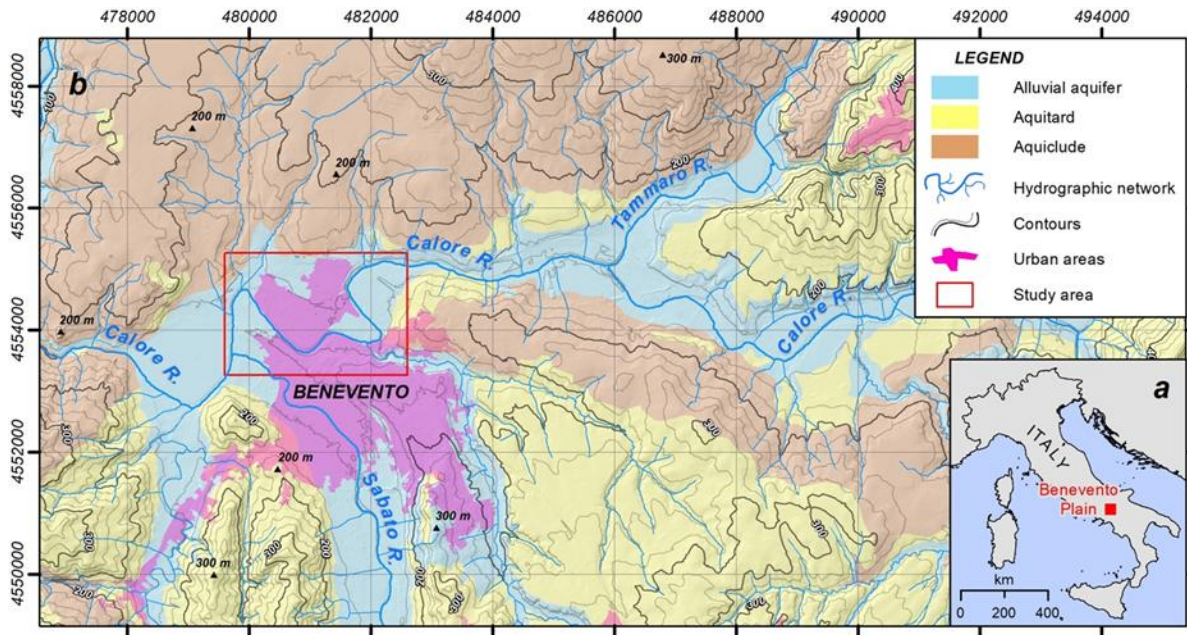


Figure 1.21. (a) Map of Italy and (b) hydrogeological sketch of the Benevento area. Alluvial aquifer: gravel and sand alluvial deposits ($K > 10^{-5}$ m/s); aquitard: arenaceous and pelitic deposits, sands and conglomerates ($10^{-5} < K < 10^{-8}$ m/s); aquiclude: clayey and marly deposits ($K < 10^{-8}$ m/s). Red rectangle bound the study area (from [Leone et al., 2024](#)).

The upper part of succession primarily consists of pyroclastic, eluvial, and colluvial deposits, anthropic deposits, slope debris, and recent alluvial deposits (upper Pleistocene – Present Days). Deep-sea deposits mainly outcrop along the hillslopes bounding the Calore River Valley to the north, while wedge-top basins deposits build up the reliefs in the easternmost and western sectors of the area. These pre-Quaternary deposits represent aquitards and aquicludes (Fig. 1.21).

The climate is Mediterranean: monthly rainfall reaches a maximum in November and a minimum in August; another rainfall peak may occur in March. The opposite pattern is observed for temperature, as that it reaches a maximum in July-August and a minimum in January (Fig. 1.22). The potential evapotranspiration estimated using the Thornthwaite formula ([Thornthwaite and Mather, 1957](#)) exceeds the total precipitation in May-September. On the other hand, the total rainfall exceeds the potential evapotranspiration in October-April. Meteoric water recharges the groundwater and surface hydrological systems during this period.

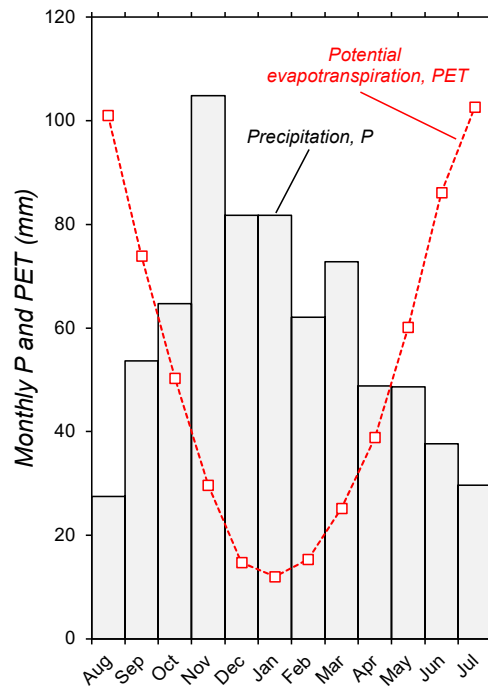


Figure 1.22. Mean monthly precipitation (P) and potential evapotranspiration (PET) estimated by Thornthwaite method. Meteorological data were acquired by the Benevento station (119 m asl.) between 2000-2023 (from [Leone et al., 2024](#)).

The alluvial aquifer is wide about 34 km² and extends in east-west direction. The thickness of the aquifer increases from the edges to the center of the valley, and has a maximum thickness of approximately 100 m across the urban area of Benevento ([Senatore et al., 2019](#)). The alluvial aquifer is laterally and in the lower part bounded by low permeability terrains. Locally, some resurgences of the impervious bedrock allow the compartmentalization of the aquifer in several reservoirs, bounded by impervious terrains (Fig. 1.23; [Celico et al., 1998](#)). On a large scale, a unique water table, with a flow direction towards Calore River watercourse or likely a paleo-river, exists. However, at a more detailed scale, the presence of impervious lenses interdigit between alluvial deposits can allow the existence of several overlapped and interconnected water tables ([Esposito et al., 2005b](#)). The hydraulic head ranges between 5-7%, along the borders, and 0.5-3%, in the central area near the urban center of Benevento city; the highest values of hydraulic head are recorded in the border stretch, near the transition between alluvial deposits and low permeability lithologies ([Esposito et al., 2005a](#)). The recharge is granted mainly by the infiltration of the effective precipitation on the ground surface equal to 2.67×10^3 m³/y and, secondarily, by water transfers from adjacent aquifers equal to 1.21×10^3 m³/y ([Celico et al., 1998](#)).

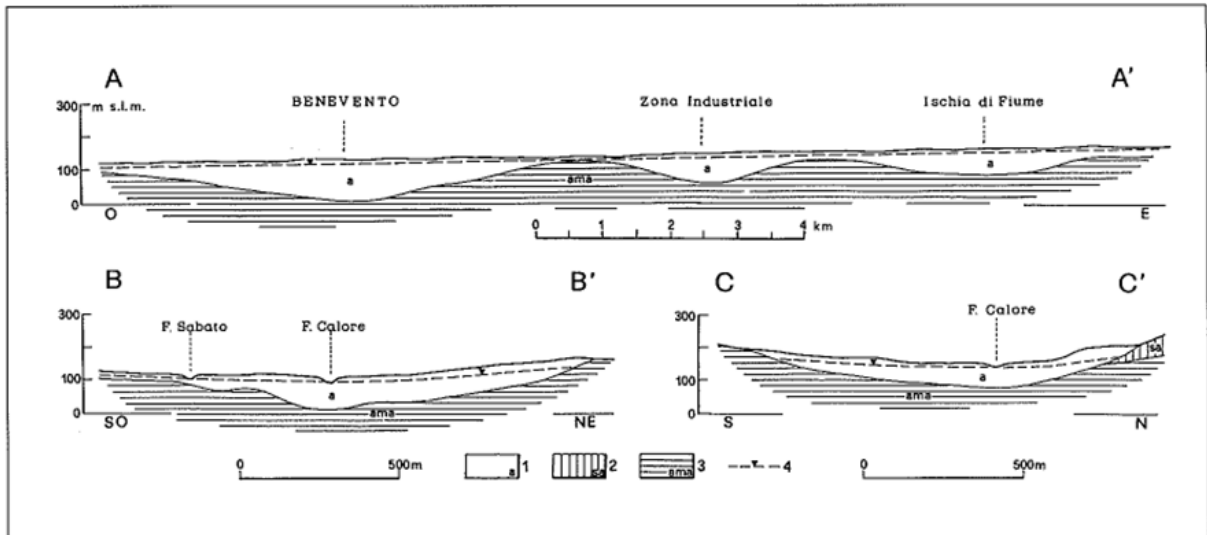


Figure 1.23. Hydrogeological cross section of Benevento Plain alluvial aquifer (from [Celico et al., 1998](#)).

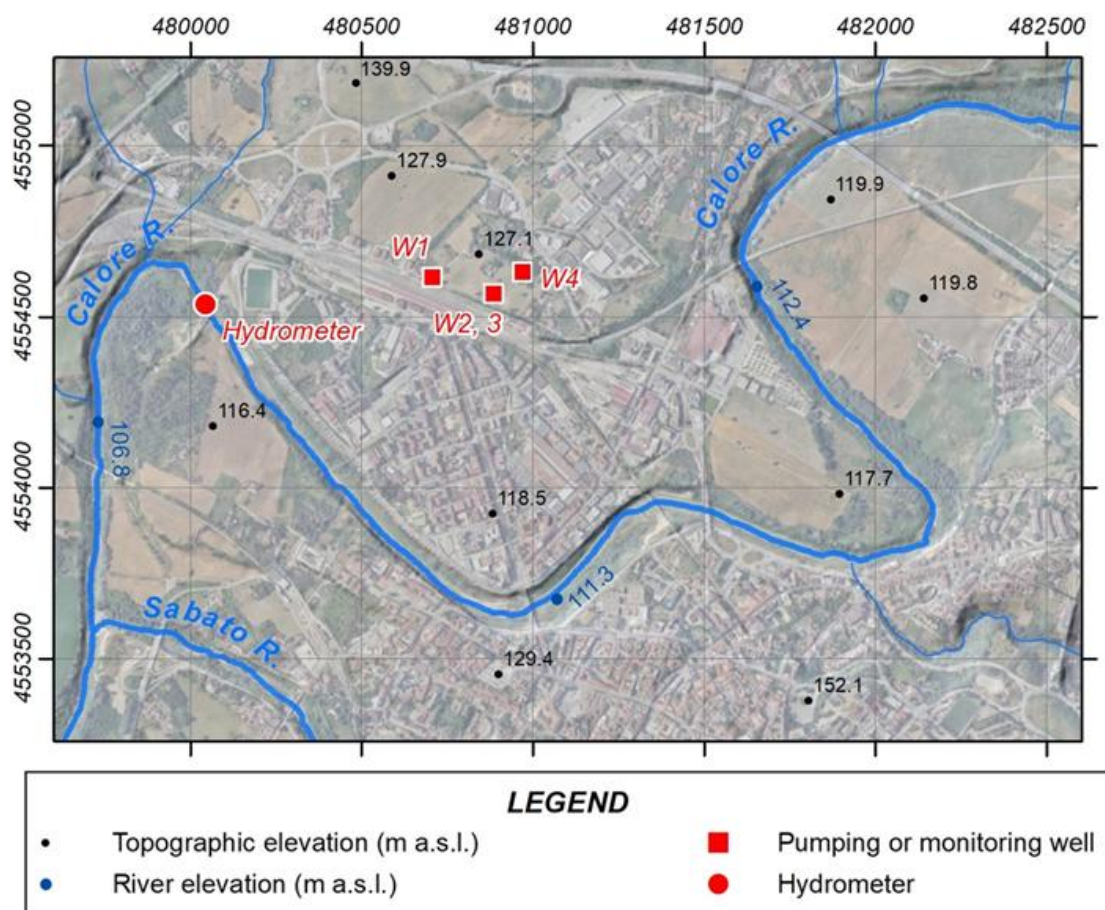


Figure 1.24. Satellite view of the study area, showing the location of the pumping well, piezometer and hydrometric station. Black dots are elevation points (elevation in m a.s.l.) (from [Leone et al., 2024](#)).

Materials and methods

The Calore River is the main feature of the area. In correspondence with the Benevento Plain, its catchment is approximatively 2073 km² and the mean discharge is of several tens of m³/s. The river has a sinuous shape and has experienced severe channel adjustments in the last 60-70 years (Magliulo et al., 2022). Near the water course, due to the groundwater pumping for drinking, industrial and agricultural purposes, a localized inversion of river-water table relationships can happen (Celico et al., 1998). During the wet season, several discharge peaks following rainfall events characterize the river hydrograph, which can reach hundreds of a few thousand cubic meters per second. As the main storms occur in autumn, the main floods occurred during this period, such as those on 2th October 1949 and 15th October 2015 (Revellino et al., 2019; Magliulo et al., 2021).

The study area is located in the sector of the Benevento plain encompassed in the urban area of Benevento plain (Leone et al., 2024). The valley floor ha ground elevations between 105 and 140 m a.s.l., with a mean elevation of 120 m a.s.l. (Fig. 1.24). This area is the alluvial aquifer located between two consecutive river bends of Calore River exploited through several private and public wells (pumping rate of 0.06 m³/s). Public wells are managed by GESESA Aqueduct Company and are used for the water supply of Benevento city.

***Chapter 2:* Numerical simulations in groundwater flow modeling**

The use of groundwater models is prevalent in the field of environmental science. Models have been applied to investigate a wide variety of hydrogeologic conditions. More recently, groundwater models are being applied to predict the transport of contaminants for risk evaluation ([Kumar, 2015](#)).

Numerical modeling is a powerful tool that serves to provide a better comprehension of groundwater flow and to obtain information about important groundwater parameters. The most important aspect of the use of such models is acquiring data on the real conditions occurring within the observed environment ([Milic et al., 2023](#)). Numerical models can be used to simulate responses due to perturbations of the system in order to evaluate the dominating influences on the more complex real-world systems ([Bundschuh and Suarez Arriaga, 2010](#)).

A groundwater flow model is a mathematical representation of groundwater flow through an aquifer, which is composed of saturated sediment and rock. Among others, the conceptual model includes the most important simplifying assumptions regarding the aquifer and the physical processing concerning groundwater flow ([USGS, 2022](#)).

The mathematical model is a set of equations which, subject to certain assumptions and boundary conditions, describes the essential physical features and processes of the groundwater system. The set of equations is solved using numerical methods (e.g. finite differences) ([Bilge, 2012](#)).

In the framework of groundwater numerical modeling, MODFLOW-based codes ([McDonald and Harbaugh 1988](#)) have been widely adopted for groundwater flow modeling, given their ability to describe flow in porous media under the influence of various drivers, including pumping through wells ([Tügel et al. 2016](#); [Ahmadi et al. 2023](#)), groundwater-surface water interactions ([Mylopoulos et al. 2007](#); [Di Ciacca et al. 2019](#); [Zhou et al. 2022](#)), and climate change ([Theodossiou 2016](#)).

Generally, alluvial aquifers are in hydraulic communication with the associated river system, which may represent a main, or the main, natural driver of groundwater flow and recharge

(Domenico and Schwartz, 1997; Brunner et al., 2017). Other natural drivers are the effective meteoric infiltration and water inflow from neighboring upgradient aquifers.

Anthropogenic stresses, especially groundwater pumping by wells, alter the natural aquifer recharge-discharge balance. Water withdrawal by wells can increase the river-to-aquifer fluxes that ensure high pumping rates during the hydrological year but represent a potential risk for groundwater circulation and pollution (Texier et al., 2022).

Complex conditions due to geological heterogeneity and a variety of hydrological processes characterize alluvial aquifers. An extensive set of equations and parameters could be required to capture such complexity, making modeling difficult (Omar et al. 2020). Therefore, in practice, model parametrization and physical formulations require some form of simplification and generalization, depending on the spatial-temporal scale and the purpose of the model (Barthel and Banzhaf 2016). As discussed by many authors (Anderson et al. 2015, among others), modeling studies often favor parsimonious approaches that minimize the number of parameters. To this end, the aquifer medium is assumed to consist of one or a few equivalent homogeneous units (Martínez-Santos et al. 2010; Lin et al. 2013; Theodossiou 2016; Zhou et al. 2022), and only relevant hydrological processes are included.

Given its widespread acceptance, in this thesis the MODFLOW code to model the groundwater flow field in the alluvial aquifer of Benevento plain was used. A parsimonious approach was adopted in the design of the numerical model to reduce uncertainty, which considers a limited number of parameters and only relevant hydrological processes controlling groundwater circulation (aquifer-river interaction, effective meteoric recharge, and pumping). In the following sections, fundamentals and theory of MODFLOW code and MODPATH software used will be described. Also, a brief overview of the user-friendly interface Processing MODFLOW is reported (section 2.5).

2.1.MODFLOW Code

MODFLOW code is based on the Groundwater Flow (GWF) Model that relies on a generalized control-volume finite-difference approach in which a cell can be hydraulically connected to any number of surrounding cells (McDonald and Harbaugh, 1988). The code can simulate, above others, effects related to well pumping, river dynamic, drain, hydraulic head dependent boundaries, direct recharge, and evapotranspiration. The user can define the model grid using of the three discretization packages: (i) a structured discretization package that defines regular MODFLOW grids (built by layers, rows and columns); (ii) a discretization by vertex package

(definition of un-structured overlapped grids constituted by layers and cells); (iii) a generic non-structured discretization package (definition of flexible grids formed by cells and their connection properties).

MODFLOW code is divided in several “*packages*”. A package is a part of the model that deals with a single aspect of simulations. Packages included with MODFLOW code encompass that correlated to groundwater flow path internal calculations (discretization, initial conditions, hydraulic conductance, and storage), stress packages (constant heads, recharge, rivers, general head boundaries, drains, and evapotranspiration) and advanced stress packages (streamflow routing, lakes, wells, multi-aquifer wells, and unsaturated zone flow). To these packagers other regarding the restitution and controlling of results are added ([Langevin et al., 2017](#)).

MODFLOW is based on a highly modular structure extended into an object-oriented framework ([Hughes et al., 2017](#)). This latter includes a robust and generalized numerical solution object, which can be used to solve many different types of models. The numerical solution object has several different matrix preconditioning options as well as several methods for solving the linear system of equations. A single forward run with MODFLOW can contain several Groundwater Flow Models that can be hydraulically connected using the GWF-GWF Exchange objects. Furthermore, several models and their exchanges can be included in a single object of the numerical simulation. Thus, models can be tightly coupled at matrix level ([Langevin et al., 2017](#)). Thanks to this structure, new capabilities and options can be added without change the oldest one.

To support the multi-model capacity in MODFLOW environment, the information regarding time simulation is a simulation level controlled. Thus, time-step lengths are determined and applied to all models. The simulation requires also information about the model, the interactions between one or more models, and the models and their interactions are solved.

Hierarchical and simulation MODFLOW components are shown in figure 2.1. The simplest design of a numerical model is constituted by a Time Module, a Numerical Solution, and a Groundwater Flow Model. This latter encompasses the packages describing the simulated hydrological processes.

In the case of more than one Groundwater Flow Model (Fig. 2.2) an Exchange to connect hydraulically the models can be used. The Exchanges are labeled as GWF-GWF. User can specify the number of Exchanges needed to link every number of models in correct setting.

When multiple Groundwater Flow Models are coupled, they are matched at the matrix level, which allows them to be solved as efficiently as if they were built in a single unstructured grid.

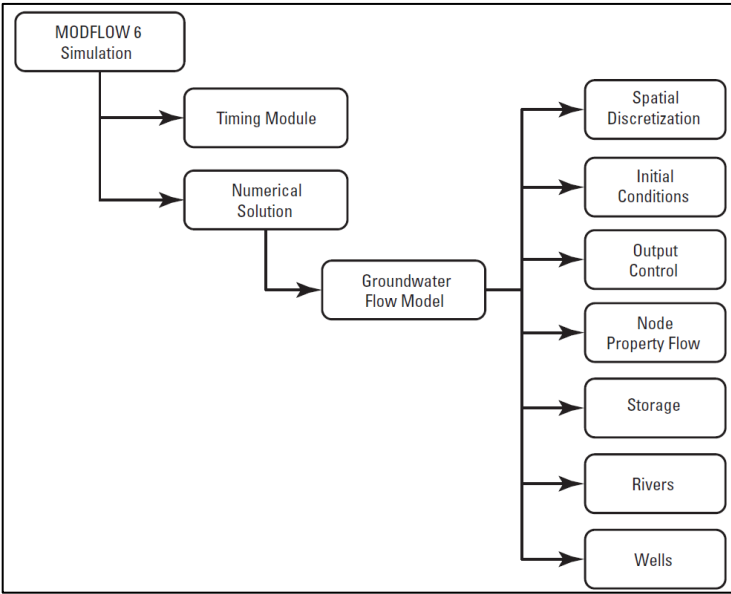


Figure 2.1. MODFLOW component for a simulation with a single Groundwater Flow Model (from [Langevin et al., 2017](#)).

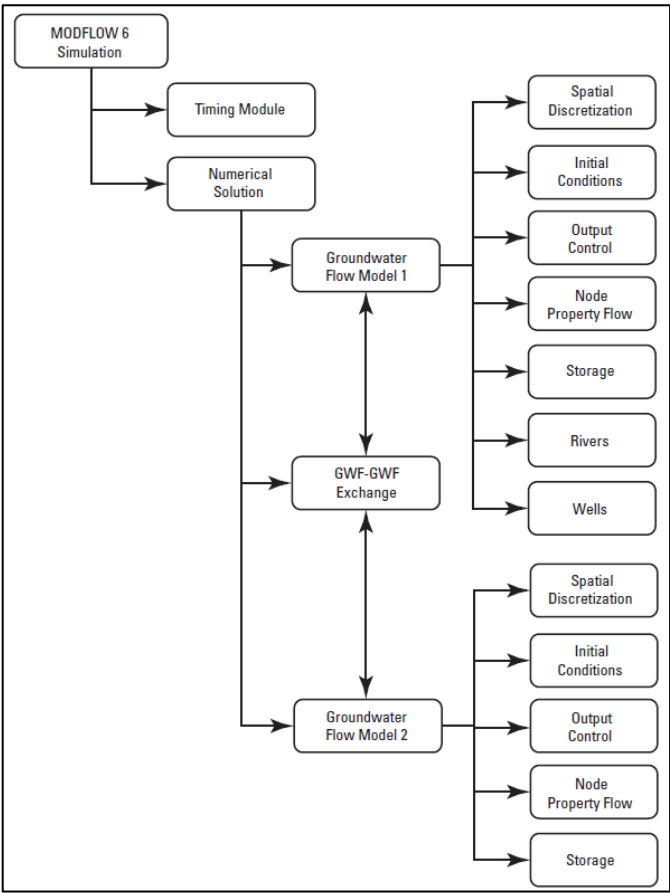


Figure 2.2. MODFLOW components for a simulation with two Groundwater Flow Models (from [Langevin et al., 2017](#)).

2.2. Finite difference method and grid discretization

The Finite Difference Method (Richardson, 1910) is a classic numerical solution technique, which is widely used in modeling groundwater and geothermal systems. Despite its limitations, this is a simple technique with a consequent easiness in programming (Bundschuh and Suarez Arriaga, 2010). The basis of this method consists of replacing differential expressions by quotients of differences. The numerators of those quotients are the difference that include the values of unknowns. Thus, numerators of those quotients are the differences that include the values of algebraic equations that can be solved using different techniques.

To create a finite difference model, the area to be modeled should first be spatially discretized (Fig. 2.3). This is done by dividing the considered domain (model area) in a finite number of cells to hydrogeological properties are attributed. In the center of each cell there is a node (i, j, k) , where i and j represent the cell index in x - and y -direction, respectively. k represents the discretization of time component in a finite number of intervals. At a given node (i, j) and given time k , the hydraulic head is represented by the value $h(i, j, k)$. For each cell, a water and solute balance is carried out for each time interval.

The mathematical model formulation is based on mass conservation and groundwater flow laws. The three-dimensional movement of constant density groundwater through a porous terrain is described by Darcy law (Darcy, 1856):

$$q = -K\nabla h = - \begin{pmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{pmatrix} \nabla h \quad (2.1)$$

Where q is the specific discharge vector [L/T], or fluid-flux vector, K is the hydraulic conductivity tensor [L/T]; K_{xx} , K_{yy} , and K_{zz} area values of hydraulic conductivity along the x , y , and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity [L/T]; h is the potentiometric head [L]; and ∇h is the head-gradient vector.

In hydrodynamic or flow simulation models groundwater flow movement (Eq. 2.1) and continuity laws are combined. The aim is to reproduce the water table fluctuations of an aquifer, characterized by natural recharge and well pumping, through space and time. In the case of isotropic aquifers, the hydraulic heads reproduced in the model, in a non-stationary case, are given by:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) + Q_s' = ss \frac{\partial h}{\partial t} \quad (2.2)$$

Where Q_s' [T^{-1}] is a volumetric flux per unit volume representing sources and sinks of water. When the flow is directed out of the aquifer system, this value is negative; vice versa this value is positive. ss is the specific storage of the porous material [L^{-1}] and t is the time [T].

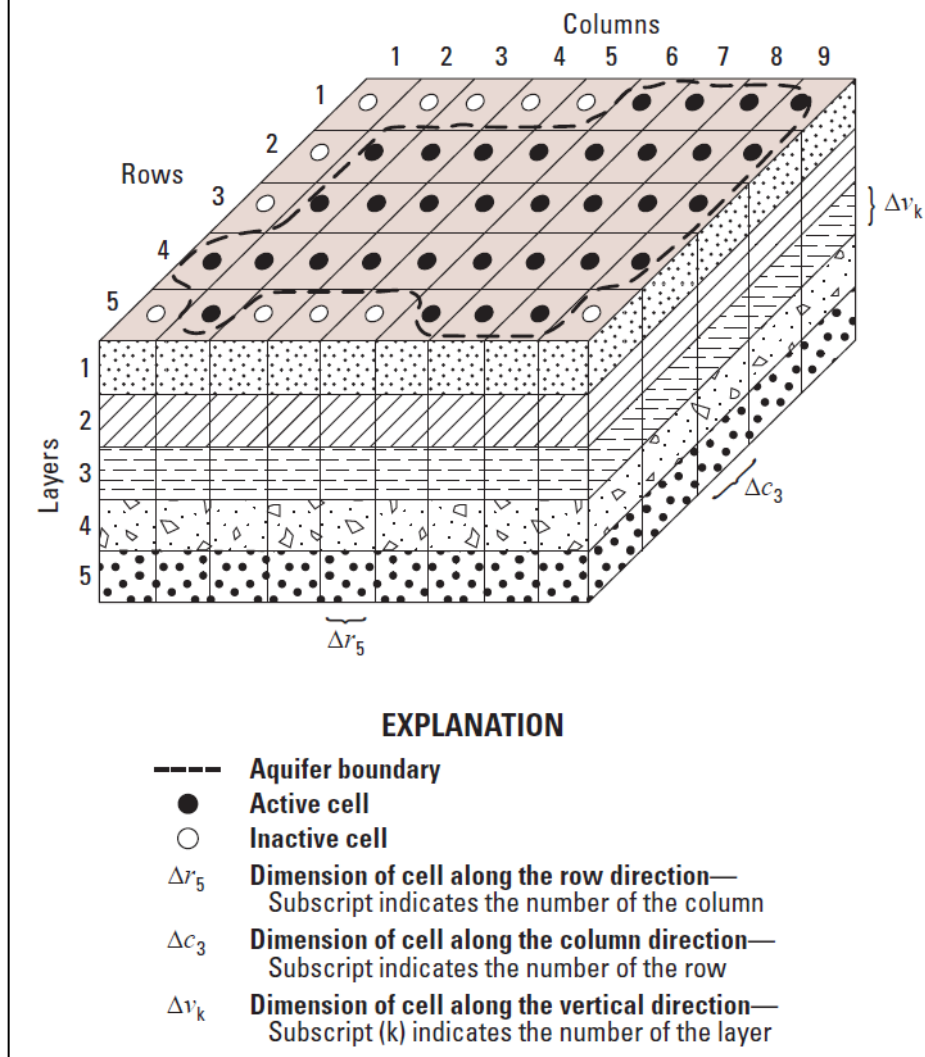


Figure 2.3. Hypothetical aquifer system discretized using a regular MODFLOW grid (from Harbaugh, 2005).

The equation (2.2), together with specifications of flow and head conditions at the boundaries of an aquifer system and specification of initial head-conditions, constitutes a mathematical representation of a groundwater flow system.

In some cases, like in that of regional studies of aquifers, the hydraulic head distribution is steady through time. Thus, the model design can be performed in stationary conditions, using the following equation:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) + Q_s' = 0 \quad (2.3)$$

The final design of the model is the combination of the equation (2.3) with the boundary conditions of the discretized area.

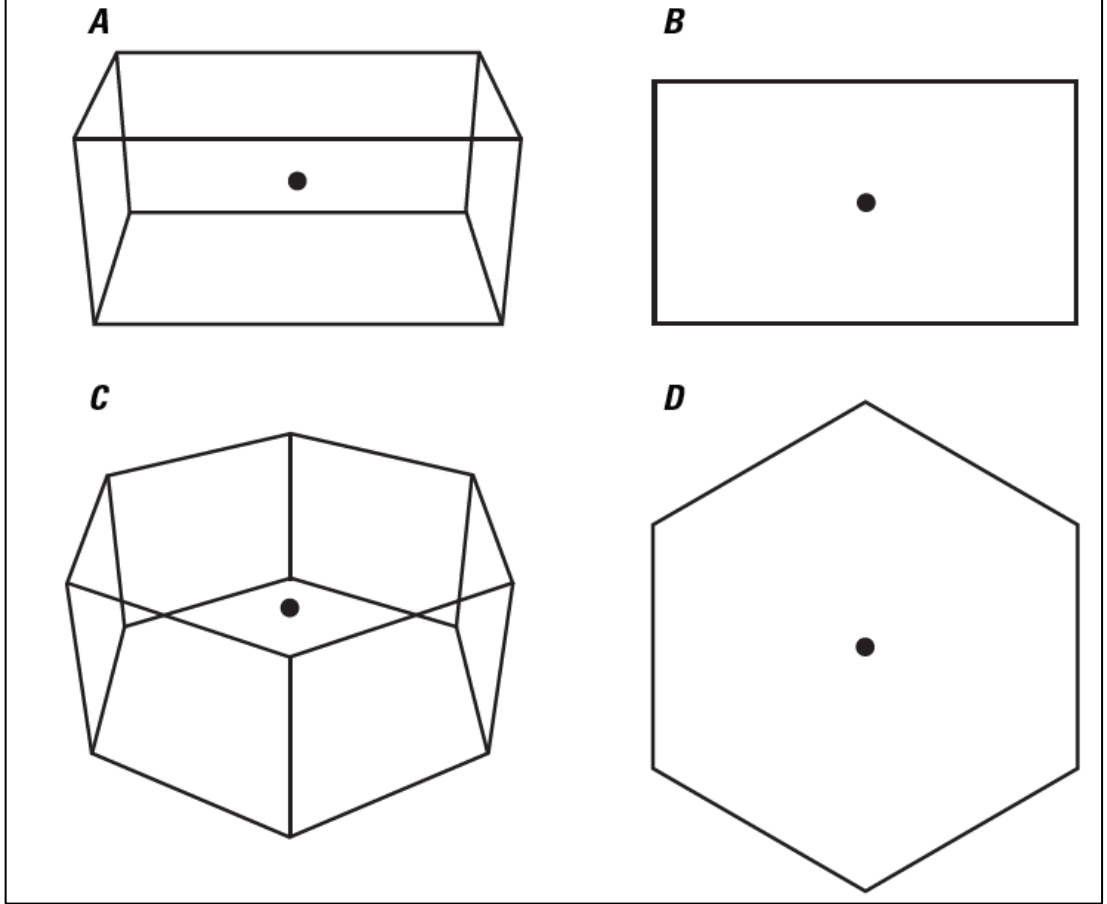


Figure 2.4. Model cells with nodes located at their centers (from [Langevin et al., 2017](#)). A: rectangular cell, oblique view; B: outline of rectangular cell as viewed from above; C: hexagonal cell, oblique view; D: hexagonal cell, viewed from above.

The model grid is constituted by several cells (Fig. 2.4). A connection between the nodes of two cells indicates that they are in hydraulic connection. In this case, water can flow through the two cells under the effect of the hydraulic gradient (Fig. 2.5). The connection can be “horizontal” or “vertical”. Using information provided by the grid or user it-self, MODFLOW calculates the connections among cells as a part of the model input. The same is for the type of connection.

The collection of all model cells and their connection is called model “grid” (Fig. 2.1). Two types of model grid can be recognized: (i) regular grids made by rows, columns, and layers of rectangular-prismatic cells; and (ii) unstructured grids whose cells need not to be rectangular

and connectivity is not restricted to rows, columns, and layers. The main advance of the unstructured connectivity is the flexibility in constructing of grids that conform to model domains with irregular geometry and complex geology.

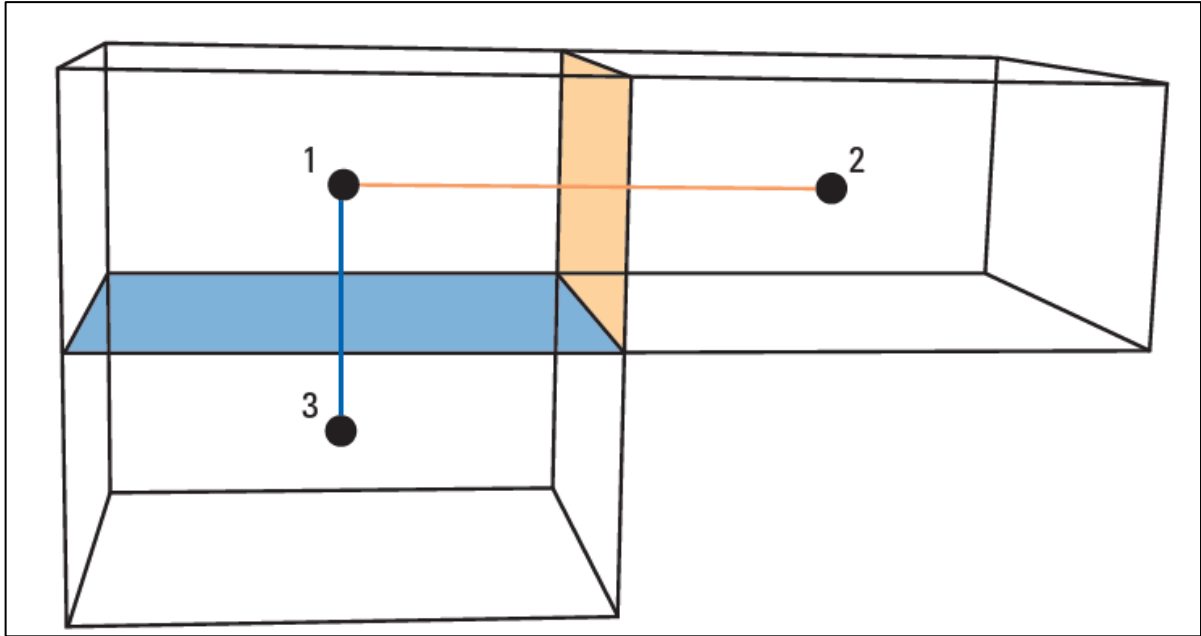


Figure 2.5. Scheme showing connections between the nodes of three model cells (from [Langevin et al., 2017](#)). Cells 1 and 2 are linked by a horizontal connection that crosses their shared vertical side (light orange). Cells 1 and 3 are linked by a vertical connection that crosses their shared horizontal bottom/top (blue).

A regular MODFLOW grid (Fig. 2.6) is a rectilinear grid of cells, whose location is described in terms of rows, columns and layers. A layer, row, and column indexing system is used. In three dimensions, a single model cell is connected, at most, to six surrounding model cells.

In the unstructured grids (Fig. 2.6), the number of connections can vary for each cell contained in the grid. The result is an unstructured equation system. In the Control Volume Finite Difference method, the cell connectivity depends from the number of the shared faces, that can vary for each of them. In a structured grid, the shared face number is constant throughout the whole grid and can be considered as a sub-set of unstructured grids ([Panday et al., 2013](#)).

In MODFLOW, cells are distinguished in active, no flux, and constant head (Fig. 2.7). The status of cells in simulation is attributed through the *General Head Package* ([Harbaugh, 2005](#)). Through the use of the IBOUND function, during the simulation, the software manage the setting of the cell throughout the grid defined prior by user.

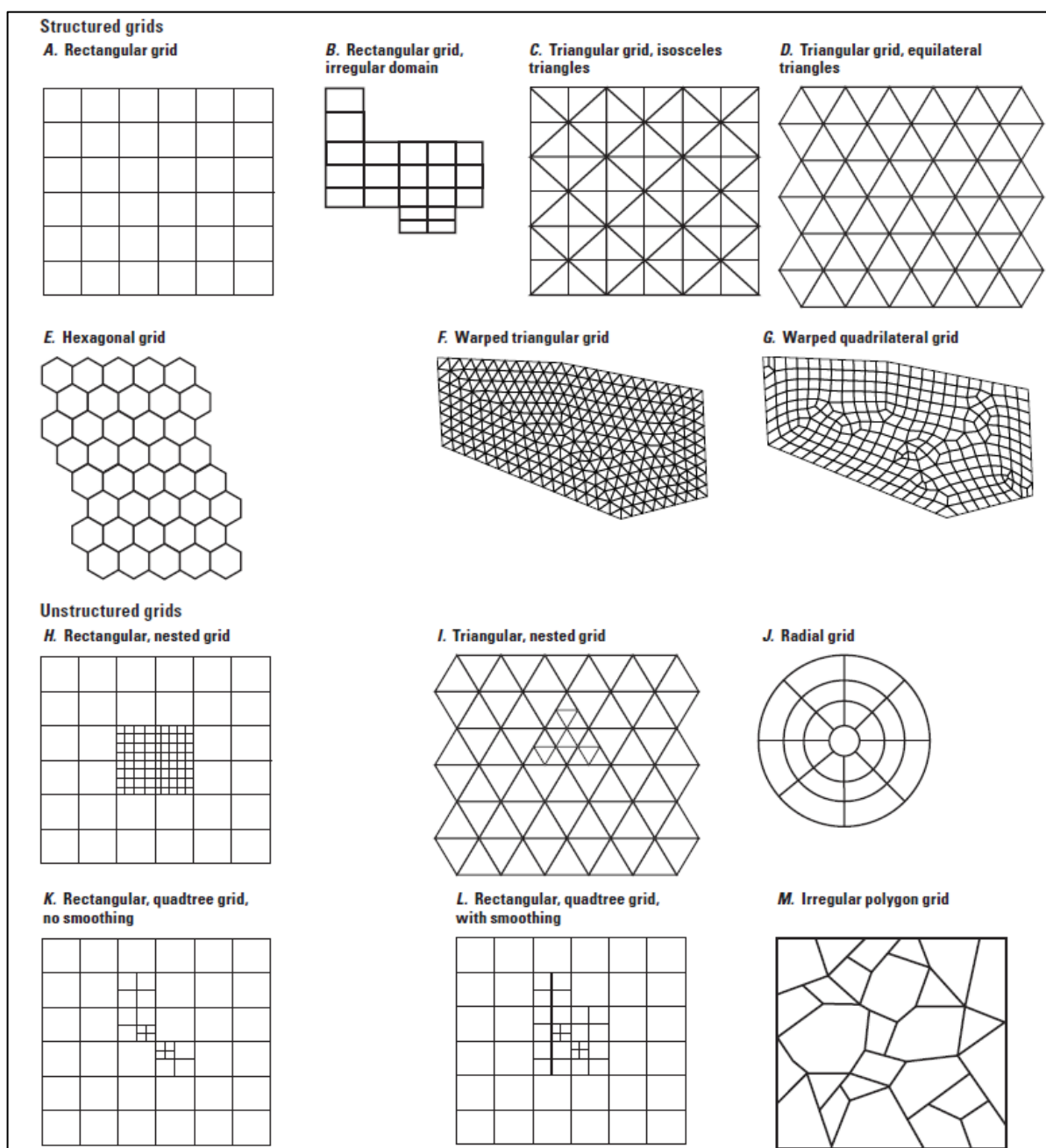


Figure 2.6. Different types of structured and unstructured grids (from Panday et al., 2013).

In active cells the hydraulic head values are not specified and can vary throughout the simulation ($IBOUND = 1$). The constant head cells ($IBOUND = -1$) are those for which the head is specified for each time, and the head value does not change as a result of solving the flow equations. No-flow cells ($IBOUND = 0$) are those for which no flow into or out of the cell is permitted. For each cell the resultant equation system must be solved simultaneously for each time step of simulation.

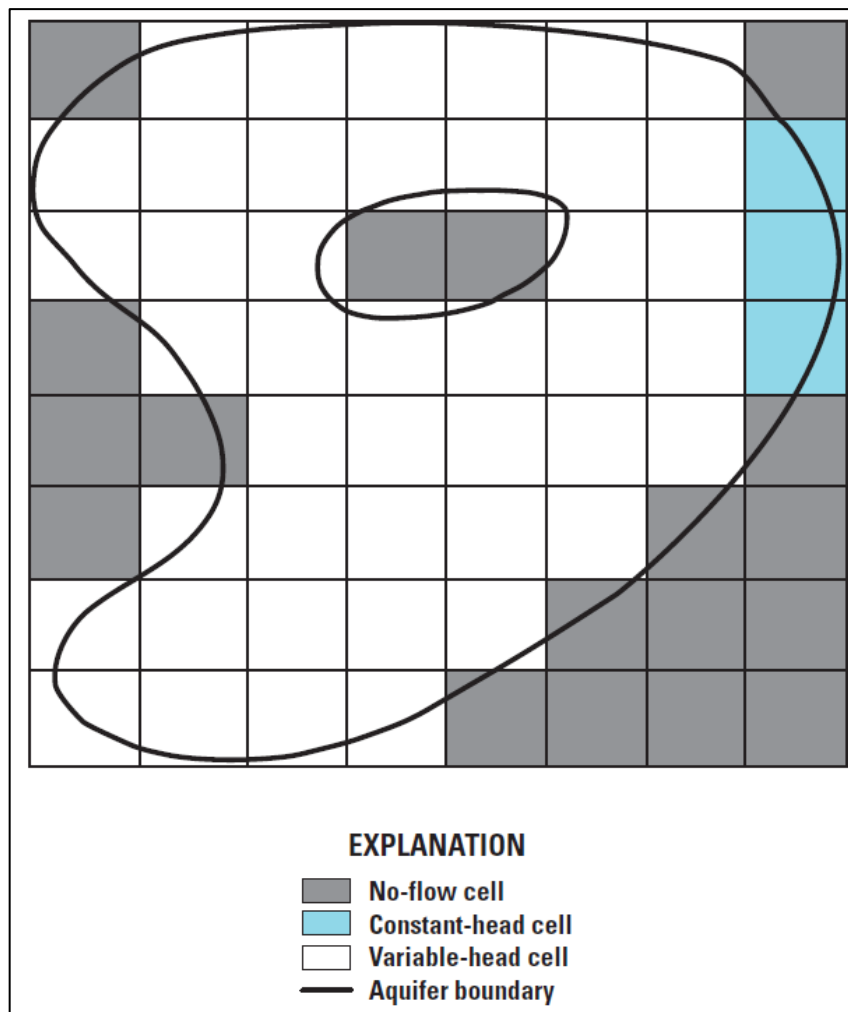


Figure 2.7. Discretized aquifer showing boundaries and cell designations (from [Harbaugh, 2005](#)).

2.3.Packages

MODFLOW code contains several packages and options (Tab. 2.1). The hydrological packages represent the cornerstone functions of MODFLOW code, available also in several oldest versions of the software ([Harbaugh, 2005](#)). These packages can be classified in three groups:

- (i) *Hydrologic/Internal* packages; internal flow package simulating flow among adjacent cells and manage modifications about storage for each cell contained in the model.
- (ii) *Hydrologic/Stress* packages; simulate a simplified and single stress type (e.g., rivers, wells, recharge).
- (iii) *Hydrologic/Advanced Stress* packages; simulate more advanced stresses.

The *Hydrologic/Internal* Packages calculate the terms needed for the solving of groundwater flow equation for each model cell or for to contain the necessary information for the calculation of the term.

Category	Package Name	Abbreviation
<i>Hydrologic/Internal</i>	<i>Discretization</i>	DIS, DISV o DISU
	<i>Initial Conditions</i>	IC
	<i>Node Property Flow</i>	NPF
	<i>Horizontal Flow Barrier</i>	HFB
	<i>Ghost Node Correction</i>	GNC
	<i>Storage</i>	STO
<i>Hydrologic/Stress</i>	<i>Specific Head</i>	CHD
	<i>Well</i>	WEL
	<i>Recharge</i>	RCH
	<i>River</i>	RIV
	<i>General-Head Boundary</i>	GHB
	<i>Drain</i>	DRN
	<i>Evapotranspiration</i>	EVT
<i>Hydrologic/Advanced Stress</i>	<i>Stream-Flow Routing</i>	SFR
	<i>Lake</i>	LAK
	<i>Multi-Aquifer Well</i>	MAW
	<i>Unsaturated Zone Flow</i>	UZF
	<i>Water Mover</i>	MVR
<i>Output</i>	<i>Model Observations</i>	OBS
	<i>Output Control</i>	OC

Table 2.1. List of packages available for use with Groundwater Flow Model.

Every *Hydrologic/Stress* Package formulates the coefficient describing a particular external (or boundary) flow. For example, *River* Package calculates coefficients describing flow between a cell and the superficial river.

The more complex *Hydrologic/Advanced Stress* Packages encompass *Multi-Aquifer Well*, *Stream Flow Routing* and *Unsaturated Zone Flow* packages.

The skill of MODFLOW is that of several *Hydrologic/Stress* and *Hydrologic/Advanced Stress* packages of the same time can be included in an individual Groundwater Flow Model. Another advantage is the use of time series registration to specify specific stress input (Langevin et al., 2017).

Other packages are enclosed in the *Output* category: *Observation* and *Output Control* packages. They manage saving and printing of Groundwater Flow Model results in outputs files.

In the following sub-sections will be described the *River*, *Recharge*, and *Well* packages used for the numerical model built in this thesis.

2.3.1. River Package

The aim of the *River* Package is the simulation of the flow effect between superficial and groundwater. To achieve this objective, for each cell affected by river percolation, the terms representing percolation from and/or to superficial features must be added to groundwater flow equation.

In the simplest case of limited hydraulic head losses between river and aquifer layers and of a complete saturated cell below (Fig. 2.8A), the flow between river and groundwater system is given by:

$$QRIV_{nb} = CRIV_{nb}(HRIV_{nb} - h_n) \quad (2.4)$$

Where $QRIV_{nb}$ represents the flow between river and aquifer; this is positive when conveyed inside the aquifer [L^3/T]; $HRIV_{nb}$ is the river water level (phase) [L]; $CRIV_{nb}$ is the hydraulic conductance of the river-aquifer interconnection [L^2/T]; h_n is the hydraulic head at the node in the cell beneath the river branch [L].

The river conductance can be calculated as follows:

$$CRIV_{nb} = \frac{K_{nb}L_{nb}W_{nb}}{b_{nb}} \quad (2.5)$$

Where L_{nb} is the river length when it crosses the cell; W_{nb} is the width of the river; b_{nb} is the thickness of the riverbed layer; and K_{nb} is the hydraulic conductivity of the riverbed material.

The equation (2.5) gives an acceptable approximation of river-aquifer interaction for a certain range of hydraulic head. However, in the cases when the water level drops under a certain point, the river percolation does not depend anymore from aquifer head. In these cases, the water level in the aquifer has fallen below the bottom of the riverbed layer, leaving an unsaturated interval beneath it (Fig. 2.8B). If it is assumed that the riverbed layer itself remained saturated, the head at its base will be the elevation at that point ($RBOT_{nb}$).

The flow through the riverbed layer is given by:

$$QRIV_{nb} = CRIV_{nb}(HRIV_{nb} - RBOT_n) \quad (2.6)$$

Where $QRIV_{nb}$, $CRIV_{nb}$, and $HRIV_{nb}$ are the same of the equations (2.4) and (2.5). Obviously, further declines in hydraulic head below $RBOT_{nb}$ do not produce any increase in flow through riverbed; the flow retain the constant value given by equation (2.6), as long as the head remains below $RBOT_{nb}$.

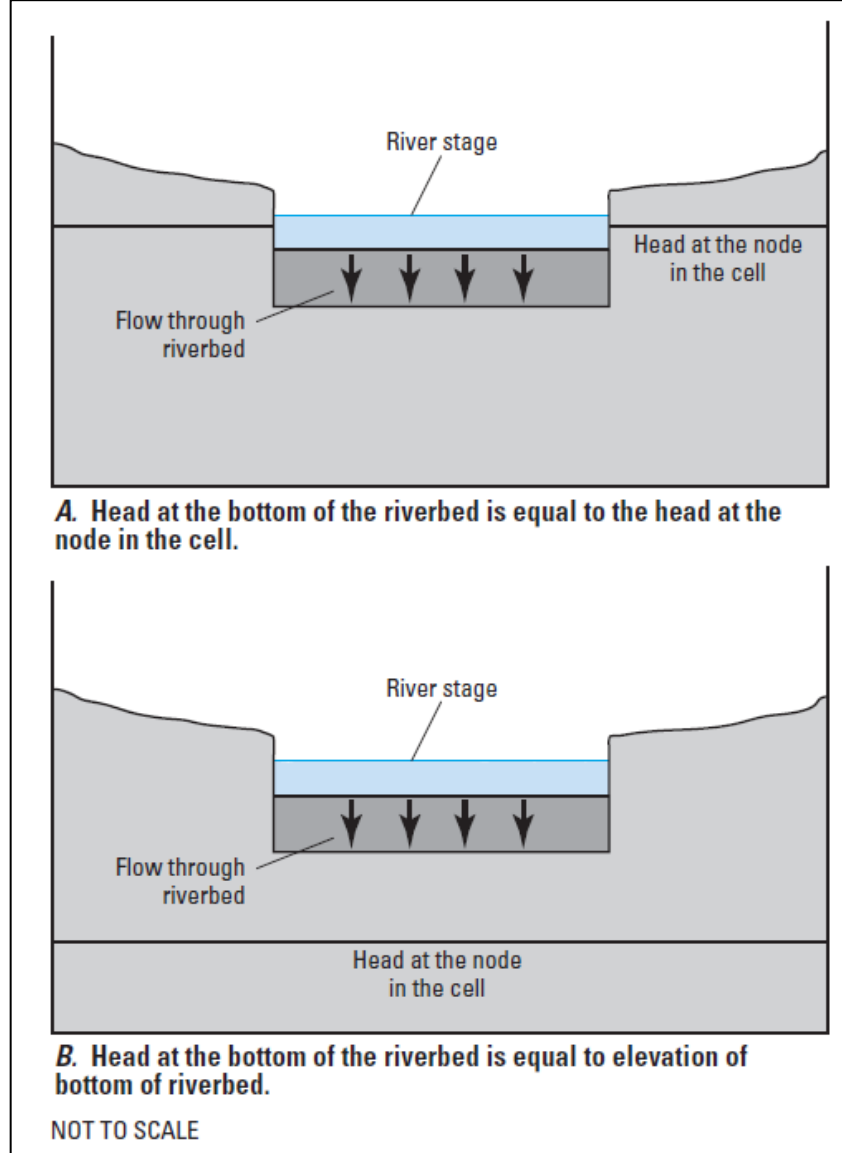


Figure 2.8. Cross sections showing the relation between the head at the bottom of the riverbed layer and the head in the cell. Head in the cell is equal to the water-table elevation (from Harbaugh, 2005).

The water transfer between the river and the underlying water table is direct without delay, and the flow rate does not exceed the saturated hydraulic conductivity of the deposits or rocks that occupy the interval between the riverbed and the water table.

Generally, such assumptions are reasonable when the unsaturated interval is thin or when long periods of steady (constant) flow are modeled and when the hydraulic gradient through the riverbed does not greatly exceed one.

MODFLOW code used these concepts in simulation of river-aquifer interaction; i.e. the flow among river and node n is simulated with the equation sets given below:

$$QRIV_{nb} = CRIV_{nb}(HRIV_{nb} - h_n) \quad h_n > RBOT_{nb} \quad (2.7a)$$

$$QRIV_{nb} = CRIV_{nb}(HRIV_{nb} - RBOT_{nb}) \quad h_n \leq RBOT_{nb} \quad (2.7b)$$

The terms constituting this set of equations are described in the previous equations (2.4), (2.5), and (2.6).

The conceptualization of river-aquifer interaction used in this work of thesis assumes that its independent from the location of the river branch in the cell and the location is uniform and constant for the whole river branch and for each stress period. So, the flow conditions do not vary during stress periods.

2.3.2.Recharge Package

This package is designed for simulate the spatially distributed recharge to groundwater system. The areal recharge occurs as a result of precipitation percolating to the groundwater system. The recharge applied to the model is defined as:

$$QR_{nb} = I_{nb}M_{nb}A_{nb} \quad (2.8)$$

Where QR_{nb} is the recharge flow value applied to the node n [L^3/T]; I_{nb} is the recharge flow [L/T] applicable to the map area (A_n) of the cell; and M_{nb} is a multilayer area (dimensionless) that can be used to scale I_{nb} (e.g. for altitude adjustment of rainfall data or to account for impervious areas in the cell).

The recharge flow values (I_{nb}) are specified by the user for each stress period. These values are multiplied by horizontal cells area (A_n) to obtain QR_{nb} . QR_{nb} is applied to cell containing the boundary recharge conditions nb , corresponding to groundwater system top and representing the uppermost of the vertical column (simplest case). Considering that the water table position can vary throughout space and time during a simulation, an additional option is required to apply the active recharge to the uppermost cell.

Typically, MODFLOW has three options for attributing recharge to the model: (i) apply recharge to layer 1; (ii) apply recharge to user-defined layer; (iii) apply recharge to uppermost active cell. The used version of MODFLOW has as a default option the third in the above list. For each option the recharge will never apply to constant head cells.

The *Recharge* Package can be used also for simulating recharge from sources different of rainfall (e.g., artificial recharge). Furthermore, it can simulate the discharge by specifying the negative values of recharge flow.

2.3.3. Well Package

This package was designed for the simulation of features regarding wells that pump or inject water to the groundwater system with a specific volume during a stress period. The volume is independent from both the area and the head of the cell. Also, this package can be used for the simulation of every feature for which can be specified the volumetric recharge and discharge values.

The flow rate ($QWEL$) for a well is specified by the user as a fluid volume per unit time at which water is added to the aquifer. Negative values of $QWEL$ are used to indicate well discharge (pumping), whereas positive values of $QWEL$ indicate an injection well. Several data value are required for each well such as the *cell-id* in which the well is located and the flow rate ($QWEL$) of the well. The wells are redefined each stress period.

The *Well* Package does not directly consider wells that are open to more of one node of the model. A common method for apportioning the well flow is to divide the flow rate according to the cell transmissivities, as follows:

$$\frac{QWEL_n}{QWEL_{nb}} = \frac{T_n}{\sum T'} \quad (2.9)$$

Where $QWEL_n$ is the flow rate from cell n to well nb [L^3T^{-1}], $QWEL_{nb}$ is the total flow rate for well nb [L^3T^{-1}], T_n is the transmissivity of the cell n [L^3T^{-1}] and $\sum T$ represents the sum of transmissivities of all nodes penetrated by the well [L^2T^{-1}].

2.4. MODPATH software

MODPATH is a post-processing particle tracking software designed for to work coupled with USGS MODFLOW code (Pollock, 1988). This software uses a semi-analytic scheme of particle tracking allowing to obtain an analytic expression of flow path of a single particle in each cell of the finite difference grid (Pollock, 2016). The particle path is calculated tracking the particle

from a cell to the next one until it does not reach a boundary, a sink/internal source or satisfy others terminating criteria (Fig. 2.9).

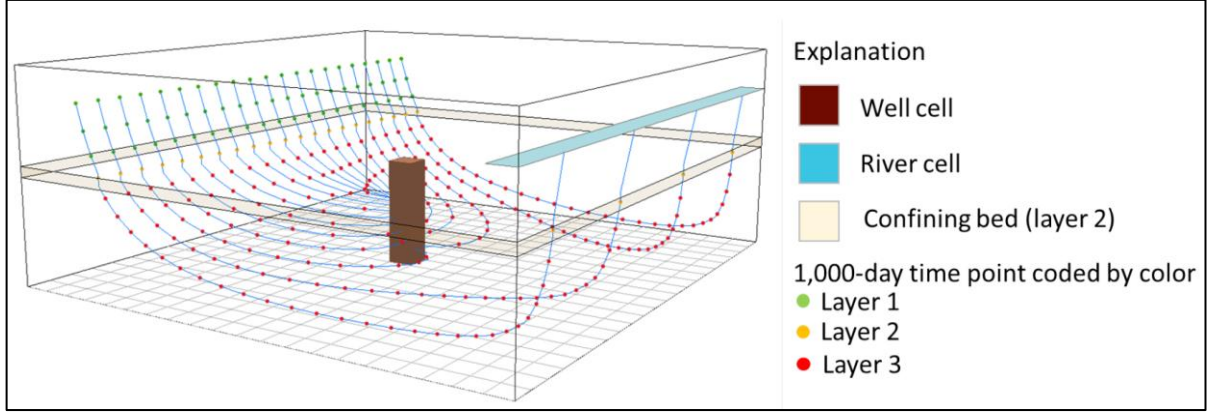


Figure 2.9.Three-dimensions MODPATH simulation with particles paths and temporal points (from Pollock, 2016).

MODPATH uses flow data contained in budget file generated by MODFLOW code elaborations to build the groundwater velocities (v). This parameter represents the basis for the calculation of the particles tracking. The software uses a simple linear interpolation for to calculate the three components (x , y , z) of velocity in the cell:

$$v_x = A_x(x - x_1) + v_{x_1} \quad (2.10a)$$

$$v_y = A_y(y - y_1) + v_{y_1} \quad (2.10b)$$

$$v_z = A_z(z - z_1) + v_{z_1} \quad (2.10c)$$

Where A_x , A_y , and A_z are the velocity gradient components in the cell:

$$A_x = \frac{(v_{x_2} - v_{x_1})}{\Delta x} \quad (2.11a)$$

$$A_y = \frac{(v_{y_2} - v_{y_1})}{\Delta y} \quad (2.11b)$$

$$A_z = \frac{(v_{z_2} - v_{z_1})}{\Delta z} \quad (2.11c)$$

Whereas a particle moves in grid cells, its components x , y , z change during time. For coordinates x , y , z of the particle in function of time we will have:

$$x_t = x_1 + \frac{1}{A_x} [(v_x)_{t_1} e^{A_x(t-t_1)} - v_{x_1}] \quad (2.12a)$$

$$y_t = y_1 + \frac{1}{A_y} [(v_y)_{t_1} e^{A_y(t-t_1)} - v_{y_1}] \quad (2.12b)$$

$$z_t = z_1 + \frac{1}{A_z} [(v_z)_{t_1} e^{A_z(t-t_1)} - v_{z_1}] \quad (2.12c)$$

In the equations (2.12) the subscripts t_1 and t are referred to location and velocity components of the particle in a specified time value. The velocity components of particle at t_1 time are known functions of particle coordinates; thus, the particle coordinated for each future time can be calculated directly from equations (2.12).

MODPATH software allow to track the particles in forward and backward direction, this latter is performed running the tracking algorithm in reverse mode (Fig. 2.10). The backward tracking is applied inverting the sign of all velocity components and then applying the algorithm as described for the forward case.

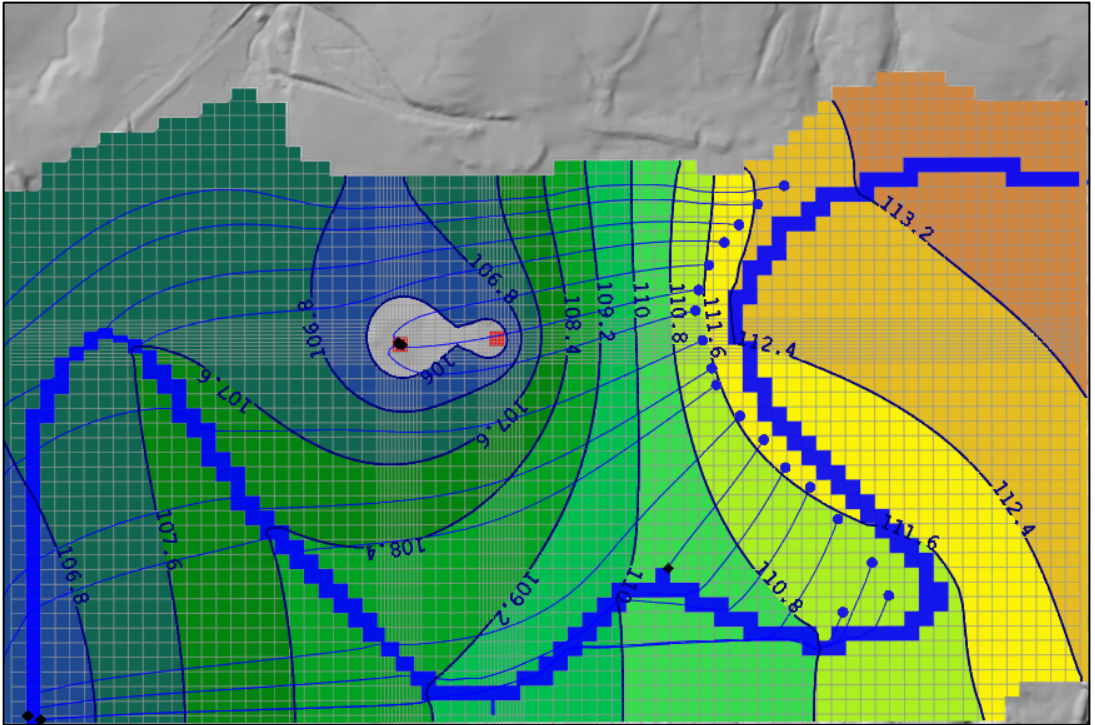


Figure 2.10. Example of forward tracking with the use of MODPATH software in a MODFLOW code simulation.

Particles are stopped whenever they reach points of termination or whenever the cumulative tracking time equals the maximum allowed value. A particle terminates when: (i) it reaches an external boundary face or an internal sink or source cell that captures the particle; (ii) it enters a cell with a zone code that designates the cell as a termination location; (iii) the cumulative tracking time has reached the maximum allowed value, or (iv) it encounters an abnormal condition that will not allow tracking to continue. In every case, MODPATH software continues to track particles until all particles have terminated.

The results of MODPATH software work are simulation files containing input data that define options for a specific MODPATH simulation, like: names of output files; tracking direction (forward or backward); simulation type or output options; location data and starting point of particle; options for the end of particle. Graphically the particle path will appear on the MODFLOW grid as a solid line terminating in a black point (Fig. 2.10).

2.5. Graphical User Interface: Processing MODFLOW

The Processing MODFLOW software is a simulation system for the groundwater flow and the transport processes modeling. The software was originally developed to support the first official release of MODFLOW. It includes the three-dimensional modular MODFLOW code of USGS (Mc Donald and Harbaugh, 1988), the particle tracking MODPATH software (Pollock, 1988), the solute transport model MT3D (Zheng, 1990), and the estimation of parameter PEST software (Doherty et al., 1994).

PMWIN uses a professional graphical user-interface, the supported models and programs, and several other useful modeling tools (Fig. 2.11). The graphical user-interface allows the easy creation and simulation of groundwater flow models (Chiang and Kinzelback, 1998).

It can import MODFLOW, MT3DMS (Zheng, and Wang, 1999), MT3D-USGS (Bedekar, et al., 2016), and SEAWAT (Langevin, et al., 2007) models from their native input data files; it can import model data from various data formats, including CSV, Shapefile, and ASCII Raster, etc., and it can export model results to raster graphics, shapefiles, charts, and/or text files. The supported model codes are consolidated to the latest official releases of model codes that are actively maintained at the time of writing, including MODFLOW-2005 (Harbaugh, 2005), SEAWAT (Langevin, et al., 2007), MODFLOW-NWT (Niswonger, et al., 2011), MODPATH (Pollock, 2016), MT3D-USGS (Bedekar, et al., 2016), PEST (Doherty, 2016), BeoPEST (Hunt, et al., 2010), and Zone Budget (Harbaugh, 1990).

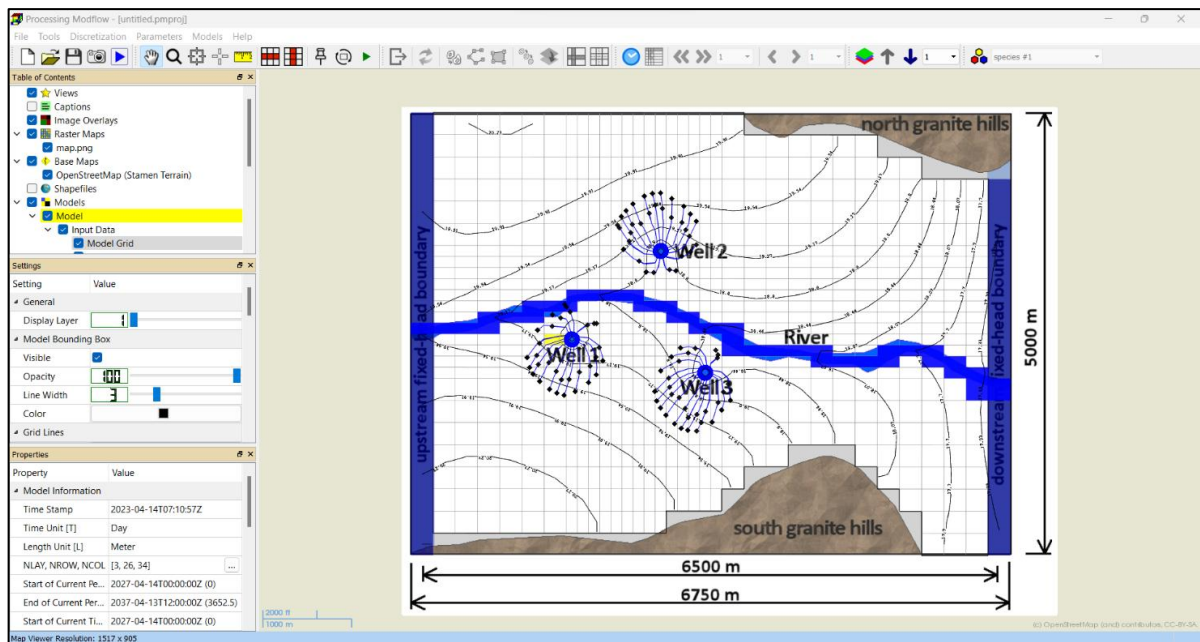


Figure 2.11. Screenshot of the main window of Processing MODFLOW X software.

The modeling tools include a Presentation tool, a Result Extractor, a Field Interpolator, a Field Generator, a Water Budget Calculator, and a Graph Viewer. The Result Extractor allows the user to extract simulation results from any period to a spread sheet. Simulation results include hydraulic heads, drawdowns, cell-by-cell flow terms, compaction, subsidence, Darcy velocities, concentrations and mass terms. The Field Interpolator takes measurement data and interpolates the data to each model cell. The model grid can be irregularly spaced. The Water Budget Calculator calculates the budget of user-specified zones and the exchange of flows between such zones. It allows the user to determine the flow through a particular boundary. The Field Generator generates fields with heterogeneously distributed transmissivity or hydraulic conductivity values. It allows the user to statistically simulate effects and influences of unknown small-scale heterogeneities. The Graph Viewer displays temporal development curves of simulation results including hydraulic heads, drawdowns, subsidence, compaction and concentrations.

Using the Presentation tool, labelled contour maps of input data and simulation results can be created. The model cells containing different values can be color-filled and quality graphics can be reported and may be saved to a wide variety of file formats, including SURFER, DXF, HPGL and BMP (Windows Bitmap). The Presentation tool can even create and display two-dimensional animation sequences using the simulation results (calculated heads, drawdowns or concentration).

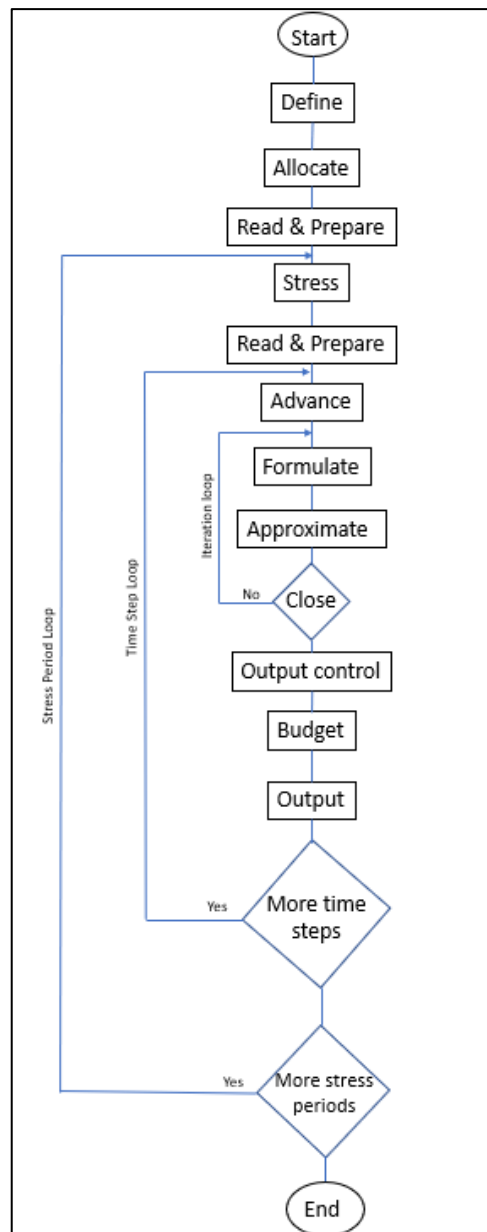


Figure 2.12. Flow diagram showing the modular structure of Processing MODFLOW X software.

Like MODFLOW code, Processing MODFLOW is a software based on finite difference solution method and simulate groundwater flow path both in two and three dimensions. This software contains a modular structure (Fig. 2.12) consisting in a main program and of several independent subroutines (called modules), in turn, grouped in packages. Packages supported by the software are (Tab. 2.1): *Basic* (BAS), *Block-Centered Flow* (BCF6), *Time Variant Specific Head* (CHD), *Direct Solver* (DE4), *Discretization* (DIS), *Drain* (DRN), *Drain with Return Flow* (DRT), *Evapotranspiration* (EVT), *Evapotranspiration with a Segment Function* (ETS1), *Flow and Head Boundary* (FHB), *General-Head Boundary* (GHB), *Generic Multi Grid Solver* (GMG), *Horizontal Flow Barrier* (HFB6), *Interbed-Storage* (IBS), *Lake Package* (LAK), *Layer-Property Flow* (LPF), *Flow-Transport Link* (LMT7), *Multi-Node Well 1* (MNW1),

Newton Solver (NWT), Output Control (OC), Preconditioned Conjugate Gradient Solver (PCG), PCG Solver with Improved Nonlinear Control (PCGN), Recharge (RCH), Reservoir (RES1), River (RIV), Streamflow-Routing (SFR2), Strongly Implicit Procedure Solver (SIP), Stream (STR), Subsidence and Aquifer-System Compaction (SUB), Seawater Intrusion 2 (SWI2), Upstream Weighting (UPW), Unsaturated Flow (UZF1), Well (WEL).

The maximum number of the cell constituting the model in x and y direction is of 120 (14,400 in total), whereas the maximum number of layers allowed is equal to 80.

Among the several modules constituting the software, importance assuming PEST and UCODE module. Their aim is to assist in data interpretation and in model calibration. If field or laboratory measurements are available, PEST and UCODE can adjust model parameters and/or excitation data in order that the discrepancies between the pertinent model-generated numbers and the corresponding measurements are reduced to a minimum.

Chapter 3: Numerical modeling of Benevento alluvial plain using Time Series Analysis and MODFLOW code

The groundwater flow path in the alluvial aquifer of the Benevento Plain, a major inland urbanized area of southern Italy, was analyzed through the use of cross correlation and numerical modeling (Leone et al., 2024).

Cross-correlation was employed to investigate the dynamic groundwater-surface water interactions. Coupled with time-frequency analysis via the Fast Fourier Transform, cross-correlation enabled the characterization of the groundwater level (GWL) response to changes in hydrodynamic level (HL) of the river.

The groundwater flow field was modeled through the use of the user-interface Processing MODFLOW X software, a simulation system for modeling the groundwater flow and transport processes based on MODFLOW code (Mc Donald and Harbaugh, 1988). A parsimonious approach was adopted in the design of the numerical model to reduce uncertainty, which considers a limited number of parameters and only relevant hydrological processes controlling groundwater circulation (aquifer-river interaction, effective meteoric recharge, and pumping).

Continuous water table monitoring was carried out in a piezometer located near to the pumping well supplies water to the city. It is pumped at a constant rate $Q = 0.06 \text{ m}^3/\text{s}$ for approximately 16 hours and is discharged for approximately 8 hours. Therefore, the information for the steady state model calibration was obtained by analyzing the 5-minute time-series of Groundwater Level, which shows a daily drawdown-recovery cycle due to intermittent pumping activity in the area (Fig. 3.1). In detail, coupling the Theis's equation (Theis, 1952) and inverse modeling, the actual drawdown that the water table would attain at the end of recovery phase was predicted.

Also, the coupling of time series analysis and numerical modeling allowed the identification of factors directly affecting the aquifer stage and circulation. In the Benevento Plain, the river appears to be the primary driver of groundwater processes, while meteoric recharge has a negligible impact. This result provides crucial information for managing and protecting local groundwater resources, which have been affected by contamination several times in recent years, raising questions about the origin of contaminant.

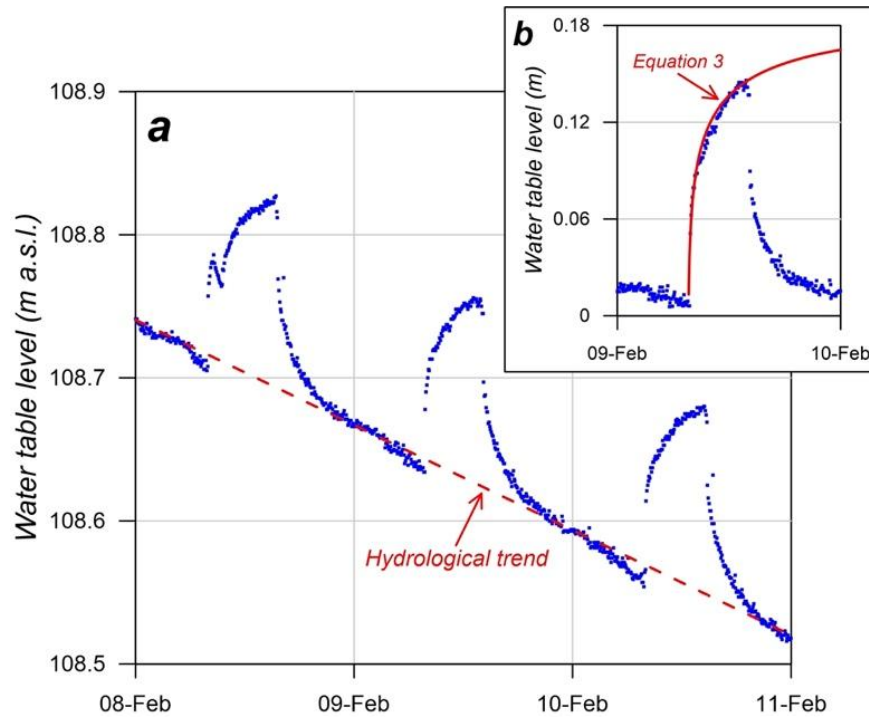


Figure 3.1. (a) 5-minute time series of water table levels measured by piezometer, period 8-10 February 2023; hydrological trend shown by red dashed line. (b) Detail of the detrended time series (obtained by subtracting the hydrological trend); the red curve represents the model during the recovery phase of the water table (from Leone et al., 2024).

3.1. Time series analysis

Time series analysis considered daily data of river hydrometric level (HL) and groundwater level (GWL) (Fig. 3.2a).

The cross-correlation was used to measure the statistical relationship, or similarity, between time series. In general, cross-correlation enables the estimation of the sample cross-correlation function $r_{xy}(k)$, CCF, which describes the degree of linear correlation between a time variable x and the lagged version of another time variable y as a function of the time lag k introduced between x and y (Box et al., 2016). The CCF varies between -1 and +1, and for a given lag k , its value corresponds to the ordinary Pearson's correlation coefficient.

In data-driven modeling, cross-correlation is employed to find the linear transfer function describing the dynamic relationship between input x and output y .

Both the raw and processed data were considered in the cross-correlation analysis. Data processing involved two steps:

- (i) A second-order polynomial function was fitted and removed from the data to reduce bias in the correction analysis due to the long-term trend component (Fig. 3.2b);

- (ii) A Fourier series was fitted to the detrended data using the Fast Fourier Transform (FFT) (Fig. 3.2c).

Since an alluvial aquifer acts as a low-pass filter, smoothed time series were reconstructed by filtering off high-frequency signals estimated by the FFT. The cutoff frequency separating low- to high-frequency signals was equal to $f_c = 0.0363 \text{ day}^{-1}$. This value was selected based on the visual inspection of the GWL time series Fourier spectrum, which enabled the identification of the frequency components that significantly contributed to the time series (Fleming et al., 2002). In the specific case of GWL in Benevento Plain, the dominant signals in time series have a frequency lower than 0.0363 day^{-1} . Fourier spectra also highlighted that the dominant signal in both detrended HL and GWL time series has a frequency of 0.008065 1/day .

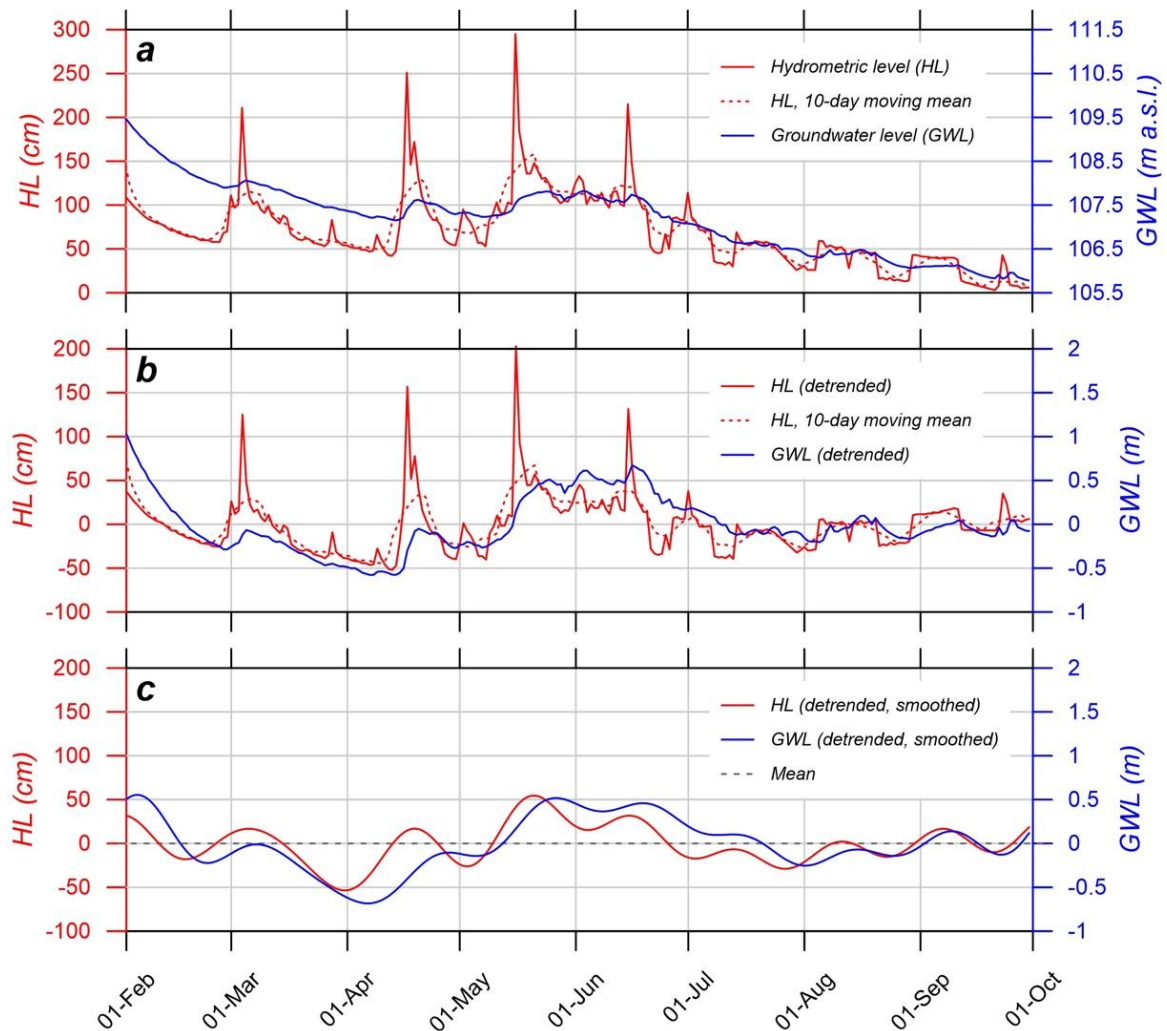


Figure 3.2. Raw and processed daily hydrological time series for the period February-September 2023. (a) Maximum (raw) daily groundwater level (GWL) and (raw) daily hydrometric level; (b) detrended time series; (c) detrended smoothed time series obtained by filtering out those signals having a frequency higher than f_c . The dashed lines represent the centered 10-day moving mean, which is a symmetric linear low-pass filter (from Leone et al., 2024).

Cross-correlation allowed to quantify the similarity in HL and GWL time series structures (Fig. 3.2b and c). The results of the analysis (Fig. 3.3) show that the detrended GWL is positively correlated with the detrended HL (curve c1 in Fig. 3.3), since the CCF shows a clear correlation peak $r_{xy}(k) = 0.59$ at a lag $k = 2$. A higher correlation peak $r_{xy}(k) = 0.77$ was found between the GWL and the 10-day moving mean of HL (curve c2 in Fig. 3.3) due to the filtering effect of the alluvial aquifer, modeled by the moving mean operator.

The CCF between the filtered (smoothed) time series (curve c3 in Fig 3.3) shows a correlation peak $r_{xy}(k) = 0.82$ at a lag $k = 4$ days, highlighting a very high degree of similarity between the structures of the filtered HL and GWL time series.

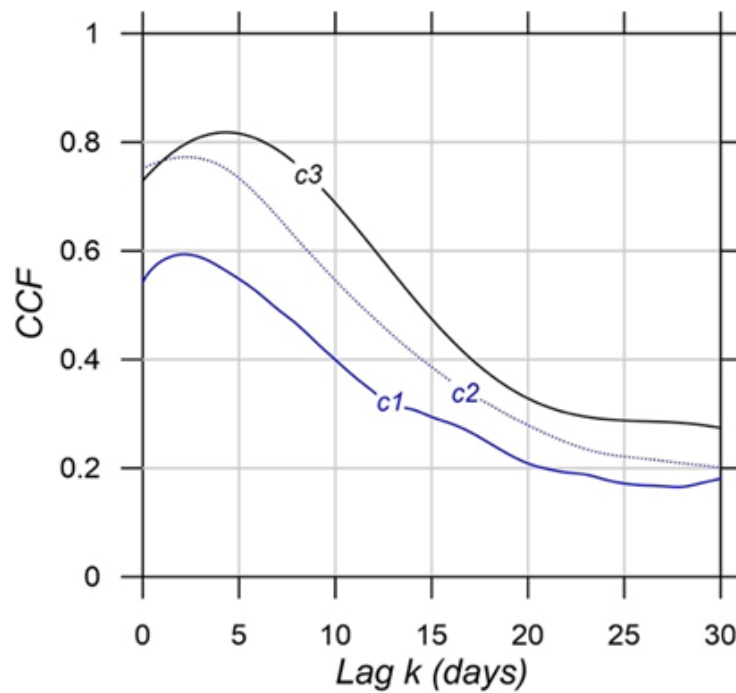


Figure 3.3. Cross-correlation functions, CCF, between time series shown in Fig. 3.2b and c. Curve c1: CCF between detrended HL and GWL; curve c2: CCF between 10-years moving mean of detrended HL and detrended GWL; curve c3: CCF between detrended filtered time series of HL and GWL (from Leone et al., 2024).

The time series analysis suggests that there is a strong correlation between the low-frequency variability in river stage and groundwater level variability. This implies that the river and the aquifer are hydraulically connected. In particular, the alluvial aquifer acts as a low-pass filter producing damping and delayed GWL fluctuations in response to changes in the river stage.

The strong correlation between the river hydrometric level and groundwater level could also be explained by the fact that the river and the aquifer respond to the same meteorological input. However, this hypothesis is excluded because meteoric (direct) recharge has a negligible

influence on groundwater circulation as demonstrated by the following modeling with MODFLOW code.

It must be stressed that most studies assume rainfall to be the main driver of GWL variability, and statistical analysis usually focuses on rainfall and GWL data (Leone et al., 2024). However, in the case of Benevento Plain aquifer, the main direct driver of groundwater circulation is the river, whose hydrological stage responds to precipitation falling across a vast watershed much wider than the Benevento Plain.

3.2. Hydraulic characteristics of the alluvial aquifer

The hydraulic conductivity K , or the transmissivity T , of an unconfined aquifer can be determined by numerical model calibration or by applying the analytical equations of Dupuit and Theis (Custodio and Llamas, 2005).

Theis's equation (Theis, 1952) permits the computation of $T = KH$, where H is the aquifer thickness, from the observation of the rate of recovery of a discharged well. The latter equation involves a quantity called residual drawdown, which represents the distance the water table lies below its equilibrium position.

Conversely, Dupuit's equation (Dupuit, 1863) relates K to the water table drawdown attained in the aquifer when a well is pumped at a constant rate Q .

In general, pumping tests are performed to determine the actual water table drawdown and recovery curve.

3.2.1. Water table drawdown-recovery

Data obtained from continuous groundwater monitoring were used to predict the actual water drawdown caused by a constant pumping rate, Q . In particular, using Theis's equation (Theis, 1952), the functional form describing the water table recovery phases observed at the end of each pumping cycle was derived. The equation parameters were then found via inverse modeling.

Daily drawdown-recovery cycles can be seen in the detrended GWL time series (Fig. 3.1). The well W pumps for approximately 16 hours, and when the pump is shut down, the water table in piezometer P starts to rise. The pumping is reactivated after approximately 8 hours, that is, before the water table reaches the equilibrium condition.

According to Theis (1935), the residual drawdown $s(t)$ is a function of time t and depends on the pumping rate Q and transmissivity T :

$$s(t) = b \ln \left(\frac{t + c}{t} \right) \quad (3.1)$$

Where b and c are constants and t is the elapsed time since the cessation of pumping. In particular, $t + c$ is the elapsed time since the start of pumping, while b is (Custodio and Llamas, 2005):

$$b = \frac{1}{4\pi} \frac{Q}{T} \quad (3.2)$$

Note that b is unknown if T is unknown.

Thus, to model the water table recovery phase observed at the end of each pumping phase an equation can be derived (Fig. 3.1b):

$$h(t) = a - b \ln \left(\frac{t + c}{t} \right) \quad (3.3)$$

Respectively, $h(t)$ and a are the levels at any instant t and the equilibrium condition (complete recovery) measured from a zero reference. The complete recovery is attained at $t = \infty$ and is unknown because the coefficient a is unknown.

3.2.2. Hydraulic conductivity by Dupuit's method

The possible range of K was inferred using Dupuit's equation (Terzaghi et al., 1996):

$$K = \frac{Q}{\pi(h_2^2 - h_1^2)} \ln \left(\frac{r_2}{r_1} \right) \quad (3.4)$$

Where Q is the pumping rate and h_2 and h_1 are the water levels measured at two piezometers located at a radial distance r_1 and r_2 from the well ($r_2 > r_1$), respectively.

For the boundary condition $h_2 = H$ where H is aquifer thickness, r_2 is equal to the cone of depression radius R . The quantity $(H^2 - h_1^2)$ can be written as:

$$(H^2 - h_1^2) = (H - h_1)(H + h_1) \quad (3.5)$$

If the water drawdown $\Delta h = (H - h_1)$ is negligible compared to H , then $H = h_1$, and the equation (3.4) can be rewritten as follows:

$$K = \frac{Q}{2\pi H \Delta h} \ln \left(\frac{R}{r_1} \right) \quad (3.6)$$

In the case of Benevento alluvial plain, the well-river distance represents the maximum possible value of the cone of depression radius R . Particularly, was assumed that the river limits the

maximum cone expansion and that Δh (0.19 m) is negligible compared to the aquifer thickness H (80 m). On these assumptions, K is on the order of 10^{-3} m/s (Fig. 3.4).

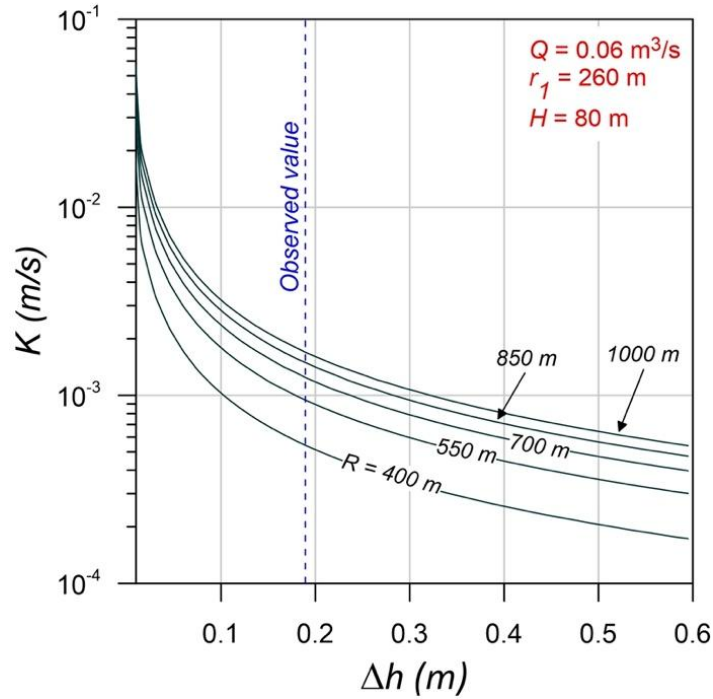


Figure 3.4. Relations between hydraulic conductivity, K , and water table drawdown, Δh , into piezometer (Eq. 3.6), for different values of depression cone radius, R (from Leone et al., 2024).

In the case of Benevento Plain, the river represents a strong hydrological boundary limiting the expansion of the depression cone. Therefore, the cone radius R does not exceed the well-river distance. In Dupuit's equation, the hydraulic conductivity K depends on the logarithm of R ; thus, for a large R , the hydraulic conductivity is merely sensible to this parameter (Fig. 3.4). Consequently, K can be estimated assuming that R equals the well-river distance. This condition makes estimating R easier and represents a possible criterion for assessing hydraulic conductivity when the actual R value is unknown. These assumptions are also confirmed by simulations experiments that clearly showed that the cone depression cannot expand beyond the river.

3.3. Numerical modeling of the aquifer

The modelled aquifer is $3000 \times 2000 \text{ m}^2$ wide and 80 m thick. It was discretized into two layers made of cubes with an edge length of 40 m, classified as “convertible types”. Grid discretization increased in the area surrounding the pumping well and the piezometer. The top of the first layer has an elevation of 120 m a.s.l., which is the mean ground elevation of the area. The elevation of the bottom of the first and second layer and that of the top of the second layers were deducted

by the difference between the value of top of the aquifer and the overall aquifer thickness. Assuming the hypothesis of a completely isotropic and homogeneous mean, the vertical and horizontal hydraulic conductivities were set equal to 0.0015 m/s, as deducted from scientific literature (Celico et al., 1998). The model simulations and calibrations were performed under steady-state conditions.

Simulations experiments were carried out to calibrate the equivalent aquifer hydraulic conductivity following the procedure discussed in the sub-section 3.3.1.

The presence of aquiclude to the north and the Calore River was taken into account to define the boundaries of the model. The topographic elevation of the measuring sites and riverbed were estimated from a 5-m DEM (Digital Elevation Model) using a GIS (Geographic Information System) software. Estimated elevations were furtherly validated based on official 1:5000 topographic maps (Regional Technical Chart of Campania Region) of the area. Constant head boundary conditions were defined at the easternmost (116 m a.s.l.) and westernmost (106 m a.s.l.) sides of the model domain. Impermeable deposits bound the alluvial aquifer to the north and the cells along this side were classified as no-flow cells. All the other cells were classified as variable head cells.

Regarding aquifer-river interactions, the streambed represents the primary interface between groundwater and surface water (Brunner et al., 2017), even though fluxes can also occur through river banks (Di Ciacca et al., 2019). Generally, this last process is overlooked when modeling local or regional aquifer, and groundwater-surface water interactions are simulated using the MODFLOW *River* Package (Martínez-Santos et al., 2010; Cousquer et al., 2017; Omar et al., 2020; Zhou et al., 2022), which assumes head-dependent fluxes controlled by the thickness and vertical hydraulic conductivity of streambed deposits. In this modeling procedure, the model described above was adopted, given that the water level in the Calore River is much smaller than the mean channel width, and aquifer-river fluxes should primarily occur through the streambed.

The morphometric features of Calore River, namely, the channel gradient and width, were calculated from a 5-m Digital Elevation Model and georeferenced Google Earth Satellite Images using a GIS. The hydraulic features of streambed were taken from the available literature (Celico et al., 1998; Senatore et al., 2019).

The *Well* package allowed to analyze the water table drawdown due to pumping wells, and the water withdraw of 0.06 m³/s was applied to the lowest layer.

Finally, the *Recharge* Package was used to simulate the distributed (meteoric) recharge to the aquifer, which was only applied to the top model layer. Meteoric recharge has been estimated through a model (Fiorillo et al., 2015b) involving the sum of the positive differences between the total precipitation P and potential evapotranspiration E from October to April (0.3 m), and by subtracting the soil moisture retention (0.1 m). Meteoric recharge has been estimated 0.2 m/year (Fig. 3.5). Considering the low topographic gradient characterizing the alluvial plain, the runoff can be neglected. In addition, torrents confluences to the Calore River are located upstream and downstream modelled area.

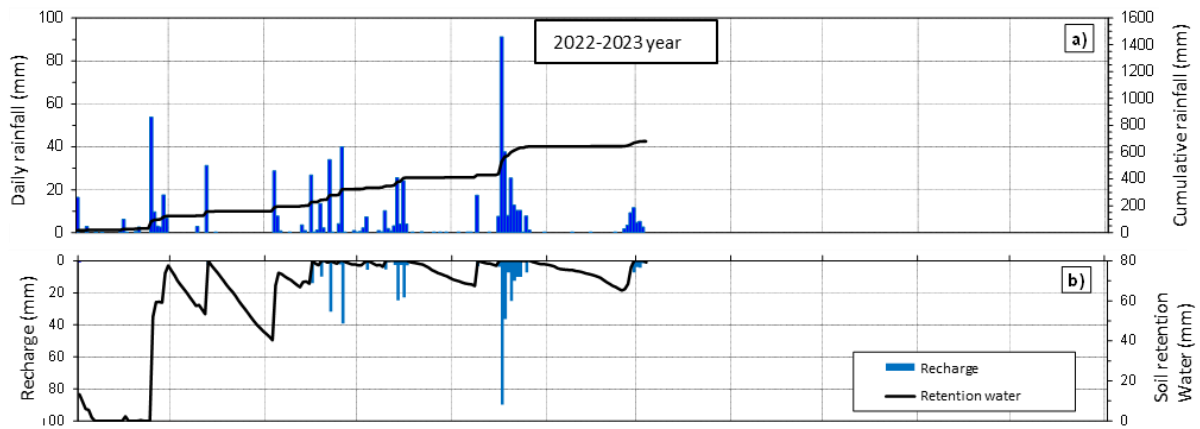


Figure 3.5. (a) Daily rainfall recorded by Benevento rain-gauge (2022-2023 year); (b) daily recharge and soil retained water simulations in Pezzapiana area.

3.3.1. Model calibration

Model calibration involves adjusting the value of K until a reasonable match between the observed and simulated water table drawdown is obtained (Fig. 3.6).

To determine the theoretical relationship between aquifer hydraulic conductivity, K , and induced water table drawdown, Δh , in piezometer, P , simulation experiments under steady-state conditions were performed (Pagnozzi et al., 2020). Five simulations were run assuming identical model boundary conditions but different values of K (from 1×10^{-4} to 1.05×10^{-2} m/s).

For different values of K , figure 3.6a-d shows the simulated water table lowering observed when the well W is pumped at a constant rate ($Q = 0.06 \text{ m}^3/\text{s}$). Note that the figure does not show the simulation for $K = 1 \times 10^{-2}$ m/s. It can also be seen that the cone of depression radius does not expand beyond the river.

Figure 3.6e illustrates the theoretical relationship between K and Δh , which is described by a power function. For $\Delta h = 0.19$ m, the aquifer hydraulic conductivity is 1.05×10^{-2} m/s, which

is within the range predicted using equation (3.6) (Fig. 3.4). Given the scale of the model, the calibrated value of K represents the equivalent hydraulic conductivity of the aquifer formation (Domenico and Schwartz, 1997). This is a widely adopted parameter in modeling practice to describe the hydraulic characteristics of heterogeneous alluvial aquifer formations (Martinez-Santos et al., 2010; Anderson et al., 2015).

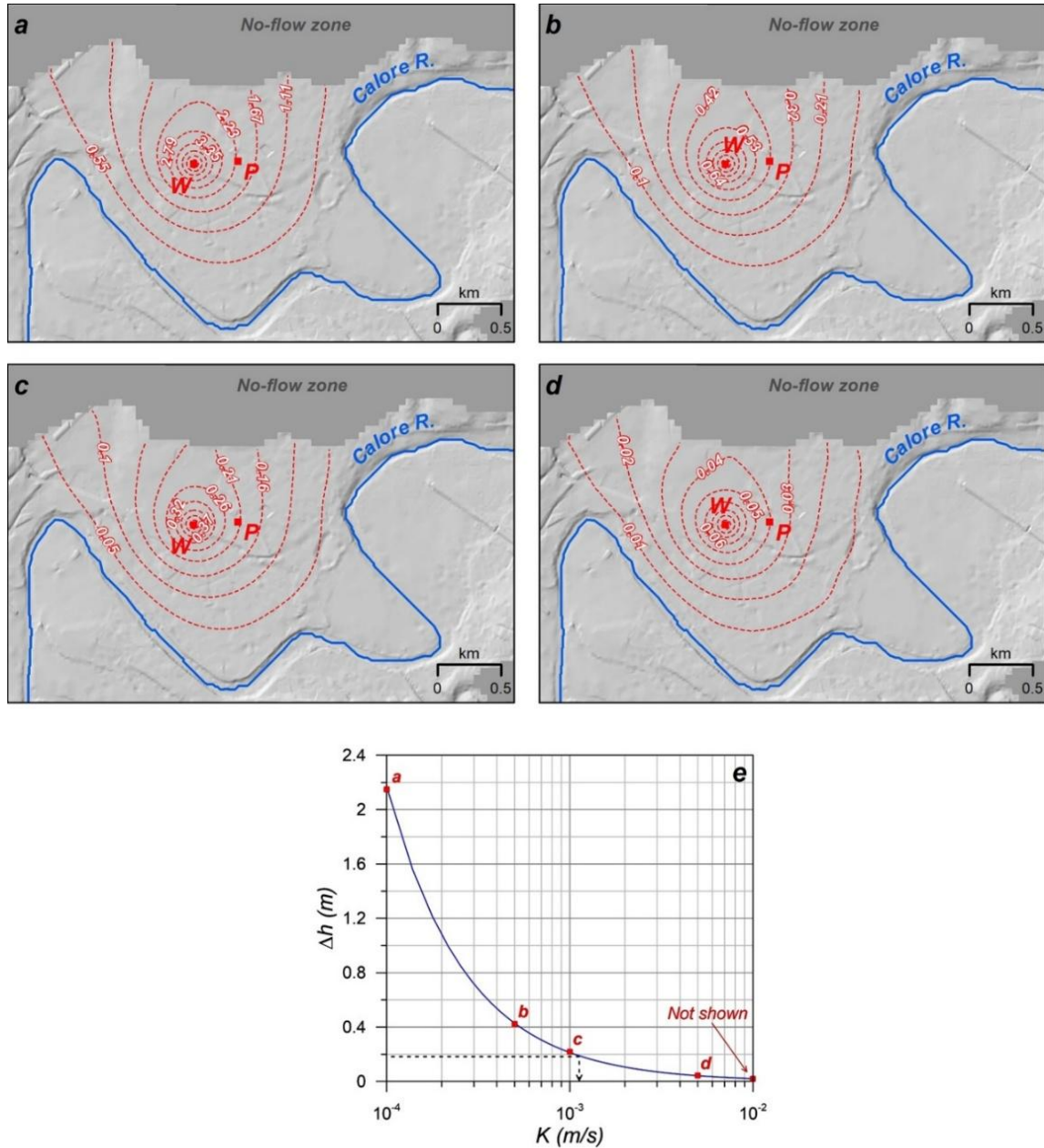


Figure 3.6. Groundwater head losses (red contours; values are expressed in meters) for different values of the hydraulic conductivity, K , induced by a constant pumping rate of $0.06 \text{ m}^3/\text{s}$, under steady state conditions. (a) $K = 10^{-4} \text{ m/s}$; (b) $K = 0.5 \times 10^{-3} \text{ m/s}$; (c) $K = 10^{-3} \text{ m/s}$; (d) $K = 0.5 \times 10^{-2} \text{ m/s}$. The basemap is represented by a shaded terrain model of the area. (e) Simulated hydraulic head losses, Δh , into piezometer P , for different hydraulic conductivities, K (simulations are shown in a, b, c and d). The observed $\Delta h = 0.19 \text{ m}$ is obtained for $K = 1.05 \times 10^{-2} \text{ m/s}$ (from Leone et al., 2024).

3.3.2. Groundwater circulation

The calibrated model was used to analyze the influence of pumping and effective meteoric recharge on groundwater circulation (Fig. 3.7).

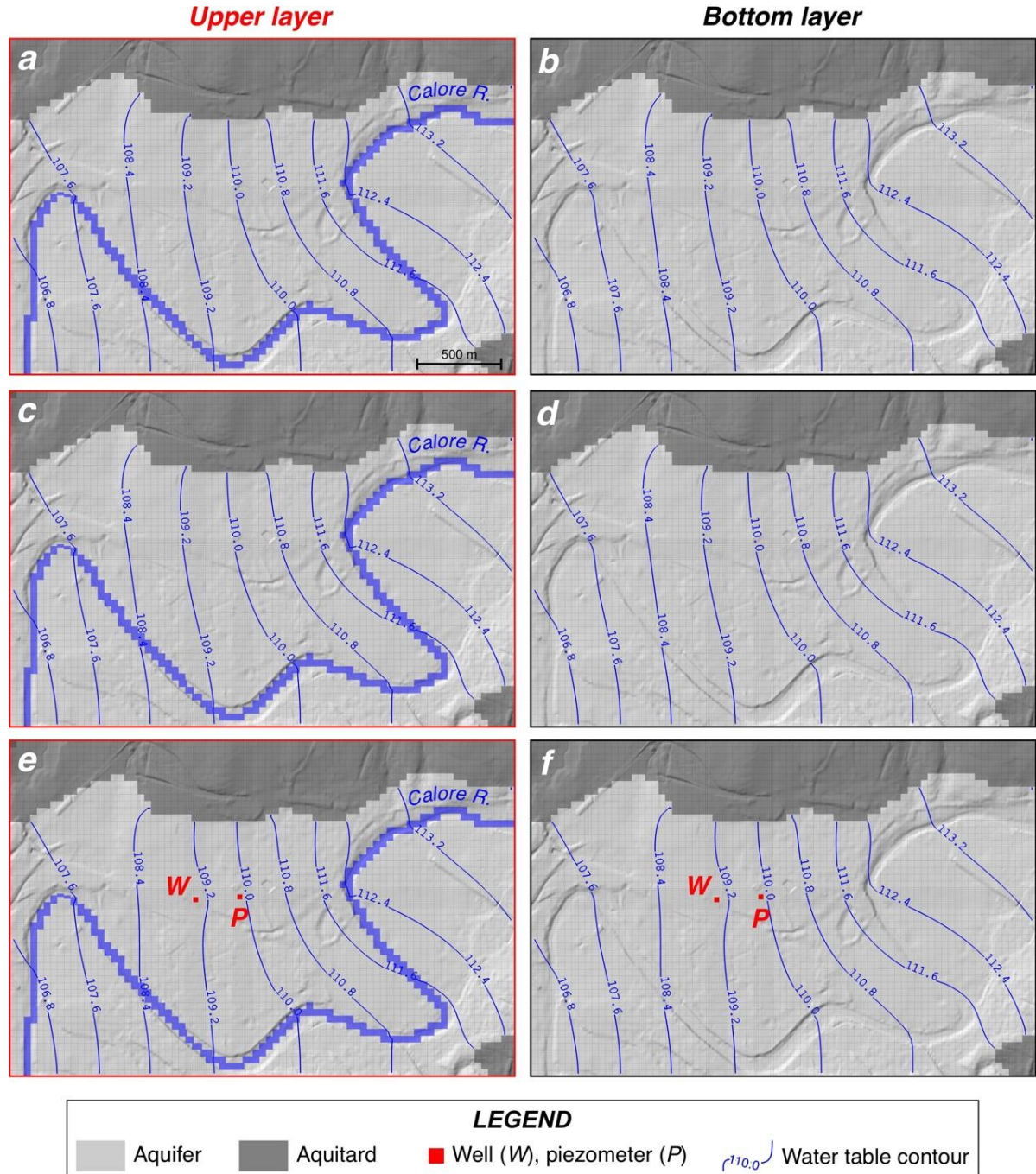


Figure 3.7. Hydraulic head distribution (in m a.s.l.) obtained for $K = 1.05 \times 10^{-3}$ m/s. Model results are shown for the upper layer (a), (c), and (e) and lower layer (b), (d), and (f), without meteoric recharge and pumping (a, b), with meteoric recharge of 0.2 m/year and no-pumping (c, d), with meteoric recharge of 0.2 m/year and pumping of 0.06 m³/s (e, f) (from Leone et al., 2024).

In figure 3.7a-b, the pumping rate and the meteoric recharge are null. In this case, the water table progressively lowers westward, and the aquifer-river interaction affects the background groundwater flow. In figure 3.7c-d, a recharge rate equal to 0.2 m/year and no pumping have been considered. The effective meteoric recharge has no significant effect on groundwater flow. In figure 3.7e-f, a recharge rate equal to 0.2 m/year and a constant pumping rate constant rate of $Q = 0.06 \text{ m}^3/\text{s}$ have been considered. The effect of the well, causing a local water table drawdown, is visible in the deformation of the hydraulic head contour near it (Fig. 3.7 e, f).

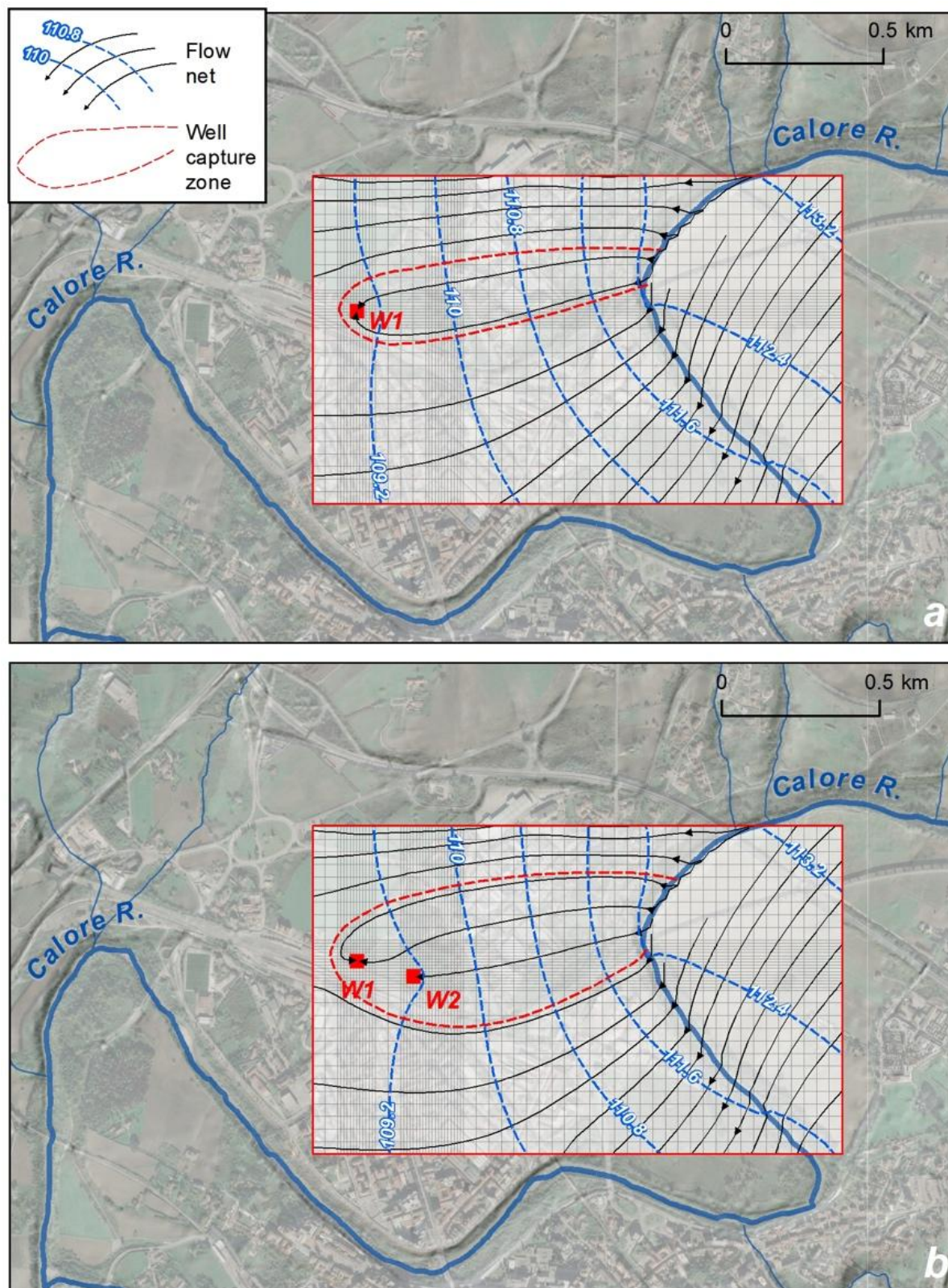
The influence zone, i.e., the region where the water level decreases due to pumping, is limited due to the river, and the inflow to the well comes primarily from the upstream area.

The numerical model highlighted that the river is the primary natural conditioning element of groundwater flow, and the effect of meteoric recharge is negligible. The high hydraulic conductivity of alluvial sequences and streambed would favor water exchanges between groundwater and surface water systems. The alluvial succession consists of ancient fluvial plain deposits alternating with channel levee and channel deposits. The buried river channel deposits are characterized by a higher permeability than the surrounding materials and represent a preferential path for groundwater flow. Considering the model scale, however, the alluvial succession was assumed to be a single homogeneous aquifer formation with an equivalent hydraulic conductivity.

The analysis carried out highlighted that the well receives water inflows from the river (Fig. 3.8a), which provides for the continuous replenishment of the aquifer, allowing for its constant exploitation. As observed in other narrow alluvial plains (widths of a few tens of meters to kilometers), the groundwater flow in area is down-plain. Due to the background flow, river-aquifer interaction, and impermeable deposits to north, the capture zone of the well is elongated in the upgradient slope direction of the water table (Fig. 3.8a).

In some cases, a second well is activated, and the total pumping discharge increases to $0.12 \text{ m}^3/\text{s}$. Under such conditions, the width of the capture zone increases (Fig. 3.8b).

The direct aquifer-river interaction is enhanced when a second well is pumped, raising several warnings about water resources protection. Indeed, although the capture zone has a relatively limited extension, the river flow may transport contaminants from a remote region to the aquifer. Therefore, the quality of the pumped groundwater strongly depends on the filtering capacity of the alluvial deposits interposed between the river and wells.



Chapter 4: Groundwater monitoring system, meteorological, hydrological, and historical data

This chapter deals with the monitoring instrument used and with the collecting techniques and sources of meteorological, hydrological, and historical data. Also, will be described the software used in drawing maps and performing analysis.

4.1. Continuous monitoring system with TD Diver

The TD-DiverTM is a compact, groundwater monitoring instrument for continuously measuring level and temperature in groundwater, surface water, and industrial waters. Data collected can be used to manage water resources, estimate hydraulic conductivity and other aquifer parameters ([Van Essen, 2018](#)).

These sensors are easy-to-use dataloggers and a robust high precision pressure sensor for long term accuracy. The absolute pressure sensor for long term accuracy.

The Diver is a datalogger housed in a cylindrical casing with a suspension eye at the top (Fig. 4.1). This latter can be unscrewed and is designed to install the instrument in the monitoring well. Also, the suspension eye protects the optical connector. The electronics, sensors and battery are installed maintenance-free into the casing. However, the diver is not designed to be opened.



Figure 4.1. Photo of a generic TD Diver sensor.

Based on the physical parameter measured (temperature, groundwater level, electrical conductivity), several modes of diver exist. The principal typologies of diver produced are those measuring temperature and depth of water table, called TD-Diver, and those that measure also electric conductivity, the CTD-Diver. In this work of thesis, the diver used for monitoring of groundwater was the TD-Diver model. The main technical features of the diver, regarding water column measured range, and maximum and typical accuracy are showed in table 4.1.

TD-Diver	Diver model				Unit of measurement
	<i>DI801</i>	<i>DI802</i>	<i>DI805</i>	<i>DI810</i>	
Water column measure range	10	20	50	100	mH ₂ O
Accuracy (max)	±2.0	±4.0	±10.0	±20.0	cmH ₂ O
Accuracy (typical)	±0.5	±1.0	±2.5	±5.0	cmH ₂ O
Long-term stability	±2.0	±4.0	±10	±20	cmH ₂ O
Resolution	0.2	0.4	1	2	cmH ₂ O
Display resolution	0.058	0.092	0.192	0.358	cmH ₂ O
Overload pressure	15	30	75	150	cmH ₂ O

Table 4.1.Main technical features of TD-Diver sensor ([Van-Essen, 2018](#)).

The TD-Diver is a datalogger designed to measure water pressure and temperature. Measurements are subsequently stored in the diver's internal memory. The diver consists of a pressure sensor measuring water pressure, a temperature sensor, and a battery that powers the electronics that collect and stores the measurements.

The instrument measures the absolute pressure, meaning that the sensor measures both water and the air pressure pushing on the water surface. So, when there is a variation in the air pressure, the measured pressure will also vary, without any variation of the water level. The air pressure can be measured by the installation of a Baro-Diver and subsequently be used in the Diver-Office software to convert the Diver pressure into water table level data.

4.1.1. Water level measurement

The diver sensors determine the height of the water column above the sensor by measuring the water pressure using the built-in pressure sensor. When the diver is not submerged in water it measures the atmospheric pressure, just like a barometer. Once the diver is submerged, the air pressure is supplemented by water pressure; thus, higher the water column the higher the measured pressure. The height of the water column above the diver's pressure sensor is determined based on measured pressure.

To measure these variations a compensation with barometric data is necessary. This procedure can be carried out using a Baro-Diver sensor installed in the same area of TD-Diver or through data provided by instruments installed by regional and national authorities.

The groundwater level (in m a.s.l.) is given by:

$$GWL = (H - L_{cab}) + (P_{GW} - P_A) \quad (4.1)$$

where H is the ground elevation (in m a.s.l.), L_{cab} is the length of the cable used to install the sensor into the piezometer (in m), P_{GW} is the water column pressure (in mH₂O) and P_A is the atmospheric pressure (in mH₂O).

The true cable length can be estimated by manually measuring the groundwater depth, D_{GW} , by a piezometric probe ($L_{cab} = D_{GW} + P_{GW}$).

4.1.2. Temperature measurement

TD-Divers measure also temperature values. For example, this data can provide information about the groundwater flows.

Temperature is measured using a semi-conductor sensor. This sensor measures temperature value and, at the same time, compensate the pressure sensor and electronics for the effect of temperature to ensure the best possible performance.

4.1.3. Diver Office user-interface

The diver sensor must be programmed with the desired sample method and interval, and monitoring point name before it is deployed. These sensors can be programmed, stopped and their data read using the Diver-Office software (Fig. 4.2). Once the software is installed, a diver can be connected to the computer through a USB reading unit.

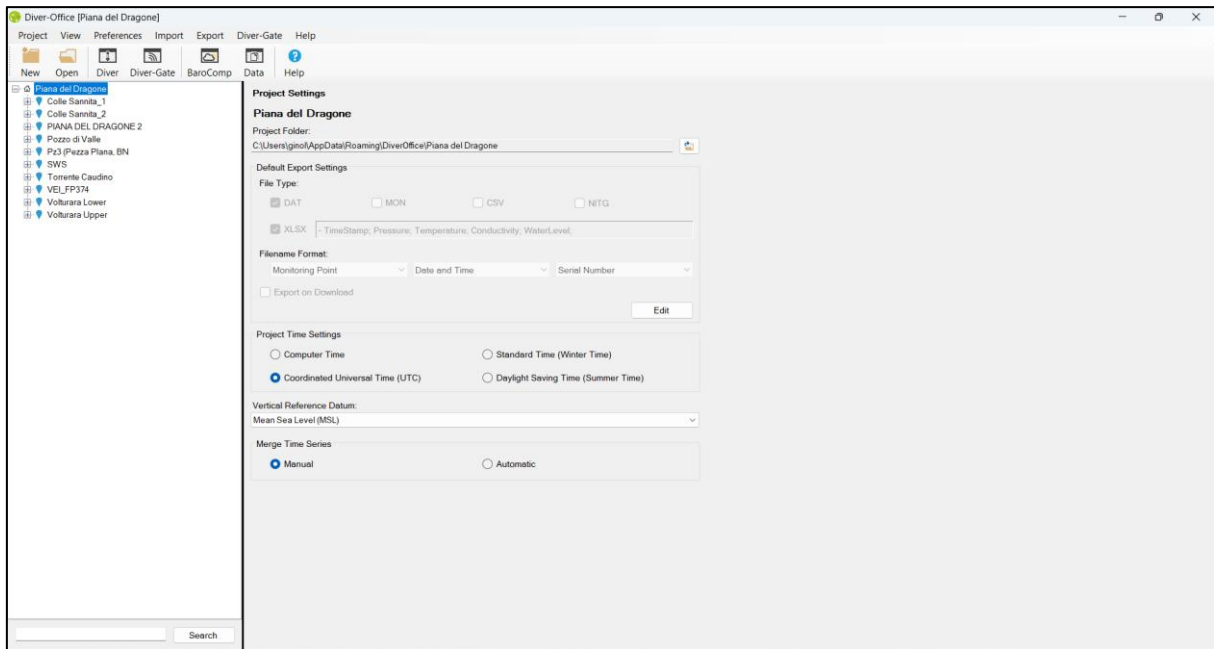


Figure 4.2. Screenshot of the user-interface used for the programming and downloading of data from diver sensor.

4.1.4. Installation in study areas

Two TD-Diver sensors were installed in the study area (Fig. 4.3; Tab. 4.2). A diver was installed in a piezometer located inside Benevento alluvial plain (Fig. 1.24), in a piezometer located about 260 m far from the pumping well. The other sensor was installed in a dismissed aqueduct well located on the reliefs bordering the polje of Dragone Plain (Fig. 1.16), about 1.3 km far from the Dragone Mouth ponor.



Figure 4.3. Diver sensors installation in (a) Benevento plain and (b) Dragone plain piezometers.

Location	Elevation of the ground surface (m a.s.l.)	Elevation of the diver sensor	Sample period (years)	Sampling frequency
Benevento alluvial plain	128.6	108.4	February- September 2023	5 minutes
Dragone Plain polje	734.0	501.4	October 2021- Nowadays	3 hours

Table 4.2. Main features of diver installed in study areas.

Diver data have been compensated with barometric measurements from the nearest stations of Benevento and Montella. The main features of these stations are listed in table 4.4.

4.2. Meteorological and hydrological data

The meteorological data were collected by national databases available.

In detail, precipitation and temperature data referred to 1970-2000 year period (Tab. 4.3) were taken by historical database of National Hydrographic and Mareograph Service, SIMN (available at <https://www.isprambiente.gov.it/it/progetti/cartella-progetti-in-corso/acque-interne-e-marino-costiere-1/progetti-conclusi/progetto-annali>; accessed 21 January 2026).

The data spanning from 2000-2025 period (Tab. 4.4; Fig. 4.4) are downloaded from the website of *Centro Funzionale Protezione Civile* of Campania Region (available at <https://centrofunzionale.regione.campania.it/dati>; accessed 21 January 2026).

Data concerning pumping well located in Benevento plain were provided by GESESA aqueduct Company and Municipality of Benevento.

The spring discharge data were provided by the aqueduct companies managing the studied massif springs. Caposele and Cassano Irpino spring discharges were provided by Acquedotto Pugliese Company. Serino springs discharge data were provided by Acqua Bene Comune Company.

Also, barometric and hydrometric data were provided by *Centro Funzionale* website. The list of the meteorological stations used in this thesis work is provided in table 4.5.

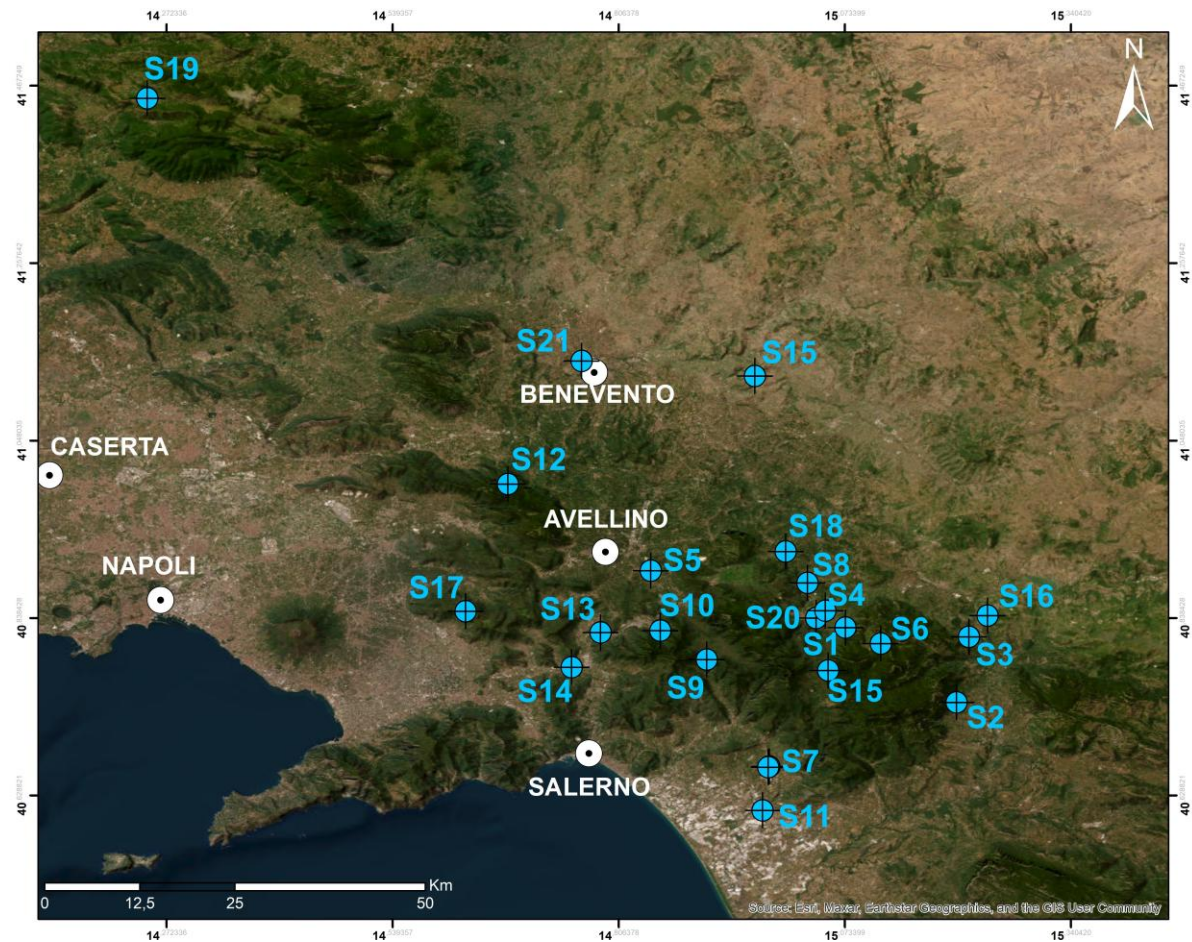


Figure 4.4. Location map of meteorological station of the *Centro Funzionale Protezione Civile* authority network.

Discharge data of springs bounding Alburni karst massif and Morcone karst reliefs were taken both by technical reports and previous literature works (Celico, 1978; Celico, 1983; Esposito et al., 2005a; Fiorillo et al., 2022; Valente et al., 2022) and by spot measurements carried out in field.

4.3. GIS software and Satellite data

Digital maps were produced through the use of QGIS and ArcMap GIS (version 10.5) software. The quoted points and the hillshade were created using the 5-meter DEM provided by the Territorial Informative System of Campania Region.

Satellite images of Cervialto karst massif and Dragone Plain were downloaded by the website platform of Copernicus (available at <https://www.copernicus.eu/en>; accessed on 21 January 2026).

Meteorological station	Elevation (m a.s.l.)	Annual mean rainfall (mm)	Annual mean temperature (°C)	Time period
Lago Matese	1013	1808	9.3	1970-1999
Campitello Matese	1432	2167	5.3	1991-1999
Roccamandolfi	810	1796	12.2	1970-1999
S. Gregorio Matese	526	1603	/	1970-1999
Piedimonte Matese	187	1243	15.7	1970-1999
Faicchio	177	1237	/	1970-1999
Pratella	157	1267	14.6	1970-1999
Guardiaregia	733	1479	12.3	1970-1999
Vairano Patenora	143	1081	/	1970-1999
Gallo	840	1424	10.1	1970-1999
Letino	907	1299	10.2	1970-1999
Venafro	178	1130	14.1	1970-1999
Sepino	716	1502	/	1970-1999
Boiano	488	1291	/	1970-1999
Monteroduni	434	989	/	1970-1999
Morccone	640	1200	/	1970-1999

Table 4.3. Meteorological data provided by the historical database of SIMN for the period 1970-1991.

Item	Meteorological station	Elevation (m a.s.l.)	Annual mean rainfall (mm)	Annual mean temperature (°C)	Time period
S1	Bagnoli Irpino	730	1628.3	13.7	2008-2020
S2	Senerchia	578	1780.8	14.2	2008-2020
S3	Caposele	428	1405.8	13.9	2008-2020
S4	Montella	489	1624	12.9	2008-2020
S5	Serino	327	1438.6	13.7	2008-2024
S6	Piano Laceno*	1100	2513.3	/	2008-2020
S7	Montecorvino	154	1311	/	2008-2020
S8	Cassano Irpino	470	1331.1	/	2008-2020
S9	Giffoni V.P.	980	1678.2	/	2008-2020
S10	Solofra	534	1881.4	15.4	2008-2020
S11	Battipaglia	65	1100	/	2008-2020
S12	S. Martino V.C.	757	2136.7	/	2008-2020
S13	S. Pietro	209	/	/	2008-2020
S14	Mercato S. Severino	141	/	16.0	2008-2020
S15	Rocchetta	670	/	13.5	2008-2020
S16	Boiara	780	/	12.2	2008-2020
S17	Quindici	840	/	12.3	2008-2020
S18	Montemarano	865	/	12.4	2008-2020
S19	Letino	1050	/	11	2008-2020

Table 4.4. Meteorological data downloaded by *Centro Funzionale Protezione Civile* of Campania Region; rainfall and temperature data. *Data of Laceno Rain Gauge were provided by Acquedotto Pugliese S.p.A. The items are shown in Fig. 4.4.

Item	Meteorological station	Elevation (m a.s.l.)	Annual mean pressure (hPa)	Annual mean hydrometric level (m)	Time period
S20	Montella Meteo 1	535	958.4	-	2021-2024
S21	Benevento	119	988.2	0.72	2023

Table 4.5. Meteorological data downloaded by *Centro Funzionale Protezione Civile* of Campania Region; barometric and hydrometric data.

4.4. Historical data

The historical data were taken through a careful literature review of ancient and modern documents concerning both the Roman aqueducts and the subsequent historical evolution of aqueduct systems of Benevento city. In particular the documents allowed the reconstruction of the aqueduct layouts and the main phases of their building.



Figure 4.5. Field surveys carried out on (a) rest of Roman aqueducts and (b) in Piscina Mirabilis reservoir (photo by Giovanni Minervini).

Also, several field surveys (Fig. 4.5) were carried out on the remains of the aqueducts located in several part of central Campania region. In particular, inspections to remains of Sannitico Aqueduct in Serino springs tapping structures and below Rocca dei Rettori building in Benevento city, and to Piscina Mirabilis and Cisterna Dragonara in Bacoli municipality were carried out. Further, rests located in Sarno (Mura d'Arce), Palma Campania (Ponte Tirone), and Naples (Ponti Rossi) municipalities have been surveyed, studied and analyzed.

Chapter 5: Continuous monitoring system and time series analysis for the comprehension of karst polje dynamics

The recharge-discharge mechanism featuring karst aquifers depends on the underground and surface hydrological features of the system. In particular, at the surface, karst systems are typified by closed depressions with endorheic (internal) runoff, which represents one of the main features in aquifer recharge processes ([Esposito et al., 2025a](#)). The largest morphological depressions are represented by poljes, reaching dimensions of tens or hundreds square kilometers, and characterized by flat floor, karstic drainage and steep peripheral slopes ([Bonacci, 2013](#); [Gams, 1978](#)).

Due to their flat morphology, poljes are often home for human settlements, and agricultural and grazing activities. The endorheic runoff is conveyed toward ponors (or swallow holes), which are discontinuities in the bedrock connected to a karst network of fissures, conduits and caves, through which the water directly sinks underground. These features determine a quick response to precipitation and a fast transit of water and contaminants from the surface to the spring outlets, making the management and protection of the karst groundwater resource challenging.

According to the hydrological regime, poljes can be divided into ([Bonacci, 2013](#)): (i) permanently flooded; (ii) periodically, partly, or completely flooded; (iii) dry poljes. Flooding and sedimentation are the main processes distinguishing poljes from other karst closed depressions ([Calic, 2011](#)). Moreover, floods in poljes can be distinguished from other types of karst floods due to their high amplitude and long duration ([Kovacic, 2010](#)). Flooding starts when the water inflow exceeds the drainage capacity of ponors and a sinking lake forms ([Bonacci, 2013](#); [Ford and Williams, 2007](#)). This hydrological condition also characterizes the growth phase of the lake. On the contrary, flooding does not occur or the lake level starts to receding. Several factors control flooding, including the intensity, duration of rainfall (and snowmelt), presence of springs, elevation and drainage capacity of ponors, transmissivity and storage capacity of the aquifer draining the polje, the presence of estavelles ([Mayaud et al., 2019](#)). The antecedent moisture condition of the soil is another factor for the runoff triggering ([Fiorillo et al., 2015b](#)).

From a hydrogeological point of view, a polje is an integral part of the karst aquifer. During heavy rainfall or prolonged wet periods, the sinking lake act as a regulating reservoir that buffers the infiltration of water (Xanke et al., 2024). Thus, the comprehension of the dynamic inside the karst polje is important to fully understand the karst aquifers recharge processes. To achieve this purpose, the wells drilled in karst and their related hydrographs can provide some information about the behavior of groundwater flow inside the aquifer (Powers and Shevenell, 1999). The behavior of recession in wells intercepting karst zones may be a good indicator of properties of the aquifer in which the wells are screened (Powers and Shevenell, 1999). Like springs, the shape of rising limb of hydrograph is largely dictated by the characteristics of a storm event, whereas the shape of recession limb of aquifer is independent from the character of the storm (Linsley et al., 1982). The most useful hydrographs are those obtained during abrupt, intense storm events in which a sharp pulse is transmitted to the karst system (Shevenell, 1996). Rapid water level responses are expected in conduits, in contrast to slower responses in the more diffuse portions of the aquifer (White, 1988). Furthermore, studying the well hydrographs, information about an aquifer's hydraulic state and lateral extent, the nature of recharge (Healy, 2010; Nimmo et al., 2015) the hydraulic connection to the aquifer and the nearby pumping wells, and the expected response to conservation-based pumping reductions can be extracted (Butler Jr et al., 2021). The combination of the spring and well hydrograph analytical techniques provide a powerful tool for the characterization of the structure and hydraulic properties of karst systems (Kovacs et al., 2015).

Small to large poljes typify karst massifs of Southern Apennines (Italy). Their endorheic catchments range from a few to several tens of square kilometers and spans over a wide elevation range of hundred meters (Fiorillo et al., 2015b; Leone et al., 2023; Valente et al., 2022). Intermittent sinking lake were documented all over the region, characterizes the wet-cold season. Where the polje floor lies at high elevation, dams have been built to exploit the potential energy of water stored in the artificial permanent lakes to generate hydroelectric energy (Leone et al., 2023). In these mountain regions, the flooding is influenced by both rainfall and seasonal snowpack; the latter represents a further temporary water storage (Leone et al., 2024).

This chapter analyzes the hydrologic behavior of the Dragone Plain karst polje, located in Terminio-Tuoro karst massif, using water table level collected by continuous monitoring from a well located in the plain and Sentinel-2 satellite images.

5.1. Description of monitoring time series

Time series of precipitation, lake storage, groundwater level and spring discharge were used to investigate the relationship between polje flooding and the recharge-discharge mechanism of the karst aquifer.

5.1.1. Precipitation, lake storage, groundwater level and spring discharges

Precipitation (rainfall and snow melt) and lake discharge represent the input signals to the karst aquifer.

Daily precipitation of Serino rain gauge was considered (Tab. 4.4). Its time series is statistically correlated with discharge time series of local springs ([Fiorillo et al., 2021](#)).

The mapping of the flooded area and the lake storage were performed using the visual-inspection of multi-temporal Sentinel-2 RGB satellite images referred to the period spanning from November 2020 to June 2024. The sampling period of the images, generally, is of about 5 days. Given the seasonal distribution of precipitation and temperature, images in the period enclosed between November to the May of the following year were analyzed. However, due to the frequently dense cloud cover, a first check of image was carried out reducing the number of interpretable images. After, the presence or absence of the lake was verified. When the lake was present, the flooded area was digitalized in GIS environment; otherwise, the absence was also recorded. For relatively small and shallow lakes, as in this case, automated flooding mapping based on satellite indices may induces significant errors due to mixed pixels, vegetation, clouds, and snow. Thus, a manual digitalization approach was preferred. The procedure above described allowed to reconstruct the evolution of the lake for well-defined period of the hydrological year (Fig. 5.1).

The mapped lake perimeter represents the level of the surface reservoir, whose elevation was extracted from a 5-m Digital Elevation Model (DEM) using standard GIS tools. Specifically, the lake surface level was assumed as the mean elevation of the lake perimeter to filter out spurious pixels due to manual mapping and irregularities in digital surface. Then, the volume of the lake was estimated as the volume between the DEM surface, representing the reservoir bottom, and the lake contour, representing the water surface. Figure 5.2 shows the relationship between the lake area and the volume and two orthogonal topographic profiles along the major and the minor axes of the lake ([Abbasi Chenari et al., 2026](#)).

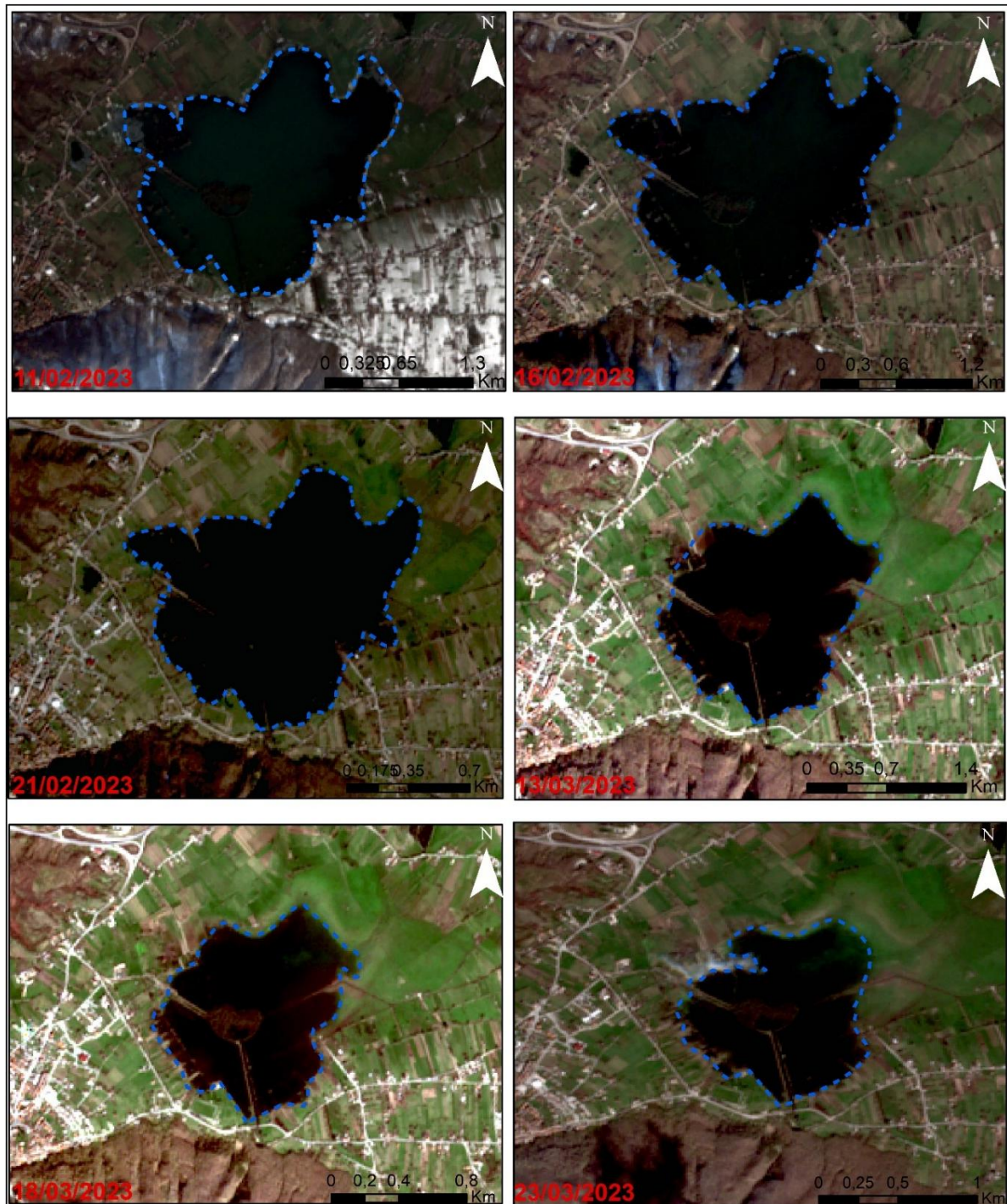


Figure 5.1.Reconstruction of the Dragone Plain Lake stages through the use of satellite images for the period 14th February 2023 to 23th March 2023.

Groundwater levels and spring discharges represent the output of the aquifer. Continuous monitoring of well data was carried out using the TD Diver sensor, while discharge data of Cassano Irpino spring group were used.

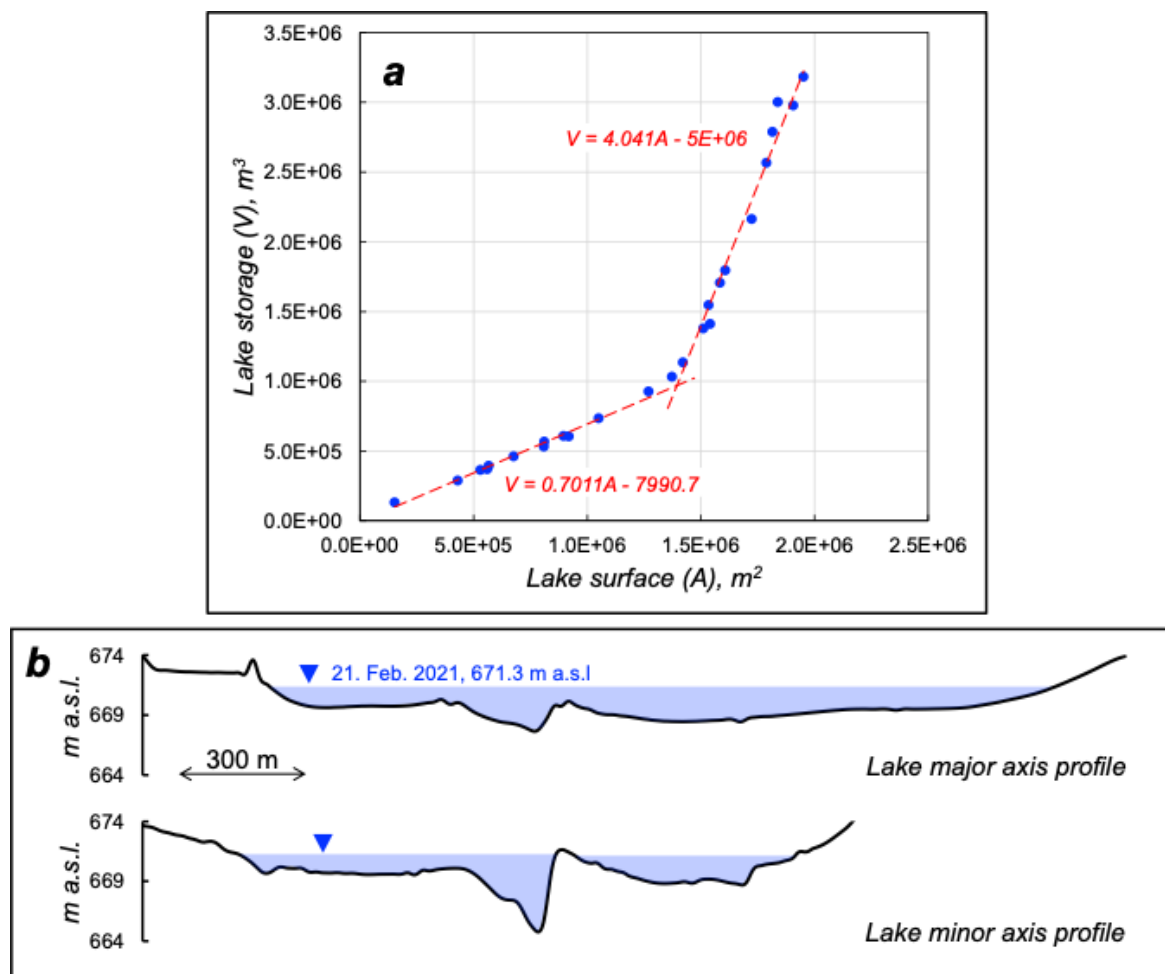


Figure 5.2. Lake area-volume relationship (a) and topographic profiles (b). The blue line represents the maximum water level observed during the monitoring period (30× vertical exaggeration) (from Abbasi-Chenari et al., 2026).

5.1.2. Time series analysis

Classical graphical analysis (Chambers et al., 2018) was carried out to understand the relationships between the investigated variables, including the link between accumulated precipitation deficit or surplus and lake formation, and impacts of the lake regime on groundwater level and spring discharge.

Furthermore, cross-correlation analysis was applied to investigate how a hydrological system transforms the input precipitation signal (Duvert et al., 2015; Leone et al., 2024).

The cross-correlation function, CCF, describes the degree of linear correlation between an input time series X and the lagged version of another output time series Y as a function of the time lag k introduced between X and Y (Box et al., 2016):

$$CCF(k) = \frac{c_{XY}(k)}{s_X s_Y} \quad (4.1)$$

Where s_x and s_y are the standard deviation of time series X and Y , respectively, and $c_{XY}(k)$ is the cross-covariance coefficient at lag k :

$$c_{XY}(k) = \frac{1}{T} \sum_{t=1}^{T-k} (X_t - m_X)(Y_{t+k} - m_Y) \quad k = 0, \pm 1, \pm 2, \dots \quad (4.2)$$

Where T is the time series length, t is the t -th the time step, and m_x and m_y are the mean of the time series. In this case, only positive lags k are meaningful.

The CCF varies between -1 and +1, and for a given lag k , its value assumes the same meaning of the ordinary correlation coefficient (Leone et al., 2020). In data-driven modeling, cross-correlation is employed to find the linear transfer function describing the dynamic relationships between X and Y . Short time lag to the CCF peak indicate a fast transit. However, the shape of the cross-correlation function is also relevant. A smooth CCF indicates a high inertia, or memory, of the process. On the contrary, rapid variations in CCF indicate a limited dampening of the input signal.

5.2. Analysis of monitoring time series

The graphical analysis focused on four hydrological years (Figs. 5.3, 5.4, 5.5, 5.6), two wet, one average, one dry, thus they can be assumed representative of the range of meteorological conditions occurring in the area.

5.2.1. November 2020-May 2021

Figure 5.3a presents the cumulative monthly rainfall curves from August 2020 to July 2021. The blue line represents the average curve calculated on the last 30-years, and the shaded area the 90% variability between the lower 5th and the upper 95th percentiles. The 2020-21 is well above average (wet year) because of the abundant winter precipitation (Abbasi Chenari et al., 2026).

Figure 5.3b shows the daily time series of precipitation, lake storage volume, and spring discharge for the period from November 2020 to May 2021. The summer to mid-autumn period

was not considered because, even if rainfall occurs, the lake does not form during this time. Piezometric data are not included in this figure as groundwater monitoring has started in October 2021. The bottom panel provides the sequence of available and interpretable Sentinel-2 satellite images. A prolonged flood occurred in this year. Probably, the lake was in its initial stage of accumulation in late December, and the Dragone Plain remained continuously flooded until early May 2021. The largest lake storage during the entire study period, about $3 \times 10^6 \text{ m}^3$, was observed in February 2021. The cumulative precipitation curve in Figure 5.3a shows a large water surplus in this month, associated with abundant winter rainfall. In the late February, lake storage remains high despite the absence of precipitation, suggesting that snowfall and subsequent snowmelt delayed the storage peak by several days after the precipitation events. Notably, the maximum lake storage also coincides with the seasonal peaks in spring discharge.

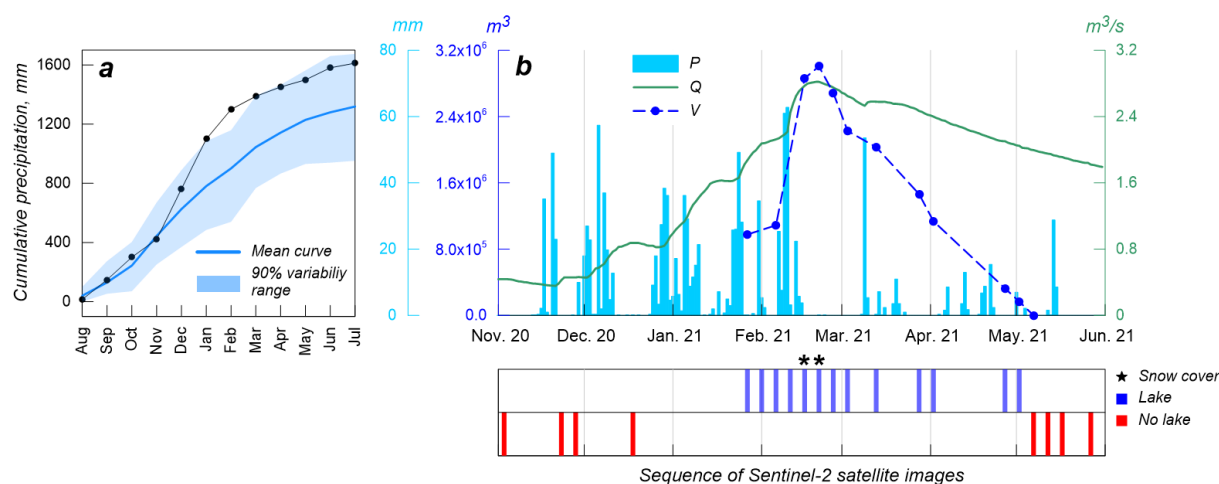


Figure 5.3. (a) Cumulative monthly precipitation curve for the hydrological year 2020-2021. (b) Daily precipitation, P, lake storage volume, V, and daily discharge, Q, of Bagno della Regina spring (Cassano spring group) for the period 1 November 2020-1 June 2021. The bottom panel provides the sequence of Sentinel-2 satellite images, and the star marks the presence of a snow cover across the polje's catchment. The lake volume has been interpolated between two consecutive satellite images (from Abbasi-Chenari et al., 2026).

The good temporal coverage of satellite images allowed us to roughly estimate the contribution of the lake to recharge. We assumed that evapotranspiration was negligible, which is reasonable during the cold period. Recharge was calculated based on the change in storage volume (ΔV) estimated between two satellite images during emptying, as $\Delta V/\Delta T$, where ΔT is the time interval between the images. Assuming that the lake recession began in the late February 2021, the maximum recession rate was about $1 \text{ m}^3/\text{s}$ (26 February to 3 March). From 3 March to 2 May, the lake baseflow would have been in about $0.45 \text{ m}^3/\text{s}$. The very low-permeability deposits underline the lake, suggests that the Dragone Mouth ponor is the only concentrated point of infiltration.

5.2.2. November 2021-May 2022

The 2021-2022 can be considered as an average hydrological year, thanks to the abundant precipitation in November-December (Figure 5.4a). Numerous satellite images are available for this period, but only a few capture the lake (Fig. 5.4b) due to the short duration of the flooding events, despite a prolonged rainfall period occurred between late-November and early-December 2021 ([Abbasi Chenari et al., 2026](#)).

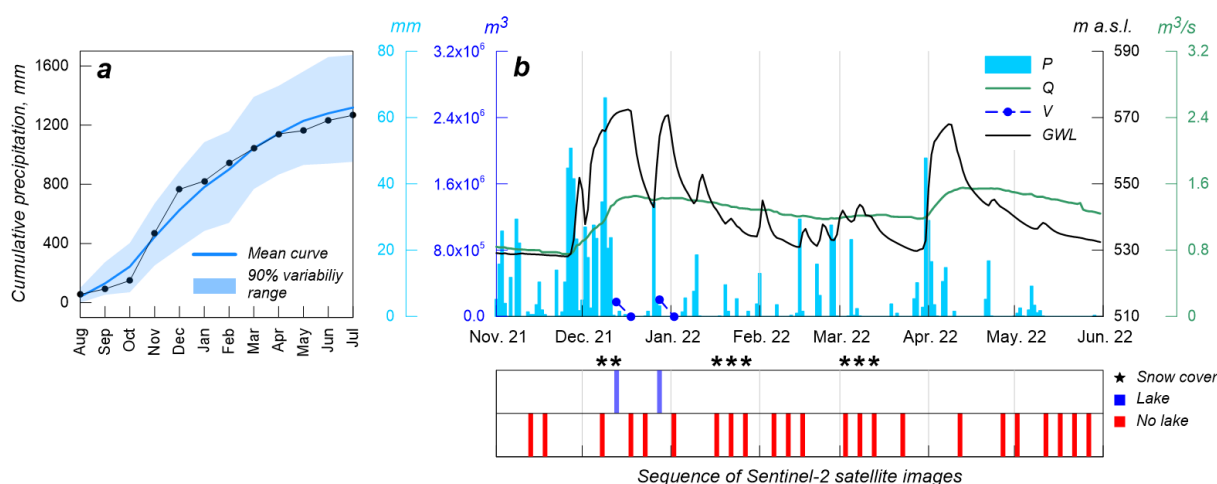


Figure 5.4. (a) Cumulative monthly precipitation curve for the hydrological year 2021-2022. (b) Daily precipitation, P, lake storage volume, V, groundwater level, GWL, and daily discharge, Q, of Bagno della Regina spring (Cassano spring group) for the period 1 November 2021-1 June 2022. The bottom panel provides the sequence of Sentinel-2 satellite images, and the star marks the presence of a snow cover across the polje's catchment. The lake volume has been interpolated between two consecutive satellite images (from [Abbasi-Chenari et al., 2026](#)).

Both groundwater of the karst aquifer and spring discharge rapidly increase to precipitation pulses. Specifically, the piezometer is placed in the main recharge zone and reaches the deep karst aquifer. The groundwater hydrograph shows several peaks, in correspondence of intense rainfall; the highest peak presents a summit flat zone, which can be interpreted as (i) recharge nearly equal to discharge, or (ii) the diffuse mechanism of overflow along the boundary of the spring catchment. The groundwater level drops rapidly as soon as the lake disappears, indicating an influence of concentrated recharge through the Dragone Mouth ponor. Therefore, based on the hydrograph shape, a lake was likely present even in early April, but no usable satellite images are available for this period.

5.2.3. November 2022-May 2023

The 2022-2023 is a wet (above-average) year (Fig. 5.5a). As shown in figure 5.5b, several flood episodes and flat summit peaks of the groundwater table level occurred. It appears that, when

the lake is completely drained, the groundwater level rapidly drops. In this case, the groundwater level shows an upper limit, due to the previous reasons explained (Abbasi Chenari et al., 2026).

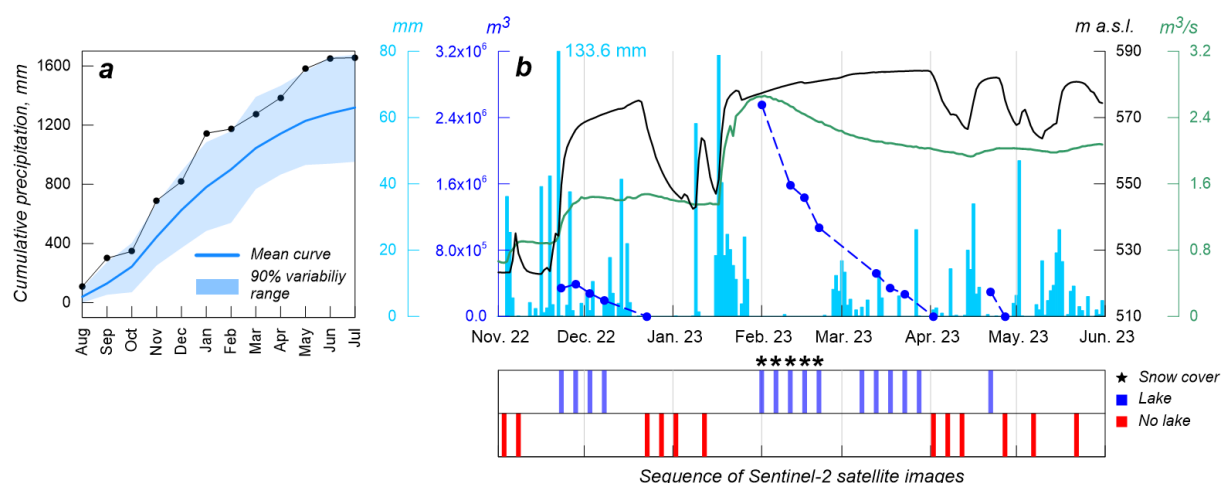


Figure 5.5. (a) Cumulative monthly precipitation curve for the hydrological year 2022-2023. (b) Daily precipitation, P , lake storage volume, V , groundwater level, GWL , and daily discharge, Q , of Bagno della Regina spring (Cassano spring group) for the period 1 November 2022-1 June 2023. The bottom panel provides the sequence of Sentinel-2 satellite images, and the star marks the presence of a snow cover across the polje's catchment. The lake volume has been interpolated between two consecutive satellite images.

The second main flood episode characterizes the period from late January to early April. Specifically, January precipitation caused polje flooding, which was associated with a rapid increase in groundwater level and spring discharge. Part of the precipitation accumulated in the spring catchment as snow, creating an additional, temporary water reservoir. Due to snowmelt and lake drainage, the groundwater level continued to rise until April, while spring discharge gradually decreased.

5.2.4. November 2023-May 2024

The 2023-2024 is a dry (below-average) year, characterized by very low precipitation during the winter period (Fig. 5.6a), and no lake formed (Fig. 5.6b). The rainfall deficit occurred since December, and induce an hydrological drought into the system. This poor rainfall causes single and minor peaks in the water table, associated with low values of the spring discharge for all the year (Abbasi Chenari et al., 2026).

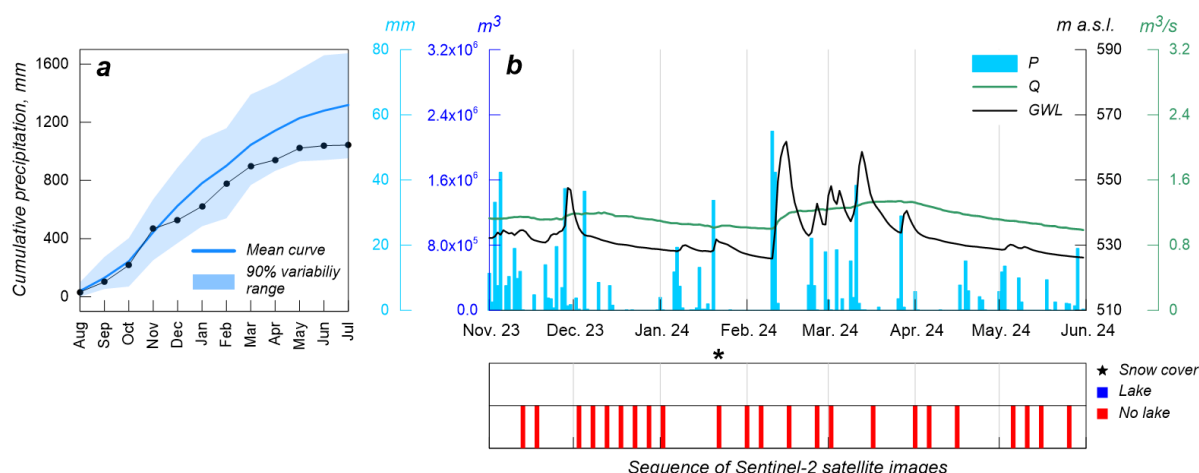


Figure 5.6. (a) Cumulative monthly precipitation curve for the hydrological year 2023-2024. (b) Daily precipitation, P, lake storage volume, V, groundwater level, GWL, and daily discharge, Q, of Bagno della Regina spring (Cassano spring group) for the period 1 November 2023-1 June 2024. The bottom panel provides the sequence of Sentinel-2 satellite images, and the star marks the presence of a snow cover across the polje's catchment. The lake volume has been interpolated between two consecutive satellite images.

5.2.5. Correlation between water level and Cassano and Serino spring discharges

Since the Dragone Plain polje is considered as the main recharge area of the Terminio-Tuoro karst massif, the water level data were compared with the spring discharge of the main basal spring groups: Cassano Irpino and Serino springs (Acquaro and Pelosi springs) (Fig. 5.7).

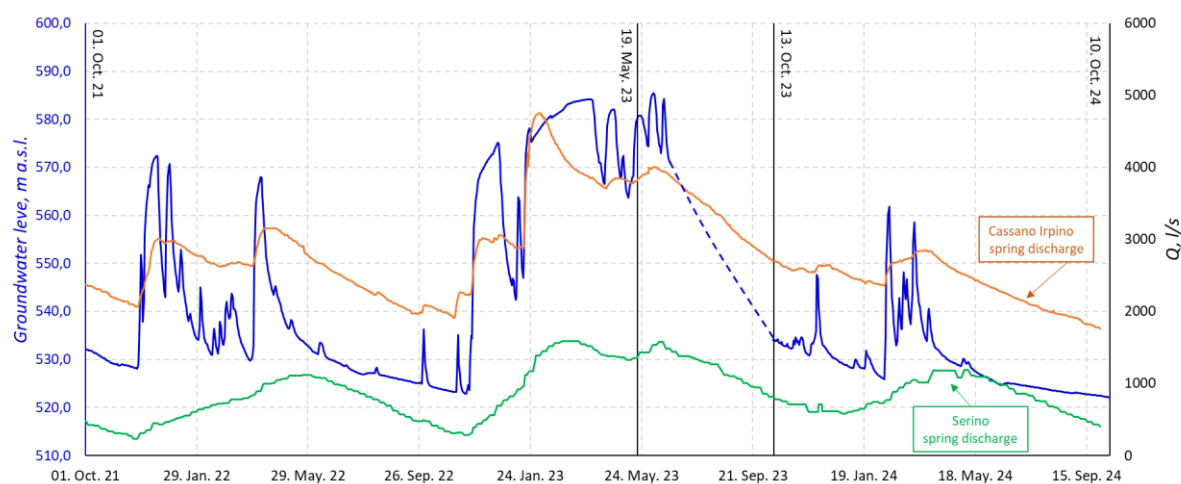


Figure 5.7. Graphical comparison between the water table level recorded in Dragone Plain and Cassano Irpino and Serino spring discharges. The dashed line indicates the interpolated data.

As shown before, Cassano Irpino spring discharge and water table level data have a synchronous trend, with peaks in piezometric level followed by peaks in the spring hydrograph. This relationship was demonstrated also by tracer tests carried out on the Dragone Mouth ponor,

that ascertained the link between the Dragone Plain polje and Cassano Irpino springs (Celico et al., 1982).

Contrary, the correlation between the water table level and Serino (Acquaro and Pelosi) spring discharge is less clear than Cassano Irpino spring group. As a matter of fact, the regime of Serino springs seems to have their own trend and, sometimes, the peaks in spring discharge appear not directly correlated with the water table level. Also, during the tracer tests (Celico et al., 1982) no tracer substance was found in Serino springs, confirming the lack of linking between the Dragone Plain polje and this group of basal springs (Fig. 1.16). However, the absence of correlation between water table levels and spring discharge trend is probably linked to the complex hydrogeological conditions that lead to the formation of the springs. In particular, to those related to the upwelling water flux mechanism through the alluvial deposits that overlies the limestone bedrock (Fiorillo et al., 2018). Furthermore, despite the Serino spring group is, also, fed by a huge sector of Terminio-Tuoro karst aquifer, it cannot be ruled out the role of the summit endorheic area in recharge processes.

5.3. Relationships between karst lake level and groundwater dynamics

The Dragone Plain Lakes represents one of the major karst lakes of southern Apennine region. The relevance of Dragone Plain Lake is connected to its almost natural conditions, allowing to investigate the role of such lake in the recharge-discharge processes of karst aquifer.

The active ponor and underground karst pathways favor a concentrated infiltration of surface water and their direct transfer into the aquifer. These features cause a rapid recharge after rainfall, highlighted by increasing of the water level in the deep piezometer, which intersects the saturated zone of the aquifer. Based on a rough estimation, the maximum observed ponor discharge reached approximately 1000 l/s in the monitoring period, equal to about 1/4 of the spring discharge. This suggest that the lake is not merely a surface water body, but it is an integral component of the karst aquifer, regulating recharge. This situation is testified in the period when the polje flooding is associated with a slow water table rising, which suddenly drops when the lake disappears (Fig. 5.5b). The whole endorheic area of the Dragone Plain has a significant role in aquifer recharge estimated in $71.6 \times 10^6 \text{ m}^3/\text{year}$ (Fiorillo et al., 2015b), equal to an average flow of approximately 2300 l/s. However, a groundwater abstraction occurs by pumping wells, with an amount of $6.3 \times 10^6 \text{ m}^3/\text{year}$ (200 l/s).

Excluding that the lake formation is connected to the water table rising, and that the ponor acts as an estavelle, flooding is controlled by intensity, duration and frequency of precipitation

events, antecedent soil moisture condition, and drainage capacity of the ponor; rapid snowmelt also appears a cause of the lake formation. However, flooding appears connected to two main mechanisms: (i) temporary flooding occurring because of the surface runoff generated by intense rainfall (e.g., November 2023; Fig. 5.5b); (ii) prolonged (seasonal) flooding occurs in wet hydrological years characterized by distributed rainfall (e.g., 2020-2021 period; Figure 5.3b). On the other hand, lake is difficult to form under long meteorological drought condition (e.g., 2023-2024 period; Figure 5.6b) and does not form during the dry season. Therefore, flooding is not a seasonally recurrent phenomenon, depending on the rainfall distribution and its intensity, antecedent soil moisture as well. The absence of temporary lake during the entire winter-spring season appears a proxy of a long meteorological drought and the consequent groundwater drought.

Monitoring time series can be used for the studies concerning the propagation of the meteorological signal through the karst aquifer. In general, groundwater level and spring discharge rapidly increase in response to precipitation (Fig. 5.3b). The system progressively smooths the precipitation input, as shown by reduction in peak frequency from groundwater level (intermediate output) to spring discharge (final output) time series. However, the way the precipitation pulses propagates seem to varies between meteorologically dry to wet years. This behavior was investigated by cross-correlation analysis, which provide the linear transfer function between two signals (Fig. 5.8). However, the strong buffering effect of the karst system limits any direct comparison between daily precipitation and spring discharge.

In wet years (Fig. 5.5b), the cross-correlation function suggests no direct correlation between daily precipitation and groundwater level (Fig. 5.8c). Polje flooding and snow accumulation-melt in the endorheic catchment significantly delay the groundwater peak and enhance the buffering effect. Also, due to the frequent precipitation pulses, the karst system responds to precipitation accumulated over several days. High correlation and no time lag occur between the groundwater level and spring discharge (Fig. 5.8d).

In mild years (Fig. 5.4b), the influence of daily precipitation on groundwater level can be observed (Fig. 5.8a), and the 8-9 days lag between precipitation and groundwater level is related to the time required for the pulses to propagate. The limited and temporary polje flooding contributes to lag the signals. The cross-correlation function provides a further 6 days lag between groundwater level and spring discharge (Fig. 5.8b). The short distance between the ponor and the deep piezometer causes the more impulsive response of the groundwater to precipitation and explain the irregular cross-correlation function (Fig. 5.8a). Differently, the

transition to a smoother cross-correlation function (Fig. 5.8b) indicates a dampening of the signal through the aquifer.

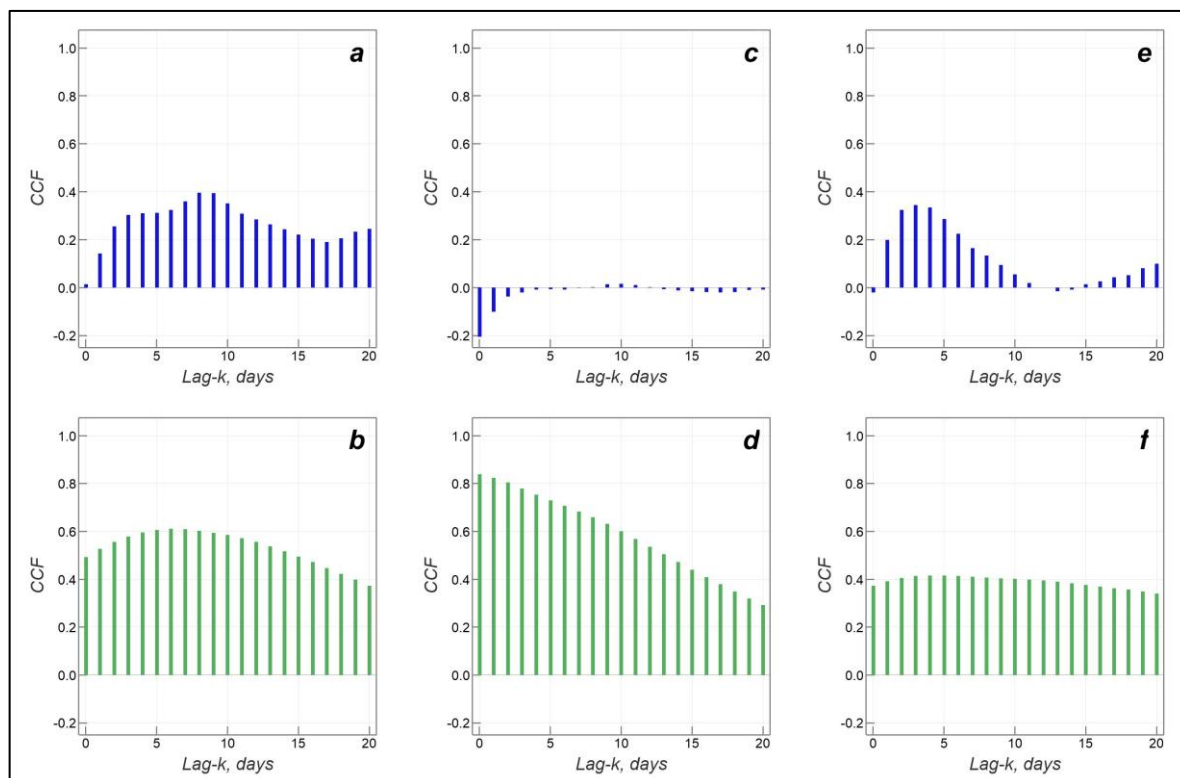


Figure 5.8. Cross-correlation functions (CCF) between precipitation and groundwater level (blue) and groundwater level and spring discharge (green). (a-b) 2021-2022 time series (mild hydrological year); (c-d) 2022-2023 time series (wet hydrological year); (e-f) 2023-2024 time series (dry hydrological year) (from [Abbasi-Chenari et al., 2026](#)).

The “undisturbed” karst system response can be investigated in dry years (Fig. 5.8d). During drought, the time lag between precipitation and groundwater level is reduced at 3 days (Fig. 5.8e) and the cross-correlation function decreases rapidly. The signal propagation is faster and the runoff is efficiently drained by the ponor and short or no polje flooding occurs. The cross-correlation function between groundwater level and spring discharge is “flat”, indicating the poor response of the karst aquifer to recharge and a prevalent inertial component ([Abbasi Chenari et al., 2026](#)).

Chapter 6: Mapping and Hydrological methods for the evaluation of groundwater recharge

The actual recharge is the portion of infiltrated water that reaches the aquifer, and it is confirmed based on groundwater studies (Kresic, 2023). Groundwater recharge is of diffusive (direct) type when derived from precipitation or irrigation that occurs fairly uniformly over large areas; while localized (or focused) recharge refers to concentrated recharge from depressions in surface topography such as streams lakes and playas (Scanlon et al., 2002). In karst aquifers, concentrated recharge is provided by endorheic areas (characterized by the presence of one or more dolines and of a polje) in which the surface runoff cannot escape and, also forming a bottom lake, infiltrate completely in the subsurface through a ponor feeding one or more basal karst springs (Fiorillo et al., 2015b).

Thus, the detailed mapping of the main karst hydrological features, including endorheic areas, dolines, ponors, caves and karst springs represent a crucial topic for a careful groundwater recharge estimation (Leone et al., 2023). The definition and delineation of karst closed depressions, including dolines, have been widely discussed in the literature. Various mapping criteria have been proposed, such as manual delineation using orthophotos (Šegina et al., 2018), contour-based methods (Bondesan et al., 1992; Wu et al., 2016), morphometric-based methods (Kozar et al., 2007; Doctor and Young, 2013; Hofierka et al., 2018; Čeru et al., 2017), and hydrologically based methods (Doctor and Young, 2013; Hofierka et al., 2018; Stefanovski et al., 2024). Knowing the location and boundary of closed depressions is the basis of morphometric studies, and it also has a practical relevance (Moreno-Gomez et al., 2017). On this last point, closed depression mapping represents a key component in groundwater recharge and vulnerability assessment, delineation of protection zones for wells and springs, planning of artificial tests, and sinkhole hazard analysis (Andreo et al., 2008; Goldscheider et al., 2008; Goldscheider, 2010; Gutierrez et al., 2011; Fiorillo et al., 2015b; Fiorillo and Pagnozzi, 2015; Fiorillo et al., 2022; Marin et al., 2021).

During the last few years, the increasing of temperature and the drop of precipitation influence groundwater recharge (Nazari et al., 2025) and, therefore, spring discharge with consequent issues about the water resource management. Therefore, the understanding of recharge

processes is important in order to quantify the groundwater resources and for the sustainable aquifer management (Gong et al., 2023). To evaluate the recharge rate and amount several methods were developed (Scanlon et al., 2002). Some of these estimation methods were designed for the application to all types of aquifers (Healy and Cook, 2002). The water budgets methods (Thorntwaite and Mather, 1955; Civita and De Maio, 2001) accounting inflows and outflows and the storage change in an aquifer are widely used in estimating groundwater recharge for every kind of aquifer. Tracers provide quantitative and/or qualitative estimates of recharge, identifying sources of recharge, providing information on velocity and travel times of water movement. The most commonly used method involving natural tracers in groundwater recharge estimation is the chloride (Cl) water balance (Eriksson and Khunakasem 1969). Other, more recently, methods involved numerical (Nimmo et al., 2015; Leone et al., 2025; Leone et al., 2026) or distributed functions (Hartmann et al., 2013) models. Furthermore, other methods of recharge estimations were developed specifically for karst aquifers taking in account their particular geological, geomorphological and hydrogeological features (Andreo et al., 2008; Allocca et al., 2014; Fiorillo et al., 2015b).

This chapter deals with methodologies used for the endorheic mapping and recharge evaluation of Alburni and Morcone karst massifs. In the case of Alburni karst massif, the endorheic areas were mapped and statistical analyzed, involving a new and innovative methodology improved than the first one proposed in Leone et al. (2023). Also, the same methodology was applied for the endorheic areas mapping of Morcone karst reliefs, emphasizing the connection among the endorheic areas and the main spring discharges draining the massif. The basic statistics have been also calculated. For these latter reliefs, a recharge evaluation, also, was carried out using the Modified APLIS method (Marin, 2009), the Daily Scale Recharge model (Fiorillo et al., 2015b) and a new methodology, firstly proposed in this study, resulting from the combination of both methodologies. Also, the recharge evaluation of Cervialto karst massif drained by Caposele spring was carried out using the lumped model KarstMod (Leone et al., 2025; Leone et al., 2026).

6.1. Dolines and endorheic areas mapping

Hydrological processes play a key role in surface morphogenesis; in turn, closed depressions may represent one of the main controlling features in the infiltration processes of overland-subsurface flow. From the hydrological perspective, surface (and subsurface) karst features could be distinguished in (Palmer, 1991; Klimchouk, 2007): (i) epigenic features, having a hydrological connection with the surface water, and forming by descending flows coming from

the recharge zones; (ii) hypogenic features, having no relation with surface hydrology, and forming by ascending groundwater flows. In particular, dolines may have a different hydrological functioning, depending on whether they have a genetic and hydraulic relation with surface water or deep groundwater circulation (Leone et al., 2023; Esposito et al., 2025a).

Morphologically, a closed depression is an area with a lower elevation than the surrounding terrain and concave upward (Klingseisen et al., 2008). Hydrologically, a closed depression drains a wider endorheic area (also called endoreic basin; Bonacci and Andrić, 2015), representing a closed watershed with internal runoff (White, 2002). In endorheic areas, runoff is entirely adsorbed through concentrated infiltration via ponors and diffuse infiltration and leakage through the cover deposits. Ponors placed at their bottom can create a direct hydraulic connection between the endorheic area and one or more springs (Valente et al., 2022). Therefore, the amount of water conveyed toward the closed depression and contributing to groundwater recharge depends from the endorheic area. Outside endorheic areas, runoff can escape and does not contribute to recharge, especially during intense rainstorms (Fiorillo et al., 2015b).

6.1.1. Types of karst closed depressions

Metric- to kilometric-scale closed depressions can be distinguished in karst terrains, namely dolines, uvalas, and poljes. These features link the surface to the underground system of fissures, shafts, and caves (Sauro, 2012).

Dolines

Dolines have diameters (or axes) from a few to a hundred meters and depths up to tens of meters (Bonacci, 1987; Bondesan et al., 1992). The shape can vary in a wide range, but typical dolines are bowl-shaped (e.g., Kozar et al., 2007), with a circular to sub-circular perimeter in plain view.

Moreover, dolines are conventionally classified into solution, suffusion and collapse based on the genetic process (Gutiérrez et al., 2008). Solution dolines (Fig. 6.1a and b) are associated mainly with an epigenic karst (Frumkin et al., 2015), being their genesis related to surface hydrological processes. Collapse dolines, also known as collapse sinkholes (Ford and Williams, 2007), originate from underground karst voids, whose widening leads to the collapse of the cavity's roof and the consequent formation of a doline on the surface (Gutiérrez et al., 2011; Nisio, 2008; Waltham et al., 2005). In turn, the genesis and evolution of these karst voids in depth are associated with hydrological processes occurring in the discharge sectors of wide

karst systems, which are characterized by the rising of CO₂ and H₂S-rich waters from depth (Frumkin et al., 2015; Klimchouk, 2011). Collapse dolines have no relationship with surface hydrology, but rather are the results of the ascendent flows characterizing the discharge sectors (Fiorillo et al., 2019). The collapse dolines involving the karst bedrock are named bedrock collapse dolines (Fig. 6.1c), while those involving the thick cover deposits mantling the karst bedrock are named cover collapse dolines (Fig. 6.1d).

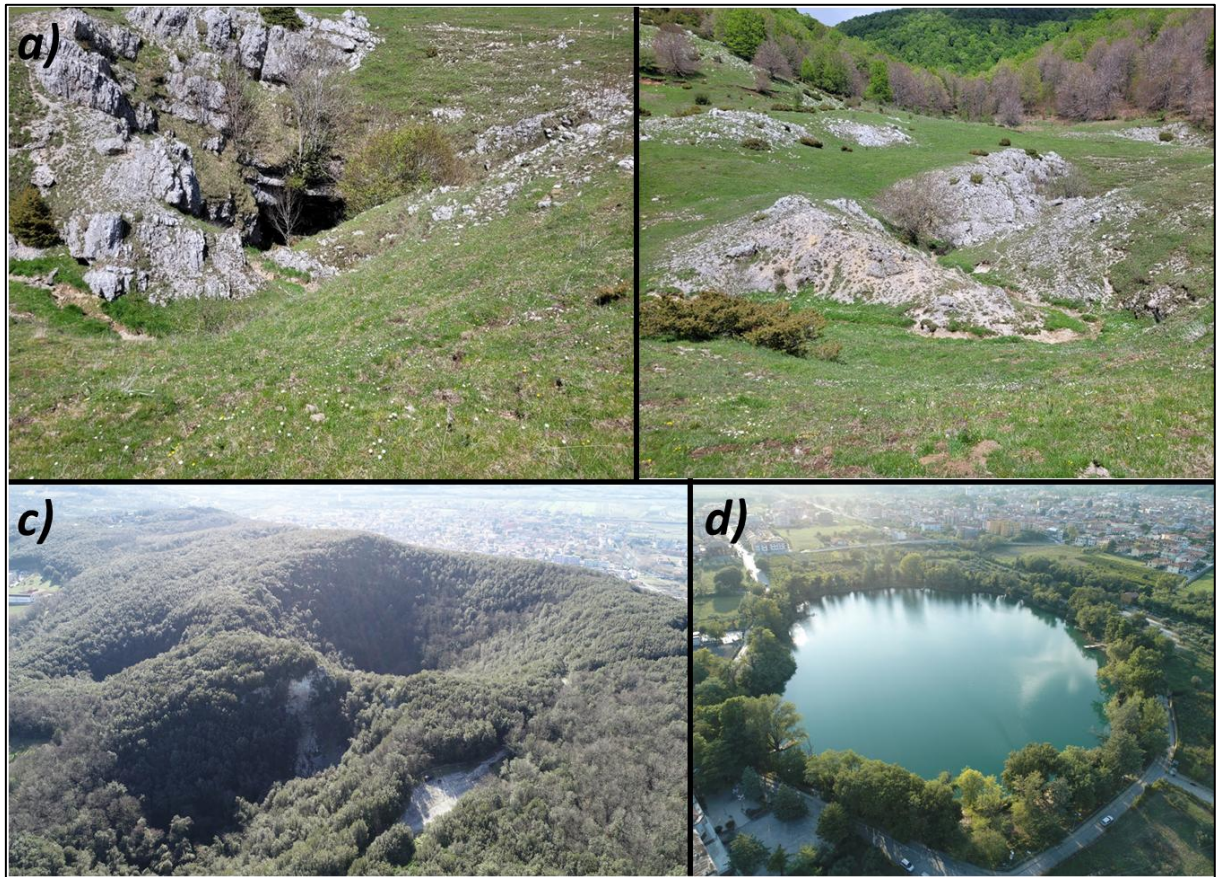


Figure 6.1. (a) Campo Rotondo (Matese massif) ponor; (b) Campo Rotondo Solution doline; (c) Pugliano Mt. (Telese Terme plain) Bedrock Collapse dolines; (d) Telese lake (San Salvatore Telesino municipality) Cover Collapse doline (Photo by (a) Francesco Fiorillo; (b) Michele Ginolfi; (c) and (d) Guido Leone).

Hydrologically, the doline can be viewed as a concentrated recharge point and a descending pipe or shaft is common on the doline floor (Klimchouk, 2000; Veress, 2016). Ponors are often associated with solution dolines and represent concentrated and directed infiltration points, even if they are buried below the cover deposits (Leone et al., 2023). Dolines represent the most frequent infiltration feature in a karst environment.

Uvalas and poljes

Uvalas and poljes are larger in size. Uvalas are compound closed depressions made of several dolines (Ford and Williams, 2007). These depressions lack surface water. Moreover, sediments are scarce, the bottom is mostly undulating or pitted with dolines, and even when the bottom is nearly flat, its transition into lateral slopes is gradual (Ćalić, 2011).

A polje (Fig. 6.2) is a closed depression with a flat floor, karstic drainage, and steep peripheral slopes (Gams, 1978; Bonacci, 2013). The tectonic setting has a significant role in their genesis, as poljes often develop parallel to the major structural trends or are associated with graben depressions (Ford and Williams, 2007; Field, 2002). Poljes drain meteoric water underground in two different ways: water infiltration may diffuse over the sedimentary cover or concentrate at dolines and ponors. An intermittent or permanent sinking watercourse often flows across the flat floor of poljes (Veress, 2016). If the drainage is poor, the polje floor gets flooded, and a lake forms (Ford and Williams, 2007; Bonacci, 2013). Flooding and sedimentation are the main processes distinguishing poljes and uvalas and contribute considerably to floor flattening and preserving the sharp transitions to the bordering slopes (Ćalić, 2011).



Figure 6.2.Matese Lake (Matese massif) karst polje (photo by Michele Ginolfi).

6.1.2. Closed depression mapping

The GIS-based mapping method consists of three phases (Fig. 6.3) described in the following text (Esposito et al., 2025a).

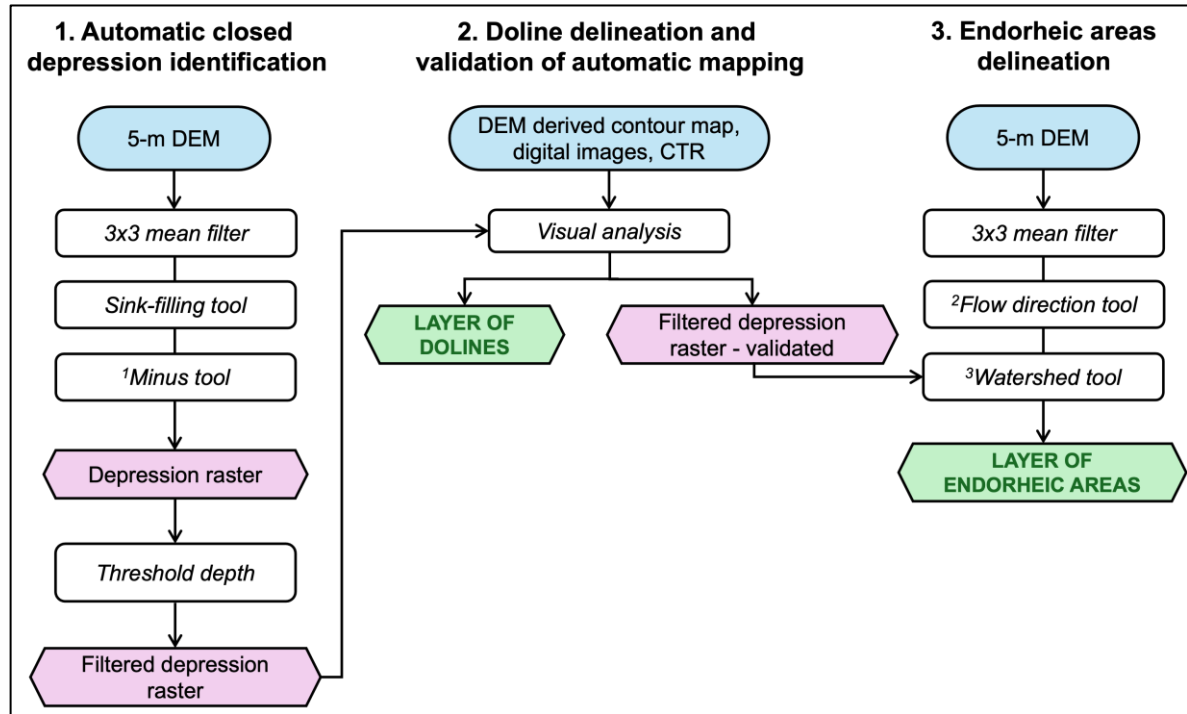


Figure 6.3. Mapping workflow (simplified; Esposito et al., 2025a). Blue, input data; pink, output raster; white, calculation by GIS tools (except visual analysis); green, output layers of karst hydrological features. ¹Minus tool subtracts the value of a raster (DEM) from the value of another raster (sink-filled DEM). ²Flow Direction tool creates a raster of flow direction from each cell to its downslope neighbor. ³Watershed tool determines the contributing area above the closed depression using the flow direction raster and the closed depression location.

The delineation of endorheic areas begins with the identification of closed depressions. Note that even ponors represent point of concentrated recharge and should be included in the mapping (Leone et al., 2023). However, ponor localization generally requires field surveys (Fig. 6.4).

Poljes can be easily delineated using topographic DEM-derived contour maps. On the other hand, doline size varies in a wide range. Doline identification and delineation depend on the cartographic scale and DEM resolution. Nowadays, doline mapping primarily involves the analysis of high-resolution remotely sensed data. It may involve the visual interpretation of satellite/aerial images and DEM-derived products, including contour maps, hill-shaded DEMs, TPI (Topographic Position Index) raster, surface curvature raster and slope raster. In this case, doline delineation is based on the principle of an abrupt change in the surface slope (or curvature). Otherwise, doline mapping may involve semi-automated and automated methods.

Each doline delineation method shows limitations in describing the depression rim. For example, the contour-based method assumes the doline rim to be horizontal. On the other hand, visual interpretation of orthophotos and DEM-derived products (e.g., hill shade, slope, and curvature) allows for capturing altitude variations in doline rim. However, these approaches could be highly subjective (Čeru et al., 2017). Therefore, there is no single approach that would work optimally in all circumstances (Šegina et al., 2018).

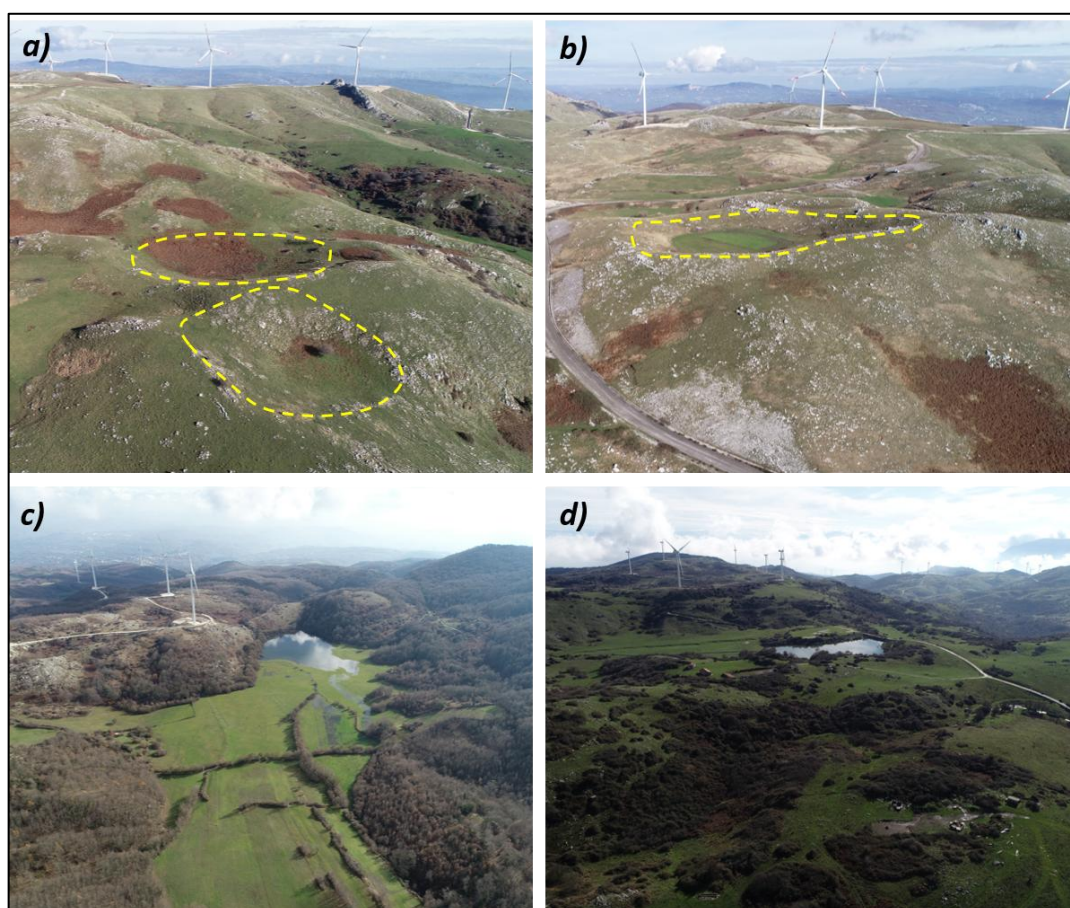


Figure 6.4. Field survey with drone technology performed during the check of the dolines mapped. (a) and (b) Dolines checked with drone surveys; the line in yellow indicates the perimeter of some dolines. (c) Drone photo of Lagospino polje and its endorheic lake; (d) Drone photo of Acqua della Lepre endorheic area (photo by Guido Leone and Michele Ginolfi).

A widely used automatic, quantitative mapping approach combines the hydrological processing of a DEM and morphometric analysis of the mapped depressions (e.g., De Carvalho et al., 2013). (i) Hydrological processing aims to calculate the so-called “difference raster” to determine the location and depth of the closed depressions (Figure 6.5; Doctor and Young, 2013). This raster is obtained by subtracting the original DEM from the depression-less DEM obtained by applying a sink-filling algorithm (O’Callaghan and Mark, 1984; Planchon et al., 2002; Wang and Liu, 2006). (ii) Not all the depressions identified in such a way represent true

geomorphic karst features. A method to discriminate false depressions from actual ones is selecting a set of true karst depressions and measuring their morphometric attributes. Then, an optimal threshold for each attribute is defined to filter out potentially false features with “anomalous” characteristics. Although this method reduces the number of false depressions, even true karst depressions may be eliminated.

The sink-filling algorithm virtually fills each closed depression up to the spill elevation (i.e., the elevation at which water ideally flows out of the depression). The spill point represents the shared (tangent) point between the upper rim of the closed depression and water dived divide of its endorheic area. Using this method, the depression upper rim is the closed contour passing through the spill point (Fig. 6.5).

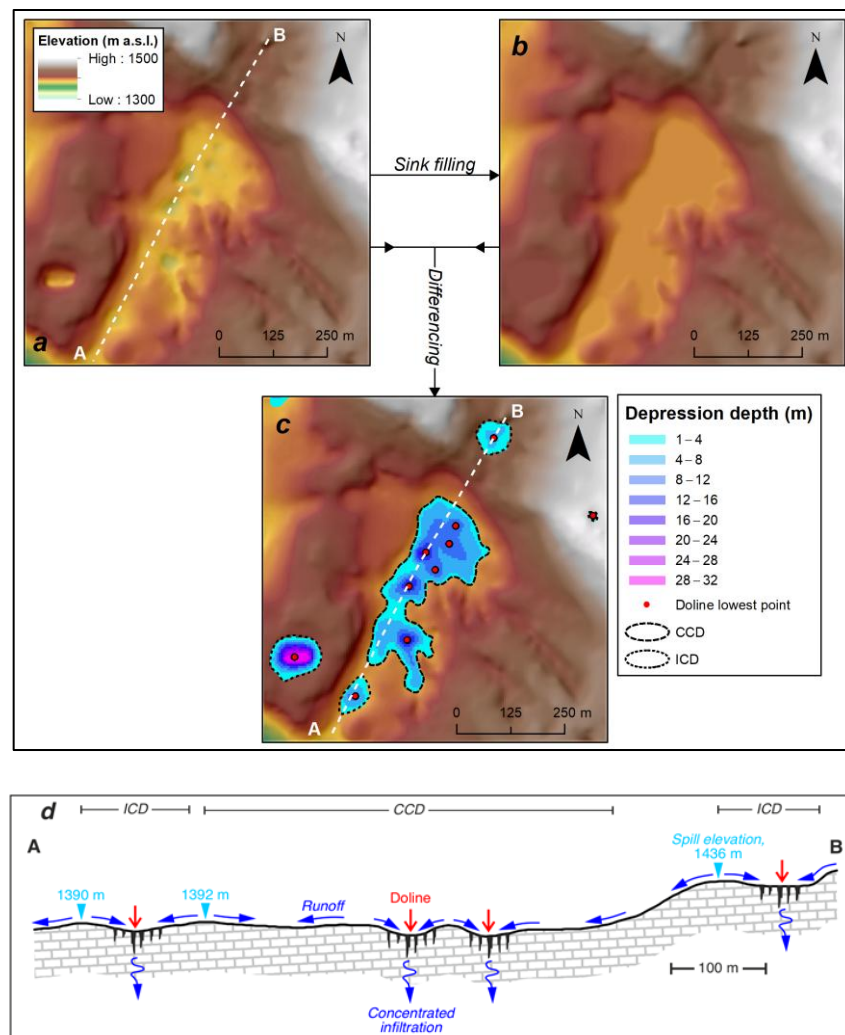


Figure 6.5. Automatic identification of karst closed depressions by sink-filling approach (from [Esposito et al., 2025a](#)): (a) original DEM; (b) sink-filled DEM; (c) filtered difference raster (arbitrary threshold depth = 1 m), representing closed depressions; depression depth is measured from the spill elevation. Abbreviations: CCD, compound closed depression; ICD, isolated closed depression. (d) Cross-section showing the topographic profile, runoff directions, and spill elevation of ICD or CCD.

The fill-based method cannot isolate single depressions located inside a larger depression (compound depression in Fig. 6.5). [Wu et al. \(2016\)](#) developed an algorithm to overcome this limitation. Their method uses a vector representation of a DEM as contours and establishes the hierarchical relationship between adjacent closed isolines. Thus, the algorithm automatically extracts isolated depressions. Contours are drawn from a smoothed DEM, assuming a reasonable regular interval. [Moreno-Gómez et al. \(2019\)](#) used the Jenks method to segment depressions, assuming irregular contour intervals.

Doline mapping

A semi-automatic approach that combines (i) the fill-based method for automatic mapping of a karst closed depression from the 5-m DEM and (ii) visual interpretation of different informative layers (Table 6.1) was applied; then, the corrected depression raster was then used as input for the automatic delineation of endorheic areas (Fig. 6.3).

Data	Year	Resolution or Scale	Author or Provider
Digital Elevation Model (DEM)	-	5 m	-
Digital orthophoto	2006, 2012	0.5 m	Geoportale Nazionale, Ministero dell’Ambiente e della Sicurezza Energetica (MASE)
Google Earth satellite images	2016–2023	-	Google
Technical Regional Chart (CTR)	2004	1:5000	Territorial Informative System of Campania Region
Topographic Map	1995	1:25,000	Italian Military Geographic Institute (IGMI)

Table 6.1. Table of the main topographic and geo-thematic data used for mapping.

The fill-based method automatically identifies closed depressions in the DEM, which was pre-processed using a 3-by-3 mean filter. In detail, this method begins by calculating the depression raster, obtained by the difference between the filtered DEM and the sink-filled DEM (Fig. 6.3). Since shallow depressions are likely to be false geomorphic karst features in the digital surface, the depression raster was filtered by a depth threshold. This value was calibrated from true doline samples and represent the 99th percentile of doline depth frequency. Specifically, using

the DEM, the dolines were remapped by applying the outermost closed contour method (contour interval of 0.5 m) and measured their depth.

The threshold value was fixed equal to 0.65 m in Alburni karst massif. In the case of Morcone karst reliefs, considering that the mapping was carried out using 20-m, 10-m, and 5-m DEM, three thresholds equal, respectively, to 0.10 m, 0.20 m, and 0.55 m were chosen.

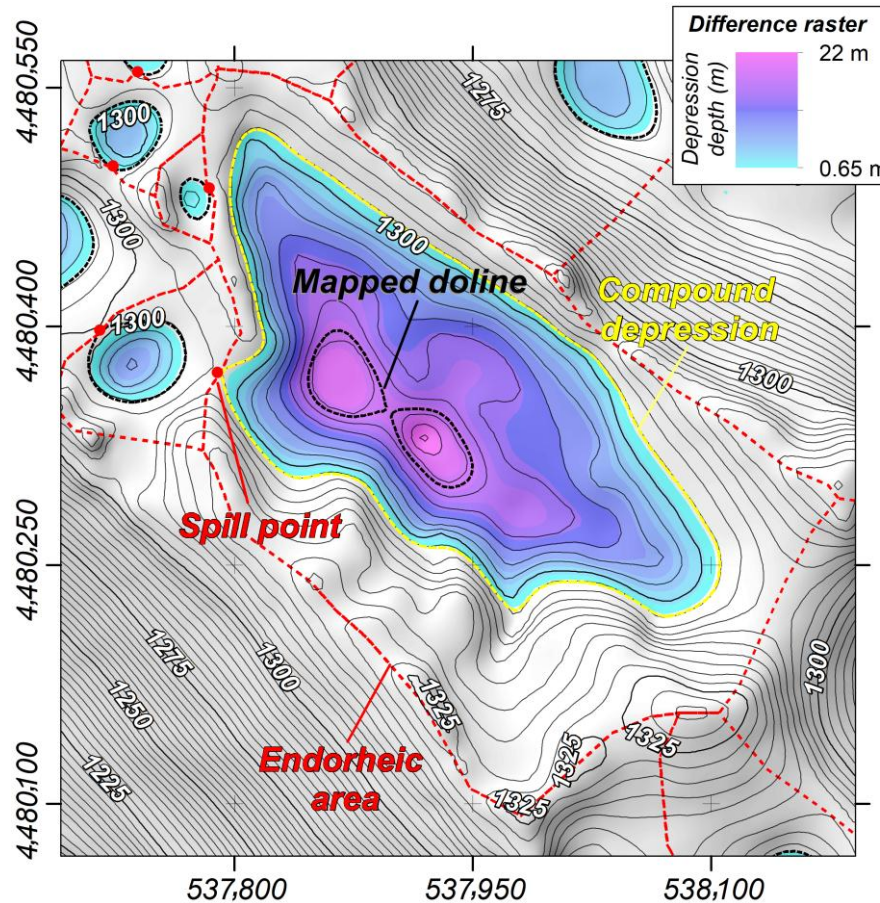


Figure 6.6. Mapping criterion of dolines and endorheic areas (from [Esposito et al., 2025a](#)). Two dolines (black lines) can be detected inside a larger depression (compound depression, yellow line). The endorheic area (red line is the water divide) represents the closed catchment of a single doline or compound depression. The spill (or overflow) point represents the shared (tangent) point between the upper rim of the closed depression and its endorheic area (red dot).

The fill-based method cannot isolate dolines that are contained within a larger depression (Fig. 6.6). To overcome this problem, the filtered depression raster was segmented into regularly spaced contours (contour interval = 0.5 m) and manually mapped dolines by the outermost closed contour method ([Bondesan et al., 1992](#); [Verbovšek and Gabor, 2019](#)). The outermost closed contour allows for the objective definition of the doline upper rim. However, the outermost closed contour does not represent the actual overflow contour of a depression. As such, this method provides smaller and shallower depressions than the sink-filling method.

Manual doline mapping was supported by visual inspection of Google Earth satellite images, digital orthophotos (0.5 m resolution), and 1:5000 topographic maps (Technical Chart of Campania Region). During this phase of the analysis, the results of the fill-based method were further validated (Figure 6.3). Furthermore, for the mapping procedure performed on dolines in Morcone karst reliefs, also the photo taken from drone surveys carried out in the area have been analyzed.

Automatic mapping of endorheic areas

Taking a watershed having centripetal drainage, the closed depression represents the volume below the contour passing through the spill point (Fig. 6.6).

Endorheic areas can be automatically delineated using the *Watershed tool* (Fig. 6.3). This tool was designed to delineate the watershed of a river (i.e., the upslope area that contributes to the river flow at a given section) and needs two input pieces of information: (i) the location of the drainage point, (ii) the flow directions, calculated using the *Flow Direction tool*. In an endorheic watershed, the drainage converges toward the closed depressions, which is represented by an ensemble of neighboring pixels. Therefore, endorheic areas can be automatically delineated considering the filtered, validated depression raster as input for running the *Watershed tool* (Leone et al., 2023).

6.1.3. Morphometric parameters

Statistical analysis was carried out considering samples of dolines and endorheic areas. In particular, for each endorheic area there are one or several dolines, so for each endorheic area and for each doline within it, the following morphometric parameters were calculated: area (A), perimeter (P), lowest, mean, and maximum elevation (H_{min} , H_{mean} , H_{max}), and longest axis orientation (Δ). Other morphometric parameters, including maximum elevation difference (ΔH_{max}), volume (V), and Circularity Index (CI), were calculated.

The maximum elevation difference, ΔH_{max} , is the difference between the highest point on the perimeter and the lowest point within the doline or endorheic area.

The volume, V , was calculated as:

$$V = A \cdot \Delta H_{mean} \quad (6.1)$$

where ΔH_{mean} is the mean depth, i.e., difference between the maximum elevation H_{max} and mean elevation H_{mean} .

The Circularity Index, CI, was calculated exclusively for closed depressions:

$$CI = 4\pi \cdot A/P^2 \quad (6.2)$$

The index ideally ranges from 0 (elongated shape) to 1 (circular shape).

The Minimum Bounding Geometry tool was used to measure doline (and endorheic area) orientation (or azimuth). The tool calculates the azimuth of the longest axis of the rectangle bounding the perimeter of the landform. Dolines having $CI < 0.9$ were considered in the analysis. Using a threshold for CI, allows for minimizing the effect of nearly circular shapes. A CI-threshold of 0.95 was suggested by [Bauer \(2015\)](#). In the studied area, dolines may still preserve a sub-circular shape for $CI = 0.94\text{--}0.95$, leading to adopt a lower threshold.

6.2. Groundwater recharge estimation

The groundwater recharge of Morcone karst reliefs have been estimated using three different methodologies: (i) Modified APLIS, (ii) newly APLIS with endorheic areas, and (iii) Daily Scale Recharge methods. In the following sub-sections, the three methods used will be detailed described.

6.2.1. Modified APLIS method

The APLIS method is used to estimate, in GIS environment, the average-annual rate of recharge in karst aquifers ([Andreo et al., 2008](#)). Also, unlike other methods used to estimate recharge rates, this method enables to establish the spatial distribution of recharge rates in carbonate aquifers on the basis of their features. This aspect is fundamental for the appropriate management and protection of groundwater, with respect to both its quantity and quality. APLIS method and its modified version ([Marin, 2009](#)) were applied in several aquifers of Mediterranean area ([Ayadi et al., 2024](#); [Nanou et al., 2024](#)), in some cases with some modifications of parameters constituting the model ([Entezari et al., 2020](#); [Alem et al., 2021](#), [Errahmouni et al., 2022](#); [Tadamouri et al., 2024](#)). Furthermore, the quantification and spatial distribution with Modified APLIS method represents a flexible method in Mediterranean area karst aquifer recharge estimation, improving the accuracy of water budget estimations ([Nanou et al., 2024](#)). [Lorenzi et al. \(2022\)](#) and [Fronzi et al. \(2025\)](#) applied the method to some Italian karst aquifers coupled with other traditional recharge methods, founding coherent results.

Elevation (m)	Rating	Slope (%)	Rating	Lithology	Rating	Soil	Rating
>2700	10	≤ 3	10	Karstified limestones and dolostones	10 or 9	Leptosols	10
2400-2700	9	3-5	9	Slighted karstified, fractured limestones and dolostones	8 or 7	Arenosols and xerosols	9
2100-2400	8	5-10	8	Fissured limestones and dolostones	6 or 5	Calcareous regosols and fluvisols	8
1800-2100	7	10-15	7	Sands and gravels	4	Euthritic regosols and solonchaks	7
1500-1800	6	15-20	6	Conglomerates	3	Cambisols	6
1200-1500	5	20-30	5	Plutonic and metamorphic rocks	2	Euthric cambisols	5
900-1200	4	30-45	4	Shales, silts, and clays	1	Histosols and luvisols	4
600-900	3	45-65	3			Chromic luvisols	3
300-600	2	65-100	2			Planosols	2
≤ 300	1	>100	1			Vertisols	1
Development of preferential infiltration landforms						Rating	
High development of preferential infiltration landforms						10	
Moderate development of preferential infiltration landforms						5	
Poor development or completely absent preferential infiltration landforms						1	
Hydrological features of outcropping terrains (F_h)						Rating	
Aquifer						1	
Other						0,1	

Table 6.2. Rating and scores of variables used in Modified APLIS method (Marin, 2009).

The recharge rate is expressed as precipitation percentage, based on five variables (Eq. 6.3): Elevation (A, *Altitude*), Slope (P, *Pendiente*), Lithology (L, *Litologia*), Infiltration landforms (I, *Infiltracion*) and Soil type (S, *Suelo*). Compared to the original, the modified version of APLIS method provided by [Marin \(2009\)](#) changed some scores attributed to the above variables (Tab. 6.2) and added a factor accounting for the hydrogeological features of the terrains outcropping in the study area (F_h) (Eq. 6.3). For each variable, categories or intervals were established. For each of these a value ranging between 1 and 10 was assigned (Tab. 6.2). A value of 1 indicates a minimal incidence of the values of this variable on aquifer recharge, while a value of 10 expresses the maximum influence on recharge.

The mathematical equation describing the method should be a sum (or overlapping) of layers corresponding to each variable constituting the model. Thus, the recharge value is provided by the sum of the physical features of aquifers considered. However, in recharge evaluation, these variables haven't the same weight or the same importance, thus they were combined in order to calculate their relative weight ([Duran et al., 2004](#)). Following these assumptions, the method equation was found ([Andreo et al., 2008](#); [Marin, 2009](#); [Mударра et al., 2019](#)):

$$R = \frac{A + P + 3 \times L + 2 \times I + S}{0.9} F_h \quad (6.3)$$

The recharge rate values R , or APLIS recharge index, resulting from this method are a function of the inherent features of the aquifer and are expressed as a percentage of precipitation falling on aquifer surface.

The recharge values resulting from the equation (6.3) ranges between a minimum value equal to 8.88% to a maximum value of 88.8% of precipitation falling on the aquifer surface. Thus, the recharge will never be equal to the 100% of precipitation value.

The average recharge rate, obtained as the average R value of the spatial units in recharge map, is divided in five different classes (Tab. 6.3; [Andreo et al., 2008](#)).

Recharge rate (%)	Class
≤ 20	Very low
20-40	Low
40-60	Moderate
60-80	High
>80	Very high

Table 6.3. Recharge rate classes resulting from Modified APLIS method (from [Andreo et al., 2008](#)).

Furthermore, using the precipitation data available for the study area and the recharge rate map calculated from the application of the above procedure, the Specific Recharge Distribution map (in m^3/m^2) of the aquifer can be made (Andreo et al., 2018).

APLIS raster map	Data	Year	Resolution or scale	Author or Provider
Elevation	Digital Elevation Model (DEM)	-	5 m	Campania Region
Slope		1976	1:100,000	
Lithology and correcting factor	Geological map	2021	1:50,000	Istituto Superiore per la Ricerca e Protezione Ambientale (ISPRA)
	Digital Elevation Model (DEM)	-	5 m	Campania Region
	Digital ortophoto	2012	0.5 m	Geoportale Nazionale, Ministero dell'Ambiente e della Sicurezza Energetica (MASE)
Infiltration landforms	Google Earth Satellite Images	2016-2023	-	Google
	Drone images	2019	-	-
	Technical Regional Chart	2004	1:5000	Campania Region
	Topographic map	1995	1:25,000	Italian Military Geographical Institute
Soil	Earth system and pedological sub-system map	1997	1:50,000	Campania Region

Table 6.4. Main geographical, topographical, and geological data used in drawing APLIS maps.

The *Altitude* and the *Slope* parameters maps (Fig. 6.7a and b; Tab. 6.4) of the area were obtained through the elaboration with Arc GIS tools of the 5m-DEM. The raster obtained are reclassified and scored as required by the recharge method.

The *Lithology* map (Fig. 6.7c; Tab. 6.4) was carried out using the information acquired from the Geological Map of Italy at scale 1:100,000, the C.A.R.G. Geological Map Project at scale 1:50,000 (ISPRA, 2021), and the geological information available from former regional (Ciarcia and Vitale, 2024) and local (Nicotera, 1953; Esposito et al., 2005a; Valente et al., 2022) studies found in scientific literature. Following the APLIS procedure, a score has been attributed to each geological unit outcropping in the study area. A higher score was attributed to karst lithologies and lower ones to the others.

The *Infiltration landform* map (Fig. 6.7d; Tab. 6.4) was obtained applying the procedure described in the section 6.1. The map was then reclassified giving the higher score to dolines

characterized with an active ponor, a middle score to doline not characterized by the presence of a ponor, and the lowest score to all other areas.

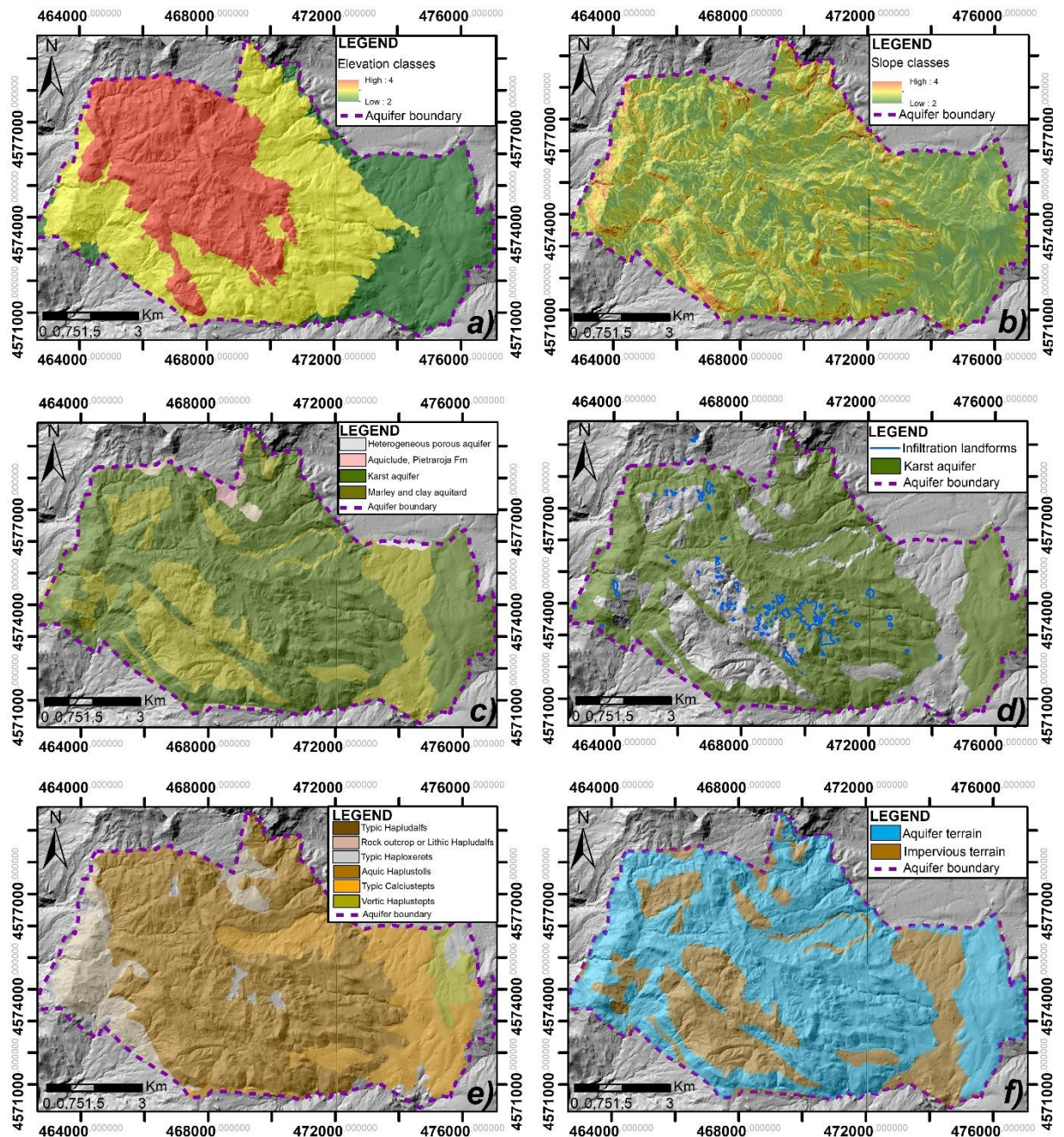


Figure 6.7. Maps created for Modified APLIS method. (a) Elevation; (b) Slope; (c) Hydrogeological map; (d) Infiltration landforms map; (e) Soil type map; (f) F_h factor map.

The *Soil type* parameter map (Fig. 6.7e; Tab. 6.4) was taken by the Regional Cartographic Database of Campania Region (<https://sit2.regione.campania.it/content/cartografia>). According to other Authors that applied APLIS in regions where soils were different to Spanish ones (Espinoza et al., 2015; Gurito et al., 2024), the classification was modified. Comparing Spanish soils features to Italian ones, a new classification was made taking in account the different soil

types. Using the same scoring, a higher score to soil with the minimum thickness and less developed texture was given. While, a lower score to soil with the maximum thickness and the well-developed texture was attributed.

The *Correcting factor* map (Fig. 6.7f; Tab. 6.4) was realized using the information taken from the previous lithology map and classifying terrains in aquifer (highest score) and non-aquifer (lowest score) lithologies.

The distribution of precipitation map was created using the 5-m DEM and precipitation data from several meteorological stations located close to study area.

The values of recharge obtained from the application of the recharge method were finally compared with discharge data collected.

6.2.2.APLIS with endorheic areas method

A new method resulting by the combination of Modified APLIS (Andreo et al., 2008; Marin, 2009) and Groundwater Recharge Model (Fiorillo et al., 2015b) technique was designed and after applied to the study area. This methodology, firstly, made a distinction between Endorheic areas, A_E , and other areas (thereafter called *Open areas*, A_O ; Fiorillo et al., 2015b). In Endorheic areas, closed depression where all the runoff is completely adsorbed (*internal runoff*; White, 2002), all the effective precipitation became a part of recharge amount. In this case, the effective afflux is equal to recharge amount (Fiorillo and Pagnozzi, 2015). The difference area between the Endorheic areas and that are not endorheic is considered as Open area. In that area, the runoff can escape from the spring catchment, especially during intense storms.

In Endorheic areas, the recharge rate is considered equal to 100% of the effective precipitation, as all the runoff water in the endorheic basin infiltrates in the underground. For the same areas, the specific recharge evaluation was performed collecting precipitation data from the rain gauge stations in the area, managed by the Italian Hydrographic Service, for the period of 1970-1999. Therefore, in GIS environment, the effective precipitation (P_{eff}) was calculated as:

$$P_{eff} = P_{tot} - AET \quad (6.4)$$

Where P_{tot} is the total precipitation and AET is the Actual Evapotranspiration, calculated using the Turc formula (Turc, 1954):

$$AET = \sqrt{\frac{P}{\left[0.9 + \left(\frac{P}{L}\right)^2\right]}} \quad (6.5)$$

Where P is the total precipitation and L is the evaporation coefficient given by the equation:

$$L = 300 + 25T + 0.05T^3 \quad (6.6)$$

Where T is the temperature data, corrected for the elevation, collected by the monitoring stations, located at different ground elevations. Using GIS tools, the effective afflux (F_{eff}) in a specific area (A) was calculated:

$$F_{eff} = \frac{\sum_1^n P_{eff}}{n} \times A \quad (6.7)$$

Where n is the number of cells in the area (A) and P_{eff} is the effective annual mean rainfall assigned to each cell in function of its ground elevation and deducted from the regression of available rain gauges located at different elevation.

The recharge rate and the specific recharge values concerning Open areas of the karst massif were made using the modified APLIS method calculation explained in the previous Section 6.2.1.

Finally considering that the overall recharge, R , of the karst massif is given by the following expression:

$$R = R_{AE} + R_{AO} \quad (6.8)$$

In GIS environment, the area's rasters were merged to obtain the overall Recharge Rate map and the overall Specific Recharge value for the study area. Like the previous Modified APLIS method, the recharge evaluation was performed for a dry, average and wet condition.

6.2.3. Daily Scale Recharge model

The Daily Scale Recharge (DSR) model (Fiorillo et al., 2015b) allows to simulate both the recharge and runoff processes through the hydrological year. The soil mantle of the mountainous area retains an amount of rainfall to satisfy the water deficit accumulated during the previous no-rainfall period, having a fundamental role in evapotranspiration processes. Several factors (e.g., the nature, the physical characteristics, the thickness of each soil layer, and the vegetation cover) control the soil storage capacity.

The Daily Scale Recharge model is based on the balance of water content in the soil mantle, transforming the daily rainfall in water content, up to field capacity, and then in recharge and runoff amount (Fiorillo and Wilson, 2004). The recharge value, R , was calculated using the following equation:

$$P_i = \Delta\theta + AET + R + RO \quad (6.9)$$

Where P_i is the daily precipitation, AET the actual evapotranspiration, $\Delta\theta$ constitutes the increase of water content of the soil, and RO is the runoff. AET depends on the soil moisture, θ , and it is assumed equal:

$$AET = PET \text{ for } \theta > \theta_{min} \quad (6.10)$$

$$AET = 0 \text{ for } \theta = \theta_{min} \quad (6.11)$$

Where PET is computed adapting the Thornthwaite model (Thornthwaite, 1948) at daily scale (Fiorillo and Wilson, 2004).

During wet periods, the soil moisture can increase up to a maximum value, θ_{max} , defined by the field capacity of the soil. When field capacity has been reached, the recharge, R , and runoff, RO , can occur, giving the so-called excess rainfall, P_{exc} :

$$P_{exc} = R + RO \quad (6.12)$$

That recharge water table and runoff waters.

The model assumes that runoff occurs if rainfall excess, P_{exc} , exceeds a specific threshold value, Tr , at daily scale:

$$\text{for } P_{exc} \leq Tr, \quad (P_{exc})_{AO} = (R)_{AO} \quad (6.13)$$

$$\text{for } P_{exc} > Tr, (P_{exc})_{AO} = (R)_{AO} + (RO)_{AO} \text{ and } (R)_{AO} = Tr \quad (6.14)$$

6.3.Lumped models for recharge evaluation: KarstMod

The conceptual (or reservoir) models are based on conceptual model built according to the results of the studies (Fleury et al., 2007). They are developed with simple discharge and equation between linked reservoirs. The simulation of each hydrological process is assigned to a compartment, or reservoir, whose discharge is a non-linear function of the storage (Hartmann et al., 2014). These reservoirs feed and empty, transforming rainfall in flow rate. Structure of these models have the advances of keeping in memory the previous water height in each

reservoir and to simulate the main steps of the aquifer functioning. The parameters of lumped models cannot be determined directly from physical catchment characteristics (Mazzilli et al., 2019). Thus, the number, arrangement, and configuration of the compartments determine model complexity and parameters, which are inferred by manual or automatic model fitting (Leone et al., 2025).

Previous studies have highlighted how lumped models are valuable tools to simulate aquifer outflows and the main processes controlling the aquifer water balance and for the simulation of spring hydrographs (Fleury et al., 2007) and, in recent years, these models have been extensively used to predict the impacts of past, ongoing, and future climate change and anthropogenic stress on stress discharge (Dubois et al., 2020; Sivelles et al., 2021; Fan et al., 2023).

KarstMod is an adjustable modeling platform for simulating the rainfall-discharge relationship of karst springs at a daily or hourly time step and for analyzing the hydrodynamics of the compartments considered in the model (Mazzilli et al., 2019; Mazzilli et al., 2022). The software can reproduce the structure of most conceptual global models of karst systems found in literature. Also, the modularity of the platform makes it possible to compare different hydro-systems within a same methodological approach. The platform provides several tools and graphs helping gaining understanding and insight in the behavior of the model. Further, they help the user to detect possible flaws in the structure and parametrization.

6.3.1. Workflow

In the first step, the user defines the model structure and fluxes uses graphical interface. In this phase the user can use his understanding of primary processes involved to design the model. A gradual complexification approach, with a careful assessment of the influence of the selected compartment and fluxes on the resulting model behavior and equifinality is recommended (Mazzilli et al., 2019).

The following step is to specify the user-defined values of rainfall (P), evapotranspiration (ET), and reservoir pumping. The user also defines the performance measure and the warm-up, calibration, and validation periods.

The model can run using both user-specified parameter values (the so-called “*run mode*”), or in automatic calibration mode (Fig. 6.8). The former allows the direct analysis of the effects of the model parameters on the results. This method is used mostly for educational and learning purposes. The latter provides a systematic exploration of the parameters space. The outcomes

of this exploration are the selection of the optimal parameter set for a selected performance measure, and a set of graphs that allow a first grasp of equifinality issue.

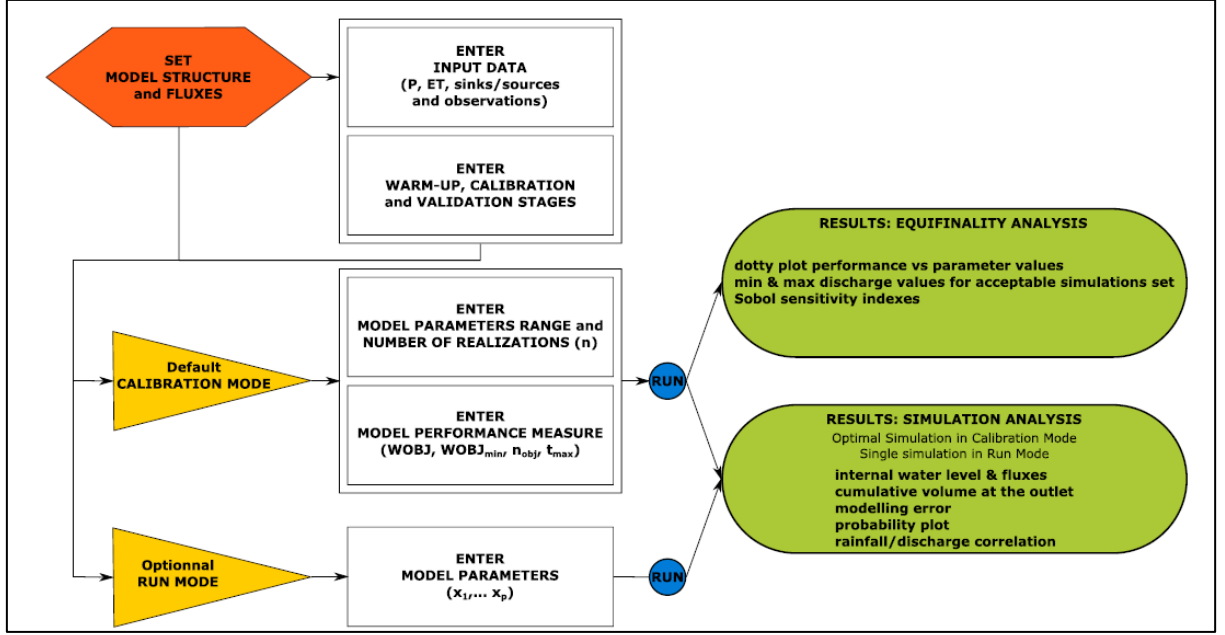


Figure 6.8. Simplified workflow of the KarstMod platform (from Mazzilli et al., 2019).

6.3.2. Meteorological modules

Daily potential evapotranspiration, PET, was estimated by the Thornthwaite formula following the Thornthwaite and Mather (1957) approach.

To simulate the snow processes a temperature-index method was used. It consists in a temperature-based snow routine that assumes air temperature as unique controlling variable (Hock, 1999; Parajuli et al., 2020). The partition of daily precipitation in a snow and a rain phase was modeled as follow:

$$P(\text{mm/day}) = \begin{cases} \text{snowfall}, & \text{if } T_d < T_s \\ \text{rainfall}, & \text{if } T_d \geq T_s \end{cases} \quad (6.15)$$

Precipitation occurs solid when daily temperature T_d falls below a threshold value T_s .

Snow accumulation on the ground and its subsequent melt were modeled as follows:

$$\text{snow melt (mm/day)} = \begin{cases} 0, & \text{if } T_d \leq T_M \\ mf(T_d - T_M), & \text{if } T_d > T_M \end{cases} \quad (6.16)$$

Snowfall accumulates on the ground as snowpack when the daily temperature is below a threshold value T_M and no water is released by snowpack. Otherwise, it melts, and the water

equivalent height released by the snowpack is linearly proportional to the temperature difference ($T_d - T_M$). Coefficient mf is the proportionality coefficient, called melt factor.

6.3.3. Structure of the model

In its complete form, the modular structure proposed in KarstMod is based on four compartments organized on a two-level structure (Fig. 6.9): (i) Compartment E (higher level); (ii) compartments L, M, and C (lower level). The higher level represents the infiltration zone and the lower level is representative of the saturated zone where the compartments L, M, and C represent the sub-systems constituting it. The user is free to assign model compartments to different conceptual model. In the compartment E, the minimum water level can either zero or lower (soil-available water content configuration; Fig. 6.9).

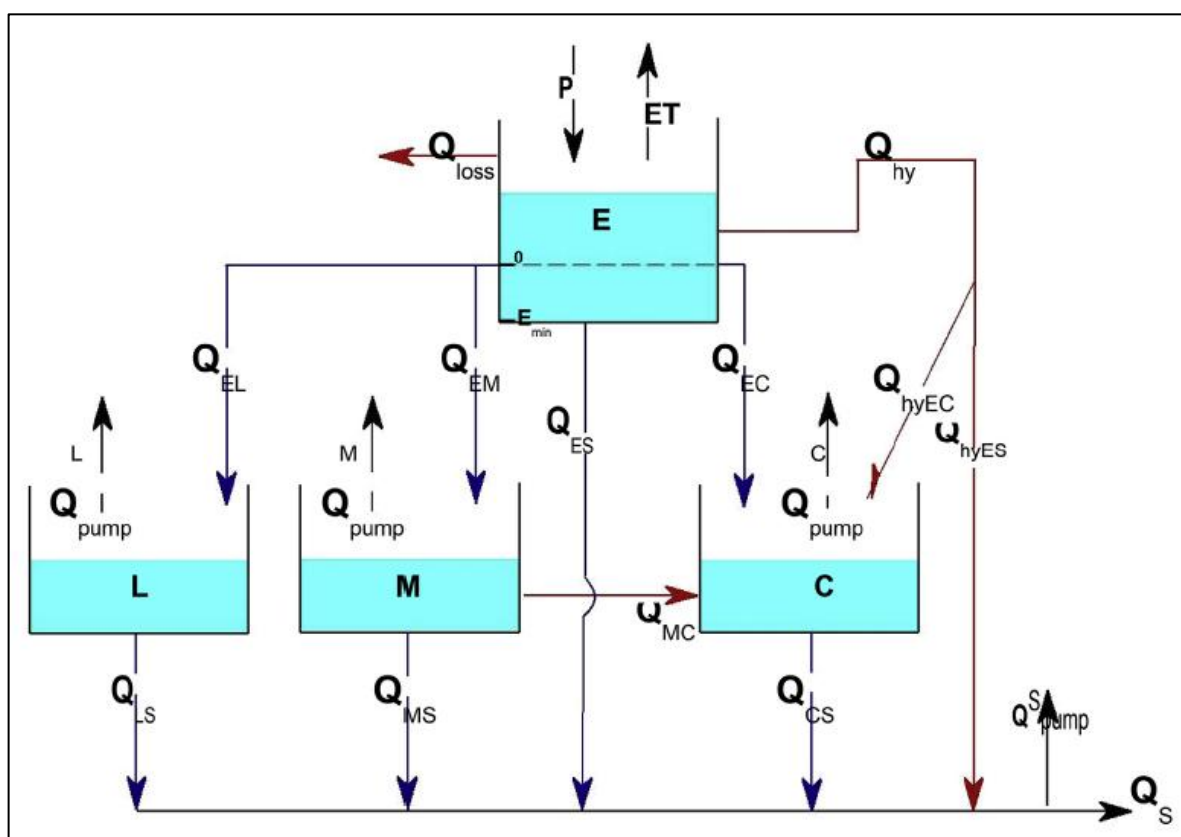


Figure 6.9. Structure of the modular platform. In this simulation, all the compartments and fluxes are activated, the minimum water level of $E_{\min} < 0$ is set for compartment E, and the hysteretic function is used (from Mazzilli et al., 2019).

Two configurations are available for each compartment: (i) classical configuration, (ii) infinite characteristic time configuration. In the first one the user may activate a number of transfer law with finite characteristic transfer time. In the second one, a transfer law with infinite

characteristic is applied. The detailed description of these two configurations is reported in [Mazzilli et al. \(2022\)](#).

To complement linear and non-linear water level, KarstMod proposes (i) a hysteretic discharge-water level function which is meant to reproduce the hysteretic dependence observed on wet-dry cycles in the vadose zone ([Lehmann et al., 1998](#); [Tritz et al., 2011](#)), (ii) an exchange function proportional to the water level difference between two compartments, which is meant to reproduce matrix-conduit interactions as supported by direct observation of several karst systems.

The model has five balance equations:

$$\frac{dE}{dt} = P - ET - Q_{loss} - Q_{EL} - Q_{EM} - Q_{ES} - Q_{EC} - Q_{hyEC} - Q_{hyES} \quad (6.17a)$$

$$if E \geq 0$$

$$\frac{dE}{dt} = P - ET \text{ if } E_{min} < E < 0 \quad (6.17b)$$

$$\frac{dL}{dt} = Q_{EL} - Q_{LS} - Q_{pump}^L \quad (6.17c)$$

$$\frac{dM}{dt} = Q_{EM} - Q_{MC} - Q_{MS} - Q_{pump}^M \quad (6.17d)$$

$$\frac{dC}{dt} = Q_{EC} + Q_{hyEC} + Q_{MC} - Q_{CS} - Q_{pump}^C \quad (6.17e)$$

Where E, L, M and C [L] are the water levels in the compartments E, L, M, and C, respectively; E_{min} [L] is the minimum water level in compartment E; P [L/T] is the precipitation rate; ET [L/T] is the evapotranspiration rate; Q_{pump}^L , Q_{pump}^M , Q_{pump}^C [L/T] are the discharge rates removed from compartment L, M and C, respectively, per unit surface area; Q_{loss} , Q_{EM} , Q_{EC} , Q_{hyEC} , Q_{hyES} , Q_{LS} , Q_{MS} , Q_{CS} , Q_{MC} [L/T] are internal discharge rates per unit surface area.

The discharge at outlet Q_S is given by;

$$Q_S = R_e x (Q_{ES} + Q_{LS} + Q_{MS} + Q_{CS} + Q_{hyES}) - Q_{pump}^S \quad (6.18)$$

Where R_A [L²] is the recharge area of the catchment and Q_{pump}^S [L/T] is the discharge rate removed at the outlet per unit surface area.

6.3.4. Model calibration

Model calibration is performed through three different periods: (i) warm-up, (ii) calibration and validation periods.

The warm-up period corresponds to the time interval after which the initialization bias is deemed negligible. Simulation results from the warm-up period are not considered in calibration. Therefore, discharge measurements at the outlet are not required during this period.

The calibration period corresponds to the time interval over which the calibration is performed, that is, model performance during this time period is used to select the optimal parameter set.

The validation period corresponds to the time interval over which the model performance is evaluated, but not used for calibration purposes.

Warm-up, calibration and validation periods are entirely controlled by the user but: (i) if the warm-up period is too short, calibration results may depend on the initial water level; (ii) the calibration period should cover a large range of hydrological conditions. Also, the model allows to calibrate the initial water level in the activated compartments. Discontinuous calibration and validation periods are allowed.

The model is calibrated using a quasi-Monte-Carlo procedure, with a Sobol sequence sampling of the parameter space (Sobol, 1977). The procedure is stopped when either n_{max} parameter sets satisfying $WOBJ$ greater than the user-defined threshold value $WONJ_{min}$ are collected, or when the elapsed simulation time reaches the maximum duration t_{max} , specified by the user. The user specifies both $WONJ_{min}$ and t_{max} .

The different model equations (6.17a-e) are solved using a fourth-order Runge-Kutta scheme and user-specified initial water levels in the selected compartments as initial conditions.

6.3.5. Model outputs

Results provided by the model are represented by the optimal simulation and equifinality analysis.

Optimal simulation analysis

The optimal parameter set is defined as the parameter set of the Sobol sequence sampling that yields the best model performance over the calibration period, with respect to the objective function $WOBJ$.

The optimal simulation is the simulation that results from a model run, using the optimal parameter set.

Regarding the optimal simulation, the following graphs are available: (i) internal and external variable and fluxes as function of time, (ii) cumulative volumes at the outlet as a function of time, (iii) simulated mass balance per time step, (iv) simulation error as function of time, (v) Q_s versus Q_{obs} plot. These graphs made possible to investigate the internal behavior of the model and to detect possible drifts. The Q_s versus Q_{obs} plot highlights the simulation error variability during the simulation period.

Further other analyses are available: (i) cumulative plots for the Q_s and observed (Q_{obs}) discharges; (ii) auto-correlogram of P , (iii) cross-correlogram between P and Q_s , P and Q_{obs} , Q_{obs} and Q_s . The discharge cumulative probability plots provide insight into processes that may influence the distribution law of discharge values.

The simple and cross spectral analyses complete the study of correlogram functions providing information on the regular time of the system, i.e. the inertia related to the nature of its storage and on the frequency of the phenomena that produce flow variations at the spring ([Mangin, 1975](#)).

Equifinality analysis

In KarstMod parameter equifinality can be investigated using the following tools:

- Dotty plots of the values of objective function (calibration period) against the values of the parameters X_i , for all the parameter sets of the Sobol sequence that satisfy $WOBJ > WOBJ_{min}$. These plots provide a preliminary analysis of the distribution of the optimum values of each parameter.
- Dotty plot of the values of the performance criteria used to define the aggregated objective function, for all the parameter sets of the Sobol sequence that satisfy $WOBJ > WOBJ_{min}$. These plots allow to investigate possible conflicts between the performance criteria (Pareto frontier) ([Gupta et al., 1998](#)).
- Variance-based, first order S_i and total S_{Ti} sensitivity indexes for the model parameters X_i . These indexes help to estimating the influence of parameters on the model output, and thus to detect over-parametrization.

KarstMod enables to use the simulation results from all parameter sets yielding $WOBJ > WOBJ_{min}$ for the evaluation of the uncertainty in simulation results. The value of $WOBJ$ over

the calibration period is used as likelihood measure for each behavioral parameter set. Based on this assumption, the software produces the following simulation results:

- Minimal and maximal discharge values simulated at time t from the behavioral parameter sets. They help to figure out the spread of the simulation results for the behavioral parameter sets;
- Limits for the 90% of confidence interval for the simulated discharges at time t ;
- The most likely value of simulated discharge, which is estimated considering both the objective function and the threshold value defined by the user to constrain the behavioral parameters sets.

Chapter 7: GIS tools for closed depressions, endorheic areas mapping and statistical analysis in karst aquifers

In karst areas, the groundwater systems are in a close relationship with surface hydrology and landforms, and the mapping of the surface features represents a key in any hydrological analysis or study, including water balance, hydrological modeling for assessing runoff and groundwater recharge (Fiorillo et al., 2015b), delineation of protection zones for wells and springs (Goldscheider, 2010), simulation of point source contamination, and making artificial water tracer tests (Goldscheider et al., 2008).

Southern Apennines are constituted mainly by karst aquifers characterized by several landforms like dolines, poljes, ponors, and sinking streams. Hydrologically, these areas are located inside a wider endorheic area, representing fissures in the karst massif which water sinks underground. Some of the main karst springs actually exploited for drinking purposes are fed by these systems, featured by one or more endorheic areas feeding one or more basal springs (e.g., Caposele and Cassano Irpino springs).

In general, the study of the infiltration landforms has a fundamental role in quantification and protection of groundwater resources (Goldscheider, 2010). In this thesis, in order to evaluate the presence and distribution of the closed depressions and their role in recharge, the hydrological features of Alburni karst massif and Morcone karst reliefs were mapped. The Alburni karst massif is renowned for its extraordinary concentration of caves and shafts (Santo et al., 2005). Moreover, closed depressions are widespread on its vast, gently dipping summit plateau, showing a high concentration of such features than other massif in this Apennine sector (Esposito et al., 2025a). On the other hand, Morcone karst reliefs are an area characterized by few closed depressions that, in turn, feeds several little karst springs assuming importance in the framework of the water supply of the neighboring municipalities. To better understanding the relationship between the endorheic areas and the linked springs, also, the results of the tracer tests performed in the past have been analyzed (Valente et al., 2022).

7.1. Closed depressions and Endorheic areas mapping of Alburni karst massif

Karst, glacial, and tectonic processes have shaped the current morphological setting of the summit plateau of the Alburni massif (Brancaccio et al., 1973), which develops along a gently dipping monoclinical structure in the SW. The plateau is displaced by faults with a limited offset (Santangelo and Santo, 1997) and is dissected into blocks, originating from small-scale horst-and-graben structures. Karstification processes have taken place recently, following the Plio-Pleistocene uplift phases and subsequent erosion of the low-permeability flysch sequences (Santo, 1988; Incoronato et al., 1978).

Conversely to other karst massif of southern Apennine, the carbonate sequence outcropping over the Alburni karst plateau is weakly fractured and the stratification can be observed across the sequence. In other karst aquifer widespread through the Apennine ridge, fractures and recent tectonic activity have disjoined the carbonate sequence affecting the hydrogeological behavior of the massifs, and transformed calcareous rocks in breccias (Fiorillo, 2009).

Locally, instead, a poorly tectonically disturbed rock mass with horizontal or gently dipping strata seems and important factor controlling the karstification processes involving the summit plateau. These structural features could explain the higher doline density characterizing the Alburni plateau compared to other karst areas of Campania region, such as Matese (Fiorillo and Pagnozzi, 2015) and Picentini (Fiorillo et al., 2015b) Mountains. In this sense, Alburni represents the unique case in the region.

The Alburni massif is characterized by a large number of dolines and endorheic catchments that tend to have a limited size favoring a concentrated recharge mechanism. These unique hydrodynamic features of the karst massif require special protection and planning measures to preserve the groundwater resource.

7.1.1. Dolines and endorheic areas mapping

A map of dolines and endorheic areas of the Alburni karst massif was drawn. 781 closed karst depressions and, correspondingly, 781 endorheic basins have been recognized (Fig. 7.1). The identified karst closed depression include isolated dolines or compound features (Figs. 6.6 and 7.2). Using the outermost closed contour method, each single doline was isolated for a total of 1001 of such features. Dolines are primarily widespread across the karst plateau.

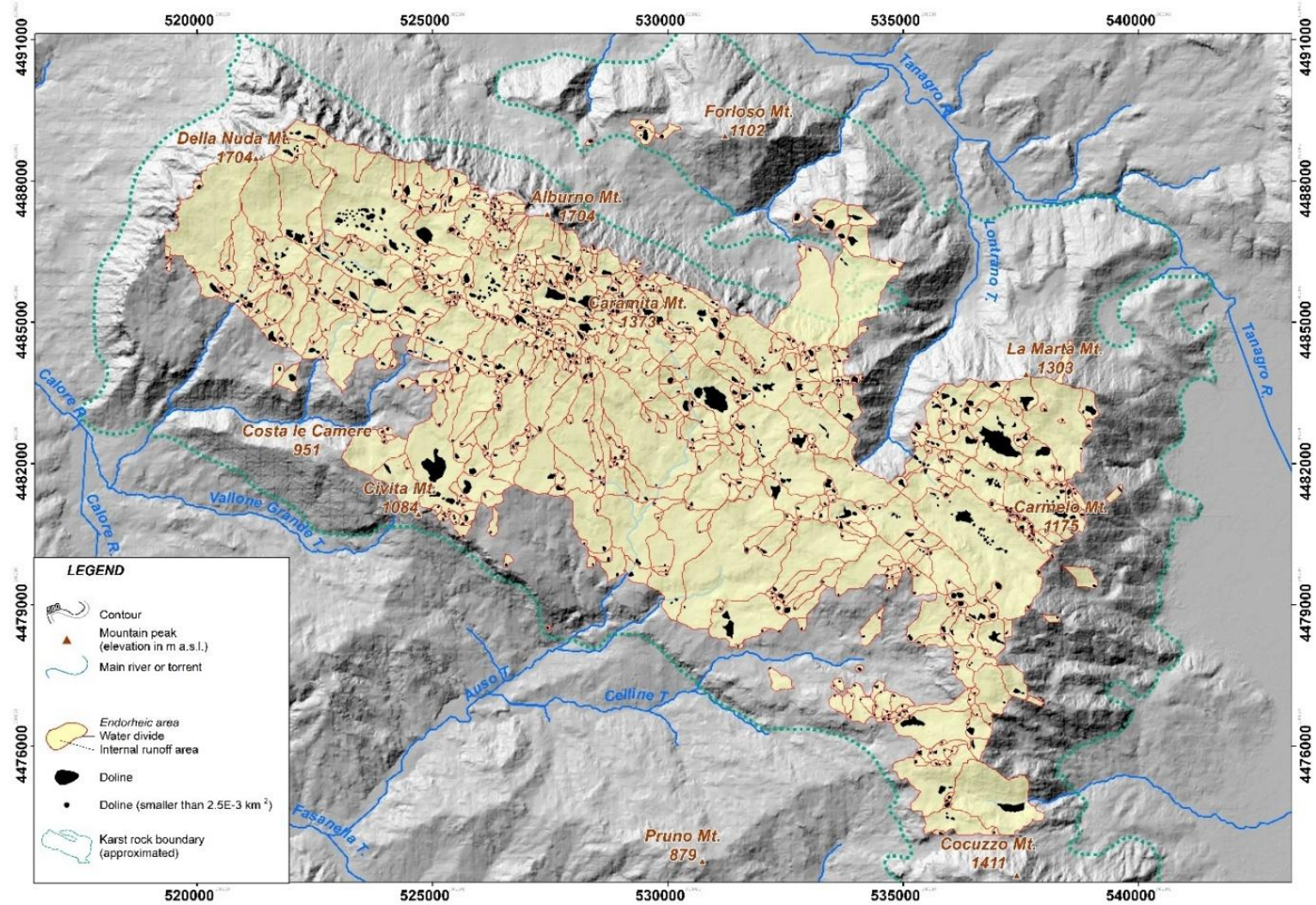


Figure 7.1. Dolines and endorheic areas map of Alburni karst massif (from [Esposito et al., 2025a](#)).

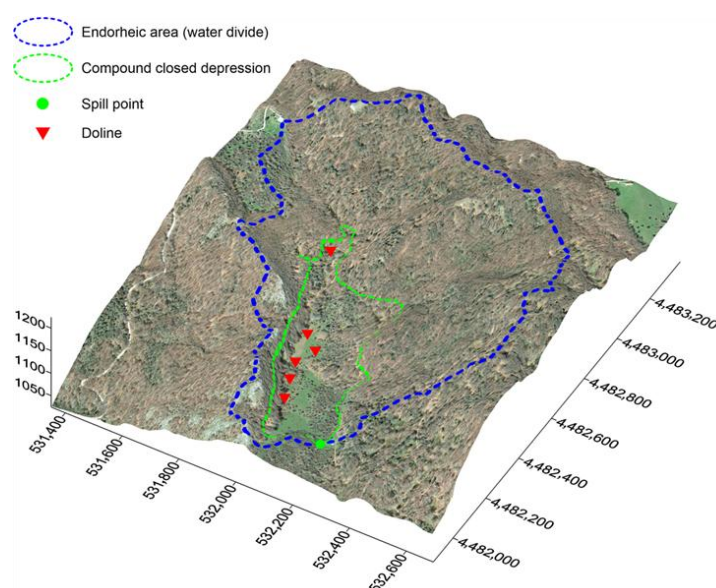


Figure 7.2. Dolines, compound closed depression and relative endoreic area, for a zone of the Alburni karst massif. The compound closed depression is defined by the highest closed contour (1093.5 m a.s.l.) passing through the spill (or overflow) point (from [Esposito et al., 2025a](#)).

The highest doline density occurs in the north-western sector of the plateau, reaching the maximum density of 34 dolines/km² (Fig. 7.3). Outside of the karst plateau, placed up-stream of the Auso (southern side) and Pertosa (northern side) spring groups, collapse dolines were identified. These dolines have not been considered in the following morphometric analysis.

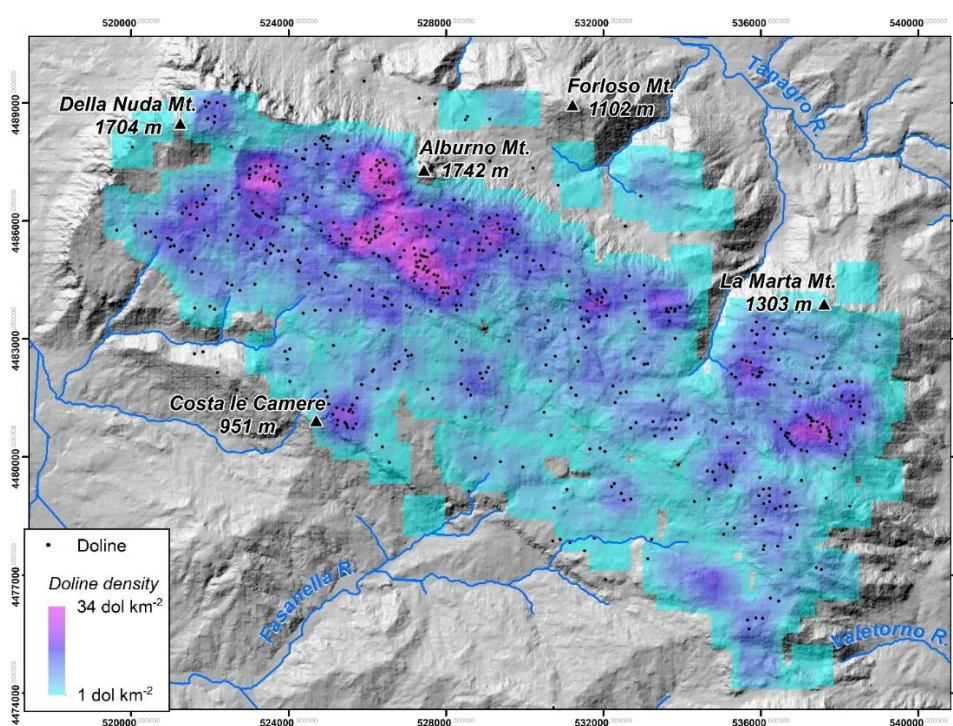


Figure 7.3. Doline density map of Alburni karst massif (from [Esposito et al., 2025a](#)).

As delineated from the analysis, the total runoff area covers 117 km^2 – approximately the 45% of the entire karst outcrop. The potential contribution of dolines to aquifer recharge depends on the extension of its catchment and can be easily visualized in the hydrological map (Fig. 7.1). Following rainfall (or snow melt) events two main aquifer recharge mechanisms could be recognized (Gunn, 1983).

The first mechanism is represented by diffuse percolation through the vadose zone, resulting in a diffuse recharge of the saturated zone. During intense and prolonged rainfall, overland and subsurface flow develops, especially when the soil is at the field capacity. Flow is conveyed toward sinking points, causing the concentrated recharge. As a consequence, wider endorheic areas provide larger concentrated recharge (Fiorillo et al., 2015b; Fiorillo and Pagnozzi, 2015). Also, the importance of the surface landforms stands in the fact that the surface hydrological features, combined with the hydraulic features of the saturated zone, control the shape of the spring hydrographs.

7.1.2. Morphometric and statistical analysis

In GIS environment, a measurement and an analysis of morphometric parameters featuring dolines and endorheic areas were performed. The analyzed parameters are: area, minimum and maximum depth, minimum and maximum elevation, A/P ratio, volume, and orientation of both dolines and endorheic areas.

The doline area (Fig. 7.4a) ranges from 1.38×10^2 to $2.75 \times 10^2 \text{ m}^2$ (0.27 km^2), with the 50% of dolines smaller than $2.29 \times 10^2 \text{ m}^2$. The depth ranges (Fig. 7.4b) from 0.25 to 48.5 m, with 50% of dolines deeper than 3.86 m. The extremely low value of the minimum depth can be interpreted as an outlier. The 1st percentile, 0.53 m, could be considered in place of the minimum. Doline dimensions are characterized by a high frequency of smaller-shallower dolines and a fewer larger-deep ones, which is common for temperate zones (Bondesan et al., 1992; Bauer, 2015). According to Troester et al. (1984), in temperate (and tropical) karst regions, doline depth distribution could be explained by an exponential equation. In the study area, doline distributions do not follow an exponential shape, even if they are strongly positively skewed. However, the frequency of smaller dolines should be considered underestimated, as doline mapping from DEMs has a lower detection limit in terms of area and depth, which is directly related to the DEM resolution.

Similar distributional shapes characterize the endorheic watersheds (Fig. 7.4d and e). The area (Fig. 7.4b) ranges from 1.69×10^3 to $4 \times 10^6 \text{ m}^2$ (4 km^2), with 50% smaller than $4.27 \times 10^4 \text{ m}^2$.

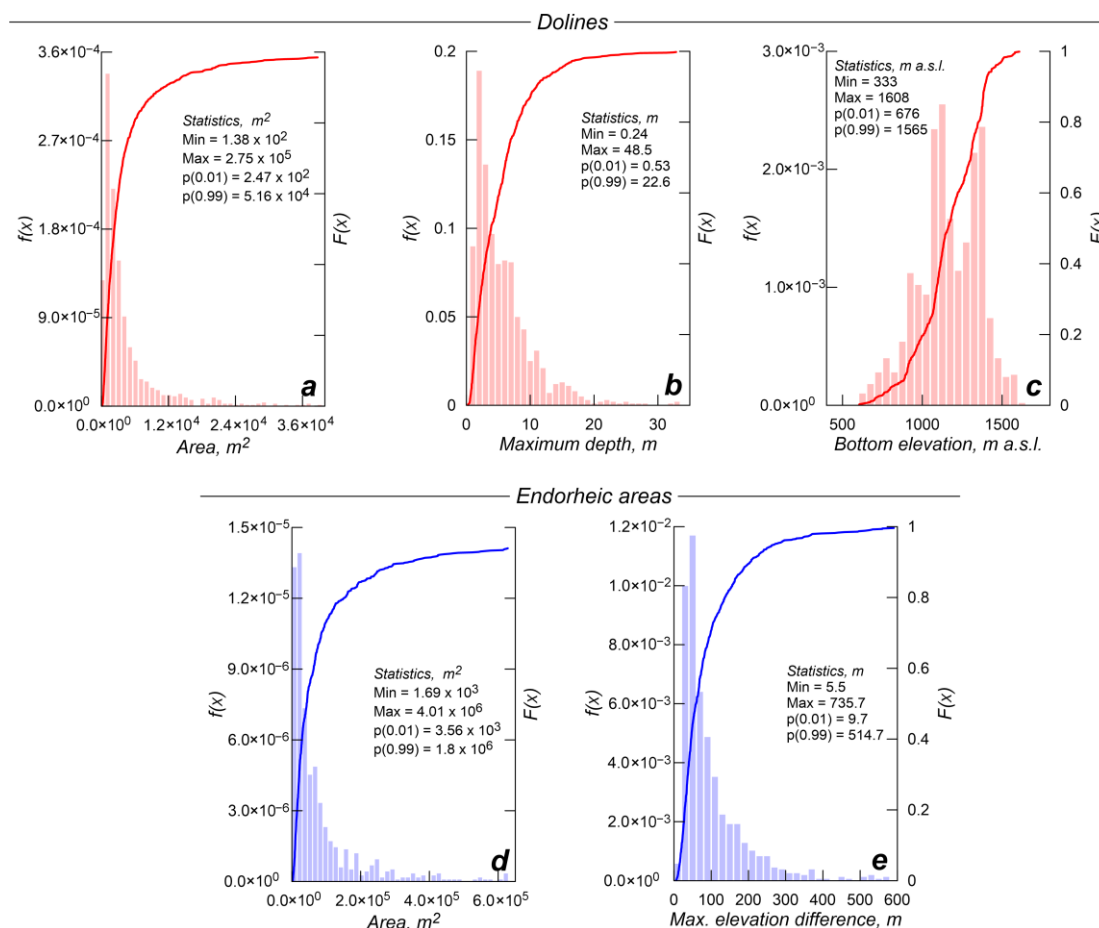


Figure 7.4. Probability density distribution, $f(x)$, and relative cumulative frequency, $F(x)$, of dolines (a–c) and endorheic areas (d,e) for different morphometric features (area, maximum depth, and bottom elevation). The main statistics are provided by figures (from [Esposito et al., 2025a](#)).

The maximum elevation difference ranges (Fig. 7.4e) from 5.7 to 735.7 m, with 50% of endorheic watershed deeper than 58.8 m. Approximately 75% of endorheic surface lies above 1000 m a.s.l.

The A/P ratio (area/perimeter ratio) has the same dimension of the mean depth (D , a length) and can be considered a measure of the doline width (Fig. 7.5a-c). A statistically significant relationship between doline width and depth was found, highlighting that the widening and deepening processes are coupled. As discussed by [Bauer \(2015\)](#), the widening-deepening coupling suggests a prevalent solution origin of the dolines. By contrast, the deepening of collapse dolines (cylindrical shape with steep walls, e.g. [Fiorillo et al., 2019](#); [Caramanna et al., 2008](#)) would not be directly coupled with the area-widening.

Doline bottom elevation (Fig. 7.4c) ranges between 604 and 1608 m a.s.l., with a mean 1165.5 m a.s.l. (and a median of 1161.3 m a.s.l.). The sample histogram highlights a multi-modal distribution.

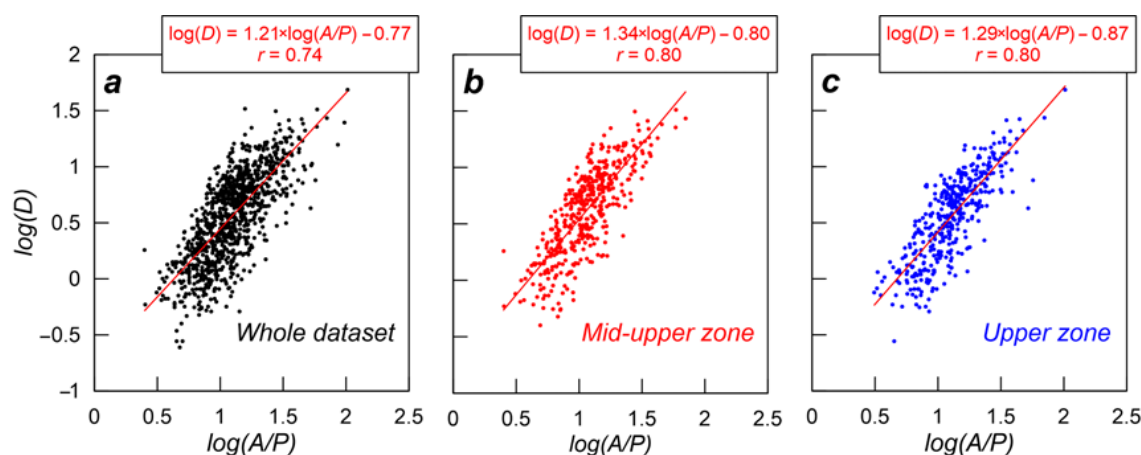


Figure 7.5. Correlation between doline area/perimeter ratio, A/P , and mean depth, D (log–log plot): (a) whole sample; (b) mid-higher elevation dolines (1050–1250 m a.s.l.); (c) higher elevation dolines (>1250 m a.s.l.) (from Esposito et al., 2025a).

The histogram of density distribution (Fig. 7.4c) shows that the doline sample may be subdivided into four sub-samples, corresponding to a lower (< 875 m a.s.l.), middle-lower (875–1050 m a.s.l.), middle-upper (1050–1250 m a.s.l.), and upper zone (>1250 m a.s.l.). In particular, the two main samples characterize the middle-upper zone ($N = 413$ dolines) and the upper zone ($N = 346$ dolines).

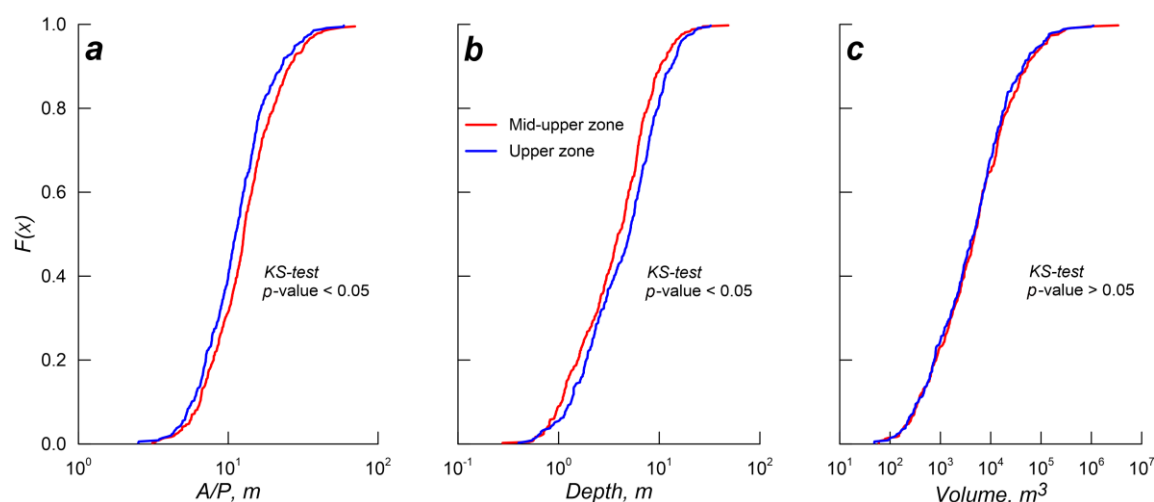


Figure 7.6. Cumulative frequency distribution (log x-scale) of two doline data sets, sampled in the mid-upper zone (1050–1250 m a.s.l., $N = 413$) and upper zone (>1250 m a.s.l., $N = 345$) of the karst massif. Different morphometric parameters were analyzed: (a) area/perimeter ratio, A/P ; (b) mean depth; (c) volume. The figure also shows the results of the Kolmogorov–Smirnov test (KS-test) (p -value < 0.05 , significant difference between the two distributions; p -value > 0.05 , no significant difference between the two distributions) (from Esposito et al., 2025a).

Figure 7.6 compares their morphometric features considering the A/P -ratio, depth, and volume. The non-parametric Kolmogorov–Smirnov (Borradaile, 2003) to assess statistically significant

differences between the frequency distributions shown in figure 7.6. The two doline samples have different morphometric characteristics. Dolines in the middle-upper zone tend to be flatter (larger and/or shallower) than dolines in the upper zone, and the differences in the shape are statistically significant. That is, there is a higher frequency of large and shallow dolines in the mid-upper zone than in the upper zone. However, the samples show the same frequency distribution when comparing doline volumes.

Figure 7.5b, c illustrates the relationships between doline A/P-ratio and depth for two subsamples. For a given value of the A/P-ratio, dolines in the mid-upper zone are generally deeper than upper zone.

The rose diagrams (Fig. 7.7) illustrate the orientation of dolines and endorheic areas (azimuth of the major axes). Dolines with a $CI < 0.9$ ($N = 967$) exhibit a general NW-SE trend with a mode of N140-150. Endorheic areas ($N = 781$) have a $CI < 0.66$ and appear elongated in three preferential directions, N40-50, N90-140, and N170-195.

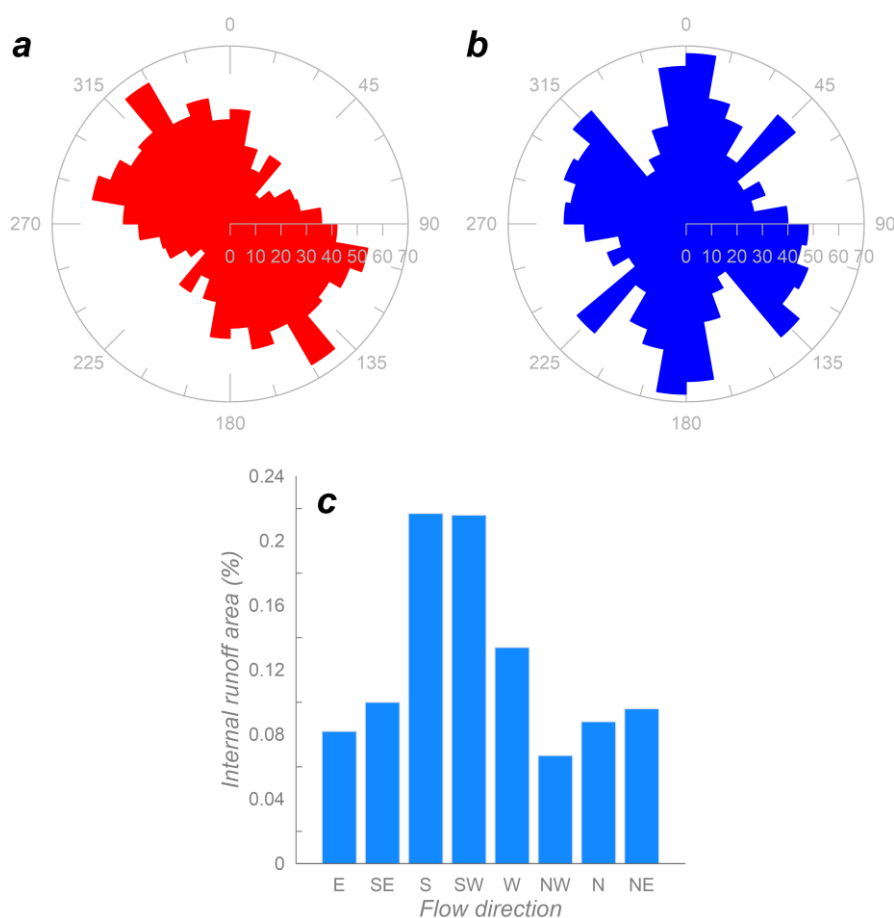


Figure 7.7. Rose diagram showing the orientation of the major axes of dolines (a) and endorheic areas (b). (c) Bar plot showing the percentage of the internal runoff area in relation to flow direction (from [Esposito et al., 2025a](#)).

The outcropping carbonate sequence is made of SW to S dipping strata, tilted by a few degrees. The major faults dissecting the karst plateau have a general trend N110-130, as well as the main morpho-structural elements. Thus, the horizontal shape of the doline tends to follow the main discontinuity lines.

The structural setting would affect the water flow and the development of endorheic areas. Using the *Flow Direction* Tool, the direction of the water flow across the summit plateau was calculated. The result is that the water flows primarily in the S and SW directions (Fig. 7.7).

7.2. Endorheic areas mapping of Morcone karst reliefs

The high degree of development of karst processes in carbonate rocks allowed the formation of several endorheic areas on the surface of Morcone karst reliefs. Considered the thick impervious soil mantle, covering the underlying karst rocks, endorheic areas have a pivotal role in aquifer recharge processes. Indeed, significant amounts of water flow are directed towards the numerous dolines, representing the most depressed point, located inside the endorheic areas and directly infiltrate in the underground through one or several ponors ([Pagnozzi et al., 2019](#)).

In addition to groundwater resources withdrawn for drinking purposes, the massif is exploited also for the production of eolian energy. Several power wind farms are currently located on the watershed of the main endorheic areas for the production of energy affecting seriously the natural environment of the area ([Valente et al., 2022](#)). Further, a project on the hydroelectric utilization of the Lagospino ponor and on the re-functionalization of Campolattaro dam for drinking purposes exists. The main achievement of the project is the transformation of Lagospino polje in a reservoir linked with that of Campolattaro dam for the pumping and discharging of water producing electric energy. This system is analogous to that built in the early twentieth century on the nearby Matese Lake, described and mapped by [Leone et al. \(2023\)](#).

For these reasons, the numerous closed depressions and, thus, endorheic areas recognized have been mapped and a basic morphological analysis was carried out in order to assess their distribution and their linking with the main springs. Also, in the following chapter, their role in recharge processes have been detailed analyzed.

7.2.1. Dolines and endorheic areas mapping

The mapping of dolines and endorheic areas in the study area was initially performed using three DEMs of having different spatial resolution: 20-meter, 10-meter and 5-meter. The mapping procedure used in all the three cases was the same described in Chapter 6.

Based on the DEM used three values of threshold were chosen for the mapping of closed depressions: 0.10 m for the 20 m-DEM, 0.20 m for the 10 m-DEM, and 0.55 m for the 5m-DEM. This latter value was deducted by the real doline depth value and is the same used for the mapping in the nearest Matese karst massif (Leone et al., 2023).

The results obtained by the three-resolution used highlight that several differences about the number, the shape, and the density of the dolines detected and mapped exist (Fig. 7.8). It's evident the importance assumed by the DEM in the mapping procedure, strongly influencing the results.

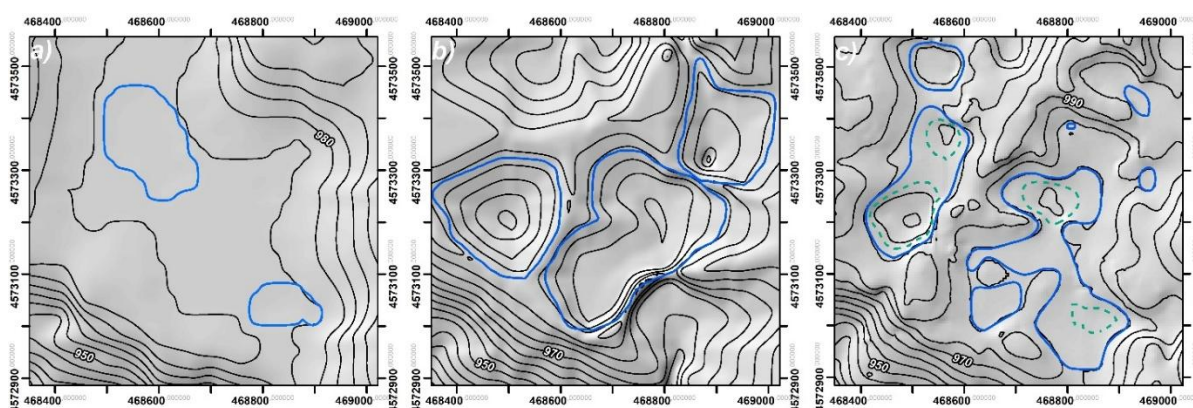


Figure 7.8. Dolines mapping procedure. (a) Dolines mapped using a 20-meter DEM; (b) Dolines mapped using a 10-meter DEM; (c) Dolines mapped using a 5-m DEM. It's clear the difference in the karst landform mapped using three different resolutions dem. The blue line represents the outermost doline perimeter; the dashed green line represents the depression contained inside the greater depression.

Hydrologically, considering the importance assuming the closing depressions in karst areas, the differences in the detecting and mapping dolines heavy affect the studies regarding the recharge estimation and vulnerability evaluation. For example, a less density of closed depression (Fig. 7.8a and b) will lead to an underestimation of recharge and to an overestimation of runoff amounts, with a consequent approximation in the overall recharge estimation. Instead, the mapping procedure performed using 5m-DEM (Fig. 7.8c) permitted the detailed mapping of the closed depressions in the area, allowing a better quantification of recharge amounts.

Furthermore, the use of the 5m-DEM allowed an improvement in the mapping resolution and also the mapping of the compound depressions identifying also the littler depressions (dashed green line in Fig. 7.8c) enclosed in the greater one (solid blue line in Fig. 7.8c). This particularity adds an additional level of detail respect to other resolutions.

Thus, the closed depressions mapping carried out using the 5m-DEM was checked with Topographical Maps, Google Earth images, and results of field surveys. In particular, only for this area, field surveys consist also of acquisition and analysis of pictures taken using the drone technology (Fig. 6.4 and 7.9). Coupled with the inspection of satellite images, they allowed an improvement of the map checking. Maps produced using the 20m- and 10m-DEMs have been discarded from the mapping procedure.

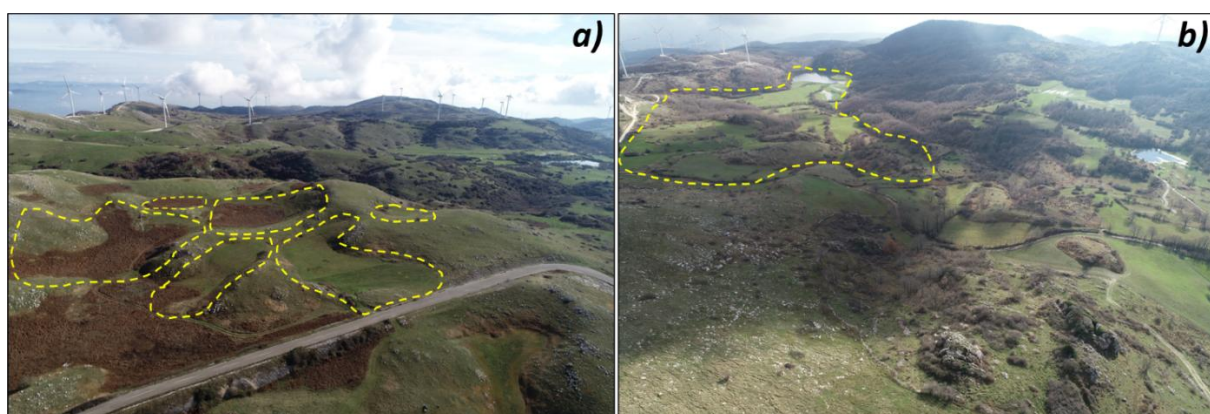


Figure 7.9. Drone images taken by field surveys. (a) Dolines captured by drone fly and (b) drone image of Lagospino polje (photo by Guido Leone and Michele Ginolfi).

After, the ArcGIS *Watershed* tool on the checked raster was used to outline the endorheic basin of each closed depression identified. The result of the procedure is a map of the dolines and endorheic areas of Morcone karst reliefs (Fig. 7.10).

The mapping of karst features resulted in the delineation of 103 dolines and 65 endorheic areas, occupying an area of about 9.4 Km² and having an average extension of 0.138 Km², covering the 12% of the whole massif area.

The major density of dolines (about 40 dolines per km²) and endorheic areas can be observed in the central-southern areas of karst reliefs. In the same sector also the largest endorheic areas, hosting the two active ponors (Lagospino and Lepre ponors; Fig. 7.11), are located. Each endorheic area is bounded by its watershed, and is therefore hydrographically closed. Many endorheic areas are adjacent, constituting a large recharge area as a whole (Fig. 7.11).

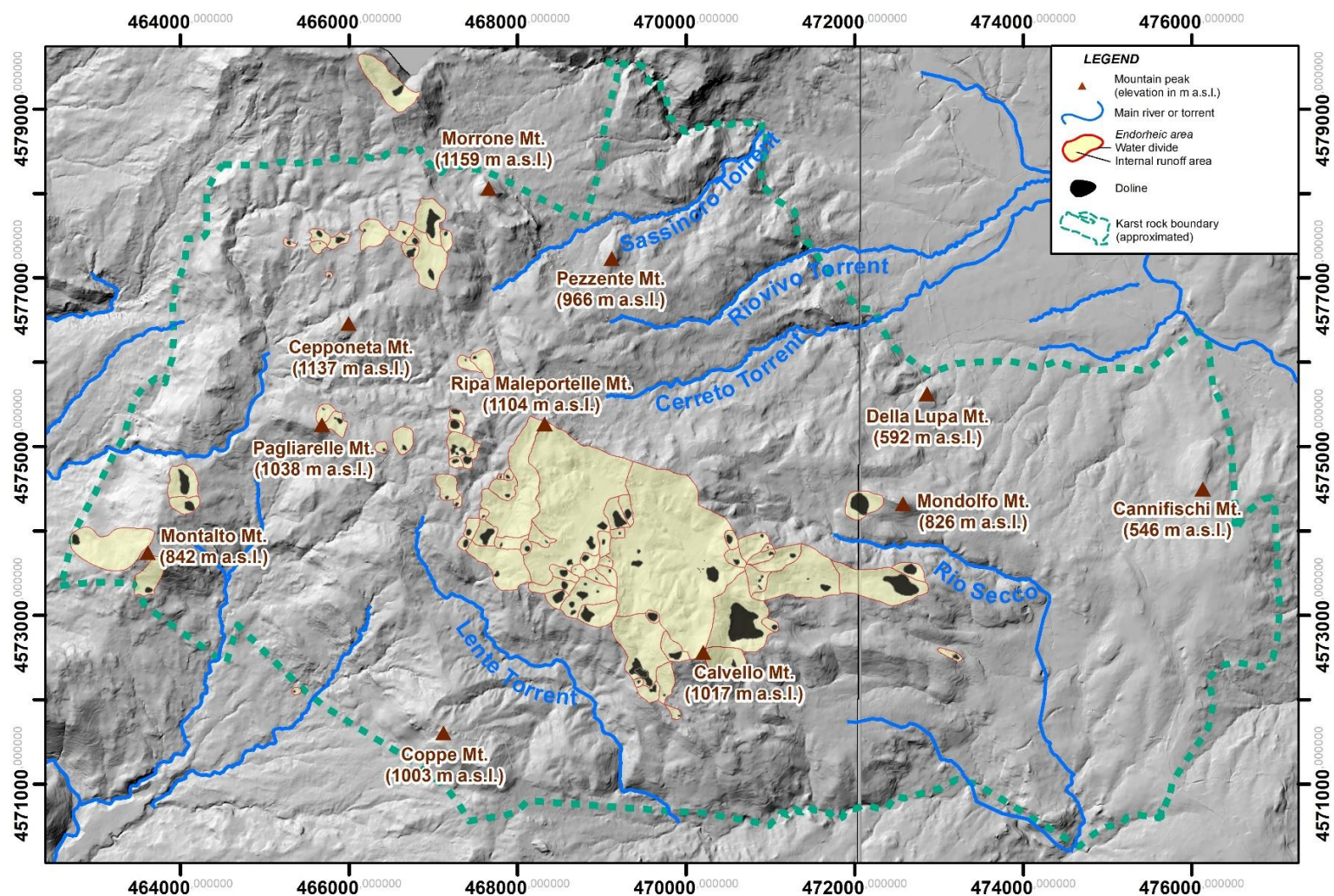


Figure 7.10. Dolines and Endorheic areas map of Morcone karst reliefs.

7.2.2. Morphometric analysis

A morphometric analysis of the main parameters of endorheic areas (perimeter, area, minimum and maximum elevations, and bottom elevations) affecting the Morcone karst reliefs was performed (Fig. 7.12 and Tab. 7.1).



Figure 7.11. Drone view of the ridge bordering the main endorheic areas of Morcone karst massif encompasses the three main poljes of Lagospino, Piano Moia and Acqua della Lepre (photo by Guido Leone).

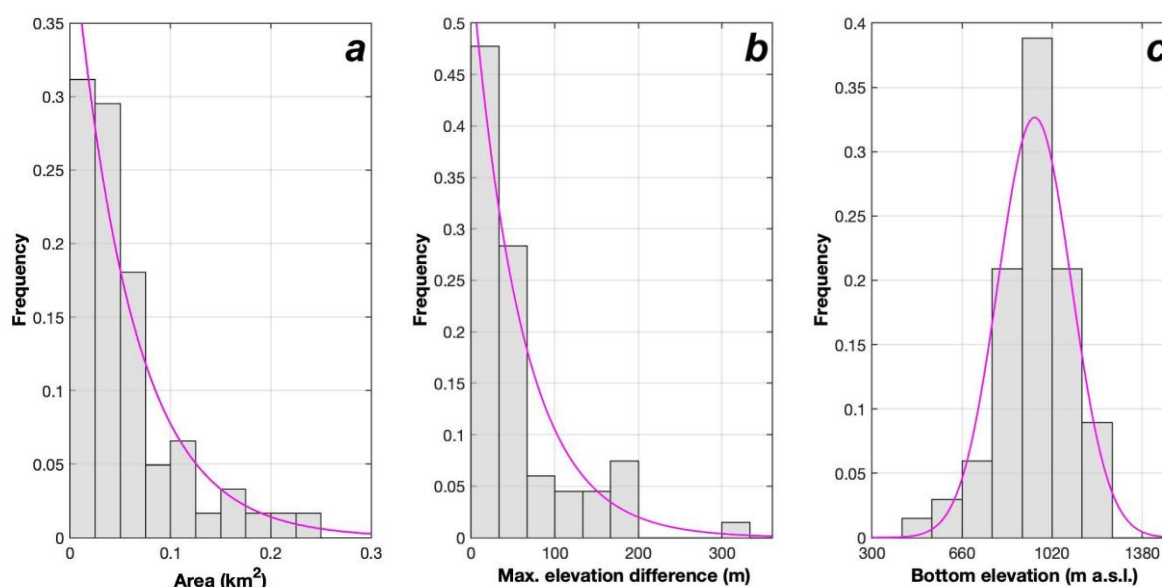


Figure 7.12. Frequency distribution of endorheic areas morphometric features: area (a), maximum elevation difference (b), and bottom elevation (c).

The endorheic area extension varies between 3×10^{-3} to 2.2 km^2 . The 50% of the endorheic areas is larger than $4.2 \times 10^{-3} \text{ km}^2$ (Fig. 7.12a). The maximum elevation difference ranges from 1 to 300 m, and the 50% of values are above 58.5 m (Fig. 7.12b). The lowest points on the

bottom of the endorheic areas lie between 439 and 1196 m a.s.l., with almost of the values above 972 m a.s.l. (Fig. 7.12c).

The morphometrical analysis showed that the largest endorheic areas are that of Lagospino (2.2 km²), Piano Moia (1.5 km²), and Lepre (0.6 km²) basins (Fig. 7.11 and Tab. 7.1).

7.2.3. Groundwater flow path through tracer tests performing

To reconstruct the hydraulic model of the aquifer, aware of the difficulties in the assessment of groundwater flow path due to karst medium heterogeneities, tracer tests in endorheic areas were performed (Fig. 7.13).

The injection points of the tracers were represented by the two active ponors: Lagospino and Lepre ponors, located inside the main endorheic areas of the massif.

The tests were carried out on 22th November 2020. Tinopal tracer was injected in Lagospino sinkhole at 12:00; Fluoresceine tracer was injected in Acqua della Lepre sinkhole 90 minutes later. Meanwhile, monitoring instruments, consisting in substances captors, were installed and checked in the springs shown in figure 7.13. In particular continuous monitoring was carried out for Sant'Elmo, Le Grotte and Sorgenza springs. The first arrival of the tracers was recorded after several hours from the injection time (15 hours later for Sant'Elmo spring, and 28 hours later for Le Grotte spring).

Item	L (m)	A (km ²)	A (%)	H _{min} (m a.s.l.)	H _{max} (m a.s.l.)	H _{max} -H _{min}	Basin
1	4902.3	0.6	6.6	964.9	1116.1	151.2	Lepre spring
2	6354.4	1.5	16.2	967.4	1116.7	149.3	Piano Moia
3	7233.8	2.2	23.8	872.2	1057.3	185.1	Lagospino
4	2804	0.3	3.7	734.1	842.6	108.5	Lago Ciancione
5	809	0.5	5.0	821.9	1012.1	190.2	Toppo Mangialardo
6	487	0.4	4.0	895.7	1017.6	121.9	Monte Calvello

Table 7.1. Morphometric characteristics of the main endorheic areas. ID: identification number in Figure 7.11; L: perimeter; A: surface in km² and in percentage respect to the entire surface covered by endorheic areas (9.34 Km²); H_{min}: height of the lowest point; H_{max}: altitude of the highest point.

The results provided by tracer tests highlighted the interconnection among the ponors and one or more of the main springs draining the massif (Sant'Elmo, Sorgenza, Ammeri, Acqua del

Campo, Macioccio; Fig. 7.13). The analysis highlighted the interconnection of Acqua del Campo and Ammeri springs with both Lagospino and Lepre ponors, indicating a complex groundwater flow path. In every case, the general groundwater flow path is directed towards east with the last discharge represented by Sorgenza spring.

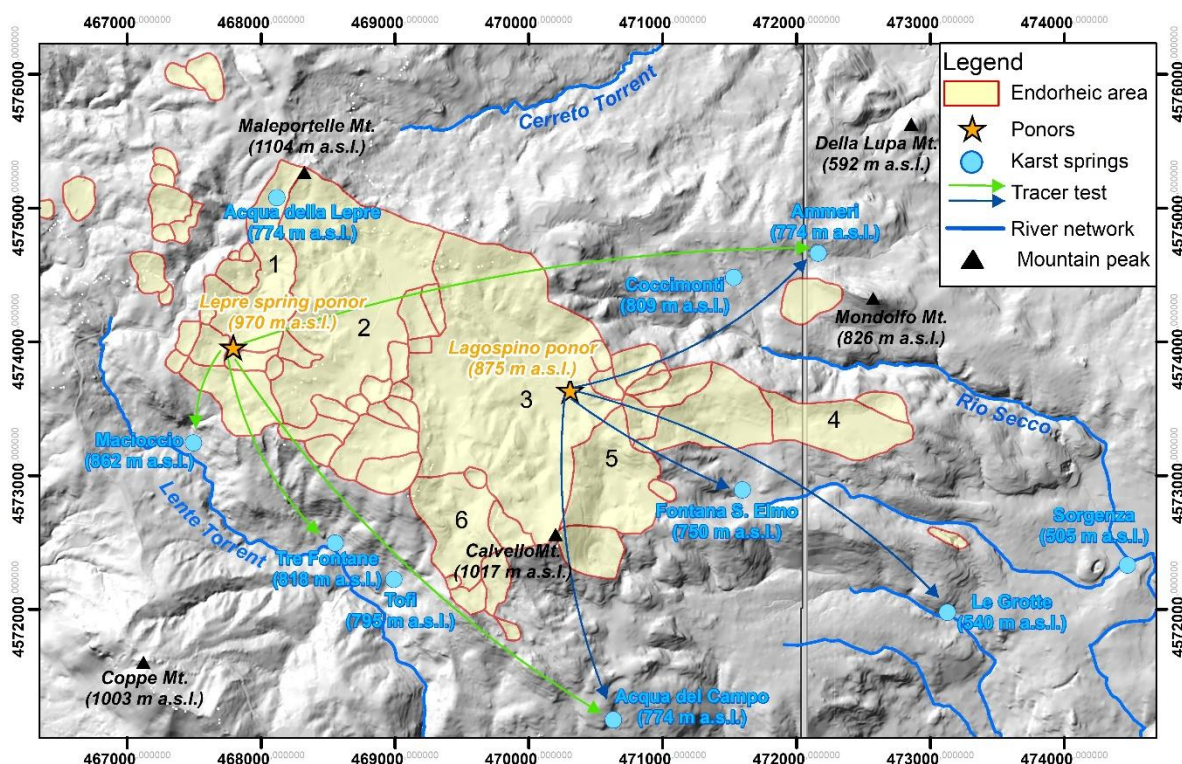


Figure 7.13. Tracer tests carried out in Morcone karst aquifer area and their relationships with the mapped endorheic areas. The item features are shown in Tab. 5.1 (redrawn from [Valente et al., 2022](#)).

The discharge and temperature also were monitored during the test. In particular, Sant’Elmo, Ammeri, and Le Grotte springs showed an evident karst behavior, with high flow peaks following rainstorms. In the case of Sant’Elmo spring, the existence of a preferential path (probably a karst conduit) with Lagospino ponor, was hypothesized. For the other springs, the network of conduit is less interconnected, and the spring hydrographs appear smoothed with respect to the precipitation input. In this case the behavior is more similar to a porous medium.

The hydrogeological model of the aquifer emphasizes the pivotal role of endorheic areas in recharge processes of the aquifer. The presence of these wide endorheic basins and active ponors (Lagospino and Acqua della Lepre) indicate a deep groundwater flow path affecting karst complexes. During heavy rainfalls, surface water accumulates in the deepest part of the endorheic areas of Lagospino and Piano Moia plains allowing the formation of a lake ([Valente et al., 2022](#)). Then, this latter is drained by ponors located in the most depressed part of the basin, becoming part of the concentration recharge of the aquifer ([Fiorillo et al., 2015b](#)).

In the underground, the groundwater flow path is characterized by several water tables located at different height in the karst lithologies of *Calcari Cristallini* Formation (Fig. 1.18). The presence of several faults dissecting the sequence and of impervious layers causes a progressive lowering of the water table towards east and controls the location of springs.

As highlighted by tracer tests, all the main springs draining the massif are fed by internal *runoff water* infiltrating in the two active ponors (Fig. 7.13). This demonstrates the presence of a complex groundwater flow path constituted by several water tables interacting each other and with the surface water dynamics. This framework let to define endorheic areas as a part of the main spring's catchments, despite the difficulties related in their delineation in karst areas (Bonacci and Andrić, 2015).

Chapter 8: Groundwater recharge evaluation and modeling of karst massifs using hydrological methods and lumped model

Karst aquifers represent complex hydrological systems due to the high heterogeneity characterizing recharge and groundwater flow. They are drained by one or more springs, whose hydrograph reflects the hydraulic aquifer nature, which ranges between two extreme typologies: (i) the conduit-flow characterized by a rapid response to rainfall; and (ii) the diffuse-flow exhibiting a buffered reaction (Bonacci, 1993; Jeannin, 2001; Kovacs and Stevanovic, 2023).

Due to karstification processes, in karst aquifer recharge can happen both diffuse and concentrate manner (Gunn, 1983). The first is connected to sinkhole/shafts and swallow holes, which allow rapid drainage of the runoff water causing a fast transit into and through the vadose zone and, subsequently, to saturated zone. Also, runoff coming from the neighboring no-karst areas can contribute to the aquifer recharge (*allogenic* recharge; White 1988). Diffuse infiltration occurs via the soil mantle or fractures of outcropping limestone, originating the percolation in vadose zone. According to the thickness and conductivity characteristics of vadose zone, these processes can take a large time range before water reaches water table (Fiorillo and Doglioni, 2010).

Using the ratio between the volume of spring discharge and the rainfall volume, which fall in the spring catchment, at annual scale, the recharge amount can be estimated (Bonacci, 2001). Considering the evapotranspiration processes and distinguishing areas characterized by different recharge conditions, like endorheic and open areas, the recharge estimation with the above methodology can be improved (Fiorillo et al., 2015b). The endorheic areas are closed depressions where runoff is completely adsorbed (*internal runoff*; White, 2002). Generally connected to one or more springs, these areas constitute an important recharge zone of karst aquifers. Outside the endorheic areas, in the so-called “open areas”, runoff can escape from the spring catchment during intense storms. These areas constitute the difference between the spring catchment area and the endorheic areas.

Simulation models, including lumped ones, are widely used for several hydrological purposes, and most of them can be used for the recharge evaluation. Recharge estimations can be indirectly obtained from other models. For example, in groundwater flow models, recharge is a parameter enclosed in the groundwater flow equation solved for the hydraulic head. In this case, the recharge estimations can be obtained through the calibration process of the model in which recharge values are arranged to simulate the modeled water levels with the measured ones. The simulation that produces the closer adaption is called best fitting and the recharge value obtained by this simulation is the recharge estimate model-generated (Healy, 2010).

In modeling practice, the complexity of karst aquifer, and thus their recharge estimation, can be depicted using a so-called distributed model, which accounts for the spatial variability of hydrologic and hydraulic properties and processes (Anderson et al., 2015). Thus, this model requires the definition of the spatial domain, the aquifer's physical properties, and boundary conditions (Chow et al., 1988; Scanlon et al., 2003). Since data availability in karst aquifers is limited (Hartmann, 2018), and physical properties (spring catchment boundaries, spatial distribution of hydraulic heads, and geometries of main conduits) are unknown in several part of the aquifers, the use of distributed model is difficult. For these reasons, modelers consider karst aquifers as lumped systems, neglecting spatial variability. In these models, karst aquifers are conceptualized as a group of reservoirs (or compartments). The modeling of each hydrologic process is assigned to a specific reservoir, whose discharge is a linear or non-linear function of the storage (Hartmann et al., 2014). The number, arrangement, and configuration of the compartments determine the complexity of the model and the number of parameters.

In this chapter, the recharge processes of the Morcone karst reliefs are analyzed using the Modified APLIS method (Marin, 2009) and the Daily Scale Recharge model (Fiorillo et al., 2015b). A new methodology, here proposed for the first time and derived from the combination of the above models, have been applied in recharge estimation. The simulations of relationships between the meteorological variables and the karst spring discharge of Cervialto karst massif, encompassing the evaluation of recharge, were also carried out (Leone et al., 2025; Leone et al., 2026).

8.1.Recharge evaluation using Modified APLIS Method

The recharge estimation was firstly carried out using the Modified APLIS methos (Marin, 2009). A seven classes Recharge Rate map (Fig. 8.1) and a Specific Recharge map for three different meteorological conditions (dry, average and wet) were drawn (Figs. 8.5-8.7).

8.1.1. Recharge Rate Map

The six parameters map (Elevation, Slope, Lithology, Infiltration Landforms, Soil type, and Correction factor maps) were merge using the ArcGIS *Raster Calculator* tool and the equation (6.3). The result is the Recharge Rate Map of the karst massif (Fig. 8.1).

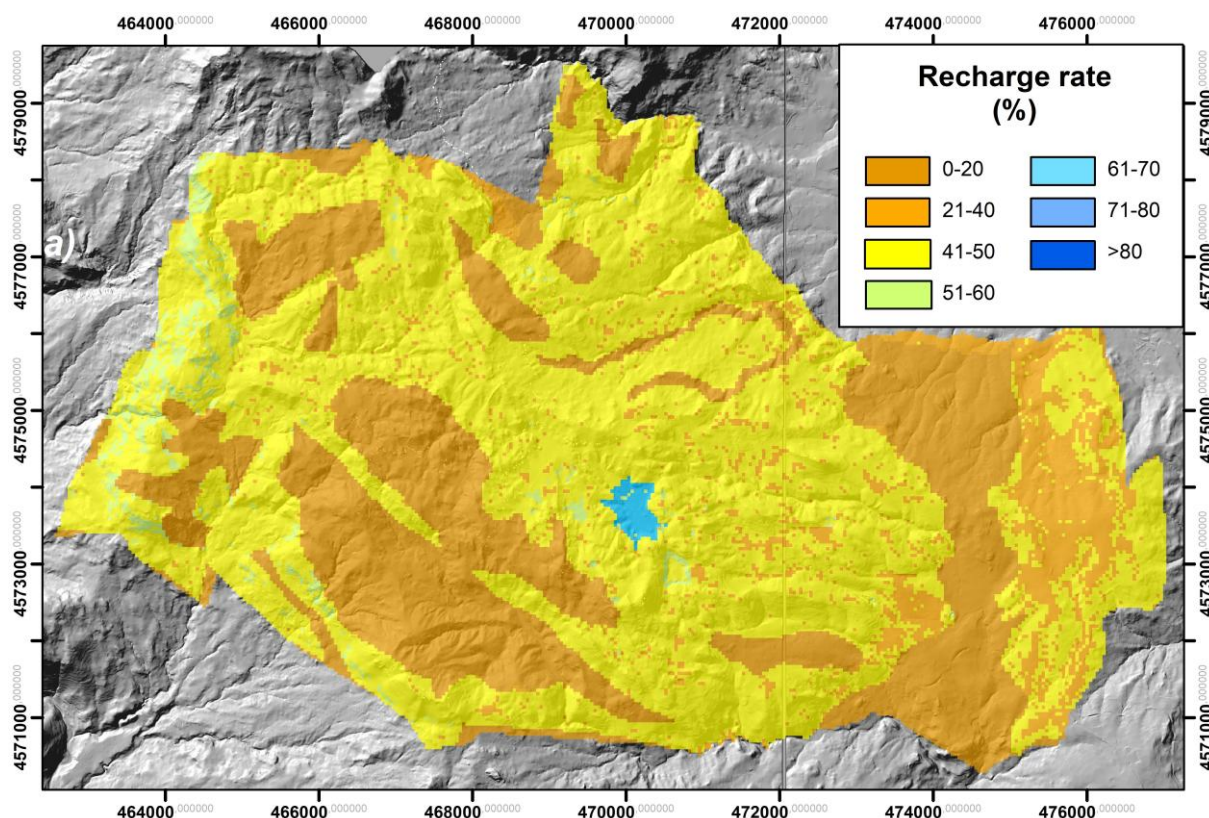


Figure 8.1. Recharge Rate map with Modified APLIS method of Morcone karst reliefs.

The modified APLIS Recharge Rate map depicts a mean annual recharge rate of 30.69%, with a minimum value of 1% and a maximum value of 68%. Lagospino polje represents the only area classified as High Recharge rate (61-70%).

Areas covered by minor depressions, like Acqua della Lepre depression, and karst areas located in the western part of the massif, are classified as area of Moderate Recharge rate with a score ranging between 51-60%. Also, karst areas constituting the other parts of the massif are classified as Moderate Recharge rate area, but with a lower score than previous one (41-50%).

The impervious complexes, instead, are classified as areas of Very Low Recharge rate (< 20%). Furthermore, some areas, mostly of them located in the eastern part of the massif, are classified as area with a Low Recharge rate (21-40%). Areas classified as Very High Recharge rate (>80%) lacking.

8.1.2. Specific recharge map

Combining the Recharge Rate and the Distribution of Precipitation maps with the ArcGIS *Raster Calculator* tool, the Specific Recharge map of the aquifer was drawn.

Distribution of Precipitation map

A Distribution of Precipitation map was drawn for a medium, wet, and dry meteorological conditions year. For this purpose, three regression laws correlating precipitation amount and elevation rate of the massif have been used.

For the medium year precipitation conditions, the regression law found for the nearby Matese karst massif by [Fiorillo and Pagnozzi \(2015\)](#), using precipitation data collected for the period 1970-1999, was used:

$$P = 0.7288H + 1105 \quad (8.1)$$

For the dry (Eq. 8.2) and wet (Eq. 8.3) years conditions other two regression laws were considered:

$$P = 0.628H + 857.37 \quad (8.2)$$

$$P = 0.3116H + 1845.4 \quad (8.3)$$

The spatial distribution of the mean annual precipitation was estimated applying the previous equations to a 20×20 m DEM, using the *Raster Calculator* tool in ArcGIS software.

Three different distributions of precipitation maps were drawn: (i) average (Fig. 8.2), (ii) dry (Fig. 8.3), and (iii) wet (Fig. 8.4) years.

Specific Recharge map

The Specific Recharge maps were drawn merging with *Raster Calculator* tool the Recharge Rate map (Fig. 8.1) with the average (Fig. 8.2), dry (Fig. 8.3), and wet (Fig. 8.4) years Distribution of Precipitation maps. Consequently, three scenarios regarding the quantification and distribution of Specific Recharge have been analyzed (Figs. 8.5, 8.6, and 8.7).

The maps highlight the distribution of the higher recharge values in the central part (Lagospino polje is the main recharge area of the massif) and in the western sector of the karst massif. In average and wet climatic conditions, the area corresponding to the main karst landforms are classified as areas with a moderate/high recharge rate. The lowest recharge areas are located in

the eastern part of the massif. The impervious areas, practically excluded by the recharge evaluation, are affected by the lowest recharge value.

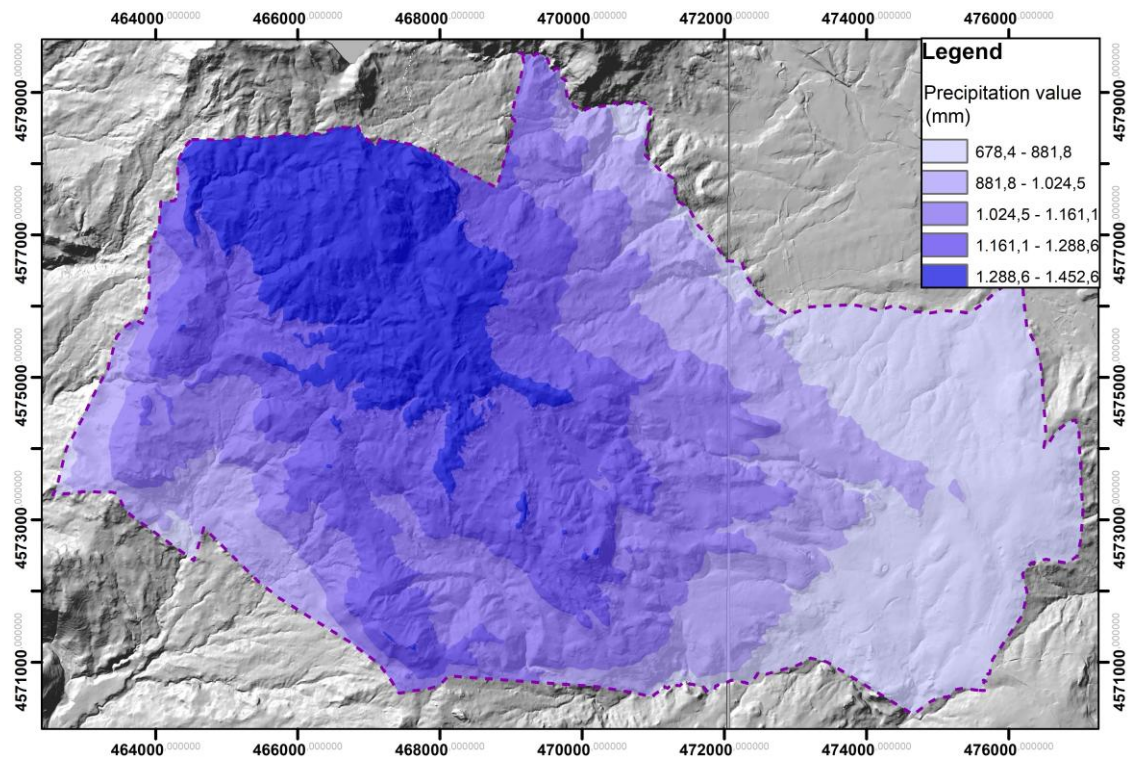


Figure 8.2.Average year Precipitation Distribution map.

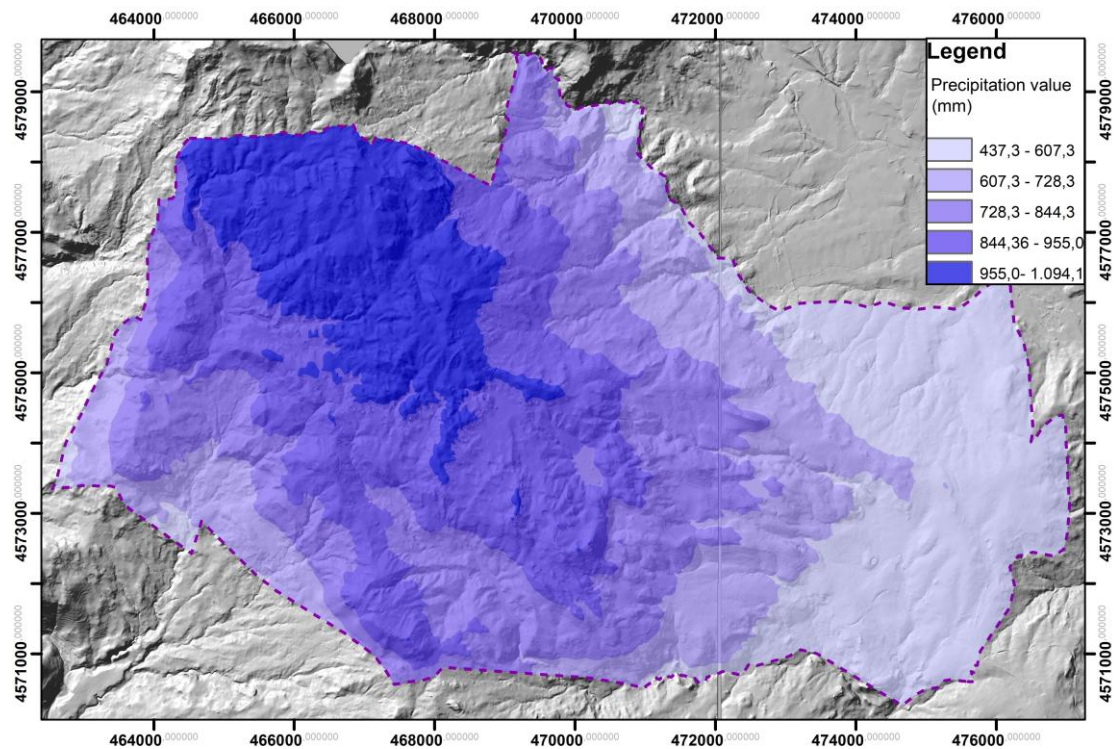


Figure 8.3.Dry year Precipitation Distribution map.

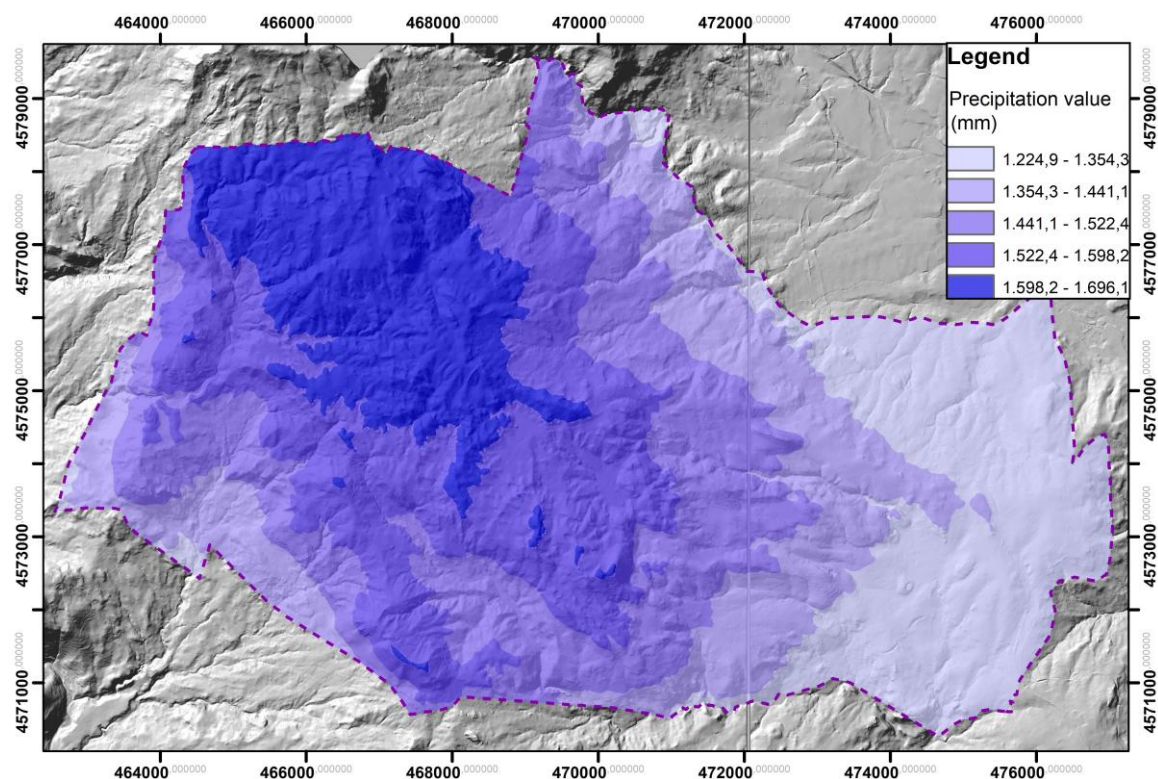


Figure 8.4. Wet year Precipitation Distribution map.

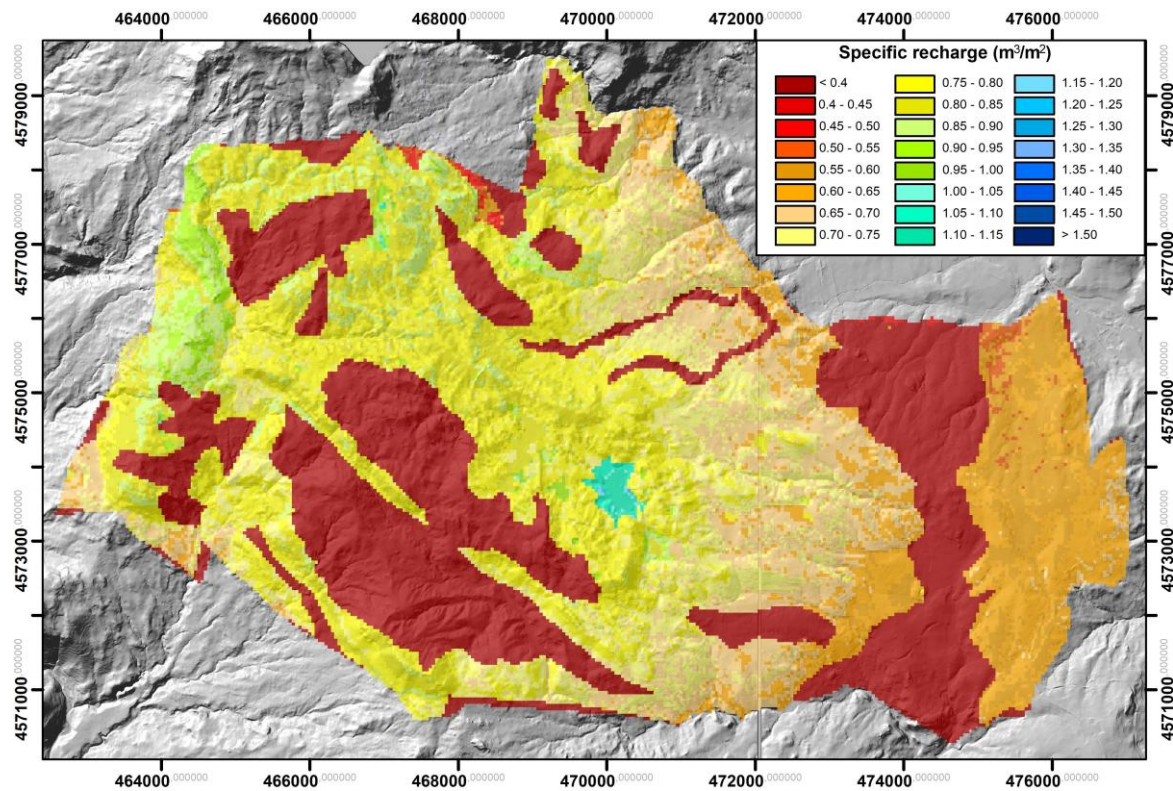


Figure 8.5. Specific Recharge map for average meteorological conditions.

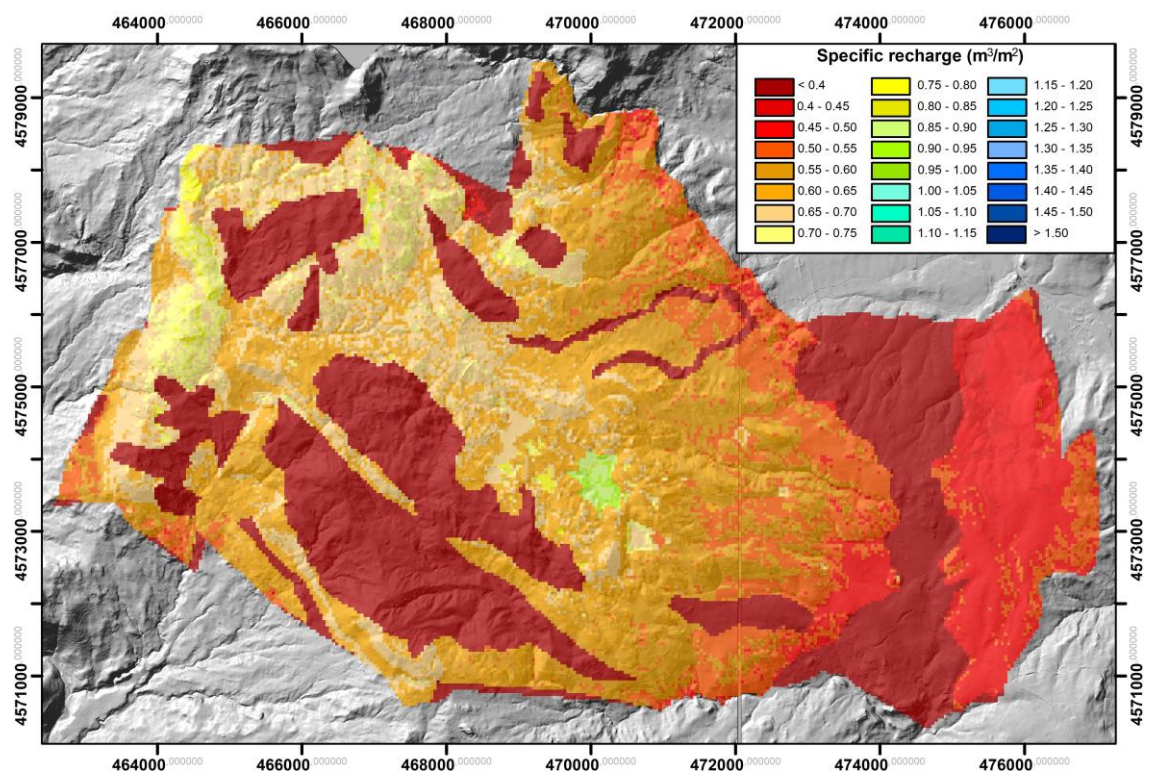


Figure 8.6. Specific Recharge map for dry meteorological conditions.

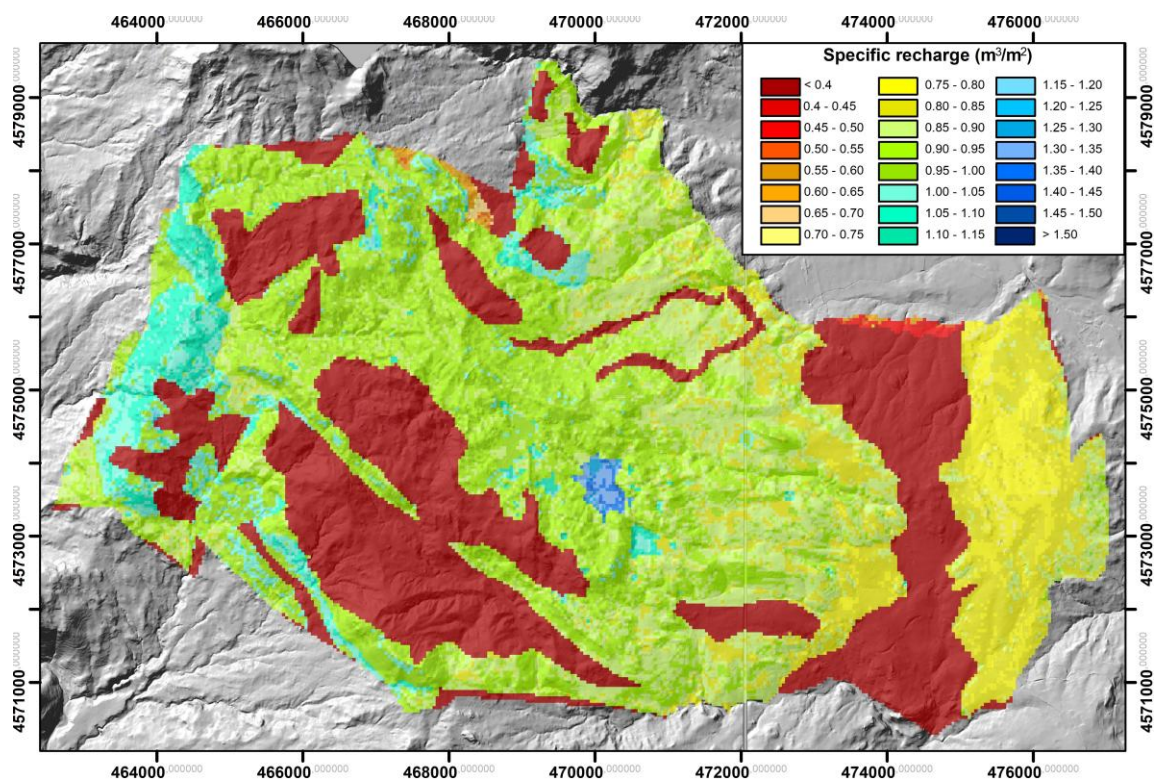


Figure 8.7. Specific Recharge map for wet meteorological conditions.

In Modified APLIS method the specific recharge distribution is mainly controlled by the infiltration forms and lithology. The major recharge rates are associated with the concentrate recharge processes happening in Lagospino polje. For this area the recharge values vary from a minimum value of $0.90 \text{ m}^3/\text{m}^2$ (dry hydroclimatic condition) to a maximum value of $1.30 \text{ m}^3/\text{m}^2$ (wet hydroclimatic condition). The contribution of the others infiltration landforms is almost negligible during the dry climatic conditions growing in importance passing to average and wet conditions. In particular, during the wet climatic conditions, the highest recharge rates are associated with karst landforms located in the central part of the massif and directly feeding the major karst springs (Fig. 8.7). This highlight, for the wet years, the important contribution provided by concentrated recharge in aquifer recharge processes. The other areas characterized by outcropping of karst rocks and with lower recharge values represent the diffuse recharge mechanism through fracture and fissures of the karst media.

8.2. Recharge evaluation using Modified APLIS Method with Endorheic areas

As the previous Modified APLIS method, a Recharge Rate map (Fig. 8.8) and a Specific Recharge map for an average (Fig. 8.9), dry (Fig. 8.10), and wet (Fig. 8.11) conditions were drawn.

8.1.1. Recharge Rate map

The Recharge Rate map (Fig. 8.9) was made distinguishing between Endorheic (A_E) and Open areas (A_O). The former, comprising the raster encompassing all the endorheic areas mapped throughout the massif, have a recharge rate equal to 100 %. This value was attributed neglecting the lithologies outcropping in the area and considering that both precipitation and runoff amounts constituting the overall recharge (Fiorillo et al., 2015b). The rating of the Open Areas is the same used in the Recharge Rate map of Modified APLIS method.

The Recharge Rate map shows a mean annual recharge rate of 38.14%, with a minimum value of 1.1% and a maximum of 100%.

Differently from modified APLIS method, the Recharge Rate maps of the APLIS with endorheic areas are characterized by areas classified as Very High Recharge rate (>80%), bounded by areas of High Recharge rate (61-70%). These areas correspond to all the endorheic areas mapped throughout the whole massif.

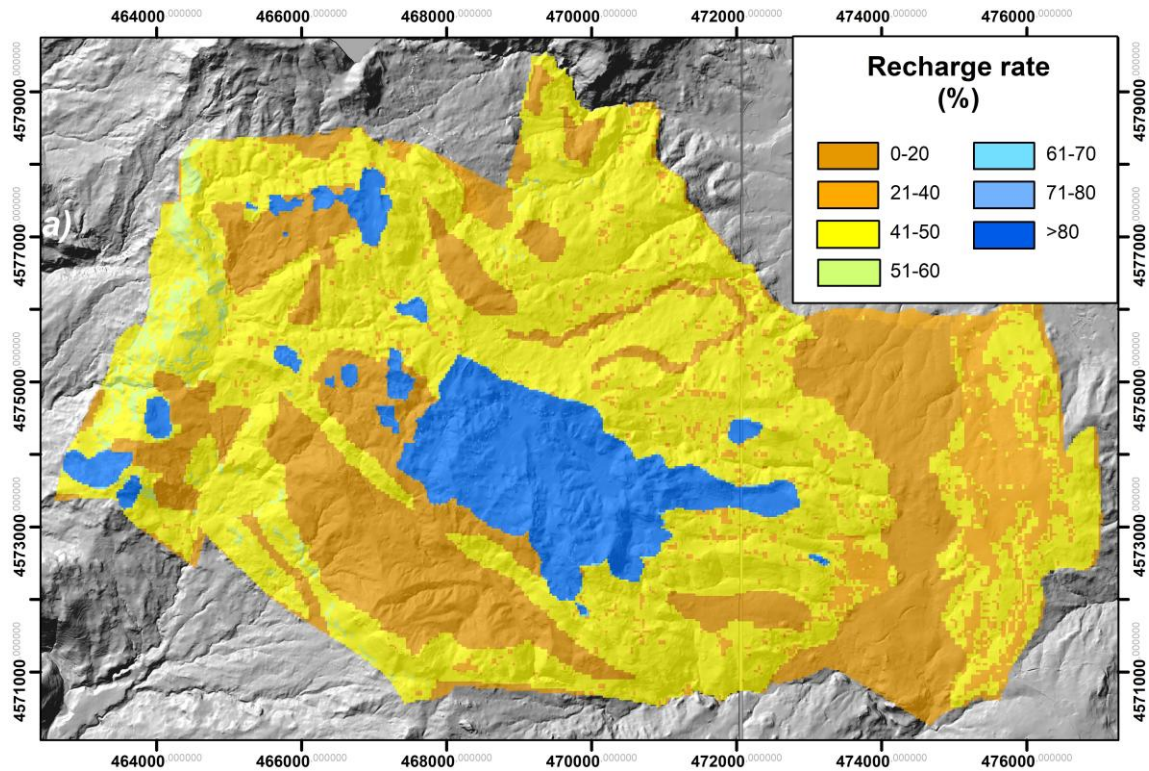


Figure 8.9.Recharge Rate map with Modified APLIS method with Endorheic areas of Morcone karst reliefs.

8.2.2. Specific Recharge map

The Specific Recharge map regarding the recharge rate in three hydrological conditions (average, dry, and wet year) were made merging the Effective Afflux provided by Endorheic areas and the Specific Recharge map of the Open Areas resulting from the Modified APLIS method.

Effective Afflux map

The Effective Afflux (F_{eff}) is given by the following equation:

$$F_{eff} = F - AET \quad (8.4)$$

Where F is the total afflux given by the Eqs. (8.1), (8.2), and (8.3); and the AET is the Actual Evapotranspiration calculated by Turc Formula (Turc, 1954; Eq. 6.5). The parameter temperature in equation (6.5) was calculated using the regression law temperature-elevation found by Fiorillo and Pagnozzi (2015):

$$y = -0.007H + 16.437 \quad (8.4)$$

The Effective Afflux was calculated for the average (Fig. 8.10), dry (Fig. 8.11), and wet (Fig. 8.12) conditions.

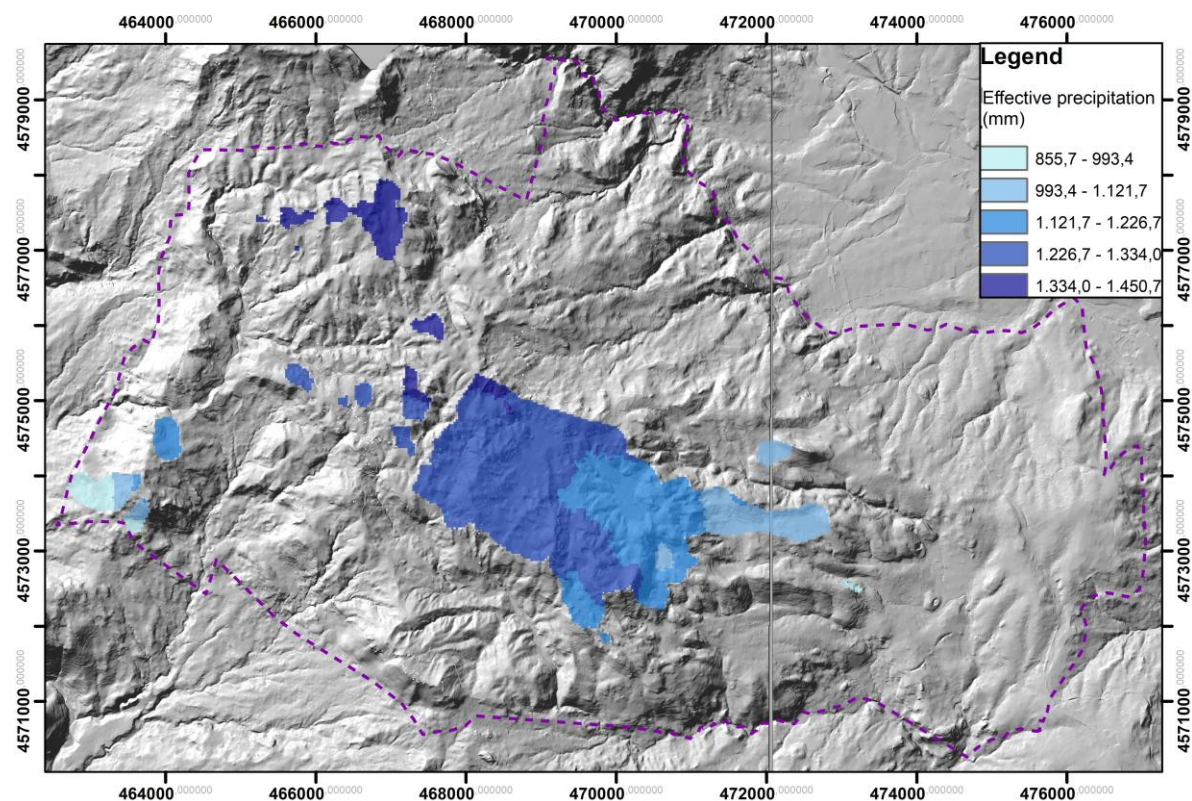


Figure 8.10. Effective Afflux in Endorheic areas for average meteorological conditions.

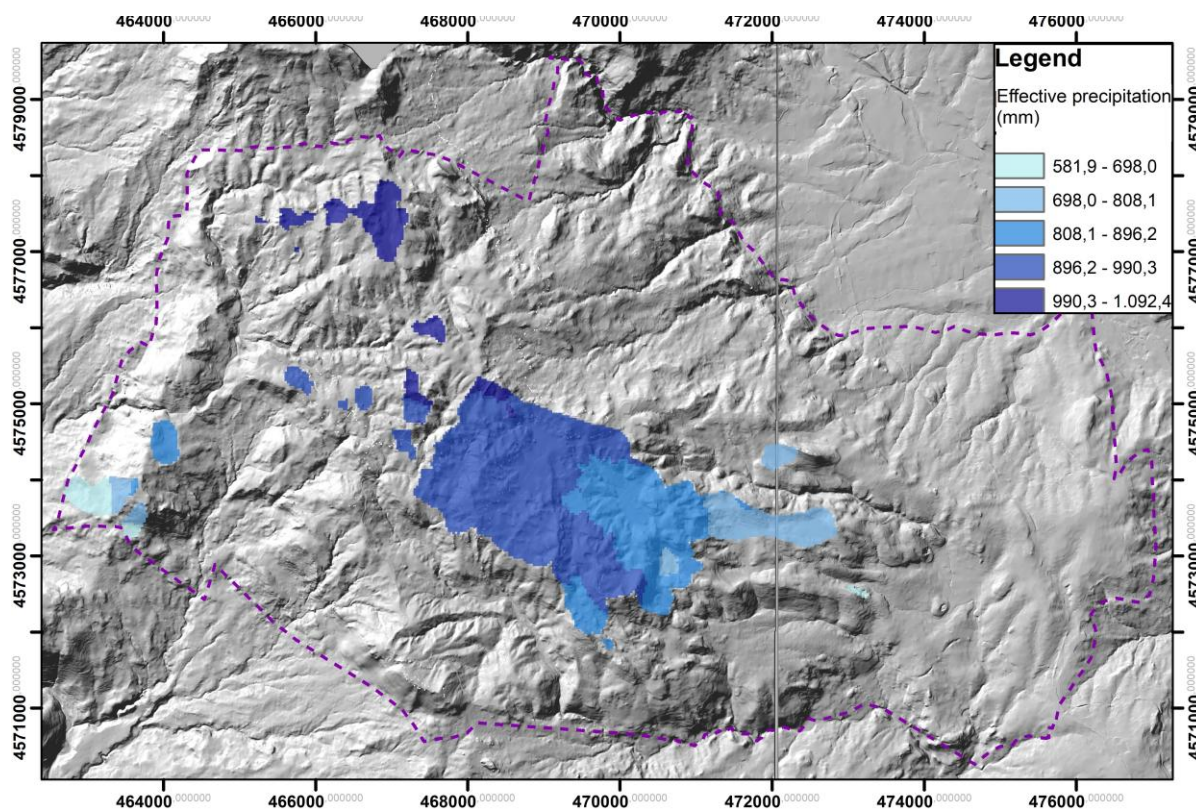


Figure 8.11. Effective Afflux in Endorheic areas for dry meteorological conditions.

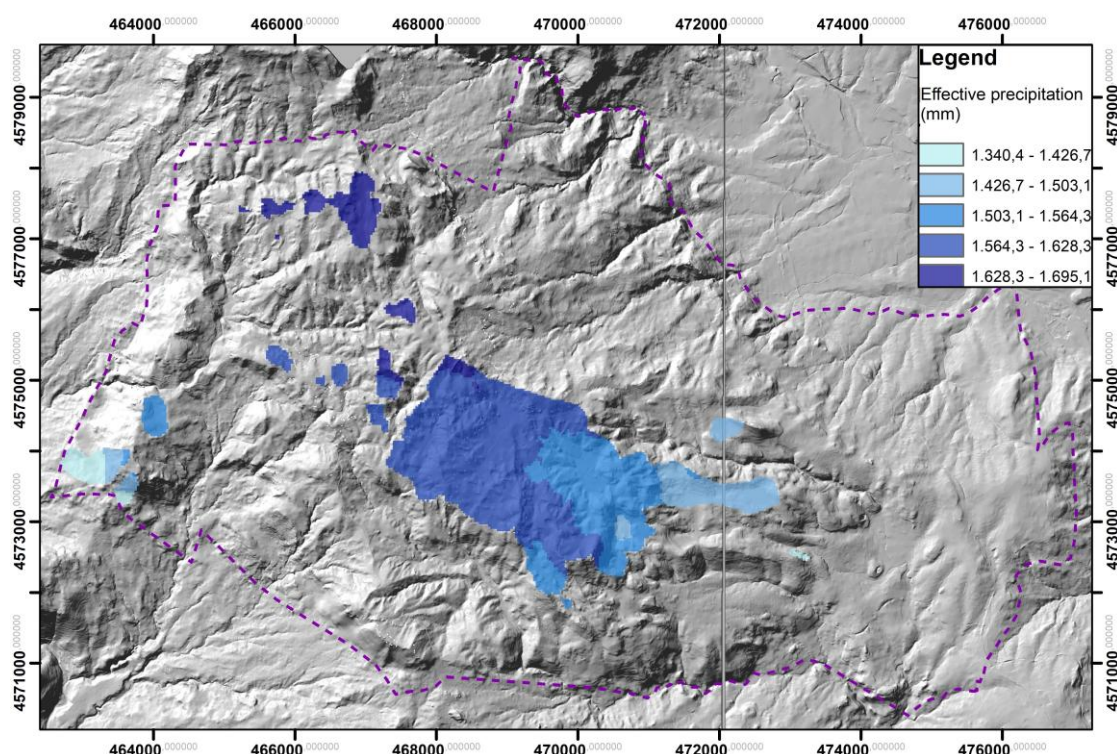


Figure 8.12.Effective Afflux in Endorheic areas for wet meteorological conditions.

Specific Recharge map

Merging the Effective Afflux map of Endorheic areas and the Specific Recharge map (Figs. 8.5, 8.6, and 8.7) made by Modified APLIS method for the Open Areas, the Specific Recharge maps for the Modified APLIS with Endorheic area method were carried out. As the previous methodology, three maps for average (Fig. 8.12), dry (Fig. 8.13), and wet (Fig. 8.14) hydrological conditions were made.

In dry and average year hydroclimate conditions, the maps show the higher specific recharge value in endorheic areas located in the North-Western part of the karst massif. For the other endorheic areas, the distribution of recharge rate varies from West to East, with a decreasing value toward the East sector of the massif. In wet year hydroclimatic condition, don't exist significant variations in distribution of specific recharge across the endorheic areas. However, a specific recharge value, a little bit lower respect other areas, affects the easternmost and westernmost areas. For all the scenarios, the specific recharge value distribution for the Open Areas is the same to that of the Specific Recharge map resulting from Modified APLIS method.

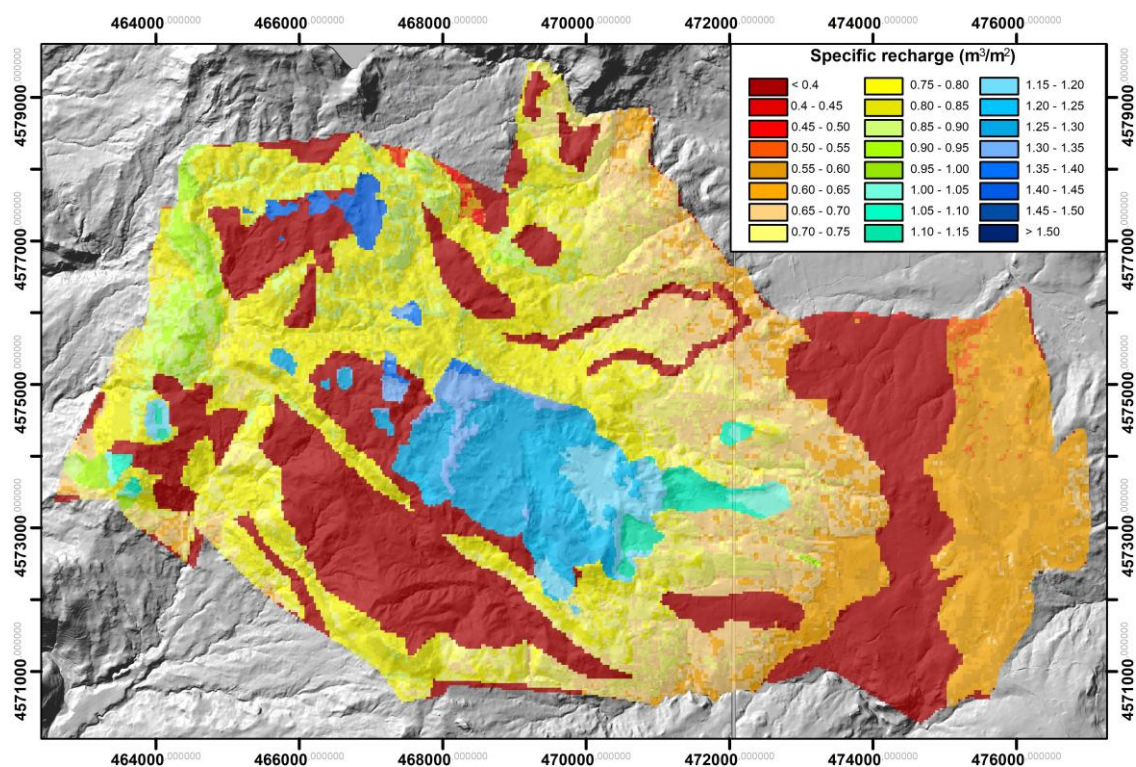


Figure 8.12. Specific Recharge map for average meteorological conditions.

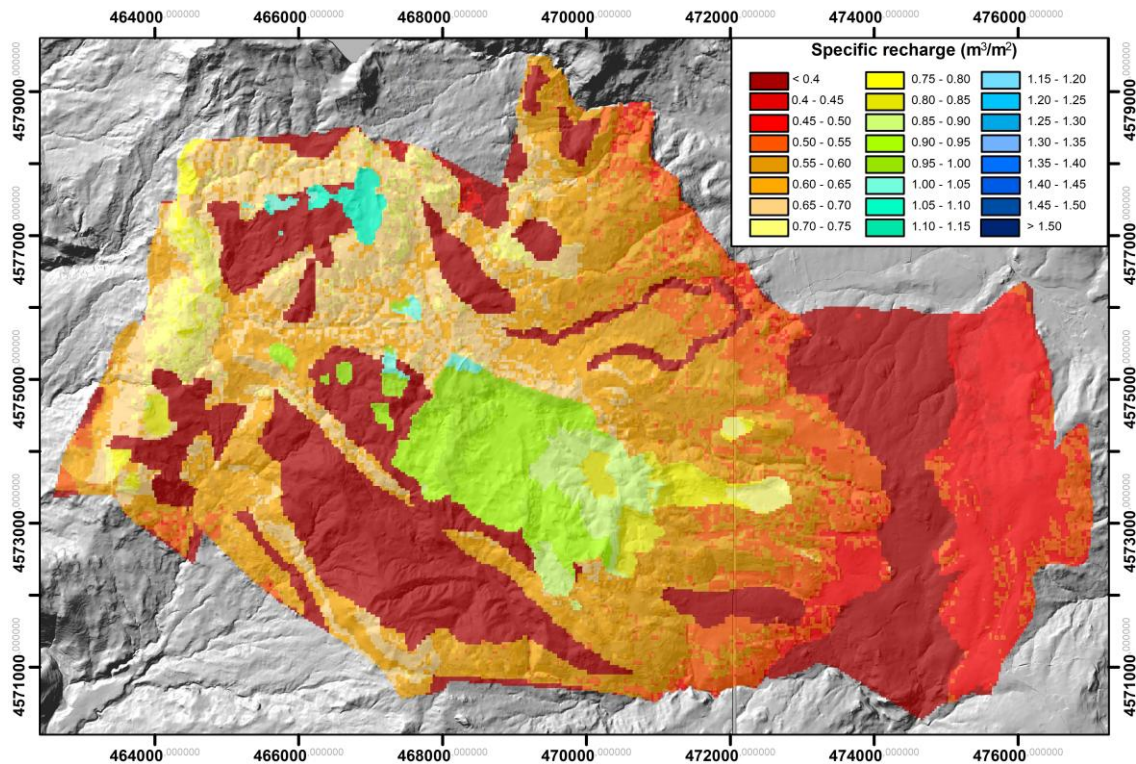


Figure 8.13. Specific Recharge map for dry meteorological conditions.

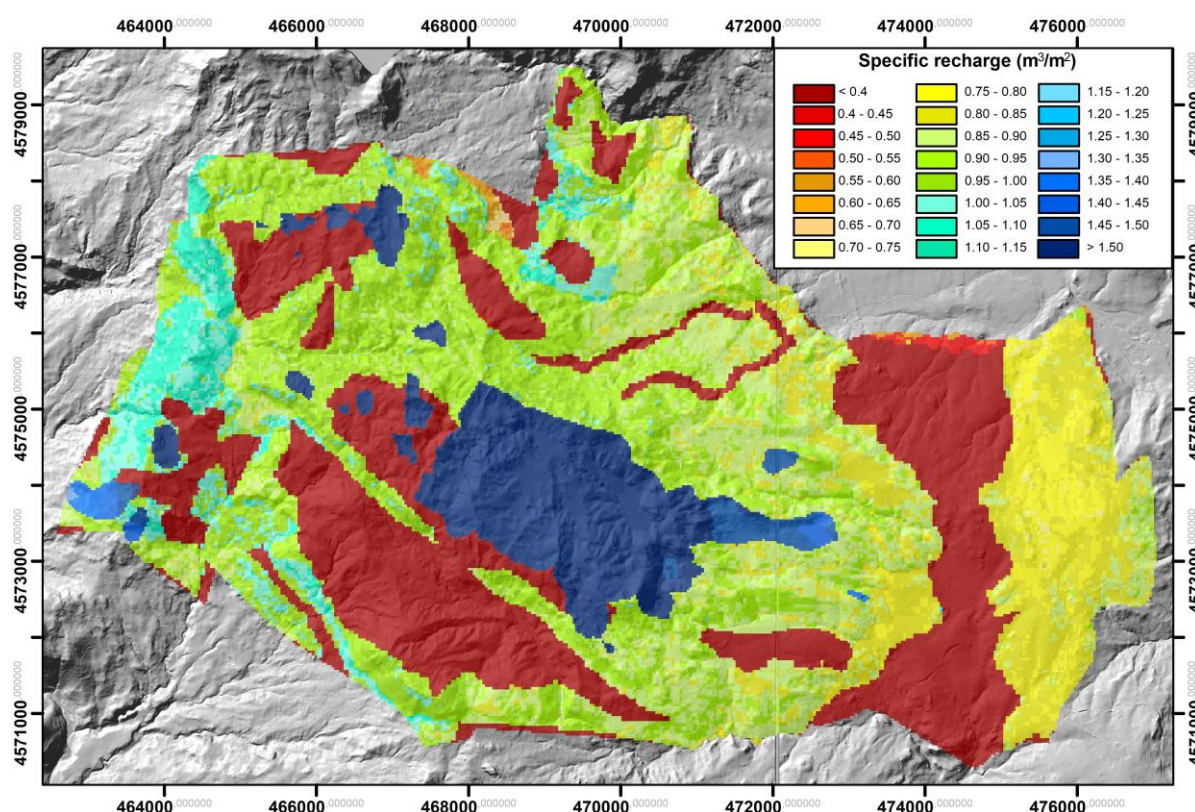


Figure 8.14. Specific Recharge map for wet meteorological conditions.

Also, there is a broadly variation of recharge rates respect to the modified APLIS method varying from $0.70 \text{ m}^3/\text{m}^2$ to $1.50 \text{ m}^3/\text{m}^2$, for dry and wet hydroclimatic conditions respectively (Fig. 8.13 and 8.14). The recharge rates increasing from dry to wet climatic conditions. In wet climatic conditions, all the endorheic areas show the highest recharge rate, implying a lower specific recharge value discretization then Modified APLIS method. Moreover, this methodology, giving major weight to endorheic areas independently of lithology, neglect partially the lithology factor considered in modified APLIS method. In all scenarios analyzed, it is clear a pattern of variation of specific recharge values: there is a trend of decreasing recharge from westward to eastward part of the massif.

8.3. Daily Scale Recharge Model

Daily Scale Recharge model (Fiorillo et al., 2015b) was performed using rainfall data from Morcone rain-gauge and temperature data collected by Roccamandolfi thermometer (Tab. 4.3). These two stations were considered because located at an elevation similar to the main elevation of the massif, and representative of the climate of the massif.

The evapotranspiration was calculated using the Thornthwaite (Thornthwaite, 1948) method:

$$PE_m = 1.6 \left[10 \frac{T_m}{I} \right]^a \quad (8.5)$$

Where T_m is average monthly temperature, I is the Heat Index given by the following equation:

$$PE_m = \left(\frac{T_m}{5} \right)^{1.514} \quad (8.6)$$

And

$$a = 6.75 \times 10^{-7} \times I^3 - 7.71 \times 10^{-5} \times I^2 + 1.792 \times 10^{-2} \times I + 0.492397 \quad (8.7)$$

The soil parameters used in the development of the recharge model are listed in the following table 8.1.

Porosity	Effective porosity	Wilting point	Field Capacity	Soil Thickness (mm)	Field Capacity (mm)
0.57	0.06	0.27	0.51	750	180

Table 8.1. Soil parameters used in Daily Scale Recharge model.

Porosity, effective porosity, wilting point, and field capacities values have been taken from the scientific literature (Fiorillo and Pagnozzi, 2015). The soil thickness was estimated based on fields surveys and on previous pedological analysis carried out in the study area. Considered a predominantly clay component in soils covering the aquifer, the soil thickness was set equal to 750 mm.

The threshold value, T_r , has been fixed to 24.3 mm using a previous study carried out for the nearby Matese karst massif by Fiorillo and Pagnozzi (2015). However, the hydrogeological conditions of the Morcone karst reliefs are quite different from the close Matese karst massif, due to the presence of *Calcare Cristallino* Formation, which does not allow a deep karstification. This condition, causes a complex and discontinuous groundwater flow, with the presence of numerous spring outlets, many of them dry up for long periods and discharge mainly during the wet season or after rainy events. In practice, instead of a few powerful springs, groundwater flows into numerous small springs, only some of which are suitable for tapping.

To compare the recharge amount obtained from Modified APLIS model and the spring volume output, the Daily Scale Recharge Model has been implemented introducing a further low threshold of 4.5 mm, fixed by the volume discharge by the permanent and tapped springs, which

never dry up. These springs can be assumed fed the saturated zone of aquifers, and connected to a deep recharge. The unmonitored and temporary springs, with small discharge, are assumed fed by the throughflow along the slope, and connected to a shallower recharge. Of course, the throughflow could also feed directly rivers and gullies.

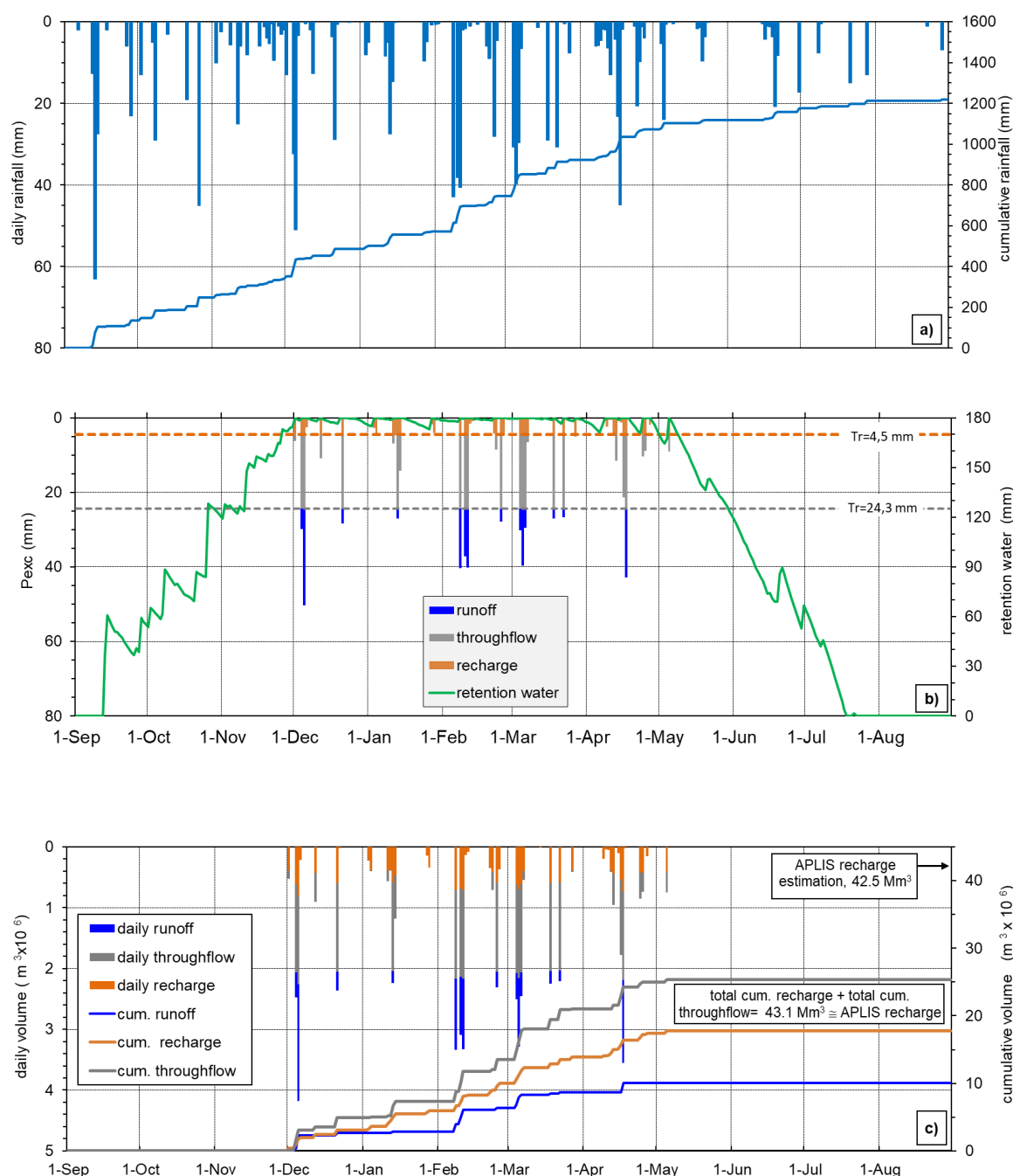


Figure 8.15. Daily Scale Recharge model for the average year 1997-1998. (a) Daily cumulative rainfall; (b) Soil water retention water computed from daily hydrological balance and daily recharge, throughflow and runoff histograms; (c) daily and cumulative recharge expressed in volume.

The recharge amount (deep and shallower recharge) provided by Daily Scale Recharge method, in an average climatic condition, is equal to 43.1 hm³/year (Fig. 8.15; Tab. 8.2). In addition, the contribution on recharge provided by endorheic and open areas was estimated in 12 % and 88% of the whole recharge amount, respectively.

In average climatic conditions, the daily rainfall is distributed through the year with the minor amounts during the summer period: Figure 8.15a shows the daily rainfall distribution in a typical year of this area, with a total cumulative rainfall of about 1200 mm. The field capacity is reached in the early December, after which the daily rainfall provides an amount of the excess rainfall, P_{exc} . This amount is transformed into deep recharge up to 4.5 mm (lower threshold); from 4.5 mm up to 24.3 mm (highest threshold) is transformed into a shallower recharge and provides the throughflow along the slopes (Fig. 8.15b and c). This condition should simulate the relatively low-permeability and the poor karst processes characterizing the *Calcarei Cristallini* Formation, that do not allow deep recharge, with the consequent formation of throughflow. This part of shallow groundwater flows to the rivers, and gullies or feeds temporary springs. When the precipitation excess overpass the 24.3 mm threshold, become runoff. Later, during the spring and summer seasons (May-August), due to the increase of evapotranspiration and decrease of rainfall, the retention water decreased and recharge ceased until the following hydrological year.

Cumulate recharge (m ³ ×10 ⁶)	Cumulate through flow (m ³ ×10 ⁶)	Cumulate recharge+ cumulate thoughtflow (m ³ ×10 ⁶)	Cumulate runoff (m ³ ×10 ⁶)
17.7	25.4	43.1	10.1

Table 8.2.Recharge evaluation carried out with Daily Scale Recharge model.

8.4.Recharge models comparison

The recharge amounts values provided by all three methodologies, regarding the three climatic conditions considered, are summarized in table 8.3. Also, the deviations between recharge values and output values (i.e, spring discharges) have been calculated.

The recharge evaluation carried out with Modified APLIS method (Marin, 2009) and Daily Scale Recharge method (Fiorillo et al., 2015b) provided similar values for recharge values

referred average hydroclimatic conditions (Tab. 8.3). This indicates that either of the two independent methods provided realistic results in recharge estimates.

	Modified APLIS								
	Modified APLIS			with Endorheic areas			Daily Recharge Scale		
	<i>Dry</i>	<i>Average</i>	<i>Wet</i>	<i>Dry</i>	<i>Average</i>	<i>Wet</i>	<i>Dry</i>	<i>Average</i>	<i>Wet</i>
Amount (hm ³ /year)	35.02	42.52	53.36	38.35	49.20	61.70	-	43.10	-
Deviation (hm ³ /year)	17.39	24.90	35.74	20.73	31.57	44.07	-	25.39	-
Deviation (%)	49.5	58.6	67.0	54.1	64.2	71.4	-	58.9	-

Table 8.3. Results of recharge evaluation of Morcone karst massif carried out using modified APLIS method and combined recharge method.

Quite different from the previous methods are the results provided by the application of APLIS with endorheic areas method. Respect to the other two methods, this technique shows an overestimation of recharge values obtained for all the three hydroclimatic conditions considered. Despite a tendency of Modified APLIS method to underestimate recharge during dry years and to overestimate it during wet years was demonstrated (Kirm et al., 2017), a combination of APLIS and endorheic areas method seems not suitable for a reliable recharge estimation. For this reason, further studies about model parameters definition and several calibration operations needed to improve the recharge model.

The confrontation among the recharge values calculated and the output from karst massif did not allow the calibration of the recharge methods applied (Tab. 8.3). These latter are represented by several spring discharge values, for which only few, spot, and discontinuous in time, measures exist. Also, these outputs of the aquifer are not representative of the overall output volumes from the aquifer, encompassing also river and stream flows and temporary springs outlets fed by throughflow and underground transfers. The soil cover, and the topographic and geomorphological setting of the massif, granted the presence of several stream and rivers fed by runoff and spring water and not monitored by any gauge station.

In addition, the karst massif is not completely isolated from nearest aquifers, allowing water transfers between the karst massif and the neighboring aquifers. On the eastern side, a water transfer between the karst aquifer and the nearest alluvial plain, constituting a part of the reservoir of Campolattaro dam, can be inferred. Furthermore, another water transfer of groundwater towards Grassano-Telese springs, located in the area South-West of Morcone karst massif, can be hypothesized (Leone et al., 2019). In detail, the karst bedrock, buried under the impervious lithologies, grant the presence of a groundwater path toward Telese Plain feeding, with an upwelling mechanism, the spring group here located.

This aspect represents an important limitation of the application of modified APLIS method in recharge evaluation for aquifer that aren't drained only by one or more springs and are characterized by several discharges and water transfers to adjacent aquifers.

8.5.Lumped model of recharge-discharge processes of Caposele karst spring

The discharge of Caposele karst spring was simulated through a reservoir model, build and calibrating using KarstMod (Mazzilli et al., 2019).

The daily precipitation and temperature at the median elevation were assumed to be representative of the daily average meteorological conditions. The average meteorological forcing was estimated based on regression analysis, using data from different stations (Tab. 4.4).

The snow routine and the daily evapotranspiration used are that described in section 6.3.

8.5.1.Model structure

Model structure consists in three reservoirs organized in two levels (Fig. 8.16). This structure was selected among other to reproduce the peculiar hydrological features of the Caposele spring (Fiorillo, 2009): (i) smooth changes in daily discharge and no discharge peaks following rainstorms; (ii) a delayed seasonal oscillation during wet years, and limited seasonal oscillation (flat hydrograph) during droughts; (iii) lower discharge limit; (iv) long internal memory effect.

The higher-level reservoir E receives the meteoric affluxes and loses water by evapotranspiration. Furthermore, reservoir E controls runoff and recharge to lower-level reservoirs that are hydraulically connected and drains toward the spring outlet. In particular the reservoir has three outlets placed at different elevations from the reservoir bottom so that the activation of runoff and recharge is a function of the water storage.

Reservoir E recharges the lower-level compartments M and C, which are directly connected to the spring outlet and have different hydraulic behavior. Reservoirs M and C are hydraulically connected, and water exchange occurs. The water transfer to reservoir C follows a hysteretic behavior (Tritz et al., 2011), which avoids abrupt drops in spring discharge during the model drying cycle (Fig. 8.16).

The model assumes that a certain amount of water can escape from the catchment. Indeed, along open slopes outside endorheic areas, runoff generated by sufficiently intense rainfall does not contribute to aquifer recharge (Fiorillo et al., 2015b).

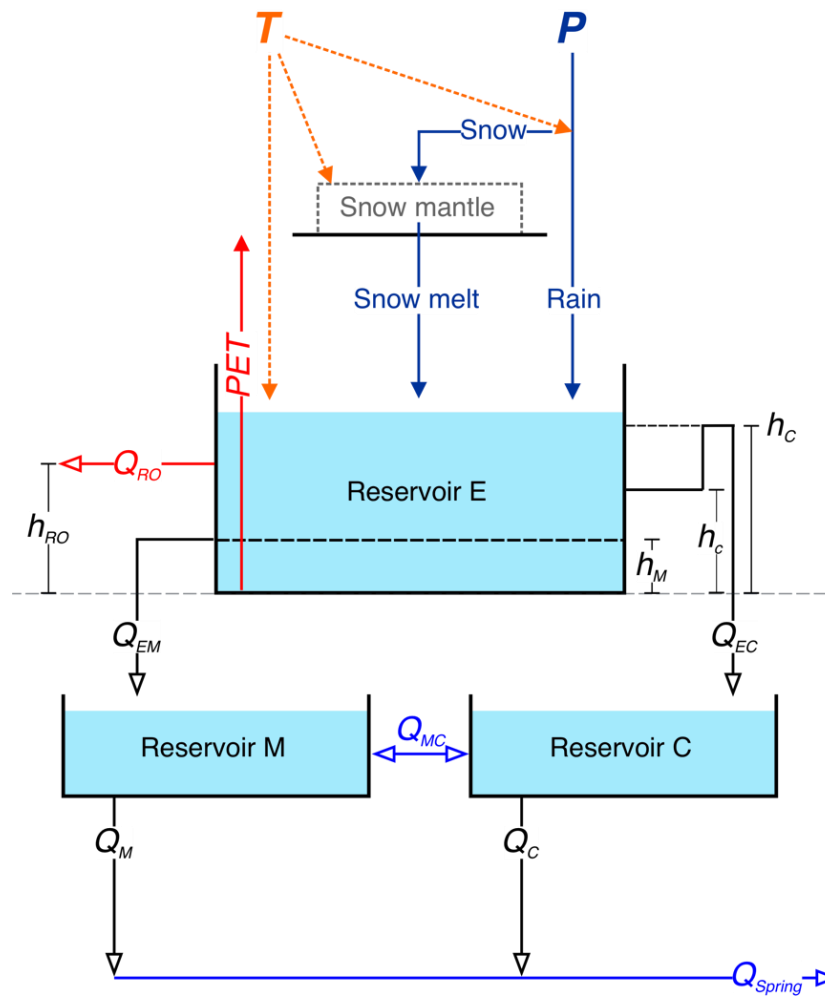


Figure 8.16. Model structure and functioning. P , T and PET are redistributed precipitation, temperature and potential evapotranspiration over the spring catchment, respectively. Temperature affects snowfall and rainfall occurrence, snow accumulation and melt, and PET . Symbol Q denotes outflowing discharge per unit surface area. Simulated spring discharge at the Caposele spring (Q_{Spring}) is the sum of the outflowing discharge from reservoirs M and C (Q_M , Q_C). Water exchange occurs between these two reservoirs (Q_{MC}). Symbol h denotes outlet height measured from the bottom of reservoir E. Discharge Q_{RO} and Q_{EM} activate when the height $h > h_{RO}$ and h_{EM} , respectively. Discharge Q_{EC} activated when $h > h_C$ and deactivate when $h \leq h_C$ (hysteretic water transfer) (modified from Leone et al., 2026).

The response of a karst catchment to rainfall strongly depends on the initial hydrological state. As such, rainfall following a dry period may generate no or mild flows, while moderate rainfall following a wet period may generate significant flows. This behavior was modeled assuming threshold-based transfer functions runoff and recharge. In particular, a hysteretic transfer function was used for faster recharge (Tritz et al., 2011). During the recharge, or wetting, cycle there is no connection between reservoirs until the water level E goes higher than h_C . During the discharge, or drying cycle, the connection persists until the water level goes lower than h_c (with $h_C > h_c$). The threshold-based hysteretic controls the activation of water transfer from E to C and modulate the amplitude of the seasonal discharge cycle. Water deficit due to a meteorological drought, thus, causes the absence of a marked seasonal peak in the simulated hydrograph (flat hydrograph). In this case, the spring discharge is sustained by flows from reservoir M .

8.5.2. Model calibration and validation

Model parameters were inferred by calibration against discharge time series; the simulation window (1 January 2020 to 31 December 2022) was divided into three sub-sets, or periods: warm-up (from 2000 to 2006), calibration (training set, from 2006 to 2013), and validation (testing set, from 2013 to 2022).

KarstMod has an automatic calibration algorithm (Mazzilli et al., 2022) that selects the sets of parameters from a sample space satisfying a minimum performance criterion, here quantified in an initial Nash-Sutcliffe efficiency coefficient $NSE > 0.75$ (Nash and Sutcliffe, 1970).

The performance is measured in the calibration period. Once a suitable samples space was identified, the minimum performance criterion was fixed at $NSE > 0.9$ and 1000 simulations were run to calculate the 90% confidence interval of the model.

8.5.3. Snow routine calibration

A total of 64 Sentinel 2A satellite images, acquired in the period November-April for the years spanning between 2017 and 2021, were used to reconstruct the spatial-temporal evolution of the snowline across the catchment (Fig. 8.17). A snow-line is the boundary between snow-covered and snow-free ground surface and its elevation depends on the snowpack water budget, described by equations (6.13) and (6.14). Snow melt can occur above the snowline.

Images were uploaded in a GIS (Geographic Information System) software and overlapped on 20 m-DEM, allowing the determination of the snowline elevation. Snowline is not uniform in

space due to terrain effects by slope, aspect and topography shading (Hock, 1999) thus the mean elevation was considered for a given day. To simulate spatial-temporal distribution of snow cover, the catchment was divided in 50 m-wide altimetric zones having different precipitation and temperature conditions. Then, the snow routine was iteratively run. At each iteration, parameters were adjusted to minimize the difference between simulated and observed snow cover, evaluated by the Nash-Sutcliffe coefficient, NSE (Nash and Sutcliffe, 1970).

This simple temperature-index model considers precipitation and temperature changes with elevation but neglects other terrain effects, such as slope, aspect and topographic shading. The values of the calibrated parameters are comparable to those found in literature, with $T_{\text{snow}} = 0.5\text{--}2.5^{\circ}\text{C}$, $T_{\text{melt}} = 0^{\circ}\text{C}$ and $MF = 2\text{mm}^{\circ}\text{C}^{-1}\text{day}^{-1}$.

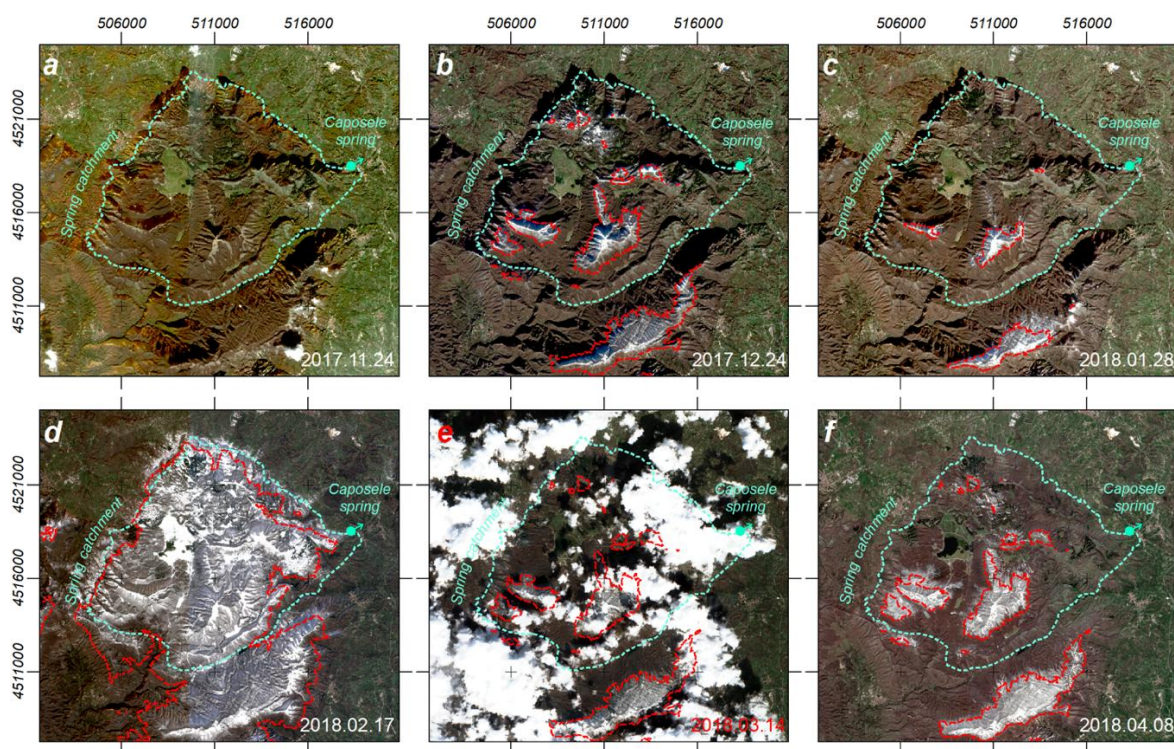


Figure 8.17. Simulated snowline (red dashed line) across the Caposele spring catchment from November 2017 to April 2018 (one image/month). The basemap is represented by Sentinel-2A RGB images. Spring catchment drawn from Fiorillo et al. (2015b) (from Leone et al., 2026).

8.5.4. Recharge and discharge processes modeling

Figure 8.18 details model functioning and compares simulated and observed daily discharge time series (Fig. 8.17e). The high values of the NSE in the calibration ($NSE = 0.96$) and validation stages ($NSE = 0.91$) indicates a high predictive ability of the model, which replicates the main hydrodynamic behavior of the Caposele spring, i.e. smooth discharge variations, a lower discharge limit at about $2.85\text{ m}^3/\text{s}$, and an almost flat hydrograph during droughts.

Such a strong diffuse-flow behavior is uncommon for karst catchments. It could be due to several factors, including the pyroclastic soil cover, a highly fractured and faulted massif, a deep-water table (average unsaturated zone thickness around 800 m), and a huge groundwater storage. Sinking holes at the boundary and bottom of endorheic areas should allow faster water transfer into the underground. However, the karst conduits appear poorly developed and interconnected and interact with the dense network of fractures. The role of the active tectonic may have resulted in the development of faults and fractures that have disjoined the karst conduits, as occurred during the 1980 Irpinia earthquake, where superficial faulting tracers were leaved (Fiorillo, 2009).

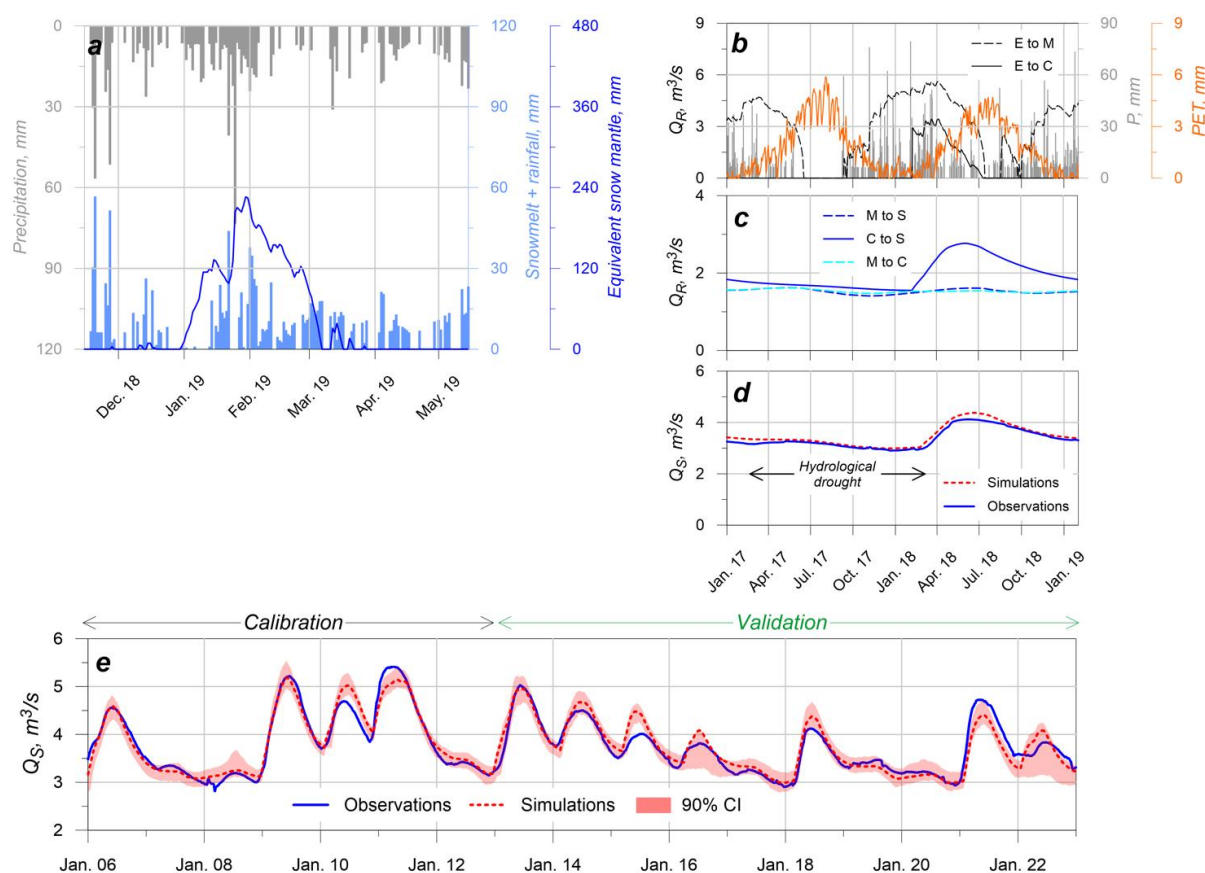


Figure 8.18. Hydrological model functioning and results (from Leone et al., 2026). (a) Snow routine: daily time series (Nov 2018-May 2019) of precipitation, depth of the snow mantle (expressed in mm of equivalent water height) and water input to the reservoir model (sum of water released by snowmelt and rainfall). Reservoir model: (b) daily time series (Jan 2017-Jan 2019) of precipitation, P , potential evapotranspiration, PET , and outflow discharge, Q_R , from reservoir E; Q_R corresponds at recharge to reservoirs M and C; (c) outflow discharge from reservoirs M and C to the spring outlet S and water exchanges between reservoirs M and C. (d) Simulated and observed spring discharge during low-flow (drought) and high-flow (flood) conditions. (e) Daily time series (2006-2022) simulated and observed discharge, Q_S , at the Caposele spring outlet. The 90% confidence interval is also shown.

The snowpack further delays the response of the karst spring to precipitation by creating a temporary water reservoir during winter. As an example, Figure 8.18a shows the time series of equivalent precipitation water retained in the snowpack at the mean catchment elevation (1200 m a.s.l.). A (almost) continuous sequence of precipitation events characterizes January 2019 (grey bars). Liquid water (blue bars) represents 45% of the total monthly precipitation, while the remaining part is retained in the snowpack. The most intense event in this sequence totally feeds the snowpack. The main melting phase starts in February, even if isolated precipitation events occurred during the following February-March, which partially feed the snowpack. The water accumulated at the ground surface during the previous weeks is gradually released and generates an almost continuous recharge over this period.

Figure 8.18b-d illustrate the simulated spring response to a wet year following a drought. Considering the configuration used for the higher-level reservoir E, the model accumulates a water deficit during the seasonal dry period, and recharge toward reservoir C is delayed to the beginning of the rainy period. Due to long period of rainfall scarcity (meteorological drought) the accumulated water deficit is high and discharge oscillation depends exclusively on reservoir M (“flat hydrograph”). Flowrates do not fall below the lower limit thanks to reservoir M. This reservoir provides the slow flow, which can change in response to long-term variations in meteorological forcing.

Chapter 9: Some hydrogeological insights about the historical water supply in Campania region

The development and the growth of societies are strictly connected to water availability, both in term of quality and quantity. Since the ancient times, important societies have populated the areas of the central-southern Apennines (Italy), a sector of Italian peninsula characterized by significant surface water and groundwater resources, the latter are stored mainly in karst and porous alluvial aquifers. Karst aquifers hosted in carbonate massifs naturally provide large quantities of high-quality water. On the other hand, porous aquifers characterize intramontane and vast coastal plain, and are mainly hosted in alluvial Quaternary deposits.

The specific hydrogeological, topographic and climate features of this Campania-Latium region represented key factors for the growth of important settlements and cities, which developed advanced hydraulic works to ensure the continuous availability of good-quality waters. In particular, given the topographic position of karst springs, water can be transferred for long distances by gravity via aqueducts, connecting the karst springs to urban area ([Esposito et al., 2024](#)).

Among the Ancient populations (Sumerian, Egyptian, Indus Valley populations, and Greeks) Romans were the first to turn the ancient aqueducts into a large masonry work serving cities ([Esposito et al., 2025b](#)). The most relevant ancient example is probably the city of Rome, built along the Tiber River, initially representing the primary source that guaranteed the water needs and luxuries such as public baths (*thermae*), decorative fountains (*nymphaea*), and private villas. However, Romans soon understood the importance of springs in mountainous areas and built ingenious aqueducts to have high-quality water, favoring the economic and demographic growth of the cities and, therefore, of the Empire. As a results, these hydraulic achievements became common across the empire. As noted by Strabone (60 BC-about 20 AD), indeed, “*Romans thought especially that Greeks neglected: the paving of streets, the water channeling, the building of sewers that could evacuate in the Tiber River all the city waste waters [...]*” ([Strabone, 23 AD](#)). Certainly, Roman aqueducts were massive structures. Their visual impact was clear in some superficial stretches, while others were developed underground. They always emerged as great main characters in the Roman Empire’s expansion. Their management and

maintenance represented two fundamental features. This was especially true because major public works, including hydraulic infrastructures realized by emperors, concealed political and social messages (D'Agostino et al., 2022).

The towns near Rome were interested by constructions of long aqueducts as occurred initially in the Latium and Campania regions, and in the Mediterranean area later. For this reason, Roman aqueducts are found from Scotland to Iraq and from the foot of Caucasus to the northern edge of Sahara Desert (De Feo et al., 2013a). The most famous aqueducts throughout the Roman Empire were those of: Pont du Gard, located in southern part of the France (Ortloff, 2021); Eifel Aqueduct, located along the Rhine River in Germany (Hoffman et al., 2019); Caesarea Aqueduct, located in Palestina, current Israel (Ecker et al., 2023); Segovia (Tomlov, 2021), Tarragona, and Merida (Dolittle, 2024) aqueducts, in Spain; and, finally, the Valens Aqueduct, located in Istanbul, Turkey (Crapper, 2020). This latter was built in the 5th Century and represents the longest Roman aqueduct ever built (Keenan Jones, 2010a). In Italy, the city of Rome was fed by at least eleven aqueducts: Aqua Appia, Anio Vetus, Aqua Marcia, Aqua Tepula, Aqua Iulia, Aqua Virgo, Aqua Alsietina, Aqua Claudia, Anio Novus, Aqua Traiana, and Aqua Alexandrina aqueducts (Bono and Boni, 1996; Deming, 2020). Regional catalogues remaining from a last compilation during the Empire of Diocletian, also list at least nineteen aqueducts reporting a number of branches from the main channels (Ashby, 1991). Everything known today about Roman aqueducts in Italy is due to Sestus Julius Frontinus (Frontinus, 2014). He was a Roman writer and architect (about 35 AD), *curator aquarum*, during the reign of Nerva and Trajan. The first aqueduct to reach the urban area of Rome, thanks to Appio Claudio Cieco, was Aqua Marcia in 312 BC (Valipour et al., 2020). After the destruction of the aqueducts of Rome, some of the springs once feeding the ancient aqueducts (Aqua Marcia, Aqua Virgo, Aqua Appia and Alexandrina, Aqua Traiana) were re-tapped only in the last two centuries and still supply the city today. Currently, almost all Italian regions have aqueducts operated for centuries, in some cases until recent historical times. In other cases, they were destroyed after the fall of the Roman Empire. The political instability that characterized Italy until its unification in 1861 did not provide the conditions for planning the building of new and long aqueducts systems.

In Campania Region of southern Italy, the Romans built two important aqueducts: Augustan (1st Century BC, also known as Aqua Augusta; Lorenz et al., 2016; Esposito et al., 2025b), for the drinking water supply of Puteoli area and for military water supply of the imperial fleet located in Capo Miseno, and Sannitico (1st Century AD) for the water supply of the city of

Benevento (Esposito et al., 2024). Other minor aqueducts, like Abella (De Feo and Napoli, 2007), Capua (Libertini et al., 2016), and Sant'Egidio (De Feo et al., 2013b) were built before and during this age. Augustan and Sannitico aqueducts tapped the powerful spring of Terminio-Tuoro karst massif (southern Italy; Fig. 1.1), Acquaro-Pelosi, and Urciuoli (mean annual discharge of 2.1 m³/s; Fig. 1.12; Tab. 1.2). This represents their particular features. These aqueducts were abandoned at some point, though exactly when is unknown, most likely due to the destruction during barbarian invasions, the floodings of the Sabato River, or landslides and seismic events affecting their layout. Actually, both Urciuoli (1885-1888) and Acquaro-Pelosi (1937) springs were re-tapped by “Serino Aqueduct” for the water supply of Naples city.

This chapter deals with the geo-hydrological characteristics allowed the choice of the Serino spring group, during Roman time, for the water supply of the two main cities of that time: Beneventum and Neapolis-Miseno. This analysis was carried out through the reconstruction of the aqueducts layout and the study of the spring discharges. Also, the historical evolution of water supply in Benevento city and the current tapping works made in Serino springs have been analyzed.

9.1. Hydrogeological framework of Ancient Campania Felix region

During Roman times, a vast territory extended between the foot slope of Massico Mountain, on the northern side, to Phlegrean Fields and the Vesuvian area, in the southern part, was known as the *Campania Felix* region (or *ager Campanus*). This name is the consequence of the vicinity of the region to the sea and the fertility of the soils. This region coincides with one of the largest structural coastal depressions in southern Italy, known as Campanian Plain. During the Quaternary age, this structural depression was filled by thick successions of continental, sea and volcanic sediments (Bernasconi et al., 1981; Ortolani and Aprile, 1985; Di Girolamo et al., 1988; Marti et al., 2016). The volcanic deposits were associated with the activity of the Phelgrean Fields and the Somma-Vesuvius volcanoes. Among these deposits, the most notable formation is the “Campanian ignimbrite” (or Campanian grey tuff, 39,395 ± 51 BPF; Delibras et al., 1979). This formation is followed by the most recent products of the volcanic activity of Somma Mountain (from about 25,000 years B.P. to 79 A.D.) and that of Vesuvius, which allowed, from 79 AD to 1944 AD, the deposition of effusive and explosive volcanic products (Santacroce, 1987). Carbonate reliefs of Meso-Cenozoic age of Mount Massico, Avella and Sarno mountains, and Lattari Mountain define the boundaries of this depression. Hydrogeologically, two main aquifer systems can be recognized (Fig. 9.1): karst aquifers associated with the carbonate reliefs, and the wide porous aquifer of the depression constituted

by alluvial and volcanic terrains. Additionally, where porous and fractured media overlap, the volcanic structures of Phlegrean Fields and Somma-Vesuvius constitute complex aquifer systems.

9.1.1. Karst Aquifers

The karst reliefs considered in this paper are those of Avella, Sarno, and Mt. Vergine and Picentini massifs. These reliefs are characterized by a high permeability resulting from karst processes and fractures, forming a wide aquifer system feeding important springs in terms of water quantity and quality. The main discharges of the Avella, Sarno, and Mt. Vergine karst aquifers are located along the boundary of reliefs at low elevations (about 30 m a.s.l.), in two main locations: the Cancellio Spring group (formed by Calabricito and Mofito springs; Fig. 9.1 and Tab. 9.1) and Sarno Spring group (comprising Santa Maria La Foce, Santa Marina in Lavorate, Mercato-Palazzo-Cerola, and San Mauro springs; Fig. 9.1 and Tab. 9.1). The San Mauro Spring is highly mineralized due to deep groundwater flow paths caused by structural features (Celico, 1978; Civita et al., 1970; Corniello et al., 1990; Petrone et al., 2024). It fed the ancient Riullo River, effluent of the Clanio River. Sarno springs fed the homonymous river that named the Sarno Plain on which, in Roman times, the two main cities of Pompeii and Nuceria Alfaterna (Fig. 9.3) and two other residential and luxury settlements, Stabiae and Oplontis, were built. These areas were all ultimately destroyed and buried by the eruption of Mount Vesuvius in 79 AD. Additionally, the other springs, such as Laura and Labso springs (elevation 185 and 190 m a.s.l.; Fig. 9.1 and Tab. 9.1), have a lower discharge and a more variable flow regime. These springs discharge in the higher Solofrana Valley and are hydraulically connected to the endorheic area of Forino Plain through a complex karst system linked to the Celzi ponor. They, also, represent the main discharges of the aquifer (Celico, 1983; Santo et al., 1998). Higher elevation springs, typically fed by “perched water tables” or karst channels connected to ponors, exhibit low and variable discharge rates during the hydrological year. The Bocca dell’Acqua karst spring, with a discharge of about 0.5 m³/s (Fig. 9.1 and Tab. 9.1), stands out, although its discharge regime is highly variable. During the pre-Augustan period, this spring served as *caput aquae* for the Abella Aqueduct which supplied the city of Nola (Libertini et al., 2014). The North Picentini karst massif group, constituted by Terminio-Tuoro and Cervialto karst aquifers, feeds several basal springs with huge mean annual discharges like the Caposele karst spring (417 m a.s.l. and 3.96 m³/s), in Cervialto massif, and Serino (370 m a.s.l. and 2.1 m³/s) and Cassano (476 m a.s.l. and 2.75 m³/s) spring groups, in Terminio karst massif (Fiorillo et al., 2018).

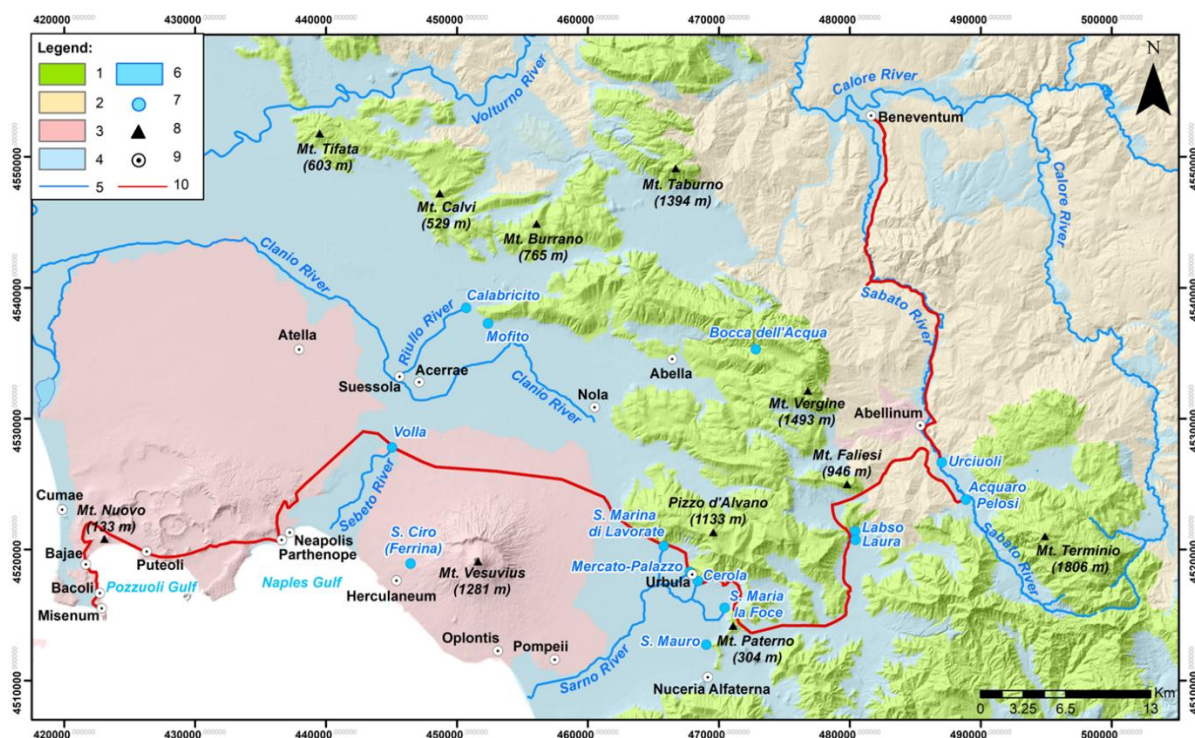


Figure 9.1. Hydrogeological sketch of western Campania. Legend: 1) Karst terrains; 2) Impervious terrains; 3) Volcanic deposits; 4) Alluvial deposits; 5) Rivers; 6) Lake; 7) Main springs; 8) Mountain peaks; 9) Main Roman cities; 10) Augustan and Sannitico aqueducts layout (from [Esposito et al., 2025b](#)).

The Serino springs are located in River Sabato Valley, along the northwestern border of the Terminio-Tuoro karst massif (Fig. 9.1). These are constituted by two main groups: Acquaro-Pelosi and Urciuoli. The former are defined as “high springs” because they emerge at an elevation of 370 m a.s.l.; the latter is defined as a “lower spring” because it emerges at an elevation of 330 m a.s.l. These springs are characterized by a long discharge time series, starting from 1886 ([Fiorillo et al., 2007](#)).

9.1.2. Porous Aquifers

The Campanian depression is filled with pyroclastic-alluvial deposits of varying grain sizes, reaching several thousand meters in thickness ([Celico et al., 1994b](#)). These deposits constitute a porous aquifer with a medium to high degree of permeability. The recharge of the aquifer occurs through precipitation that falls directly onto the plain, as well as from underground, transferring from bounding carbonate reliefs and from structures of the Phlegrean Fields and Vesuvius volcano. Throughout geological history, the plain underwent a significant morphological evolution due to several factors including tectonic movements, the abundant pyroclastic cover supplied by the eruption activity of the nearby Vesuvian and Phlegrean volcanic centers, the Campanian ignimbrite eruption, the glacio-eustatic variations, and the

following re-incision phases by the main surficial water courses (Brancaccio et al., 1995). For instance, during the last Versilian eustatic uplift (7–8000 years BP), wetland environments developed both along the narrow stretch near the actual coast and within the broad streambed created by Clanio-Regi and Volturno rivers on the plain surface (Brancaccio et al., 1995). Additionally, significant subsidence events during the Holocene led to a lowering of the Phlegrean Fields volcanic structure toward the southeast, particularly along the Posillipo-Ponti fault. This resulted in the formation and evolution of the structural depression known as Volla or Sebeto Valley (Fiorelli, 1926; Bellucci, 1992). Overall, this territory has been characterized by wetlands created by the superficial runoff, waters flowing in several rivers from Vesuvius and surrounding areas, including the Sebeto River network originated by Bolla or Volla springs (Fig. 9.1) located here (Tab. 9.1). These springs represented the caput aquae of Bolla Aqueduct (also known as “Water House”).

Spring Group	Spring Name	Hydrogeological Unit	Elevation (m a.s.l.)	Discharge (m ³ /s)
Serino	Acquaro-Pelosi	Terminio-Tuoro	370-380	0.92
	Urciuoli		330	1.2
Sarno	S. Maria La Foce	Avella-Vergine	26–28	2.6
	Mercato-Palazzo			3.0
	Cerola			0.6
	S. Marina di Lavorate			1.80
	S. Mauro			0.40
	Calabricito			0.7
Cancello	Mofito	Pizzo d’Alvano	32	0.5
	Laura		185	140
	Labso		199	120
	Bocca dell’Acqua		930	0.5
	S. Ciro (Ferrina)		126	n.a.
	Gauro	Gauro	n.a.	n.a.
	Volla (or Bolla)	Campanian Plain	14	0.0065

Table 9.1. Features of the main spring groups in Campania Felix region and Serino springs. n.a. means not available (from Esposito et al., 2025b).

9.1.3. Volcanic Aquifers

There are two main volcanic aquifers located inside the study area: Phlegrean Fields and Somma-Vesuvius aquifers (Fig. 9.1). The Phlegrean Fields aquifer is located between the ancient cities of Neapolis, Puteoli, and Baiae, which is modern-day Bacoli (Fig. 9.1). This aquifer is situated within one of the primary active volcanic centers in the Campania region, which developed during the stretching tectonic phases of the Plio-Quaternary period. This process created the Campanian Plain by collapsing the sedimentary bedrock. The volcanic activity originated two significant eruption events of a great magnitude. The first produced the grey Campanian tuff (or Campanian ignimbrite $39,395 \pm 51$ BPF; [Marti et al., 2016](#)). Following this, there was very intense volcanic activity inside the caldera that resulted in the formation of the yellow Neapolitan tuff (15,000 years BP; [Orsi et al., 1992](#); [Scarpati et al., 1993](#); [Deino et al., 2004](#)). Recent studies have indicated a third event of higher energy happened during the last 29,000 years: the Masseria del Monte tuff eruption ([Albert et al., 2019](#)). In the past 15,000 years — after the yellow Neapolitan tuff eruption — the volcanic activity has primarily been explosive and freato-magmatic, generating numerous ash-fall deposits interlayered with pyroclastic flows, leading to the formation of scoria and tuff fans. It is clear that, in the Phlegrean Fields area, the underground stratigraphic sequence varies from location to location depending on factors like position, thickness, and grain size. Thus, this geological structure results in a complex hydrogeological structure characterized by a groundwater flow, almost to local scale, constituted by an overlapped water table configuration. At a greater scale, the groundwater flow can be considered unique due to the lack of wide and powerful impervious layers ([Civita et al., 1973](#); [Celico et al., 1986](#); [Celico et al., 1987](#)). The whole area is affected by natural phenomena like the emission of endogen vapors (fumaroles) and idromineral and thermal springs that, during Greek and Roman times, favored the diffusion of thermal buildings founded in Pozzuoli and Baia municipalities, along Averno Lake, and also in Agnano district and inside the calderas of Astroni and Bagnoli district of Naples (Fig. 9.3). Several Roman writers like Marcus Vitruvius Pollione, Plinius the Older, and Orazio recognized the medicinal and therapeutic properties of thermal waters discharging in this area. Also, some emperors, starting from Augustus, made that area their favorite destination. These complexes were destroyed in the following years and centuries, probably due to the Monte Nuovo eruptions that in a single night (between the 29 September and 6 October 1538) caused deep modifications underground changing the groundwater flow path. This eruption led to the disappearance of various springs and the destruction of numerous *thermae* buildings. It is likely that thermal

springs also existed at the base of Gauro Mountain, one of the area's major elevations, which ranges from 290 m a.s.l., of Corvara Mountain, to 331 m a.s.l., of Barbaro Mountain (the term “*gauro*” means “magnificent” in Greek). In the literature, were not found papers about the springs mentioned above, excluding the work written by [Libertini et al. \(2014\)](#), in which the authors assert that “*Puteoli was supplied also by a local aqueduct coming from the near Gauro Mountain (Gaurus Mons) and surrounding hills*” (Tab. 9.1).

The other hydrogeological volcanic area is the Somma-Vesuvius structure, located in the southern part of Campanian Plain (Fig. 9.1). This is a strato-volcano constituted by pyroclastic and lava deposits erupted up to the last eruption that happened in 1944. As highlighted above for the Phlegrean Fields, alternating medium–high-permeability and low-permeability (mainly ashes) lithotypes, inside the hydrogeological unit, allow a groundwater flow path with overlapped and interlinked water tables. The fissured lava layers and the loosened and coarse-grained pyroclastic deposits represent a good aquifer ([Bellucci et al., 1993](#); [Celico et al., 1994b](#)). These deposits host a radial flow water table that, along the northern boundary, feeds the surrounding alluvial plain while, along the southern one, the water table discharges into the sea ([Celico et al., 1997](#)). Important springs with a great amount of discharge are absent, while many springs with a lower discharge (<5 L/s, [Celico et al., 1997](#)) are present. In particular, along the northern boundary, there are the Olivella Spring, located in S. Anastasia municipality at an elevation of 382 m a.s.l., Chiantelle Spring, with the highest discharge point located at an elevation of 675 m a.s.l. and disappearing and a lower one located near Pollena, and Gavete Spring in Somma Vesuviana municipality. Furthermore, along the southern boundary, there is S. Ciro (or Ferrina) Spring, located in Ercolano municipality (at an elevation of 126 m a.s.l.), currently tapped for bottling with the name “Mineral Water S. Ciro” (Fig. 9.1; Tab. 9.1). Probably, this spring represented the *caput aquae* of a supply system feeding the city of Herculaneum in pre-Augustan times ([Camardo, 2007](#)).

9.2. Historical insights on Augusta and Sannitico aqueducts

The Augustan aqueduct measured approximately 106 Km along its main axis and about 135–140 km when including lateral branches, making it the longest aqueduct built during that period ([Keenan Jones, 2010a](#); [Libertini et al., 2014](#); [Keenan Jones, 2010b](#)). The construction of Aqua Augusta was commissioned by Emperor Augustus and took place between 33 and 12 BC. It was first designed by Marco Vipsanio Agrippa (about 63–12 BC, ancient Campania), who was a Roman *curator aquarum* ([De Feo and Napoli, 2007](#)). This remarkable project supplied water

to a vast geographical area, extending beyond several natural hydrographic basins in the Neapolitan Bay area. Its purpose was to supply water to the two principal harbors of the empire: the military one of Misenum and the civilian one of Puteoli. The construction of the aqueduct is likely connected to the realization of port works promoted by Emperor Augustus in the Phlegrean area. It also served several other cities (like Puteoli, Nola, Atella, Neapoli, Cumae, Acerrae, Baia, and Misenum; [Miccio and Potenza, 1994](#)). Evidence of its use includes a rediscovered inscription (Fig. 9.2) near the Acquaro and Pelosi spring discharge area, which discusses restoration work carried out during the reign of Emperor Constantine the Great (about 324 AD). The order followed in listing the cities is undoubtedly linked to their water consumption ([Colucci-Pescatori, 1991](#)). The aqueduct also aimed to supply water to colonies and settlements linked to Augustan power in the aforementioned cities, as well as to notable villas in the region ([Libertini et al., 2014](#)). This explains the remarkable economical investment, estimated at 140 and 450 million sestertii (1 or 2 years of non-military expenses of the state; [Duncan Jones, 1994](#)).



Figure 9.2.Constantine epigraph in current Acquaro-Pelosi spring tapping work (Photo by Giovanni Minervini).

The exact time when the aqueduct ceased operations is actually unknown. Surely, it experienced damage, at least in the branch towards the city of Pompeii during the Vesuvian eruption of 79 AD, following several periods of scarce maintenance. This necessitated major restoration efforts during the era of Emperor Constantine the Great, as evidenced by the aforementioned inscription (Miccio and Potenza, 1994; Mariniello, 1988). In 410 AD, Alric, Visigoth king, devastated Rome and the Campania region, assaulting Neapolis and Nola, particularly, and seriously damaging the surrounding areas (Savino, 2005). It is thus very likely that, during these events, the aqueduct was seriously damaged at some key points and that the seriousness of the general crisis, both from the economical and organizational points of view, did not allow its restoration. Furthermore, it is important to remember that, from 456 AD onwards, Campania region underwent several raids by Vandals from the sea. This demonstrates that the Roman fleet could not fight barbarian invasions from the sea (Savino, 2005). Probably, in that period, the main aim for the existence of the Augustan Aqueduct, the need to supply the military harbor of Misenum with water, ceased.

During Roman times, the Sannitico Aqueduct fed Benevento city (Fig. 9.3). Long about 32.5 km and with an average slope of 5 ‰, this aqueduct was built in 1st Century AD (Tolle Kasteinbein, 1993) and primarily picked up the Urciuoli spring discharge (Fig. 9.1). Despite several injuries (Joannoswki, 1983; Cristilli, 2005) and maintenance interventions, among which the reconstruction of the channel during the 4th Century (Rea, 1978; Pescatori-Colucci, 1996), the Sannitico Aqueduct was still functioning in 8th – 11th Century A.D. Next, following several Lombard civil wars and natural catastrophes (mainly floods of Sabato River, landslides, and seismic events), Roman aqueduct was destroyed (Peduto, 1992).

9.2.1. Augustan Aqueduct layout

Main channel layout

Several authors have studied the Aqua Augusta Aqueduct layout; the Neapolitan engineer Pietrantonio Lettieri (1797–1805) was a pioneer in this field. He, appointed by the Spanish viceroy Don Pedro from Toledo, in four years, followed the remains and the traces of the ancient aqueduct of Naples and wrote a detailed description. Even more detailed was the study by Felice Abate (first half of the 19th Century). He, with the essay “*Studi sull’Acquedotto Claudio e Progetto per rifornire di acqua potabile la città di Napoli*” (Lettieri, 1862), proposed the reinstatement of the Roman aqueduct to bring to Naples the water from Serino springs again. Other relevant studies were those by Sgobbo (1938) and Elia (1938).

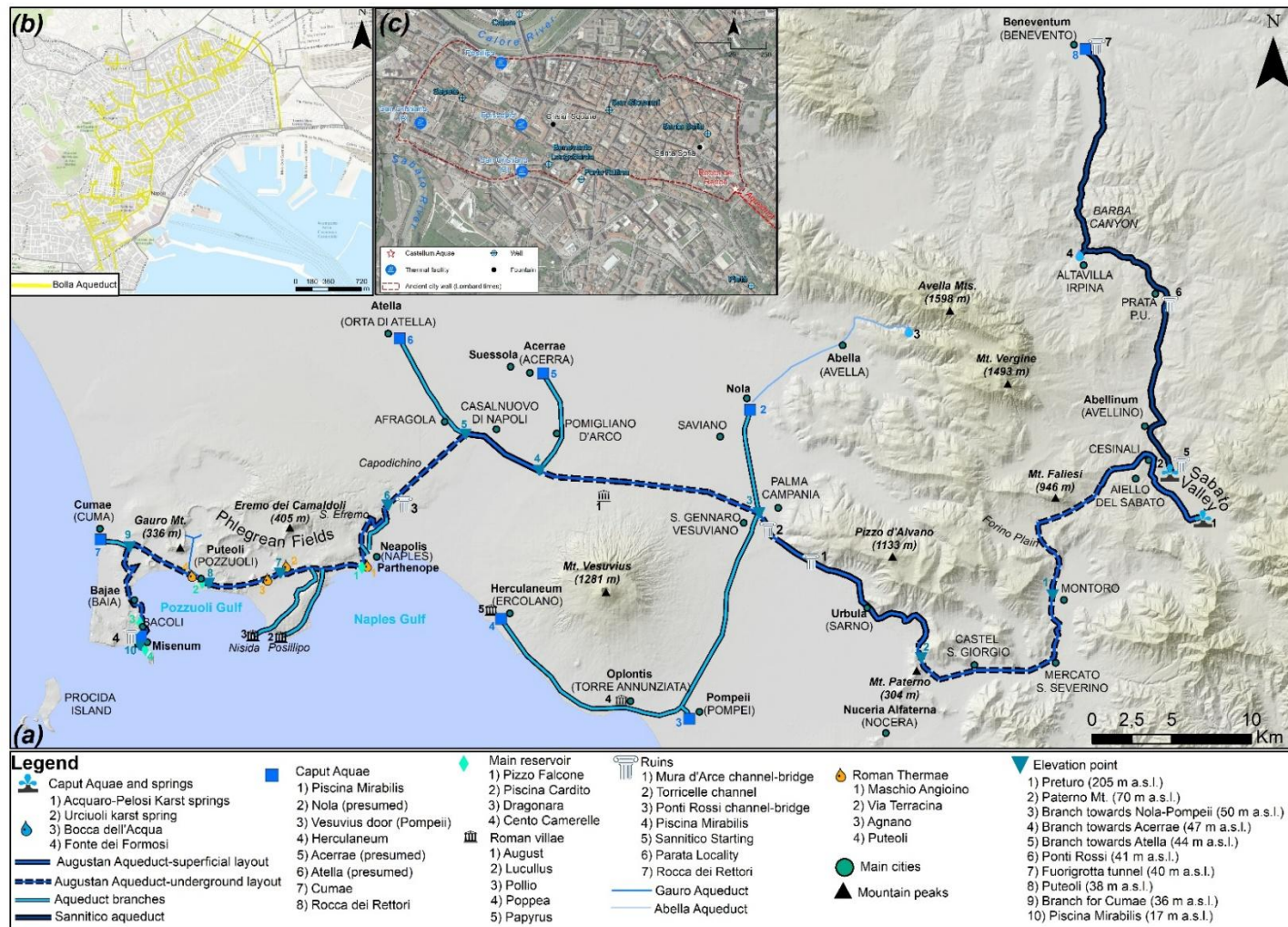


Figure 9.3. (a) Layout of Augustan and Sannitico Aqueducts; (b) Layout of Bolla Aqueduct in Naples city; (c) Roman and Medieval water supply in Benevento city (modified from [Esposito et al., 2025b](#)).

The Roman aqueduct was developed mainly underground (Fig. 9.3a); currently, only some stretches are known (De Simone and Ferrari, 2024). When the Romans conquered Samnium and the land of Irpinium (Samne wars, second half of the 4th Century and the beginning of the 3rd Century BC), they had the access to fresh and abundant waters discharged by Picentini mountains. Indeed, Acquaro-Pelosi springs, located at 370 m a.s.l., were chosen as *caput aquae* of the Augustan Aqueduct (Figs. 9.3a; Table 1). Later (1st Century AD), Urciuoli Spring was also tapped, becoming the *caput aquae* of Sannitico Aqueduct, feeding Benevento (Fig. 9.3a) (Esposito et al., 2024).

From Serino, the Augustan Aqueduct ran on the left side of the Sabato River (Figure 9.3a). It arrived in the current Mercato di Serino district and passed the valley (Pescarola Valley and Contrada Stream) on a channel-bridge flanking Serino mountains and Cesinali municipality towards Aiello del Sabato (Colucci-Pescatori, 1991). This is one of the more rugged stretches, and several remains of the channel-bridge in Pescarola Valley and Contrada Stream were found. From this point, the aqueduct passed the Forino Plain through an underground path and reached the Preturo locality (in the current Montoro municipality) and Pandola (in the current Mercato San Severino municipality). It left, on the left side of the city of Mercato San Severino, passed below the Tor di Marcello district, part of the current Castel San Giorgio municipality, and went towards Taverna di Lazzaro and Serra Paterno localities. Next, along the hill, the aqueduct passed above Urbula (actually the city of Sarno), reaching the Episcopio locality, and went towards Torricelle locality (current Palma Campania municipality). Several remains can be seen along the stretch between Sarno and Palma Campania municipalities, for example, in Mura d'Arce locality (Sarno municipality; Fig. 9.4a) and in Torricelle/Ponte Tirone district (Palma Campania municipality; Figs. 9.3 and 9.4b). Immediately after the channel-bridge of Mura d'Arce locality, the aqueduct is no longer visible. Slightly before this locality, the layout was divided into two branches: the first continued on the channel-bridge; the other flanked the hill. It was thought that the original layout was the second one, but it was modified using the channel-bridge due to the instability of the crossed terrains (Cosimi, 2008). Indeed, slightly after Monaco Stream, both branches merge into one tunnel. It is reasonable that it carried on underground until Torricelle locality, flanking the hill in Palma Campania municipality. From this locality, presumably, the channel, even underground, goes towards west (Abate, 1862), passing San Gennaro Vesuviano municipality, leaving on the right side of Nola and Saviano municipalities, reaching the Masseria La Preziosa locality. Starting from this locality, the channel continues on arches until reaching Pomigliano d'Arco, Casalnuovo, Afragola, S. Pietro

a Patierno, and S. Giuliano municipalities; in this latter part the channel is still visible in Ponti Rossi locality (Figs. 9.3 and 9.4c). From there, the aqueduct passed underground through S. Efremo hill, Santa Maria delle Vergini, reaching the S. Agnello locality (currently Naples municipality). In this district the aqueduct divided itself into two branches: one served Naples, passing Constantinople's door and reaching S. Patrizia locality (Fig. 9.3b); the other passed the foot of S. Elmo Hill towards Chiaia locality, reaching Terracina ([Lorenz et al., 2016](#)) and Agnano *thermae* ([Preziosi, 2001](#); [Belock, 1890](#)). Later it continued, passing above Bagnoli district, towards Pozzuoli. The final end of the aqueduct was the *castellum aquae* Piscina Mirabilis, located in the actual municipality of Bacoli (Figures 9.3a and 9.4d).

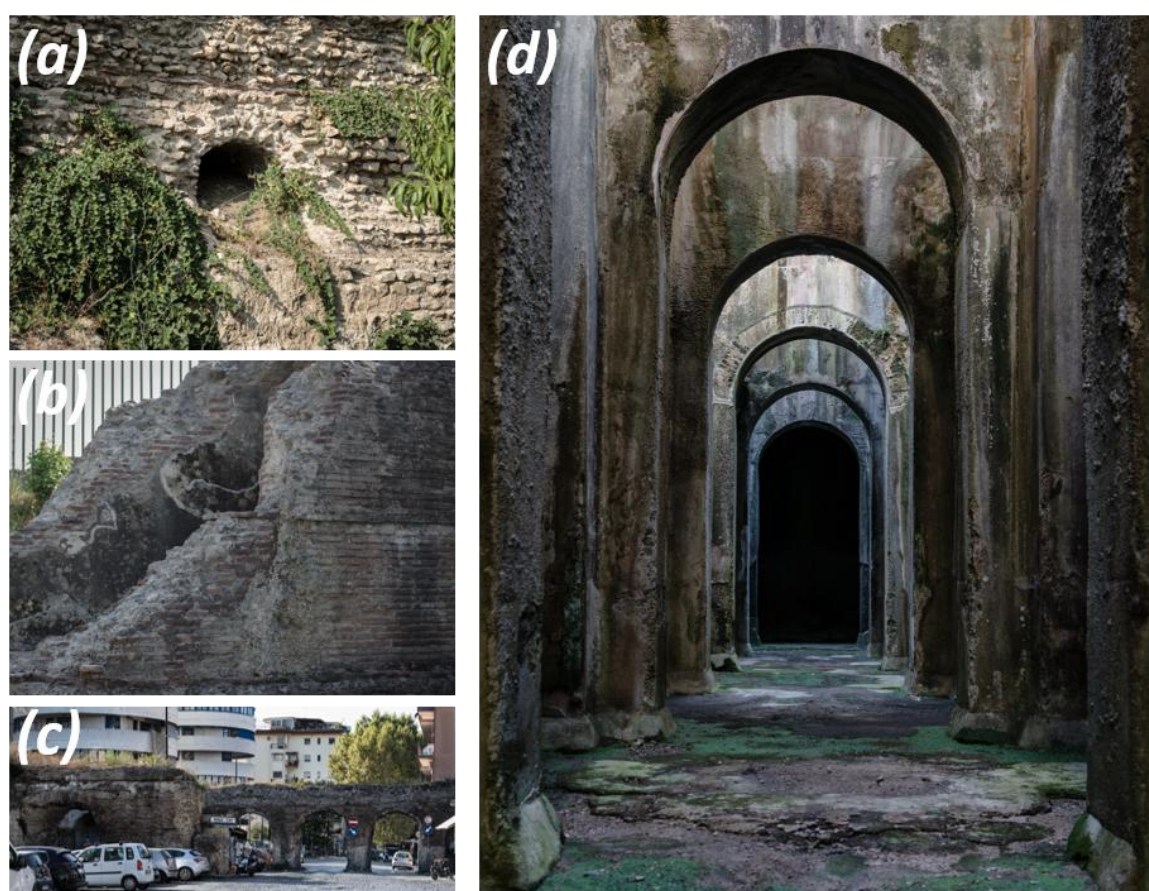


Figure 9.4. Augustan Aqueduct remains in (a) Mura d'Arce locality (Sarno municipality); (b) Ponte Tirone locality (Palma Campania municipality); (c) Ponti Rossi locality (Naples municipality). (d) Interior of Piscina Mirabilis *Castellum Aquae* (Bacoli Municipality) (from [Esposito et al., 2025b](#)).

Secondary branches

The Aqua Augusta Aqueduct fed several localities through several secondary branches that were developed, from 49 km ([De Feo and Napoli, 2007](#)) up to 60 km ([Lorenz et al., 2016](#)).

The first branch, about 9 km long, was at the city of Nola, located at an elevation of 12 m a.s.l. less than the elevation of the starting point of the branch from the main channel of the aqueduct (Figure 9.3a). In particular, the remains of an ancient aqueduct are still visible in the Ciesco della Fata locality, built by inhabitants of Nola in 410 BC (5th Century BC). Saint Paolino, bishop of Nola, founded this aqueduct, and probably it marked the Augustan Aqueduct layout (Libertini et al., 2014). Some authors hypothesize that, before the arrival of the Augustan Aqueduct, the city's water supply was provided by another Roman aqueduct. The spring sources were located in the area of Abella mountains (Libertini et al., 2014). Abella was an ancient Campania city that became a Roman colony, located at about 10 km NE from Nola (Figs. 9.1 and 9.3a). Although actually there are no reliable references about the Abella Aqueduct, and it is reasonable to hypothesize that the Sant'Egidio, Acqua del Monte, and Bocca dell'Acqua springs (the latter located at an elevation of 900 m a.s.l., not so far from the Capo Summonte locality) were the primary sources of the Abella Aqueduct (Figs. 9.1 and 9.3a). Probably, the water supply was scarce, mainly during the dry season during which these springs dry out. Thus, the arrival of Aqua Augusta Aqueduct improved the city's water supply and water quality.

Aqua Augusta Aqueduct likely fed Pompeii *civitas* through a branch (Fig. 9.3) from Palma Campania. In Pompeii, this branch reached Porta Vesuvio, one of the main accesses to the city, located at an elevation of 42 m a.s.l. (Fig. 9.5). It is probable that from Pompeii the aqueduct continued towards Oplontis (with a path of about 0.4 Km), currently Torre Annunziata municipality, and to Herculaneum, currently the city of Ercolano. It served, with a layout of about 25 Km, the luxury houses located along its path (Matsui et al., 2009; Figure 9.3a). Near and inside the ancient city of Herculaneum some remains of a Roman aqueduct and of a *castellum aquae* were exhumed (Sgobbo, 1938). As in the case of Pompeii, the aqueduct contributed to the city's water supply until that time, which was supplied by several wells. The remnants of two water wells were found by archaeologists and excavated to reach the water table: forum thermae well, with a depth of 8.25 m (Maiuri, 1958), and that of Erma di Bronzo House (Maiuri, 1958). Inside the remnants of the hypothesized Augustan channel, archaeologists did not exhume the lime concretions that, for example, were found in the branch of the main aqueduct towards Pompeii. This detail led to the hypothesis that Herculaneum was supplied by an aqueduct fed by a local spring, lacking lime, located at the foot slope of Vesuvius, like S. Ciro (also known as Ferrina) Spring currently situated in Ercolanum municipality (Camardo, 2007; Fig. 9.1).

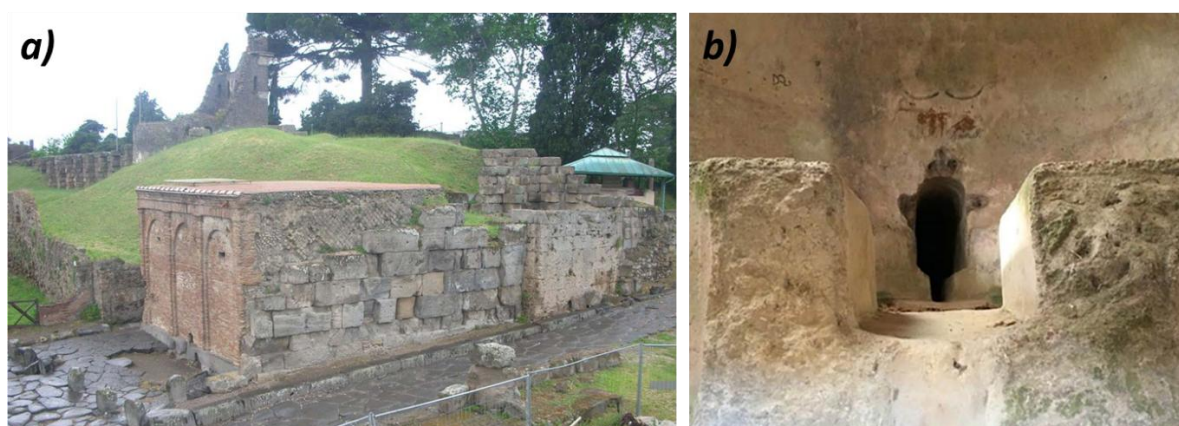


Figure 9.5. (a) Castellum Aquae located near Porta Vesuvio in Pompeii; (b) Aqueduct water inlet channel in north side of water tower (source:

<https://pompeiiinpictures.com/pompeiiinpictures/Fountains/fountain%2061500.htm>).

The Constantine epigraph assures the existence of this branch. It is reasonable to think that this branch had an elevation of about 48 m a.s.l. (Fig. 9.3a) and reached Acerrae, located at 31 m a.s.l., passing through an area with a lower elevation (23–26 m a.s.l.; Fig. 9.3a). Thus, in this section, the aqueduct probably had to run on a channel-bridge. The close village of Sessula (Fig. 9.1), was fed by other water sources (Libertini et al., 2016), and in particular the Calabricito and Mofito springs (Fig. 9.1).

In the era before Augustan times, Neapolis was partially nourished by another aqueduct, most likely of Roman origin (Celano, 1962) fed by Bolla (or Volla) springs located in Sebeto depression (Fig. 9.1). These springs were located at an elevation of 18.5 m a.s.l. The aqueduct was built using terracotta pipes (De Feo et al., 2010) and started in Naples, near Tribunali district (Miccio and Potenza, 1994). It was primarily used for the water supply of some mills located in Sebeto Valley (Fiengo, 1990) and to bring water to a little area of “New City”. The Augustan Aqueduct in Neapolis split into two main branches (Fig. 9.3a and b). The first branch served the upper part of the city, whereas the second branch served the lower part of the city. Just before the tunnel towards Fuorigrotta district, there was a branch of the Augustan Aqueduct. This branch was recently found and investigated; it started from an elevation of 38 m a.s.l. and ran inside Posillipo Hill (De Simone and Ferrari, 2024). It served the rich villas located in the area (Fig. 9.3a). Immediately after the Fuorigrotta tunnel, there was another branch that was developed along the hill flank until reaching the channel-bridge located on the sea on the island of Nisida. In this locality, there was the luxury house of Lucio Licinio Lucullus, built in the 1st century AD in Naples.

Castellum Aquae (Piscina Mirabilis) and other reservoirs

The Piscina Mirabilis (Figs. 9.3, 9.4d, and 9.6a) constituted the end of the Aqua Augusta Aqueduct, and thus its *castellum aquae*, dating to the contemporary age of the aqueduct itself (De Feo et al., 2010). Located in the ancient Misenum (current Miseno locality, Bacoli municipality), its noteworthy importance depends on the fact that it was the most significant military reservoir during Roman times. Its dimensions were discussed for a long time (Maiuri, 1958; Borriello and D'Ambrosio, 1979; Caputo and Costigliola, 2016; Adam, 1988). The length, the width, and the height of the building are, respectively, about 70, 25, and 12 m. Since many authors assert that some parts of the reservoir are hidden, some differences exist in estimating the overall volume. These differences in reservoir dimensions make it difficult to estimate its volume, which varies from 10,700 m³ (Caputo and Costigliola, 2016) to 12,600 m³ (De Feo et al., 2010; Caputo and Costigliola, 2016). The elevation of the inflow point (Fig. 9.6b) from the Augustan Aqueduct channel to the Piscina Mirabilis reservoir is estimated at about 17 m a.s.l. (D'Agostino et al., 2022). On the real functioning of the mechanism of this reservoir, the tapping works, and the water network branches inside the city and towards Misenum Harbor, some doubts still exist.



Figure 9.6. (a) Internal view of Piscina Mirabilis reservoir, on the wall is still visible *cocciopesto*; (b) conduit conveying water in reservoir; several conduits were present, some of them actually are not still visible (photo by Giovanni Minervini (a) and Libera Esposito (b)).

Near the *Piscina Mirabilis castellum aquae*, there were two great reservoirs, probably a part of the grand villas, Grotta Dragonara and Cento Camerelle (the latter known also as Nerone's jail; Fig. 9.7). In Puteoli, the aqueduct fed several reservoirs, among them *Piscina Cardito* (Preziosi, 2001), from the 2nd century AD, and *Piscina Lusciano*, from the 1st century AD. In Baiae, the aqueduct fed a tunnel constituted by two reservoirs, named *Crypta Neapolitana* (De Feo and Napoli, 2007; Adam, 1988, Catalano, 2013; Passchier and Schram, 2004).



Figure 9.7. (a) Cento Camerelle reservoir, internal view; (b) Underground reservoir in Cento Camerelle (photo by Michele Ginolfi).

9.2.2. Sannitico Aqueduct layout

The Sannitico Aqueduct started from Urciuoli spring (*Caput Aquae*), located in Cesinali municipality, and followed the path of Sabato River (Fig. 9.3a). After it crossed the municipalities of Atripalda (ancient Abellinum), Prata di Principato Ultra (some remains were found in Parata del Molino locality), Altavilla Irpina, and Chianche (Cristilli, 2005; De Feo et al., 2009; Fig. 9.8).

Another minor spring, named Fonte dei Formosi, and located near Altavilla Irpina village, also supplied the aqueduct but with negligible discharge compared with the Serino springs (Fig. 9.9).

Castellum Aquae (Rocca dei Rettori reservoir) and layout in the city

The ending of this aqueduct system was represented by a *Castellum Aquae*, whose remains are currently located under Rocca dei Rettori Castle (Preziosi, 2001; Figs. 9.3a, 9.9, and 9.10). From this reservoir, it branched off an underground urban aqueduct network that supplied several parts of the ancient Benevento city, including several thermal facilities (Fig. 9.3c).



Figure 9.8. Remains of Sannitico Aqueduct (a) entering and (b) detail of the internal channel (photo by Libera Esposito).



Figure 9.9. Detailed map showing the path of Sannitico Aqueduct (1st Century AD) conveying waters of the Urciuoli karst springs to Benevento city. Legend: 1) Hypothesized Aqueduct path; 2) Main springs; 3) *Castellum Aquae* (Rocca dei Rettori); 4) Main toponyms; 5) Mountain peak; 6) Towns; 7) River network (from [Esposito et al., 2024](#)).



Figure 9.10. Sannitico Aqueduct: (a) Ruins located along Avellino Street in Benevento city; (b) The *opus reticulatum* highlights the main channel remain under Rocca dei Rettori building; (c) Remains of the main channel in the underground of the Rocca dei Rettori castle; (d) Detail of the main channel modified (from [Esposito et al., 2024](#)).

In eighteen and nineteen centuries, the remains of this network were found during the reconstruction of some buildings following the 1702 earthquake and are still visible along Avellino Street ([De Nicastro, 1719](#); [Isernia, 1895](#); [Zazo, 1977](#); [Zazo, 1980](#); Fig. 9.10a). During the first half of the 2nd Century AD, the Roman aqueduct represented the main water supply for several thermal facilities built into the town, such as the thermal complex of San Cristiano Street ([Isernia, 1895](#); [Rotili, 1958](#)). *Thermae* Commodiane located in the underground of Cardiale Pacca Square and in Posillipo Street, and *thermae* located in Episcopio Street ([Rotili, 1986](#)). The remains of these thermal facilities, located in city walls, are still partially visible (Fig. 9.11).

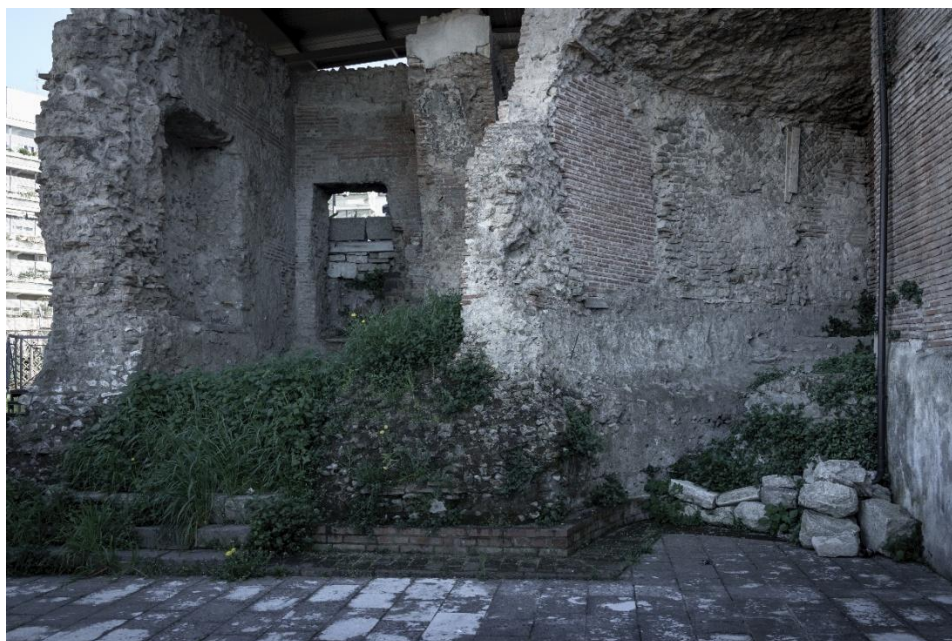


Figure 9.11. Remains of Roman Thermal facilities in Posillipo street (photo by Giovanni Minervini).

9.3. The Serino springs (Caput Aquae)

The spring group's mean annual overall discharge is of about $2.25 \text{ m}^3/\text{s}$ (Tab. 9.1; Fiorillo et al., 2007). Both Acquaro-Pelosi and Urciuoli springs show a permanent regime with an average monthly spring discharge just over $1.2 \text{ m}^3/\text{s}$ (Fig. 9.12). Urciuoli Spring discharge, less variable, shows limited fluctuations compared to Acquaro-Pelosi. In this latter case, there are greater fluctuations (Fig. 9.12a). Among the two spring groups, the most productive and that with the most stable discharge is Urciuoli Spring ($1.25 \text{ m}^3/\text{s}$ Fig. 9.12b).

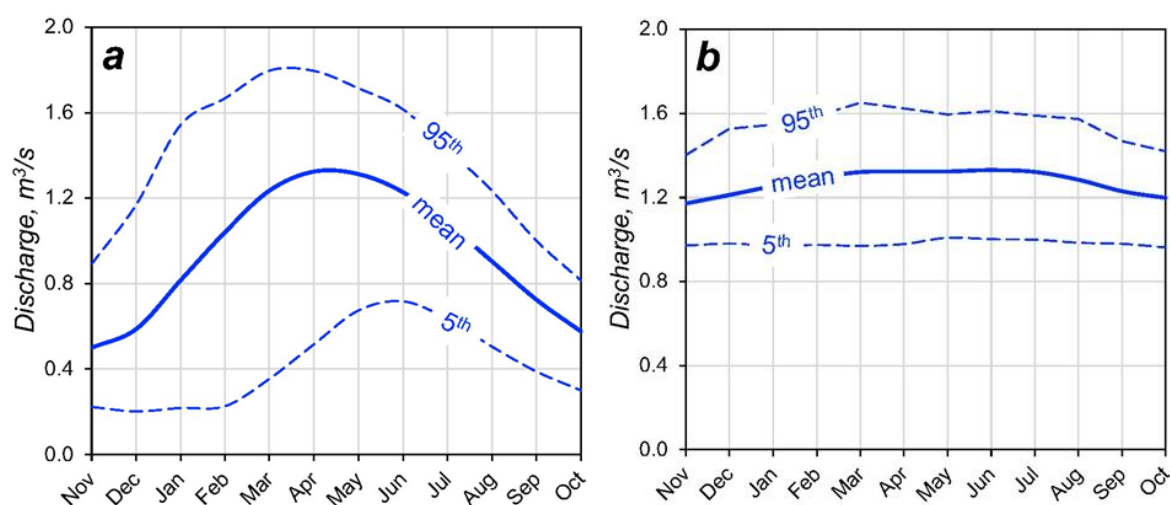


Figure 9.12. Monthly mean discharge of (a) Acquaro-Pelosi and (b) Urciuoli springs (period 1934–2018); 5th and 95th percentile discharges are shown (from Esposito et al., 2025b).

Romans first solved the problem of Benevento water supply conveying water from Urciuoli spring to the city, granting a steady and huge water supply. Considering the aqueduct remains still present under Rocca dei Rettori castle (Fig. 9.10d), the main original channel has a maximum width of about 0.54 m and a height ≥ 0.84 m. The channel is filled by a layered deposit, mostly made by precipitation of calcium carbonate and debris. Calcium carbonate is directly precipitated from the flowing water, considering the karst origin and the bicarbonate nature of the Urciuoli spring. Generally, this type of deposit characterizes the transport and storage elements of ancient hydraulic works sourced from karst environments (Keenan Jones et al., 2022; Sümelihiindi and Passchier, 2023).

It forms below the water level, and its overall thickness is not uniform as it decreases upward (Fig. 9.10d). The layers are almost parallel, and the materials at the channel are the oldest. The maximum height reached by the deposition level is about 0.65 m from the channel floor, despite the uppermost and thinnest part of the deposit having been eroded over time. This deposition level should provide the maximum water flow height throughout the original channel at the beginning of the precipitation-sedimentation process. In particular, aqueduct discharge can be obtained by Manning's equation (Chow et al., 1988) based on channel features. Approximating the original channel section to a rectangle, the discharge, Q , is related to flow height, h_f , by:

$$Q = \frac{R(h_f)^{2/3} \cdot S^{1/2}}{n} \cdot A(h_f) \quad (9.1)$$

where $R(h_f)$ is the hydraulic radius and $A(h_f)$ is the flow section, both function of h_f ; S is the bed slope, and n is Manning's roughness coefficient. Assuming a maximum water flow level of 0.65 m, with a coefficient n between 0.01-0.015 (Chow, 1959), the maximum aqueduct discharge ranges from 0.58 to 0.86 m³/s. Assuming the past and recent spring discharge regimes are similar (Demordy et al., 2014), this amount would be guaranteed also during extreme hydrological drought which affected the Urciuoli spring ($Q < \mu - 2\sigma$), and only a part of the total spring discharge was conveyed toward Benevento. However, water leaks along the aqueduct path cannot be ruled out, and probably all whole spring discharge was tapped. Under such hypothesis, more than 50% of the water tapped was lost during the path.

The deposit accumulation has caused the narrowing of the flow section and an increase of the wall roughness, associated with a lowering of the deposition level over time. This suggests a

decrease in the aqueduct discharge, probably due to the abandonment and degradation of the hydraulic work rather than natural factors.

Differently, the high springs of Acquaro-Pelosi have been chosen to constitute the *caput aquae* of the Augustan Aqueduct, as reported by many authors who have addressed this topic.

9.3.1. *Caput Aquae choice*

Caput aquae (Fig. 9.13a) needed to address three primary requirements: (i) an elevation that granted water outflow by gravity, with average hydraulic heads in the order of 0.4–1.0‰ (D’Agostino et al., 2022); (ii) a high spring discharge to accommodate the population being supplied, along with minimal fluctuations throughout the hydrological year or such to guarantee a certain flow rate during the long Mediterranean dry season; (iii) excellent quality features of spring waters. For these reasons, springs in the Phlegrean and Vesuvian areas were ruled out, leading to the necessary selection of karst springs. Geographically, the nearest were Sarno springs (Fig. 9.3a) that, together with Mofito and Calabricito springs, were fed by the Avella-Vergine-Pizzo d’Alvano Mountains karst aquifer. The Sarno springs are characterized by a high discharge (an overall amount of about 8.5 m³/s; Tab. 9.1; Petrone et al., 2024) and emerge at an elevation ranging between 26 and 28 m a.s.l. Notwithstanding the short distance separating them from the Phlegrean Fields area, and their high discharge, their lower elevation of discharge did not allow them to be chosen as the *caput aquae* of the aqueduct. To support this, it has to be considered that the Aqua Augusta Aqueduct has a ground elevation of about 70 m a.s.l. corresponding to Mura d’Arce locality, which is close to and downstream of all the Sarno springs (Fig. 9.13b).

Always in the areas nearest Phlegrean Fields, can be considered as “origin” of Aqua Augusta, Abella springs, and in particular the Bocca dell’Acqua spring (Fig. 9.1), as it is characterized by high discharge (Aquino et al., 2006); however, this spring is characterized by very variable discharge due to its high ground elevation, and can dry out during summer. Thus, they were not chosen as the *caput aquae*, and Romans had to look to more distant water sources, overcoming difficulties of other types, such as the need to cross multiple watersheds along the route.

The choice of the Serino springs as the *caput aquae* determined the need to overcome the local watershed between the Sabato River and the Campania Plain, though a series of tunnels, which is not easy to imagine at that time.

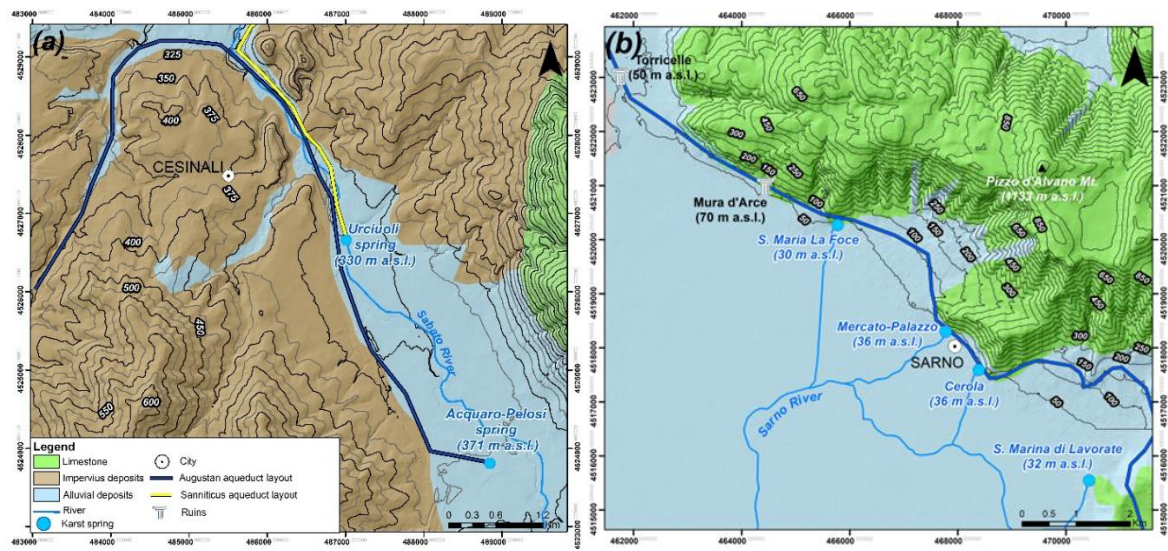


Figure 9.13. Aqueduct paths and hydrogeological sketch map of (a) *Caput aquae* area of Serino springs area and (b) Sarno springs and Mura d'Arce area (from Esposito et al., 2025b).

From Serino springs, the Augustan channel reached Piscina Mirabilis, about 106 km away, declining more or less delicately, as deduced from slope analysis (Tab. 9.2). The average slope of Aqua Augusta is equal to about 2.5‰, as also found in the literature (Libertini et al., 2014). This value also agrees with the average slope values in other Roman aqueducts (0.4–1.0‰). Some stretches show a higher slope than others, where it is necessary to hypothesize the existence of “dropshafts” (Chanson, 2002), hydraulic systems characterized by a vertical junction which connects two sub-horizontal segments of the main channel, allowing dissipation of the energy of the water flow (Fig. 9.14).

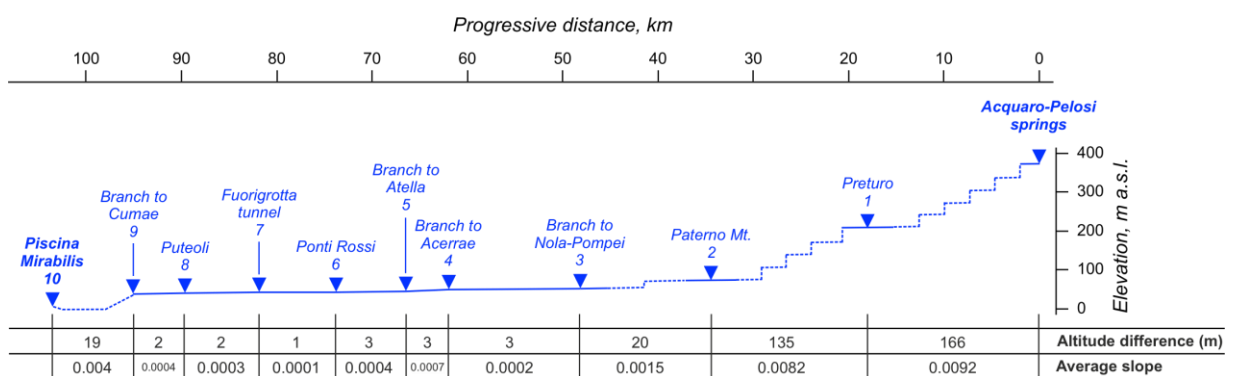


Figure 9.14. Aqua Augusta Aqueduct path with elevation points (blue triangles) and average slope values. The solid line represents the aqueduct layout; the dashed one represents sections of the main channel supposed to be interrupted by the presence of dropshafts to maintain the slope of the main channel ≈ 0.0004 . The numbers are referred to the elevation points in Figure 9.3a (from Esposito et al., 2025b).

Stretch (Number)	Starting Elevation (m a.s.l.)	Ending Elevation (m a.s.l.)	Distance (km)	Slope
1	371	205	18.0	0.0092
2	205	70	16.4	0.0082
3	70	50	13.7	0.0015
4	50	47	13.8	0.00022
5	47	44	4.5	0.00067
6	44	41	7.4	0.00041
7	41	40	8.0	0.00013
8	40	38	7.8	0.00026
9	38	36	5.5	0.00036
10	36	0	8.4	0.0043

Table 9.2. Slope values for some stretches of the Augustan Aqueduct.

The reasons leading Vipsanio Agrippa in the choice of the high-elevation spring of Acquaro-Pelosi (instead of the lowest-elevation spring of Urciuoli) as the main source of this magnificent and important hydraulic work with many inhabitants to feed seems not supported by hydraulic and hydrogeological evidence. First, it is noteworthy to consider the spring discharge regime of the Serino group (Fig. 9.12). Indeed, during drought periods, springs can discharge only a few hundred liters per second for several months; during the historical drought period of the year 2002, Acquaro Spring dried out (Fiorillo et al., 2007). During the Roman period, the mean background climate of the Mediterranean basin was broadly similar to that of the present day (Demordy et al., 2014). The two spring groups responded to the same climatic inputs, and this response is governed by the hydraulic and hydrological features of the karst aquifer. Therefore, it can be assumed that, even if the absolute discharges differed from the present ones, the regime was similar in relative terms (with Urciuoli having higher discharge than Acquaro-Pelosi). Assuming a stationary regime during the last 2000 years, these discharge features seem not to support the decision of Romans to feed the Augustan Aqueduct only with the Acquaro-Pelosi spring group.

Furthermore, the hydraulic mechanism of emergence characterizing these springs, constituted by several discharges located on the Sabato River alluvial plain, was not so easy to tap in terms of the overall spring discharge. This is because the realization of several complicated underground drainage tunnels was necessary, while for Romans it was easiest to take pointed springs, like Aqua Marcia springs (representing the *caput aquae* of the homonymous aqueduct built in the 3rd Century BC; Deming, 2020).

Furthermore, it is interesting note that the main channel of Acquaro-Pelosi springs crosses the area of Urciuoli Spring (Fig. 9.13a), located 3.5 km downstream and with an elevation 40 m lower than the Acquaro-Pelosi one. These features did not prevent their usage as *caput aquae* of the Augustan Aqueduct, neither in slope nor in layout, rather they could have considerably enhanced its flow.

Another consideration deals with Sannitico Aqueduct fed by (and only as tested by literature sources) lower springs of Urciuoli, affected by a more stationary hydrological regime and by a higher mean annual discharge (Figure 9.12b). In literature several authors believed that Sannitico Aqueduct was built about one century later than the Augustan Aqueduct, but on this dating several doubts can be raised. Indeed, the archaeological remains founded in Pratola Serra municipality (Avellino Province), based on the architectural technique, allow to hypothesize the existence of this aqueduct since the early decades of the 1st Century AD (Cristilli, 2005). This hypothesis seems plausible if can be considered that the city of Benevento (*castellum aquae* of Sannitico Aqueduct) was a pivotal settlement during Roman times from 86 BC when the city became a *municipium*. In that time, indeed, Benevento was settled on the crossing of *Minucia* and *Appia* roads, the main streets that linked Rome with the city of Brundisium, representing the main harbor controlling the Middle East territory since the 2nd Century BC. Here the famous Roman Cesarea Aqueduct was built during Herod's government (1st Century BC), and it appears very plausible that Sannitico Aqueduct already existed at that time.

Already in the 1st Century BC, this city exhibited a particular period of prosperity and well-being shown by the existence of magnificent public buildings. Examples are represented by the Santi Quaranta complex (1st Century BC – 1st Century AD?), a long and magnificent cryptoporticus located at the entrance of Appia Road in Benevento coming from Rome (Galasso, 1999), and by the Roman amphitheater (later 1st Century BC – early 1st Century AD; Giampaola, 2011), a monumental building near Santi Quaranta. It was widely ascertained that the amphitheater was a place where gladiators fought and that the city had to be one of the branch offices of the Ludus Magnus gladiator school, the most important in Rome (Rotili, 1986). Thus, it is reasonable to hypothesize that Benevento needed a water supply before the 1st Century BC. Esposito et al. (2024) hypothesized a maximum spring discharge arriving in Benevento ranging from 0.58 to 0.86 m³/s. As mentioned earlier, supposing that past and current spring discharge regimes are similar, it may be that this amount could also be granted during extreme droughts that hit Urciuoli Spring (Fig. 9.13b). Furthermore, the overall spring discharge was only partially conveyed towards Benevento and more than 50% of the water

tapped was lost. In fact, hypothesizing a link between the Augustan and Sannitico aqueducts, it could be possible that a huge part of Urciuoli Spring discharge fed the Aqua Augusta Aqueduct.

These reasons, together with the huge water demands of the Neapolitan area served by the Augustan Aqueduct (Tab. 9.3), lead to think that Augustan and Sannitico aqueducts were a part of a unique and great hydraulic design, built approximately in the same period. Thus, the two aqueducts could be interconnected according to the water demand, allowing hydraulic exchanges in the layout where the two paths run parallel in Sabato River Valley (Fig. 9.12a). The hypothesis of an interconnection between the two hydraulic systems is, among others, reported in the book “*Pompeii*” by [Robert Harris \(2003\)](#), which describes the last four days of Pompeii before the 79 AD eruption and forerunner signals that affected the hydrogeological balance and the reduction of flows of Aqua Augusta. This is the phenomenon investigated by the main character (a young engineer sent from Rome as *curator aquarum*) who illustrates to Plinius the Older an intervention plan for repairing a supposed failure in the main channel following the branch for Pompeii: “*I never seen Serino sources, but from this map it results that they rush into a basin from which start two branches. The major part of the water is toward west, to us, but a minor channel go towards north to feed Beneventum. If we convey all the water to north, closing the bulkheads towards west, we leave dry the channel towards west and we can enter for repairing*”. It is not clear from which source Harris extrapolated this hypothesis, even if there are several bibliographical references ([Adam, 1988](#); [Hodge, 1992](#); [D’Arms, 1970](#)). This writing clearly assumes the connection between the two aqueducts and supports the idea of a unique and great hydraulic design, which was built in the 1st Century BC.

9.4. Augustan Aqueduct and water supply

During pre-Augustan times, the water supply of inhabitants of *Campania Felix* was granted by cisterns that collected rainfall water, wells located in the most depressed areas and near the coastline, and springs. These springs represented the *caput aquae* of some small aqueducts of local significance.

During Augustan times, the idea of the design of Serino Aqueduct emerged ([Morretta, 1990](#)). Indeed, Augustus believed the Campania region to be strategic and of secondary importance only to Rome. This ambitious construction was part of a broader planning initiative that needed to address the requirements of the “*classis praetoria misenas*”, the commercial harbor of Puteoli, and the population’s needs. Augustan work, focused mainly on the Phlegrean area, was

also aimed at realizing and improving public buildings, public thermal structures, and baths linked to the construction of private houses and the adjustment of street networks. In the Phlegrean area, the construction of *Crypta Neapolitana* serves as an example of efforts to improve the connectivity between Puteoli and Neapolis (Morretta, 1990). Certainly, Neapolis, like Puteoli that became “*Colonia Julia Augusta Puteoli*”, enjoyed particular attention from the emperor. At the same time, Baiae, Bacoli, and Cumae were occupied mainly by residential villas equipped for fish breeding (Morretta, 1990). As mentioned earlier, in the epigraph about the restorations of Aqua Augusta during the time of Constantine the Great are listed the cities fed by aqueducts in order of priority following the amount of water consumption (Puteoli, Nola, Atella, Neapolis, Cumae, Acerrae, Baiae, and Misenum; Miccio and Potenza, 1994). Notably, Pompeii and Herculaneum are absent from this inscription, as they were buried under volcanic deposits from the eruption of Mount Vesuvius in 79 AD. Thus, an estimation of population in the Campania region during the Augustan age is shown in Table 9.3. The table shows that the overall population is about 200,000 inhabitants, most likely slaves excluded.

Town	Number of Inhabitants	References
Puteoli	<40,000	Camodeca (2018)
Nola	<100 *	Estimated by authors considering information in Beloch (1890)
Atella	21,800	
Neapolis	30,000–50,000	Beloch (1890)
Cumae	N.d.	
Acerra	N.d.	
Baiae	N.d.	
Misenum	10,000	Vegezio (4th–5th century)
Herculaneum	4000	Camodeca (2018)
Oplontis	N.d.	
Pompeii	20,000	Beloch (1890)

Table 9.3. Roman cities in Campania Felix region and related numbers of inhabitants during the Augustan age (from Esposito et al., 2025b). *The extension of the city was inferred by Libertini et al. (2014).

9.5. Historical evolution of the water supply of Benevento city

The strategic position of Benevento city, especially during the Roman period, the favorable climate conditions, and the geomorphological features of the plain have allowed different civilizations to develop in this area.

9.5.1. Historical framework

Some archaeological remains, dated Neolithic (8th Century BD), were found in the city center (Vari Square), testifying to the first human settlement in the area ([Amato et al., 2017](#)).

The city's history is intimately linked to Samnites, which built the first organized and defendable settlement in the area (4th Century BC; [Torelli, 2002](#)). In 268 BC, after the Roman and Samne wars, Benevento became a Roman colony located at the crossroads of Appia and Minucia Roads (the future Appia Traiana Road; [Iasiello, 2007](#)). During Roman times, the city reached its maximum growth ([Rotili, 1958](#)), as testified by several remains and hundreds of epigraphic inscriptions ([Caruso, 2013](#)). The prosperity of the city was guaranteed by its position located near the Appia Road and near the confluence between the Sabato and Calore Rivers. This last condition provided the water supplies needed for agricultural and drinking purposes.

After the fall of the Roman Empire (476 AD) and the Gothic Wars (490 AD), Lombards, led by King Zottone, conquered the city (570 AD), making it the capital of their duchy.

In 1077 AD, after several civil wars between Salerno and Benevento (849 AD), and after Saracens and Normans invasions (about 1077 AD; [Zigarelli, 1979](#)), with the death of the last Lombard's king, Landolfo IV, the papal domination of the city started ([Bogia, 1763](#)). De facto, Benevento city became an enclave of the Papal State inside the Kingdom of Two Sicilies ([Zigarelli, 1979](#)). During this long period, the city has undergone several alternating facts ([De Antonellis, 2008](#)), becoming a possession of the Swabian House. Fief of the Papal State, the city was governed by a rector first and a governor, then. In 1688, there was a period of equilibrium and serenity due to the Cardinal Vincenzo Maria Orsini government, next Pope Benedetto XIII. He really loved the city and, especially after the 1688 and 1702 earthquakes, funded several public and reconstruction works. This domination lasted until 1860, in consequence of the Italian Independence War.

After the occupation by Napoleon's soldiers (in 1806), the domination of the city came back to the Papal State (in 1815) and ended with the unification of Italy in 1861. Thus, the papal period of the city lasting for about eight centuries.

Therefore, Roman, Lombard, and Papal times represent the three main historical periods of expansion and retirement of city walls that affected the urbanistic framework of the city. From the primitive Roman nucleus, constituted by a *castrum romano* and a part outside the city walls (Borgia, 1763-1769; Mazarini, 1823; Rende, 2004), the city expanded during the Lombard period. During the 9th and 10th Centuries city's walls expanded following the left sides of Calore River; the expansion then reached the right side of Sabato River. Still today, this part represents the shape of the city. During Papal Times, no expansion and/or modifications of the city's urbanistic framework occurred, but several churches and historical monuments were built (De Lucia, 1930; Zazo, 1980). Finally, after World War II and the destruction of a great part of the city, there was an uncontrolled expansion of the city until the 1970s. these historical phases have caused a complex evolution of aqueduct systems that currently supplies the city. This complexity results in difficulties in supplying and managing water resources.

9.5.2. Roman Times

During Roman times, the city water supply was granted mainly by Sannitico Aqueduct (Esposito et al., 2024). This framework changed after the falling of the Roman Empire with the beginning of the Lombard domination of the city.

The analysis carried out on Urciuoli karst spring, highlighted that this latter was probably the largest and best-quality water supply of the city since today. It is particularly interesting to note that the amount of karst groundwater feeding Benevento during Roman Times was probably higher than today (0.3 m³/s).

This suggests that during the Roman Times the maximum number of inhabitants (Tab. 9.4) could be compared with the current or more, according to extraordinary public infrastructures left by Roman as the amphitheater (Galasso, 1999), the theater (Meomartini, 1889), the thermal sites already described and so on.

9.5.3. Lombard Times

During the 6th Century, Lombards conquered Benevento city and primarily occupied the highest part of the town ([Fragnito and Grella, 2023](#)). Consequently, strategic human settlements near Sabato River were abandoned, and the area was exploited for agricultural (farming, grazing) and productive purposes ([Tomay, 2009](#)).



Figure 9.15. (a) Lombard wells located in Santa Sofia’s church cloister and (b) in headquarters of Benevento Longobarda Association; (c) Public well supplying Benevento city during Papal Times located in the actual Mercato Plaza; (d) Fountain in Orsini square fed (Papal Times) by the Orsinian Aqueduct (from [Esposito et al., 2024](#)).

The Roman aqueduct still guaranteed water supply and fed the thermal facilities located in the city center. During barbarian invasions, the Roman aqueduct was wholly destroyed; then in the 9th Century, King Radelchi funded its reconstruction ([De Feo et al., 2009](#)). Water coming from the aqueduct was still employed to feed the thermal facilities (Fig. 9.3c) and was integrated by several sources, including groundwater from wells drilled in the plain (having depths ranging from 8 to 12 meters), a few cisterns catching rainfall water, Calore River, and some minor spring located near the city (among them there was Fontana Fabbricata spring; [De Lucia, 1930](#);

[Zazo, 1980](#)). Following the destruction of the Roman Aqueduct, the city's water supplies were assured only by these latter sources. Two examples are represented by the remains of three wells belonging to this period; the first was realized entirely into a Roman capital and located in the Cloister of Santa Sofia Church (12th Century; Fig. 9.15a); the other two wells, realized with some Roman rests and reached a depth of several meters, were used for water supply of a ceramic factory (Fig. 9.3c). These latter are still present in Triggio District addressed by the headquarter of the Cultural Association Benevento Longobarda (Fig. 9.15b).

After the destruction of the Roman aqueduct, during the Lombards (partially) and Papal periods, the city was supplied by poor-quality water from several wells and other sources located inside and close to the city bulk. In any case, these sources were inadequate to satisfy the water demand of the population. Indeed, during the 16th Century, citizens of Benevento protested against the Spanish viceroyalty about the tapping project of Serino springs for the supply of the Neapolitan area because these springs fed the Sabato River and their possible exploitation led to a decrease of the river flow ([Zazo, 1980](#)). It must be stressed that we did not find any documents about an agreement between Benevento enclave and the Kingdom of Two Sicilies on the city's water supply.

9.5.4. Papal Times and Unification of Italy

After the Middle Ages, Benevento City underwent further phases of rebuilding and reshaping, especially after destructive earthquakes and floods.

Considering the condition of geographical and geopolitical insulation due to the enclave status, it can be reasonably hypothesized that the main water supplies of Benevento were represented only by sources that fell inside the city territory or outside and near the city walls ([Zigarelli, 1979](#)).

Until the 16th Century, there were five public wells ([De Lucia, 1930](#)), known as Porta Rufina well (near the public marketplace, now Mercato Square; Fig. 9.15c), Pietà well (in front of the chapel of the same name), San Giovanni fuori Port'Aurea well (in front of Commenda di Malta church), Calore well (near the Sant'Onofrio's Church, break down in 1927) and Sèpare or Sepete well (near the Orphanage of San Filippo Neri). Furthermore, some private wells provided water to the population ([Bencardino, 1991](#)), while part of the productive activities (such as mills, factories, ecc.) employed the waters of Sabato and Calore Rivers ([Isernia, 1895](#); [Bencardino, 1991](#); [Del Prete, 2009](#)). Some centuries later, in the 20th Century, mills were

replaced by the Santa Barbara hydroelectric power plant that exploited the Sabato River flow energy; the plant was then to acquire by the Rummo factory and later dismissed ([Del Prete, 2009](#)).

In 1598, Architect Valente de Valenti drafted a project to uplift the Sabato River's water flow for local supplies. In 1599, however, this project was set aside in favor of another project realized by Engineer Carlo Sorrentino, which involved the tapping of the Monte della Guardia springs, located in the hilly zone, 1 km south of the city.

During the 18th Century, after the 1702 earthquake, cardinal Vincenzo Maria Orsini, future pope Benedetto XIII, funded the design and construction of the new aqueduct of Benevento, known as Orsinian Aqueduct ([Gambardella, 1979](#); [Pezone, 2008](#)). In 1705, Carlo Buratti resumed the project about tapping Monte della Guardia springs by an underground tunnel.

In addition, other primary water sources, already found by Engineer Sorrentino a century later, were represented by some little springs located in the low permeability deposits, which are all extinct except three. These latter are Fontana Fabbriata, Fontana del Cantaro, and Fontana Sorici springs; probably, the first two, having a discharge lower than 1 l/s, are those actually located in Torrecuso and Pietrelcina municipalities, respectively ([Esposito et al., 2005b](#)).

In 1711, the aqueduct building ended at the first public fountain, located in front of Cappuccini Convent in S. Felice locality, was inaugurated ([Pezone, 2008](#)). The other two fountains were inaugurated in 1718 (Fig. 9.3c); the first fountain was located inside the city walls, near Santa Sofia's Church ([Pezone, 2008](#)), while the second was located in Orsini Plaza ([Zazo, 1980](#)), near San Bartolomeo's Church ([De Lucia, 1930](#); Fig. 9.15d).

In 1719, with the realization of the fourth fountain in Fragola District, the Orsinian Aqueduct fed the lower part of the city (S. Domenico, S. Vittorino, Carmelitani, S. Antonio, Badia di S. Sofia, Collegio dei Gesuiti, Vescovato and Palazzo Apostolico districts) and, consequently, the whole city had a water supply ([Zazo, 1980](#)). In 1740, the aqueduct was partially dismissed because of the maintenance costs. In subsequent years, new water sources to the aqueduct systems were added; however, they could not supply the growing water demand of the city ([Zazo, 1980](#); [Del Prete, 2009](#)). Several years later the aqueduct was finally completely dismissed.

Moreover, to supplement the Orsinian aqueduct in the city's water supplies, another water source was found: a tunnel, realized in clay materials, that picked up the water flow of Torrente San Nicola was realized. This hydraulic infrastructure was still functioning until the early 20th Century when it was dismissed in favor of new supplies from Cautano Aqueduct.

Following the unification of Italy, the city of Benevento was involved in the local context, ending his isolation. Until the fascist dictatorship, the city of Benevento underwent a series of urbanistic interventions, among them there was the recovery of the town's aqueduct systems (Bencardino, 1991).

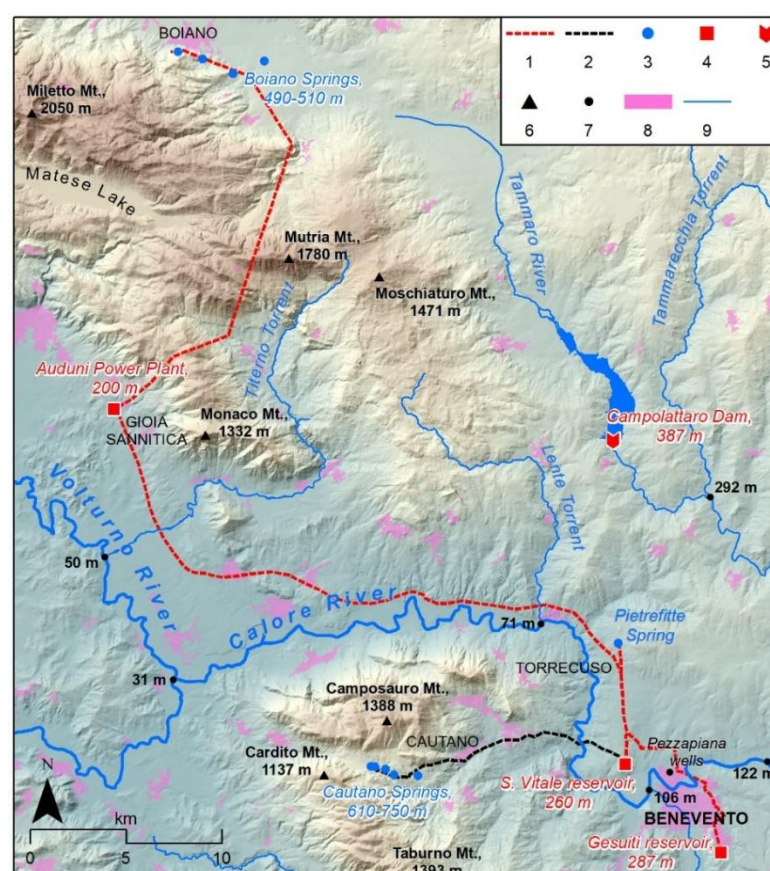


Figure 9.16. Map showing the path of the XX Century (Cautano Aqueduct) and present aqueduct (Biferno Aqueduct). Legend: 1) Biferno Aqueduct; 2) Cautano Aqueduct; 3) Main springs feeding aqueduct systems; 4) Main aqueduct facilities; 5) Dam; 6) Mountain peak; 7) Elevation points; 8) Towns; 9) River network (from Esposito et al., 2024).

During 1930s the Orsinian Aqueduct was renovated and re-used with the tapping of some new springs (Zazo, 1980), including the Sorienza, Spezzacarafa, Mensareia, Abazia, Sambuco, and Gamberi springs (Cautano springs in Fig. 9.16), which also provided the water supply to several small neighboring towns (Civita et al., 1970b; Civita et al., 1971).

Historical period	Number of inhabitants (maximum)	Water source	Main distribution system	Estimated water quality at the source H, high M, medium L, low P, poor	Minimum estimated water amount (dry period)
Roman Times (I Century A.D. – V A.D.)	60,000 ¹	Karst springs, Serino (Picentini Mts.)	Sannitico Aqueduct	H	Up to 500 L/s ⁶
Longboard Times (VI-XI Century A.D.)	10,000	Karst springs, Serino (Picentini Mts.)	Sannitico Aqueduct, until VIII Century	H	?
		Alluvial aquifer, Benevento	local wells and cisterns	L	-
		Local springs, Monteguardia- Benevento	Orsinian Aqueduct	M	0 l/s
Papal Times (XI-XIX Century A.D.)	14,000 ²	Alluvial aquifer, Benevento	local wells	L	-
		Water river, Benevento	hydraulic derivation (channels)	P	-
Modern age (early XX Century A.D.)	40,000 ³	Karst springs, Cautano (Camposauo Mt.)	Cautano Aqueduct	H	50 L/s ⁷
		Karst springs, Boiano (Matese Mt.)	Biferno Aqueduct	H	178 L/s ⁸
Modern age (from the second half of XX Century to nowadays)	60,000 ⁴	Local springs, Pietrefitte- Torrecuso	local aqueduct	M	3.2 L/s ⁸
		Alluvial aquifer, Benevento	local wells, Pezzapiana locality	L	120 L/s ⁸
Near future	50,000 ⁵	Dam water, Campolattaro	Aqueduct under construction	L	362 L/s ⁹

Table 9.4. Main Historical periods, number of inhabitants and water supplies of Benevento city. References: ¹Collarile (2023); ²Galanti (1789); ³ISTAT (1960); ⁴ISTAT (2023);

⁵Inferred by the Authors; ⁶Mean discharge of Urciuoli spring is between 1200 and 1600 L/s from Fiorillo et al. (2007); ⁷Data from Civita et al. (1971); ⁸Data provided by GESESA Aqueduct Company; ⁹Data from Technical Report of the Project of the Potabilization of Campolattaro Dam.

They are located in Prata Valley (Fig. 9.16), between Taburno and Camposauro reliefs, and have a discharge ranging from 50 to 80 l/s. the aqueduct network followed the path of the current Vitulanese road and finally joined the Orsinian aqueduct. This aqueduct system was still functioning at the beginning of the 1980s, when it was definitively dismissed. Successively, new and modern aqueduct system were built.

9.6. Nowadays water supply

The political instability that characterized Italy until its unification in 1861 did not provide the conditions for planning the building of new and long aqueduct systems. Even in Rome, the city's water supply system from Acqua Marcia springs was restored only after the unification of Italy.

In Campania region, in 1888 the Serino Aqueduct was built, which conveyed water from Serino springs toward the city, as in Roman times. Other main and strategic aqueducts systems were designed and built from the beginning of twentieth century: Pugliese Aqueduct (1910s), Alto Calore Aqueduct (1930s), Campano Aqueduct (1950s), and so on. In particular, Pugliese Aqueduct was built to bring water from the Caposele karst spring first and then from Cassano Irpino springs, to Apulia solving one of the chronic problems of this region and favoring its economic development.

9.6.1. Serino Aqueduct

Following several attempts in the past centuries and different design proposals ([De Biase, 2006](#)), during the second half of the 19th Century, a project to catch the water discharged from Serino spring group and conveying them to Naples was drawn. The first arrival of Urciuoli spring water in Naples was in 1885 and, later in 1937, were added also water collected from Acquaro-Pelosi springs.

In 1881, works for the building of the tapping structure of Urciuoli spring (Fig. 9.17), located between Cesinali and Santo Stefano del Sole municipalities, started ([De Biase, 2006](#)). Following a detailed geological study, the groundwater feeding springs were isolated waterproofing the riverbed of the streams crossing the spring discharge area. Later, three underground drainage tunnels (North, West and Main channels) were drilled in order to collect, through several opening in coating, the spring waters ([Miccio and Potenza, 1994](#)). The depth of each tunnel varies depending on that of the water table and their length is equal to 270, 155

and 90 meters. All the tunnels convey water in a three-floor building, two of them located underground.

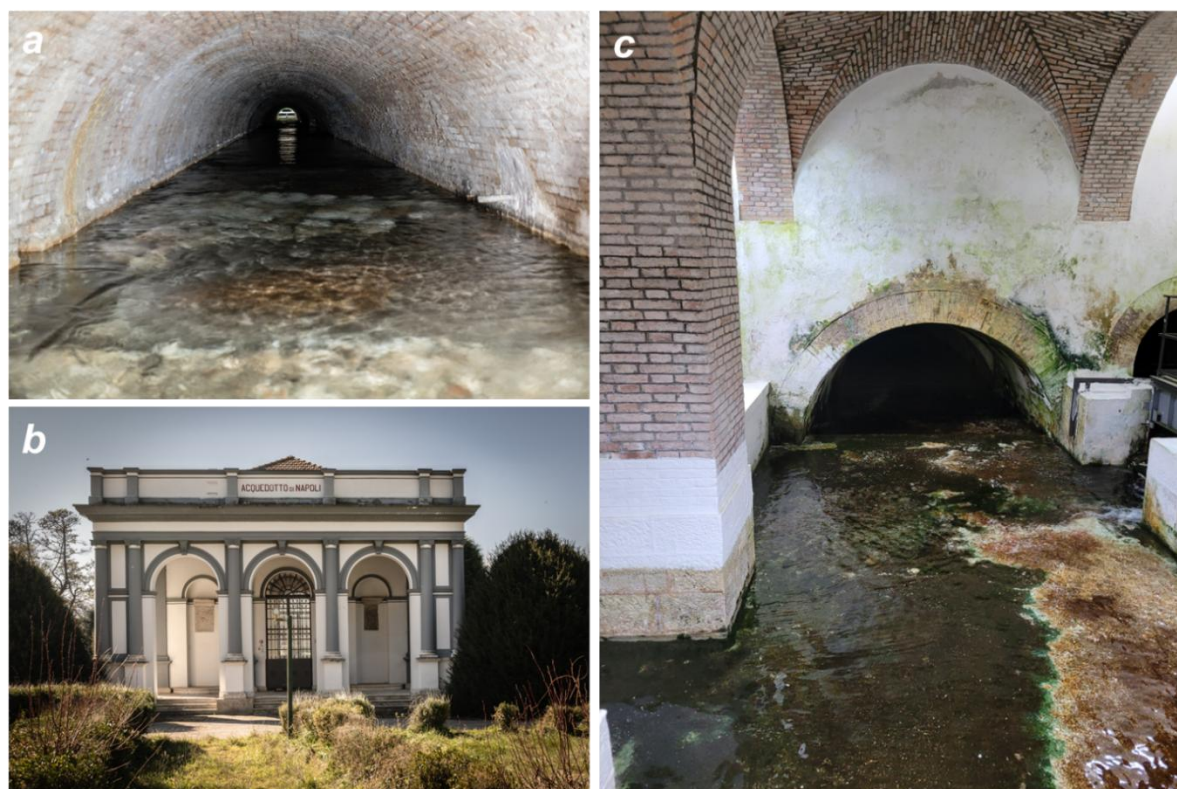


Figure 9.17. Urciuoli spring tapping structure (a) internal view of the drainage tunnel and external (b) and internal (c) view of the reservoir located in the spring area (photo by Libera Esposito and Giovanni Minervini).

In 1934, the tapping structure of Acquaro-Pelosi springs (Fig. 9.18), located in Santa Lucia municipality, started. These springs are located 3 km uphill of Urciuoli springs, in a flat area along the Sabato River. Two drainage tunnel, 400 m long and 4 to 7 m depth, were excavated into alluvial deposits (Fiorillo et al., 2018). They convey water in a collecting chamber that, in turn, through an underground tunnel transfers water to the reservoir located in Urciuoli spring area.

Both the spring areas, are limited by a protection zone (Esposito, 2001). In particular, in Acquaro-Pelosi spring area three wells and seven piezometers were drilled and, actually, are used for the water table monitoring in the area (Fig. 9.18).

In the lower floor of the reservoir located in Urciuoli spring area the free conduit started. The path of the aqueduct, realized in 1885 and functioning still today, is the same of the Bateman project drawn in 1870s. The channel follows the left side of Sabato River starting from Urciuoli

spring and crossing Cesinali, Atripalda (first jump of 6.25 m), Avellino, Montefredane, and Prata municipalities reaching Altavilla Irpina (Fig. 9.19).

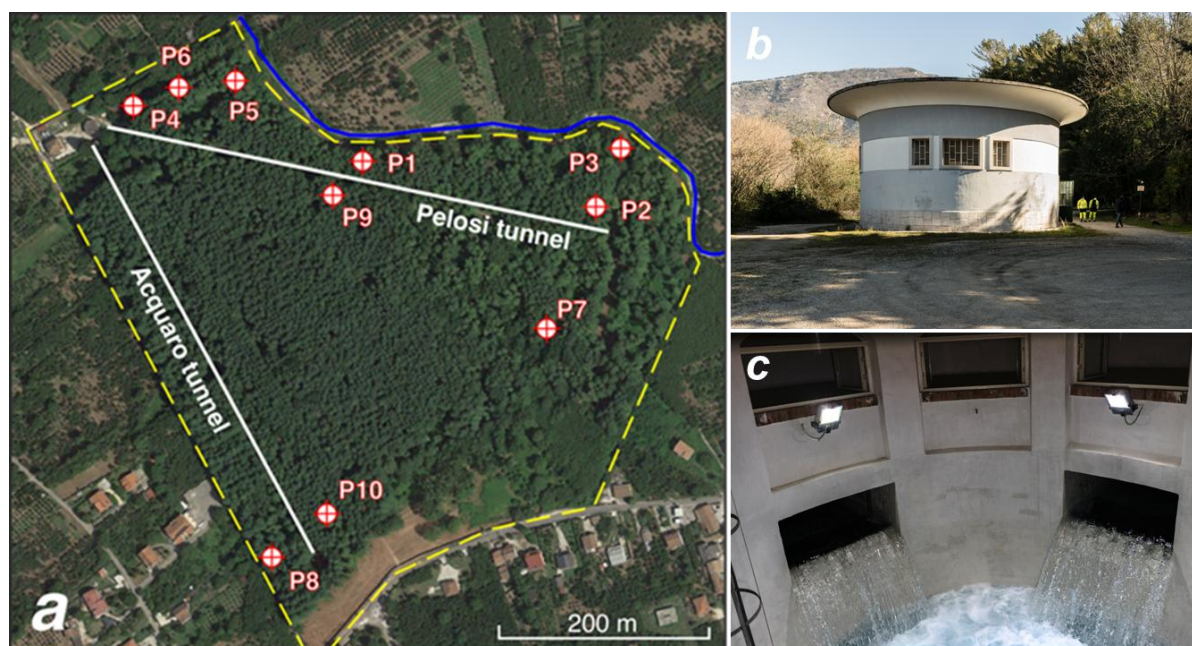


Figure 9.18. Acquaro-Pelosi spring area. (a) Location of drainage tunnels and wells (from Fiorillo et al., 2018) and external (b) and internal (c) view of the tapping structure (photo by Libera Esposito and Giovanni Minervini).

It leaves Sabato Valley through a tunnel arriving in Pannarano municipality and, following an alternating superficial and underground path, arrives in San Martino Valle Caudina municipality. Passing on the left sides of Cervinara and Arpaia city centers, after a second jump (41.79 m), the conduit flanks the reliefs bordering Forchia, Arienzo, and San Felice municipalities reaching, in end the reservoir located on Cannello hill.

From Cannello the great syphon starts and, with a straight path toward Capodichino district, crosses Acerra, Afragola, and Casoria municipalities reaching Capodimonte and Scudillo reservoirs (Miccio and Potenza, 1994). From these reservoirs, the water is conveyed in the aqueduct network of the city for satisfy the water demand.

In 2015, the works of a new conduit, called *Grande Opera Idraulica*, have been concluded. A new pressure conduit, with a 2-meter diameter, roughly following the path of the original channel, was realized. Also, for this conduit, the ending point is represented by Cannello hill, at a lowest elevation respect to the original channel, where it links with Scudillo and Capodimonte reservoirs.



Figure 9.19. Map showing the path of the Ancient Roman aqueducts and of Serino Aqueduct.

9.6.2. Benevento water supply

Nowadays the city of Benevento has a complex aqueduct scheme, and the water supply involves a city division into three different areas.

The main water source is represented by water coming from Campano Aqueduct (Fig. 9.16). in particular, the discharge of Biferno karst springs is conveyed through a tunnel crossing the eastern sector of Matese Mountains toward the Gioia Sannitica hydraulic divider, located in Auduni District (EIC, 2021; Leone et al., 2022).

Then, karst groundwater is transported through a conduit crossing the Volturno and Calore Valleys and reaches the highest zones of Benevento city (Capodimonte and Cancellaria districts, city center, Avellino Street, ecc.). The overall discharge is $0.2 \text{ m}^3/\text{s}$. The lowest zone of the town, as Triggio, Ferrovia, and Libertà districts, are fed by groundwater pumped by the two wells located in the Pezzapiana district alluvial aquifer, a part of the wider Benevento alluvial plain aquifer (Figs. 1.24 and 9.19). The maximum pumping discharge is about $0.12 \text{ m}^3/\text{s}$. The MODFLOW modeling (Chapter 3) highlighted the hydraulic connection between the Calore River and alluvial aquifer in this area. The cross section (Fig. 9.20) shows the groundwater flow in the Pezzapiana district with the localization of drinking wells and the monitoring piezometer, illustrating the direct relationship between pumping wells and river-aquifer transfers.

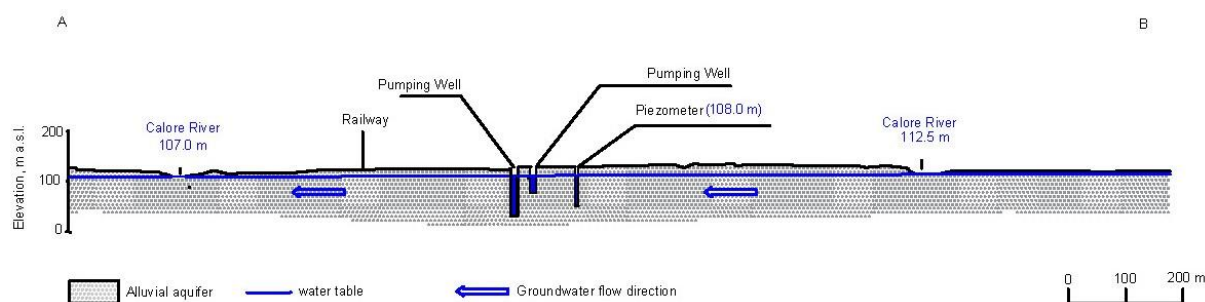


Figure 9.20. Hydrogeological cross-section of Pezzapiana industrial area of Benevento, with the localization of wells and monitoring piezometer (water level refer to February 2023; from [Esposito et al., 2024](#)).

Future scenarios

The water supply in Benevento city is going to change entirely again in the future when the infrastructural works (purifier and hydraulic distribution works) of the Campolattaro dam (Fig. 9.21) are completed, but not still beginning.



Figure 9.21. Campolattaro dam reservoir (photo by Michele Ginolfi).

The Campolattaro dam is an earth dam located in a middle-upper part of the Tammaro River, built in the first half of 90s, with a reservoir of $156 \times 10^6 \text{ m}^3$ and a catchment area of 253 km^2 ([Magliulo et al., 2021](#)). When the aqueduct system will be completed, Benevento city will be

supplied by water flowing in Tammaro River. The advantage of this supply lies in the definitive independence on extra-regional water, as the Biferno springs are disputed by both Naples urban area and Molise region, and should guarantee more stable water supplies during droughts. However, the quality of the dam water reservoir cannot be compared with that of karst springs (Tab. 9.4). In this term, the advantage of this further changing of water supplies of Benevento is controversial ([Esposito et al., 2024](#)).

Conclusions

This work of thesis deals with the hydrogeological framework and the related issues regarding the internal areas of Campania Region (southern Italy). These areas are strategic in the framework of the Southern Italy water supply. Indeed, several karst springs (e.g., Serino, Cassano Irpino and Caposele) represent the principal water supply of the main aqueduct systems in this part of Italy. For these reasons the main types of aquifers having a key role in the historical and current water supply of the major part of the cities falling in this area have been studied.

The Benevento alluvial plain aquifer is exploited for both drinking and industrial purposes and represents a primary water source for Benevento city. The climate and hydrogeological features of this aquifer are similar to those of other alluvial aquifer widespread in Internal areas of Campania region, and generally in southern Apennine chains, making it a case study. The continuous monitoring data and the following numerical modeling of the groundwater flow path, carried out using a combination of time series analysis and numerical modeling (MODFLOW code and MODPATH software) methods, highlight the relationships between river and alluvial aquifer. A direct aquifer-river interaction was found, with the river replenishing continuously the alluvial aquifer, allowing for its continuous exploitation. This groundwater dynamic rises several considerations and warnings about the water resource exploitation and protection. Indeed, independently from the extension of the well capture zone, the river flow may transport contaminants coming from a remote region of the aquifer. In such context, the protection zone of the wells cannot be merely dependent on the capture zone, and the role of river-aquifer interactions must be considered in the scope of groundwater resource protection. Furthermore, the quality of the pumped groundwater strongly depends on the filtering capacity of the alluvial deposits interposed between river and pumping wells. The methods used in this thesis represent an improvement and optimization of the information achievable from groundwater monitoring in the framework of dynamic aquifer conditions (intermittent pumping) and are a valuable approach for the estimation of the hydraulic features of an alluvial aquifer and its interaction with river. A future improving of this topic would deal with an implementation of a more detailed sensitivity analysis on parameters constituting MODFLOW model (e.g. hydraulic conductivity distribution and riverbed conductance).

In southern Apennines, small-to large scale dolines and endorheic areas characterize the summit sectors of the principal karst massifs and reliefs. A new and innovative procedure, using the

sink-filling and the outermost closed contour methods, was used to map the superficial karst features of Alburni karst massif and Morcone karst reliefs. In the case of Alburni karst massif, the applied mapping method allowed the delineation of hundreds of adjacent endorheic areas forming a mosaic across the karst plateau featuring this massif. A large number of concentrated infiltration points drains the karst plateau allowing the quick transfer of meteoric water to the basal water table and, then, to the spring outlets. Quite the opposite, for Morcone karst reliefs, less dolines and endorheic areas were mapped. However, through the performing of tracer tests, a strict relationship between water infiltrates in ponors and the main springs draining the aquifer was found. The water infiltrating in ponors directly feeds the underground water tables system and, thus, the main springs draining the aquifer used for local water supply. For both karst aquifer, a map concerning an overview of the main karst features related to surface water processes and groundwater circulation was made. These maps are very useful in many practical applications, including delineating protection zones for well and springs, making artificial tracer tests, and water balance, but also in environmental safeguard, and ecological development. In particular, these maps are useful for the vulnerability assessment since ponors and dolines represent a major pathway for contaminants that bypass unsaturated zone filter and directly reach the karst network. Therefore, concentrated recharge through dolines plays a decisive role in assessing the intrinsic vulnerability of a karst aquifer, as contaminants can easily reach groundwater and be rapidly transported in karst conduits over large distances. Also, the role of a given doline's catchment in aquifer vulnerability will depend on the degree to which the protective cover is bypassed. In reality, doline discharge is also connected to the rainfall (or snowmelt) event features, since runoff intensity depends on the rainfall intensity. Thus, maps coupling dolines and endorheic areas, are particularly useful especially for the recharge evaluation since endorheic areas represents zones of the karst catchment from which effective precipitation cannot escape by runoff and infiltrates as a whole.

The continuous monitoring system installed in a key point of a karst polje actively involved in aquifer recharge processes, coupled with satellite images inspection, allowed the comprehension of karst massif recharge processes. In particular, the monitoring activities allowed to define the contribution of Dragone Plain polje in recharge-discharge processes of Terminio-Tuoro karst massif that feeds several basal springs. Satellite images allowed to reconstruct the formation and the expansion of the lake that occur only in winter and early spring precipitation periods, controlled by antecedent soil moisture conditions. The absence of temporary lake during the entire winter-spring season appears a proxy of a long meteorological drought and the consequent groundwater drought. The continuous monitoring of groundwater

level allowed to observe the recharge episodes in karst aquifer saturated zone and the relationships between precipitation and temporary Dragone karst lake. The karst lake, and snow mantle as well, represents temporary water reservoir which delay aquifer recharge. Concentrated drainage by the Dragone Mouth ponor alone provide a local recharge of hundreds of liters per second, and it can likely exceed one thousand. While local, this recharge has an impact on the discharge of Cassano springs. The impact of climate change, in terms of global warming and rainfall distribution during the hydrological years, acts on the frequency of the karst lake formation and its magnitude. This monitoring activity, and the following study, has a practical relevance regarding the management and protection of the quality of groundwater resources, considering the effects by the superficial waters from Volturara Village conveyed by the surface drainage system inside the ponor and the impacts from agricultural and grazing activities.

The recharge evaluation, therefore, is a crucial topic for the sustainable groundwater management in karst aquifer also facing climate changes and overexploitation problems. Taking in account these tasks, the recharge evaluation of Morcone karst reliefs was carried out using the Modified APLIS method and the Daily Recharge Scale Model, combined with a new methodology firstly developed in this thesis. The recharge evaluation highlights the contribution provided both by dolines and endorheic areas in groundwater recharge. Also, the different responses of the aquifer to dry, average, and wet climatic conditions have been analyzed showing the major contribution provided by concentrated recharge specially in wet climatic conditions. Furthermore, recharge processes have been detailed described allowing the split of recharge in effective groundwater recharge, feeding water table, and the throughflow water, feeding rivers, gullies and minor springs, when a specific threshold is overpassed. In a climate change framework, this is a crucial topic since, throughflow and recharge depends from the high-intensity rainfall also. The results obtained by the Daily Recharge Scale Method allowed to validate that obtained by Modified APLIS method. However, results from the new methodologies overestimates the recharge values, indicating that further model calibrations are needed for its improvement. In every case, the lacking of calibration of results obtained by methodologies with spring outputs, lead to the necessity of a more continuous and frequent monitoring of spring discharges with the aim to detail the groundwater circulation and transfers among neighboring aquifers. Using a lumped model approach, the so-called KarstMod software, the recharge-discharge processes of Caposele spring, draining Cervialto karst massif have been analyzed. Extensive processing of precipitation and temperature data was carried out aimed to (i) imputing missing data in time series, (ii) estimate the average meteorological signal

across the spring catchment, and (iii) simulate snowfall, snow-pack accumulation-melt processes, and potential evapotranspiration. In particular, the snowpack accumulation-melt process has non negligible impact on the spring flow, as it affects the amount of free water available for runoff and infiltration, delaying aquifer recharge. For Cervialto karst aquifer, no direct influence of daily rainfall is observable on the spring flow, whose variation is smooth during the hydrological year. The model structure and functioning created can predict the buffered response of the karst spring to rainfall and the different hydrological behavior during wet and dry years. However, some hydrological features and processes (e.g., concentrated recharge, unsaturated zone percolation) were not specifically modeled. The calibrated model has shown high predictive ability, allowing to establish the recharge-discharge relationships for the investigated karst catchment. Therefore, it would represent a valuable tool in investigate the effects of climate change on karst groundwater resources and programming the future management of Caposele spring.

The analysis of historical documents and related paper, combined with careful field surveys and the hydrogeological framework and considerations about the Serino karst springs and the Benevento alluvial plain allowed to investigate the reasons behind the design and construction of Augustan and Sannitico aqueducts. Also, insights about the historical evolution of Benevento city water supply were made. Based on topographic and geo-hydrological features of urban settlements and population distribution of Campania Felix region, the Acquaro-Pelosi springs as *Caput Aquae* of Aqua Augusta Aqueduct and Urcioli spring for Sannitico Aqueduct were the most suitable choice, compared to all other possible ones. In the case of Acquaro-Pelosi springs, the steady flow regime and the very good hydrochemical properties of the spring water, together with the ground elevation, drove their selection criteria at the expense of others located a small distance away and, in some cases, with a higher spring discharge (e.g., Sarno springs group). Some historical considerations and specific geo-hydrological features have highlighted how the Aqua Augusta and Sannitico Aqueducts should have many links. Both could be part of a unique and great hydraulic system built in the 1st Century BC to supply residential areas of great importance (cities and patrician villas) or military areas (Miseno Harbor and Benevento). In the stretch where the two aqueducts run parallel to each other (in Sabato River Valley), it is difficult not to hypothesize their connection, as well as because the Urcioli spring has a higher and more stable flow than Acquaro and Pelosi springs and the water demand throughout the coastal area (from Pompeii to Misenum) was greater. Furthermore, Benevento itself appears to have been an important Roman city since the 1st Century BC, and therefore the construction of the two aqueducts was likely actually the project of a single, grandiose hydraulic water supply

system. Chronologically, this wide hydraulic system appears second only to those already supplying Rome since the 3rd Century BC, with the Aqua Marcia Aqueduct, which first tapped a karst spring. After the fall of the Roman Empire, the Augustan aqueduct was abandoned. Only in the late nineteenth Century (more than one thousand years later) the Serino springs were tapped again to feed Naples area with a new aqueduct. This new aqueduct guaranteed again high-quality water and was the first aqueduct of Naples. Successively, other karst springs were systematically tapped to supply the city (Torano, Maretto, Sarno, and Gari springs).

The historical and urbanistic evolution of Benevento showed how the city's water supply has represented a complex and articulated issue. The analysis carried out highlights that Urciuoli karst spring has probably been the largest and best-quality water supply of the city since today. Indeed, during the historical epochs, the quality of the water supply decreased drastically, since the main water supply was represented by river flow water. Only in the 20th Century, the quality increased thanks to karst water supply provided by Cautano springs, firstly, and by Biferno springs, later. However, in the future, due to the project regarding the drinking use of waters stored in Campolattaro dam for the water supply of Benevento, the water quality will experiment a further decrease. Thus, the evolution and the future perspectives on the water supply of Benevento city show the precise requirement for drinking water and the difficulties related to the provision and management of water resources. In a framework of limited water sources, also related to climate change and groundwater pollution, water supply became an essential issue in city life. Therefore, sustainable management of ground and superficial waters is desirable, considering local water sources and applying serious management and protection policies of water sources. These latter should be linked to a sort of "adaption" of human activities in the local environmental setting, minimizing the anthropic impact and protecting the water sources from quantitative and qualitative degradation.

References

Abate F. (1862) – *Studi Sull’acquedotto Claudio e Progetto per Fornire Di Acqua Potabile La Città di Napoli*; Stamperia Dell’iride: Naples, Italy, 1862.

Abbasi Chenari S., Leone G., Ginolfi M., Esposito L., Fiorillo F. (2026) - *Flooding of Dragone Plain Polje and its Impacts on the Karst Groundwater Resource (Terminio-Tuoro Massif, southern Apennines, Italy)*. Submitted to Water.

Adam J.P. (1988) - *L’Arte di Costruire Presso i Romani. Materiali e Tecniche*; Longanesi & C.: Milan, Italy, 1988; ISBN 88, 304-0855-7.

Agosta F., Manniello C., Cavalcante F., Belviso C., and Prosser G. (2021) – *Late Cretaceous transtensional faulting of the Apulian Platform, Italy: Marine and Petroleum Geology*, v. 127, <https://doi.org/10.1016/j.marpetgeo.2020.104889>.

Ahmadi A., Chitsazan M., Mirzaee SY, Nadri A (2023) – *The effects of influence radius and drawdown cone on the areas related to the protection of water wells*. J Hydrol 617. <https://doi.org/10.1016/j.jhydrol.2022.129001>

Albert P.G., Giaccio B., Isaia R., Costa A., Niespolo E.M., Nomade S., Pereira A., Renne P.R., Hinchliffe A., Mark D.F., et al. (2019) – *Evidence for a Large-Magnitude Eruption from Campi Flegrei Caldera (Italy) at 29 Ka*. Geol. Soc. Am. **2019**, 47, 595–599. <https://doi.org/10.1130/G45805.1>

Alem H., Soudejani A.E. & Fallahi M. (2021) – *Estimate the amount of groundwater recharge in hard formations, case study: Marshad, Iran*. Applied Water Science, 11:6. <https://doi.org/10.1007/s13201-020-01317-w>

Allocca V., Celico F., Celico P., De Vita P., Fabbrocino S., Mattia C., Monacelli G., Musilli I., Piscopo V., Scalise A.R., Summa G., Tranfaglia G. (2007) – *Note illustrative della Carta Idrogeologica dell’Italia meridionale*. Istituto Poligrafico e Zecca dello Stato, Roma. ISBN 88-448 0215-5.

Allocca V., Manna F., De Vita P. (2014) – *Estimating annual groundwater recharge coefficient for karst aquifers of the Southern Apennines (Italy)*. Hydrol Earth Syst Sci 18: 803-817.

- Amato V., Ciarcia S., Rossi A., Santoriello A. (2017) – *The urban geoarchaeology of Benevento, Southern Italy: evaluating archaeological potential*. *Geoarchaeology* 33:110–111. <https://doi.org/10.1002/gea.21658>
- Anderson M.P., Woessner W., Hunt R.J. (2015) - *Applied Groundwater Modeling. Simulation of Flow and Advective Transport*. Elsevier. <https://doi.org/10.1016/C2009-0-21563-7>
- Andreo B., Barbera J.A., Mudarra M., Marin A.I., Garcia-Orellana J., Rodellas V. & Perez I. (2018) – *A multi-method approach for groundwater resource assessment in coastal carbonate (karst) aquifers: the case study of Sierra Almijara (southern Spain)*. *Hydrogeol. J.* 26: 41-56. DOI: 10.1007/s10040-017-1652-7.
- Andreo B., Vias J., Duran J.J., Jimenez P., Lopez-Geta J.A., Carrasco F. (2008) – *Methodology for Groundwater Recharge Assessment in Carbonate Aquifers: Application to Pilot Sites in Southern Spain*. *Hydrogeol. J.* **2008**, 16, 911–925.
- Aquino A., Aquino S., Ginolfi M., Trocciola A., Somma R. (2019) - *Analisi idrogeologica ed ambientale della piana endoreica del Dragone (Irpinia) ed il suo impatto sullo sviluppo socio-economico nel Meridione d'Italia*. I rischi catastrofali. Azioni di mitigazione e gestione del rischio. CNR Edizioni.
- Aquino D., Petrella E., Florio M., Celico P., Celico F. (2015) – *Complex hydraulic interactions between compartmentalized carbonate aquifers and heterogeneous siliciclastic successions: A case study in southern Italy*. *Hydrol. Process.* **2015**, 29, 4252–4263.
- Aquino S. and Giulivo I. (2002) – *La piana del Dragone un lembo di territorio da proteggere*. Irpinia Illustrata.
- Aquino S., Allocca V., Esposito L., Celico P. (2006) – *Le Risorse Idriche Della Provincia di Avellino (Appennino Meridionale, Italia)*; Arti Grafiche Cinque: Avellino, Italy, 2006.
- Ascione A., Ciarcia S., Di Donato V., Mazzoli S., Vitale S. (2012) – *The Pliocene–Quaternary wedge-top basins of southern Italy: An expression of propagating lateral slab tear beneath the Apennines*. *Basin Research*, 24, 456–474.3
- Ashby, T. (1991) – *Gli Acquedotti dell'Antica Roma*; Quasar: Rome, Italy, 1991.
- Ayadi Y., Mokadem N., Khelifi F., Khalil R., Dhawadi L. & Hamed Y. (2024) – *Groundwater potential recharge assessment in Southern Mediterranean basin using GIS and remote sensing*

tools: case of Khalled-Teboursouk basin, karst aquifer. Applied Geomatics 16: 227-693.
<https://doi.org/10.1007/s12518-024-00573-8>

Barthel R., Banzhaf S. (2016) – *Groundwater and Surface Water Interaction at the Regional-scale – a review with Focus on Regional Integrated models. Water Resour Manage* 30:1–32.
<https://doi.org/10.1007/s11269-015-1163-z>

Bauer, C. (2015) – *Analysis of Dolines Using Multiple Methods Applied to Airborne Laser Scanning Data. Geomorphology* **2015**, 250, 78–88
<https://doi.org/10.1016/j.geomorph.2015.08.015>

Bedekar Vivek [et al.] (2016) - *MT3D-USGS version 1.0.0: Groundwater Solute Transport Simulator for MODFLOW: U.S. Geological Survey Software Release*, 30 September 2016 [Report]. - Reston, Virginia : [s.n.], 2016.

Bellucci F., Corniello A., De Riso R. (1993) – *Geology and Hydrogeology of the Somma-Vesuvio Volcano (Southern Italy)*. In Proceedings of the Memories of XXIV IAH Congress Hydrogeology of Hard Rocks, Oslo, Norway, 2 July 1993.

Bellucci F., Giulivo I., Pelella L., Santo A. (1991) – *Carsismo Ed Idrogeologia Del Settore Centrale Dei Mt. Alburni (Sa)*. Geol. Tec. **1991**, 3, 5–12.

Bellucci F., Giulivo I., Pelella L., Santo A. (1995) – *Monti Alburni: Ricerche Speleologiche*; De Angelis: Rome, Italy, 1995.

Bellucci, F. (1992) – *Nuove Conoscenze Stratigrafiche Sui Depositi Vulcanici Presenti Nel Sottosuolo Del Settore Meridionale Della Piana Campana*. Ph.D. Thesis, Geophysics and Vulcanology, University of Naples Federico II, Naples, Italy, 1992.

Beloch K.J. (1890) – *Campanien, Geschichte Und Topographie Des Antiken Neapel Und Seiner Umgebung*; Morgenstern: Breslau, Poland, 1890

Bencardino, F. (1991) – *Benevento funzioni urbane e trasformazioni sociali tra XI e XX secolo “Benevento urban functions and transformations societies between the 11th and 20th centuries”*. Edizioni Scientifiche Italiane.

Bernasconi A., Bruni P., Gorla L., Principe C., Sbrana A. (1981) – *Risultati Preliminari Dell’esplorazione Geotermica Profonda Nell’area Vulcanica Del Somma-Vesuvio*. Rend. Della Soc. Geol. Ital. **1981**, 4, 237–240.

Bilge H. (2012) – *Upper Lachlan Groundwater Flow Model*, NSW Office of Water, Sydney

- Bolognini M., Celico P., Tescione M., Aquino S. (1994) – *La Produttività Dei Pozzi in Acquiferi Carbonatici Molto Carsificati: L'esempio Dei Monti Alburni (SA)*. Geol. Romana **1994**, 30, 671–686.
- Bonacci O (1993) – *Karst spring hydrographs as indicators of karst aquifers*. Hydrol Sci J 38:51–62 <https://doi.org/10.1080/02626669309492639>
- Bonacci O. (1987) – *Karst Hydrology with Special References to the Dinaric Karst*; Springer: Berlin/Heidelberg, Germany, 1987.
- Bonacci O. (2001) – *Monthly and annual effective infiltration coefficient in Dinaric karst: example of the Gradole karst spring catchment*. Hydrological Sciences Journal 46(2): 287–300.
- Bonacci O. (2013) - *6.11 Poljes, Ponors and Their Catchments*. In Treatise on Geomorphology; Elsevier: Amsterdam, The Netherlands, 2013; pp. 112–120. ISBN 978-0-08-088522-3.
- Bonacci O., Andrić I. (2015) – *Karst Spring Catchment: An Example from Dinaric Karst*. Environ. Earth Sci. **2015**, 74, 6211–6223. <https://doi.org/10.1007/s12665-015-4644-8>.
- Bonardi G., Ciarcia S., Di Nocera S., Matano F., Sgrosso I., Torre M. (2009) - Carta delle principali unità cinematiche dell'Appennino meridionale. Nota illustrativa. Italian Journal of Geosciences (2009) 128 (1): 47–60.
- Bondesan A., Meneghel M., Sauro U. (1992) – *Morphometric Analysis of Dolines*. Int. J. Speleol. **1992**, 21, 1–55.
- Bono P., Boni C. (1996) – *Water Supply of Rome in Antiquity and Today*. Environ. Geol. **1996**, 27, 126–134.
- Borgia S. (1763) – *Memorie istoriche della pontificia città di Benevento*. Roma “Historical memories of the pontifical city of Benevento”.
- Borgia, S. (1763-1769) – *Memorie istoriche della pontificia città di Benevento dal secolo VIII al secolo XVIII divise in tre parti, raccolte ed illustrate da Stefano Borgia. Referendario dell'una, l'altra Segnatura, governatore della medesima* “Historical memoirs of the pontifical city of Benevento from the 8th century to the 18th century divided into three parts, collected and illustrated by Stefano Borgia. Referendary of one, the other Signature, governor of the same”. Roma, dalle Stamperie del Salomoni.
- Borradaile G. (2003) – *Statistics of Earth Science Data: Their Distribution in Time, Space, and Orientation*; Springer: Berlin/Heidelberg, Germany, 2003; ISBN 978-3-642-07815-6.

- Borriello M.R., D'Ambrosio A. (1979) - *Baiiae-Misenum*. Forum Ital. Reg. I **1979**, XIV, 179.
- Box GE, Jenkins GM, Reinsel GC, Ljung GM (2016) – *Time Series Analysis - Forecasting and Control*. John Wiley & Sons, Hoboken, New Jersey.
- Brancaccio L., Cinque A., Romano P., Roskopf C. (1995) – *L'evoluzione Delle Pianure Costiere Della Campania: Geomorfologia e Neotettonica*. Mem. Soc. Geol. Ital. **1995**, LIII, 313–336.
- Brancaccio L., Civita M., Vallario A. (1973) – *Prime Osservazioni Sui Problemi Idrogeologici Dell'Alburno (Campania)*. Boll. Della Soc. Geol. Dei Nat. Napoli **1973**, 82, 13–35.
- Brunner P, Therrien R, Renard P, Simmons CT, Frassen HJH (2017) – *Advances in understanding river-groundwater interactions*. Rev Geophys **55**:818–854.
<https://doi.org/10.1002/2017RG000556>
- Bundschuh J., César Suárez A.M. (2010) – *Introduction to the Numerical Modeling of Groundwater and Geothermal Systems: Fundamentals of Mass, Energy and Solute Transport in Poroelastic Rocks (1st ed.)*. CRC Press. <https://doi.org/10.1201/b10499>
- Butler Jr J.J., Knobbe S., Reboulet E.C., Whittemore D.O., B.B. Wilson, G.C. Bohling (2021) – *Water well hydrographs: an underutilized resource for characterizing subsurface conditions*. Groundwater, DOI: 10.1111/gwat.13119
- Calcaterra D., De Riso R., Ducci D., Santo A. (1992) – *Aspetti geomeccanici ed idrogeologici nel settore sud-orientale del Monte Terminio (Appennino meridionale)*. Geologica Romana, 30, pagg. 53-66, Roma, 1994.
- Ćalić, J. (2011) – *Karstic Uvala Revisited: Toward a Redefinition of the Term*. Geomorphology **2011**, 134, 32–42.
- Camardo D. (2007) – *Ercolano: La Gestione Delle Acque in Una Città Romana*. Oebalus Studi Sulla Camp. Nell'antichità **2007**, 7, 167–187.
- Camodeca G. (2018) – *Puteoli Romana: Istituzione e Società*; Unior Press: Naples, Italy, 2018.
- Caputo P., Costigliola F. (2016) – *Il “Ritrovamento” Del Punto Di Alimentazione Idrico Di Piscina Mirabilis: Riflessioni Su Approvvigionamenti Idrici Del Porto e Della Città Di Misenum*. Piscina Mirabilis: Storia, Scoperte e Studi. Ric. Stor. Epigr. **2016**, 14, 18.1–18.11.

- Caramanna G., Ciotoli G., Nisio S. (2008) – *A Review of Natural Sinkhole Phenomena in Italian Plain Areas*. Nat. Hazards **2008**, 45, 145–172. <https://doi.org/10.1007/s11069-007-9165-7>
- Caruso P. (2013) – *Antiqua Beneventana. La storia della Città romana attraverso la documentazione epigrafica* “*Antiqua Beneventana. The history of the Roman city through epigraphic documentation*”. Edizioni “La Provincia Sannita”.
- Castracani A.M., Celico P., Di Giulio S., Ghiara M.R., Stanzione D., Valletta M. (1993) – *Idrogeologia e idrogeochimica del settore meridionale dei Monti del Sannio*. Bollettino Servizio Geologico d’Italia, Vol. CXII.
- Catalano R. (2013) – *Acqua e Acquedotti Romani. Fontis Augustei Aqueductus*; Arte Tipografica: Altamura, Italy, 2003; ISBN 88-87375-54-2.
- Celano C. (1962) – *Notizie Del Bello Dell’antico e Del Curioso Della Città di Napoli*; Chiarini: Naples, Italy, 1962.
- Celico N., Celico P., Ghiara M.R., Piscopo V., Stanzione D., Aquino S. (1994) – *Caratteristiche Geochimiche Delle Acque Sotterranee Dell’area Del Somma-Vesuvio (Campania, Italia)*. Geol. Romana **1994b**, 30, 709–724.
- Celico P. (1978) – *Schema idrogeologico dell’Appennino carbonatico centro-meridionale*. Memorie e Note Istituto di Geologia Applicata di Napoli, 14, 1-97.
- Celico P. (1981) – *Prima interpretazione degli effetti del terremoto del 23 novembre 1980 sul regime delle principali sorgenti dell’Irpinia (Campania)*. Rend. Acc. Scienze Fis. E Matem., Napoli, Serie IV, Vol. XLVIII, anno CXX, pagg. 532-563.
- Celico P. (1982) – *Brevi considerazioni sul regime idrologico delle sorgenti che alimentano la città di Napoli*. Notiziario sezionale del Club Alpino Italiano, Anno XXXVI, n. 1, Napoli.
- Celico P. (1983) – *Idrogeologia dei massicci carbonatici, delle piane quaternarie e delle aree vulcaniche dell’Italia centro-meridionale (Marche e Lazio meridionali, Abruzzo, Molise e Campania)*. Quaderni CASMEZ, 4(2), p. 225.
- Celico P., Aliberti F., Biscardi D., De Fusco R., Mazzacca F.R., Paoletti A. (1986) – *Relazioni Tra Idrodinamica Sotterranea e Caratteristiche Fisico-Chimiche Delle Acque Minerali di Castellammare Di Stabia*. In Proceedings of the Atti Congresso Internazionale Igiene Medica Termale, Castellammare di Stabia (Na), Italy, 24 October 1986.

- Celico P., Civita M. (1976) – *Sulla tettonica del massiccio del Cervialto (Campania) e le implicazioni idrogeologiche ad essa connesse* [On the tectonics of the Cervialto Massif (Campania) and the hydrogeological implications connected to it]. Boll Soc Nature 85: 555–580
- Celico P., Conte F., Di Santo A., Luise G., Piscopo V. (1998) - *L'acquifero alluvionale della Piana Di Benevento (Campania): un tipico esempio di serbatoio naturale di compenso a rischio inquinamento*. Quad Geol Appl
- Celico P., De Vita P., Pagano D., Ronca A., Stanzione D., Vallario A. (1987) – *Idrogeologia Ed Idrogeochimica Dei Campi Flegrei: Relazioni Tra Chimismo Delle Acque e Idrodinamica Sotterranea*. In Proceedings of the Atti Convegno Bradisismo e fenomeni connessi, Napoli, Italy, 1987; pp. 33–42, 167–185.
- Celico P., Esposito L., De Gennaro M., Mastrangelo E. (1994b) – *La Falda Ad Oriente Della Città Di Napoli: Idrodinamica e Qualità Delle Acque*. Geol. Romana **1994a**, 30, 653–660.
- Celico P., Magnano F., Monaco L. (1982) – *Prove di colorazione del massiccio carbonatico del Monte Terminio-Monte Tuoro*. Notiziario Club Alpino Italiano. Napoli, Italia, volume 46, pp. 73-79.
- Celico P., Pelella, L., Stanzione D., Aquino S. (1994a) - *Sull'idrogeologia e l'idrogeochimica Dei Monti Alburni*. Geol. Romana **1994**, 30, 687–698.
- Celico P., Russo D. (1981) – *Studi idrogeologici sulla Piana del Dragone (Avellino)*. Estratto dal Bollettino della Società dei Naturalisti in Napoli. Vol. XC.
- Celico P., Stanzione D., Esposito L., Ghiara M.R., Piscopo V., Caliro S., La Gioia P. (1997) – *Caratterizzazione Idrogeologica e Idrogeochimica Dell'area Vesuviana*. Boll. Soc. Geol. Ital. **1997**, 117, 3–20.
- Čeru T., Šegina E., Gosar A. (2017) – *Geomorphological Dating of Pleistocene Conglomerates in Central Slovenia Based on Spatial Analyses of Dolines Using LiDAR and Ground Penetrating Radar*. Remote Sens. **2017**, 9, 1213.
- Chambers J.M., Cleveland W.S., Kleiner B., Tukey P.A. (2018) - *Graphical Methods for Data Analysis*; 1st ed.; Chapman and Hall/CRC, 2018; ISBN 978-1-351-07230-4.
- Chanson H. (2002) - *An Experimental Study of Roman Dropshaft Hydraulics*. J. Hydraul. Res. **2002**, 40, 3–12. <https://doi.org/10.1080/00221680209499868>.

Chiang W.H., Kinzelback W. (1998) – *Processing MODFLOW. A simulation system for modeling groundwater flow and pollution*. Springer, Hamburg, Germany.

Chow V. T. (1959) - *Open-channel Hydraulics*. McGraw-Hill, New York.

Chow V.T., Maidment D.R. Mays L.W. (1988) - *Applied hydrology*: New York, McGraw-Hill, McGraw-Hill series in water resources and environmental engineering, 572 p.

Ciarcia S. and Vitale S. (2024) – *Orogenic evolution of the northern Calabria-southern Apennines system in the framework of the Alpine chains in the central-western Mediterranean area*. The Geological Society of America. <https://doi.org/10.1130/B37474.1>

Ciarcia S., Di Nocera S., Matano F., Torre M. (2003) - *Evoluzione tettono-sedimentaria e paleogeografica dei depocentri “wedge-top” nell’ambito del “foreland basin system” pliocenico dell’Appennino meridionale (settore Irpino-Dauno)*. Bollettino della Società Geologica Italiana, 122, 117–137.

Ciarcia S., Vitale S. (2013) - *Sedimentology, stratigraphy and tectonics of evolving wedge-top depozone: Ariano basin, southern Apennines, Italy*. *Sediment Geol* 290:27–46. <https://doi.org/10.1016/j.sedgeo.2013.02.015>

Civita M (1969) - *Idrogeologia del massiccio del Terminio-Tuoro (Campania)* [Hydrogeology of the Terminio-Tuoro massif (Campania)]. *Mem Note Istituto Geol Appl Univ Napoli* 11:5–102

Civita M., De Maio M. (2001) – *Average groundwater recharge in carbonatic aquifer: a GIS processed numerical model*. 7th Conf. On Limestone Hydrology and Fissured Media, Besançon, 20-23 Sept. 2001, pp. 93-100.

Civita M., De Masi R., de Riso R., Vallario A. (1970b) - *Possibilità di rinvenimento di nuove fonti di approvvigionamento idrico nella media valle dell’Isclero e nella bassa valle del Calore (Campania) “Possibility of finding new sources of water supply in the middle Isclero valley and in the lower Calore valley (Campania)”*. Estratto da *Geologia Tecnica*, rivista bimestrale tecnica e informativa, n. 6.

Civita M., De Riso R., Nicotera, P. (1970a) - *Sulla Struttura Idrogeologica Alimentante Le Sorgenti Del Fiume Sarno e Le Falde Pedemontane Profonde Della Parte Sud-Orientale Della Conca Campana*. In *Proceedings of the Atti II Convegno Internazionale sulle Acque Sotterranee*, Palermo Palermo, Italy, 26–27 October 1970.

- Civita M., de Riso R., Vallario A., De Masi R. (1971) - *Idrogeologia del massiccio del Taburno-Camposauro "Hydrogeology of the Taburno-Camposauro massif"*. Mem. Soc. Geol. It., 10, 65-120.
- Civita M., Medici G.B., de Riso R., Nicotera P., Nota d'Elogio E. (1973) - *Memorie Descrittive Della Carta Idrogeologica Della Campania Nord-Occidentale*. In Proceedings of the Atti II Convegno Internazionale sulle Acque Sotterranee, Palermo, Italy, 25–27 october 1973.
- Collarile, M. (2023) - *Iside signora di Benevento "Isis lady of Benevento"*. Edizioni Iorio.
- Colucci-Pescatori, G. (1991) – *Evidenze Archeologiche in Irpinia*. In La romanisation du Samnium aux II^e et I^{er} Siècles av. J.-C.; Centre Jean Bérard: Naples, Italy, 1991.
- Corniello A., De Riso R., Ducci D. (1990) - *Idrogeologia e Idrochimica Della Piana Campana*. Mem. Soc. Geol. Ital. **1990**, 45, 351–360.
- Cosimi E. (2008) - *Fons Augusteus. Le Mura d'Arce Di Sarno Ed Il Doppio Canale Di Palma Campania*. Gradus **2008**, 3, 23–42.
- Cotecchia V., Salvemini A. (1981) – *Correlazione fra eventi sismici e variazioni di portata alle sorgenti di Caposele e Cassano Irpino, con particolare riferimento al sisma del 23 novembre 1980*. Geol. Appl. e Idrog., 16, Bari.
- Cousquer Y, Pryet A, Flipo N, Delbart C, Dupuy A (2017) - *Estimating River Conductance from Prior Information to Improve Surface-Subsurface Model Calibration*. Groundwater 55(3):408–418. doi: 10.1111/gwat.12492
- Crappier M. (2020) - *The Valens Aqueduct of Constantinople: Hydrology and Hydraulics*. Water Hist. **2020**, 12, 427–448. <https://doi.org/10.1007/s12685-020-00254-4> .
- Cristilli A. (2005) - *L'acquedotto Romano di Pratola Serra (Avellino) "The Roman aqueduct of Pratola Serra (Avellino)"*. Rendiconti dell'Accademia di Archeologia, Lettere e Belle Arti, Vol. LXXXIII, 2004-2005, p. 187
- Custodio E, Llamas MR (2005) - *Idrologia sotterranea*. Dario Flaccovio Editore. Bologna, Italy.
- D'Agostino P., Merone R., Pugliese F. (2022) - *Hypotheses for the Phlegrean Section of the Aqua Augusta Campaniae. Between Multidisciplinary Investigation and Hydraulic Functioning*. In Proceedings of the History of Engineering, Naples, Italy, 16–17 May 2022.

- D'Argenio B., Pescatore T., Scandone P. (1973) - *Schema geologicodell'Appennino meridionale (Campania e Lucania)*. Atti del Conv. Moderne vedute sulla geologia dell'Appennino. Acc. Nazion. Lincei, 182, 49–72.
- D'Arms J. (1970) - *Romans on the Bay of Naples; a Social and Cultural Study of the Villas and Their Owners from 150 B.C. to A.D. 400*; Harvard University Press: Cambridge, UK, 1970.
- Darcy, H. (1856) - *Les Fontaines Publiques de la Ville de Dijon*; Victor Dalmont: Paris, France, 1856.
- De Antonellis, G. (2008) - *Storia di Benevento "History of Benevento"*. Benevento, Realtà Sannita.
- De Biase O. (2006) – *L'acqua del Serino. Sorgenti ed Acquedotti*. La Stampa Editoriale Srl.
- De Carvalho O., Guimares R., Montgomery D., Gillespie A., Trancoso Gomes R., De Souza Martins É., Silva, N. (2013) - *Karst Depression Detection Using ASTER, ALOS/PRISM and SRTM-Derived Digital Elevation Models in the Bambui Group, Brazil*. Remote Sens. **2013**, 6, 330–351.
- De Feo G., Angelakis A.N., Antinou G.P., El-Gohary F., Hau B., Passchier C.W., Zhang X.Y. (2013) - *Historical and Technical Notes on Aqueducts from Prehistoric to Medieval Times*. Water **2013**, 5, 1996–2025. <https://doi.org/10.3390/w5041996>.
- De Feo G., De Gisi S., Malvano C. (2010) - *The Greatest Water Reservoirs in the Ancient Roman World and the "Piscina Mirabilis" Misenum*. Water Sci. Tecnhnology Water Supply **2010**, 10, 350–358.
- De Feo G., Del Prete S., Manco M., Maurano F., Tortora A. (2013b) - *L'acquedotto Romano Ipogeo e La Fontana Helvius a Sant'Egidio Del Monte Albino (Salerno, Campania)*. Opera Ipogea **2013**, 2, 3–12.
- De Feo G., Malvano C., De Gisi S., De Biase O. (2009) - *The ancient aqueduct from Serino to Beneventum, in southern Italy: A Technical and Historical Approach*. Proceedings CD of 2nd IWA International Symposium on Water and Wastewater Technologies in Ancient Technologies, Bari, Italy,
- De Feo G., Napoli R.M.A. (2007) - *Historical Developement of the Augustan Aqueduct in Southern Italy: Twenty Centuries of Works from Serino to Naples*. Water Sci. Technol. Water Supply **2007**, 7, 131–138.

De Lucia S. (1930) - *Fra Vincenzo Maria Orsini e le sue opere sociali "Fra Vincenzo Maria Orsini and his social works"*. Samnium, Anno III, VIII, n. 2-3, 24-44.

De Nicastro G. (1719) - *Memorie istoriche intorno alla corona regale usata dai serenissimi prencipi di Benevento longobarda "Historical memories around the royal crown used by the most serene princes of Lombard Benevento"*, ms. [Benvento 1719], in Scritture di Storia Beneventana, Benevento, Biblioteca arcivescovile F. Pacca, fondo manoscritti, Storia di Benevento, ms. 7.

De Rita D., Giordano G. (1996) - *Volcanological and structural evolution of roccamonfina volcano (southern Italy)*. In W. J. Mc Guire, A. P. Jones, & J. Neuberg (Eds.), *Volcano instability on the earth and other planets*, 110 (pp. 209–224). London: Geological Society.

De Simone D., Ferrari G. (2024) - *Acquedotto Augusteo Della Campania Notizie Preliminari Sul Tratto Fuorigrotta-Coroglio (Napoli)*. J. Fasti Online **2024**. Available online: www.fastionline.org/docs/FOLDER-it-2024-576.pdf (accessed on 08 November 2025).

De Vita P., Allocca V., Celico F., Fabbrocino S., Cesaria M., Monacelli G., Musilli I., Piscopo V., Scalise A.R., Summa G., Tranfaglia G., Celico P. (2018) - *Hydrogeology of continental southern Italy*. Journal of Maps, 14(2), 230–241.

<https://doi.org/10.1080/17445647.2018.1454352>

De Vivo B., Rolandi G., Gans P.B., Calvert A., Bohrsen W.A., Spera F.J., Belkin H.E. (2001) – *New constraints on the pyroclastic eruptive history of the Campanian volcanic Plain (Italy)*. Mineral Petrol, 73, 47-75.

Deino A.L., Orsi G., de Vita S., Piochi M. (2004) - *The Age of Neapolitan Yellow Tuff Caldera-Forming Eruption (Campi Flegrei Caldera—Italy) Assessed by $^{40}\text{Ar}/^{39}\text{Ar}$ Dating Method*. J. Vulcanol. Geotherm. Res. **2004**, 133, 157–160. [https://doi.org/10.1016/S0377-0273\(03\)00396-2](https://doi.org/10.1016/S0377-0273(03)00396-2)

Del Prete R. (2009) - *La città e i suoi fiumi. Il cammino delle acque beneventane nella storia della sua comunità (sec. XVII-XX) "The city and its rivers. The path of the waters Benevento in the history of its community (17th-20th centuries)"*. Edizioni Il Chiostro.

Delibras G., Di Paola G.M., Rosi M., Santacroce R. (1979) - *La Storia Eruttiva Del Complesso Vulcanico Somma-Vesuvio Ricostruita Dalle Successioni Piroclastiche Del Monte Somma*. Rend. Soc. Ital. Mineralogia Petrogr. **1979**, 35, 411–438.

- Deming D. (2020) - *The Aqueducts and Water Supply of Ancient Rome*. Groundwater **2020**, 78, 152–161. <https://doi.org/10.1111/gwat.12958>
- Demordy B.J., van Beek R.P.H., Meeks E., Klein Goldewijk K., Scheidel W., van der Velde Y., Bierkens M.F.P., Wassen M.J., Dekker S.C. A- (2014) - *Virtual Water Network of the Roman World*. Hydrol. Earth Syst. Sci. **2014**, 18, 5025–5040. <https://doi.org/10.5194/hess-18-5025-2014>
- Di Ciacca A, Leterme B, Laloy E, Jacques D, Vanderborght J (2019) - Scale-dependent parameterization of groundwater–surface water T interactions in a regional hydrogeological model. J Hydrol 576:494–507. <https://doi.org/10.1016/j.jhydrol.2019.06.072>
- Di Girolamo P., Morra V., Ortolani F., Pagliuca S. (1988) - *Osservazioni Petrologiche e Geodinamiche Sul Magmatismo « orogenico Transizionale » Della Campania Nell'evoluzione Della Fascia Tirrenica Della Catena Appenninica*. Boll. Della Soc. Geol. Ital. **1988**, 107, 561–578.
- Di Meo N. (1932) – *La storia della bonifica del Dragone*.
- Doctor D.H., Young J.A. (2013) - *An Evaluation of Automated GIS Tools for Delineating Karst Sinkholes and Closed Depressions From 1-Meter Lidar-Derived Digital Elevation Data*. In Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Carlsbad, NM, USA, 6–10 May 2013; pp. 449–458.
- Doherty J., Brebber L., Whyte P. (1994) - *PEST - Model-independent parameter estimation. User's manual*. Watermark Computing. Australia.
- Doherty John (2016) - *Model-Independent Parameter Estimation User Manual: 6th Edition*. [Report]. - Brisbane, Australia : Water Numerical Computing, 2016.
- Domenico P.A., Schwartz F.W. (1997) - *Physical and Chemical Hydrogeology*. Wiley, Singapore
- Doolittle W.E. (2024) - *Roman and Medieval Aqueduct Bridges on the Landscape of Spain: Issues of Construction*. Preprints **2024**, 2024020082. <https://doi.org/10.20944/preprints202402.0082.v1>
- Dubois E., Doummar J., Pistre S., Larocque M. (2020) - *Calibration of a lumped karst system model and application to the Qachqouch karst spring (Lebanon) under climate change*

conditions. Hydrol. Earth Syst. Sci. 24, 4275–4290 (2020). <https://doi.org/10.5194/hess-24-4275-2020>

Ducci D., De Masi G., Delli Priscoli G. (2008) - *Contamination Risk of the Alburni Karst System (Southern Italy)*. Eng. Geol. **2008**, 99, 109–120.

Duncan Jones R. (1994) - *Money and Government in the Roman Empire*; Cambridge University Press: Cambridge, UK, 1994.

Dupuit J. (1863) - *Etudes Theoriques et Pratiques sur le Mouvement des Eaux dans les Canaux Decouverts et a Travers les Terrains Permeables*. Dunod, Paris, France.

Durán JJ, Andreo B, Vías J, López-Geta JA, Carrasco F, Jiménez P (2004) - *Classification of carbonate aquifers in the Betic Cordillera in accordance with recharge rates (in Spanish)*. Bol Geol Miner 115(2):199–210

Duvert C., Jourde H., Raiber M., Cox M.E. (2015) - *Correlation and Spectral Analyses to Assess the Response of a Shallow Aquifer to Low and High Frequency Rainfall Fluctuations*. J. Hydrol. **2015**, 527, 894–907, doi:10.1016/j.jhydrol.2015.05.054.

Ecker A., Tepper Y., Karasik, A. A. (2023) - *Milestone without a Road: A Distance Marker below an Arch of the High Aqueduct to Caesarea*. Atiqot **2023**, 110, 11. <https://doi.org/10.70967/2948-040X.1086>

Elia O. (1938) - *Un Tratto Dell'acquedotto Detto "Claudio" in Territorio Di Sarno*. Camp. Romana **1938**, I, 99–112.

Ente Idrico Campano (2021) - *Relazione Piano d'Ambito Regionale ai sensi dell'art. 149 del D.Lgs. 152/2006 e ss.mm.ii. ed art. 16 della L.R. Campania 15/2015* "Regional Area Plan Report pursuant to art. 149 of Legislative Decree 152/2006 and subsequent amendments. and art. 16 of the L.R. Campania 15/2015". <https://www.enteidricocampano.it/download/relazione-piano-dambito-regionale/>

Entezari M., Karimi H., Heidari H.G. & Aghdam M.J. (2020) – *Estimation of groundwater recharge level in karstic aquifers using modified APLIS model*. Arabian Journal of Geosciences, 13:198. <https://doi.org/10.1007/s12517-020-5173-7>

Eriksson E, Khunakasem V (1969) - *Chloride concentrations in groundwater, recharge rate and rate of deposition of chloride in the Israel coastal plain*. J Hydrol 7:178–197

- Errahmouni A., El Messari J.E.S. & Taher M. (2022) – *Estimation of groundwater recharge using APLIS method – Case study of Bokoya massif (Central Rif, Marocco)*. Ecological Engineering & Environmentale Technology, 23(4), 57-66. <https://doi.org/10.12912/27197050/149956>
- Espinoza K., Marina M., Fortuna J.H. & Altamirano F. (2015) – *Comparison of the APLIS and Modified-APLIS Methods to estimate the recharge in fractured karst aquifer, Amazonas, Peru*. B. Andreo (Eds) Hydrogeological and Environmental Investigations in Karst Systems, Environmental Earth Sciences, 1. DOI: 10.1007/978-3-642-17435-3_10.
- Esposito L. (2001) - *Delimitation “reasoned” of the areas of safeguard of the sources of the Serino (Avellino-Italy)*. Geologia Tecnica e Ambientale, 1/2001. [in Italian]
- Esposito L., Bruno R., De Paola P.A. & Aquino, S. (2005c) - *Hydrogeology and vulnerability of the alluvial aquifer of the Benevento Plain (Campania)*. Geologia Tecnica e Ambientale.
- Esposito L., Bruno R., De Paola P.A., Aquino S. (2005b) - *Hydrogeology and vulnerability of the alluvial aquifer of the Benevento Plain (Campania)*. Geologia Tecnica e Ambientale.
- Esposito L., Celico P., Guadagno F.M., Aquino S., De Paola P. (2005a) – *Idrogeologia del Sannio*. L’Acqua 4/2005.
- Esposito L., Ginolfi M., Leone G., Fiorillo F. (2024). *Hydrogeological and historical aspects of the water supply of Benevento town since the Roman age*. Acque Sotterranee - Italian Journal of Groundwater, 13(3), 145 – 156 <https://doi.org/10.7343/as-2024-774>
- Esposito L., Ginolfi M., Leone G., Fiorillo F. (2025b) - *Geo-Hydrological Characteristics that Contributed to the Choice and Configuration of the Ancient Roman Aqueduct Aqua Augusta from Serino Springs*. Water **2025**, 17, 3342. <https://doi.org/10.3390/w17233342>
- Esposito L., Leone G., Ginolfi M., Chenari S.A., Fiorillo F. (2025a) - *Mapping of Closed Depressions in Karst Terrains: A GIS-Based Delineation of Endorheic Catchments in the Alburni Massif (Southern Apennine, Italy)*. Hydrology **2025a**, 12, 186. <https://doi.org/10.3390/hydrology12070186>
- Fan X., Goeppert N., Goldscheider N. (2023) - *Quantifying the historic and future response of karst spring discharge to climate variability and change at a snow-influenced temperate catchment in central Europe*. Hydrogeol. J. 31, 2213–2229 (2023). <https://doi.org/10.1007/s10040-023-02703-9>

- Field M. (2002) - *Lexicon of Cave and Karst Terminology with Special Reference to Environmental Karst Hydrology*; EPA National Center for Environmental Assessment: Washington, DC, USA, 2002; p. 214.
- Fiengo G. (1990) - *L'acquedotto Di Carmignano e Lo Sviluppo di Napoli in Età Barocca*; Bibl. Dell'Archivio Stor. Ital.; Olschki: Florence, Italy, 1990; Volume 26.
- Fiorelli T. (1926) - *Cenni Sull'andamento Della Falda Acquifera Nel Sottosuolo Della Zona Tra Napoli e Pomigliano d'Arco in Relazione Colla Costituzione Geologica e La Topografia Ed Idrologia Superficiale Del Territorio Medesimo*. Ann. Genio Civ. **1926**, 7, 613–626.
- Fiorillo F (2009) - *Spring hydrographs as indicators of droughts in a karst environment*. J Hydrol 373:290–301. <https://doi.org/10.1016/j.jhydrol.2009.04.034>
- Fiorillo F, Doglioni A. (2010) - *The relation between karst spring discharge and rainfall by the cross-correlation analysis*. Hydrogeology Journal 18: 1881–1895.
- Fiorillo F, Esposito L, Guadagno FM (2007) - *Analyses and forecast of water resources in an ultra-centenarian spring discharge series from Serino (southern Italy)*. J Hydrol 336:125–138.
- Fiorillo F, Pagnozzi M, Ventafridda G (2015b) - *A model to simulate recharge processes of karst massifs*. Hydrol Process 29:2301–2314. <https://doi.org/10.1002/hyp.10353>
- Fiorillo F, Wilson RC. (2004) - *Rainfall induced debris flows in pyroclastic deposits, Campania (southern Italy)*. Engineering Geology 75(3-4): 263–289.
- Fiorillo F., Esposito L., Testa G., Ciarcia S., Pagnozzi M. (2018) - *The Upwelling Water Flux Feeding Springs: Hydrogeological and Hydraulic Features*. Water **2018**, 10, 501.
- Fiorillo F., Leone G., Pagnozzi M., Catani V., Testa G., Esposito L. (2019) - *The Upwelling Groundwater Flow in Karst area of Grassano-Telesse Springs (Southern Italy)*. Water **2019**, 11, 872. <https://doi.org/10.3390/w11050872>
- Fiorillo F., Leone G., Pagnozzi M., Esposito L. (2021) - *Long-Term Trends in Karst Spring Discharge and Relation to Climate Factors and Changes*. Hydrogeol. J. **2021**, 29, 347–377, doi:10.1007/s10040-020-02265-0.
- Fiorillo F., Pagnozzi M., Adesso R., Cafaro S., D'Angeli I.M., Esposito L., Leone G., Liso I.S., Parise M. (2022) - *Uncertainties in Understanding Groundwater Flow and Spring Functioning in Karst*. In Geophysical Monograph Series; Currell, M.J., Katz, B.G., Eds.; Wiley: New York, NY, USA, 2022; pp. 131–143. ISBN 978-1-119-81859-5.

- Fiorillo F., Parise M., Petitta M., Stevanovic Z. (2024) – Italian karst springs in the MIKAS Project. Eurokarst Congress, 11th – 13th June 2024, Rome.
- Fiorillo F., Petitta M., Preziosi E., Rusi S., Esposito L., Tallini M. (2015a) - *Long-term trend and fluctuations of karst spring discharge in a Mediterranean area (central-southern Italy)*. Environ Earth Sciences, 74, 153-172.
- Fiorillo, F.; Pagnozzi, M. (2015) – Recharge Processes of Matese Karst Massif (Southern Italy). *Environ. Earth Sci.* **2015**, 74, 7557–7570, doi:10.1007/s12665-015-4678-y.
- Fleming SW, Lavenue AM, Aly AH, Adams A (2002) - *Practical applications of spectral analysis to hydrologic time series*. Hydrol Process 16:565–574. DOI: 10.1002/hyp.523
- Fleury P., Plagnes V., Bakalowicz M. (2007) - *Modelling of the functioning of karst aquifers with a reservoir model: application to Fontaine de Vaucluse (South of France)*. J. Hydrol. 345 (1), 38e49. <http://dx.doi.org/10.1016/j.jhydrol.2007.07.014>.
- Ford D., Williams P. (2007) - *Karst Hydrogeology and Geomorphology*; JohnWiley & Sons Ltd.: West Sussex, UK, 2007; ISBN 978-1-118-68498-6.
- Fragnito A., Grella V.A. (2023) - *Il Ducato Longobardo di Benevento “The Lombard Duchy of Benevento”*. Dall’Origo Gentis alla Divisio Ducatus. Delta 3 Edizioni.
- Frontinus S.L. (2014) - *De Aquaeductu Urbis Romae*; Createspace Independent Publishing Platform: Scotts Valley, CA, USA, 2014.
- Fronzi D., Cambi C., Fiorucci F.M., Lisio I.S., Manucci A., Mazzocca M., Mirabella F., Parise M., Tazioli A., Valigi D. (2025) - *Updating of traditional groundwater budget and recharge assessment by using APLIS method from the karst Scirca spring (Central Italy)*. In Eurokarst 2024, Advances in Karst Science. DOI: 10.1007/978-3-031-84338-9_4.
- Frumkin A., Zaidner Y., Na’aman I., Tsatskin A., Porat N., Vulfson L. (2015) – *Sagging and collapse sinkholes over hypogenic hydrothermal karst in a carbonate terrain*. Geomorphology, 229, 45–57. <https://doi.org/10.1016/j.geomorph.2014.08.001>
- Galanti G.M. (1789) - *Della descrizione geografica e politica delle Sicilie “Of the geographical and political description of Sicilies.”*. Tomo Terzo. Presso i Soci del Gabinetto Letterario. Napoli.
- Galasso G. (1999) - *The Benevento Amphitheater Reappears*. Archeo **1999**, 11, 14–15.

- Gambardella, A. (1979) – Architettura e committenza nello Stato Pontificio tra barocco e rococò “*Architecture and commissioning in the State Pontifical between Baroque and Rococo*”. Un amministratore illuminato: Giuseppe Renato Imperiali, Napoli, 1979.
- Gams I. (1978) - *The polje; The problem of definition; With special regard to the Dinaric karst*. Z. Fuer Geomorphol. **1978**, 22, 170–181.
- Giampaola D. (2011) - *Napoli Stazione Chiaia—Linea 6 Della Metropolitana Di Napoli, Valorizzazione e Gestione Integrata Del Patrimonio Archeologico*. In Proceedings of the XIV Borsa Mediterranea del Turismo Archeologico, Paestum, Italy, 17 November 2011.
- Goldscheider N. (2010) - *Delineation of Spring Protection Zones*. In Groundwater Hydrology of Springs; Krasic, N., Stevanovic, Z., Eds.; 2010; pp. 305–338.
- Goldscheider N., Meiman J., Pronk M., Smart C. (2008) - *Tracer Tests in Karst Hydrogeology and Speleology*. Int. J. Speleol. **2008**, 37, 27–40. <https://doi.org/10.5038/1827-806X.37.1.3>
- Gong C., Cook P. G., Therrien R., Wang W., Brunner, P. (2023) - *On groundwater recharge in variably saturated subsurface flow models*. Water Resources Research, 59, e2023WR034920. <https://doi.org/10.1029/2023WR034920>
- Gunn J. (1983) – *Point recharge of limestone aquifer, a model from New Zealand karst*. Journal of Hydrology, 61: 19-29. [https://doi.org/10.1016/0022-1694\(83\)90232-9](https://doi.org/10.1016/0022-1694(83)90232-9).
- Gupta H.V., Sorooshian S., Yapo P.O. (1998) - *Toward improved calibration of hydrologic models: multiple and noncommensurable measures of information*. Water Resour. Res. 34, 751e763. <http://dx.doi.org/10.1029/97WR03495>.
- Gurito R.A., Ferreira Galvaro P.H., Alcantara Mourao M.A. & de Silva Assuncao P.H. (2024) – *Estimating groundwater potentiality of the Vieira River Karst Watershed, Verde Grande Hydrographic Region, MG*. Aguas Subterraneas, v. 36, n. 2.
- Gutierrez F., Galve J.P., Lucha P., Castaneda C., Bonachea J., Guerrero J. (2011) - *Integrating Geomorphological Mapping, Trenching, InSAR and GPR for the Identification and Characterization of Sinkholes: A Review and Application in the Mantled Evaporite Karst of the Ebro Valley (NE Spain)*. Geomorphology **2011**, 134, 144–156.
- Gutierrez F., Guerrero J., Lucha P. A. (2008) - *Genetic Classification of Sinkholes Illustrated from Evaporite Paleokarst Exposures in Spain*. Environ. Geol. **2008**, 53, 993–1006.

- Handy M.R., Schmid S.M., Bousquet R., Kissling E., Bernoulli, D. (2010) - *Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps*: Earth-Science Reviews, v. 102, p. 121–158, <https://doi.org/10.1016/j.earscirev.2010.06.002>
- Harbaugh Arlen W. (1990) - *A Computer Program for Calculating Subregional Water Budgets Using Results from the U.S. Geological Survey Modular Three-dimensional Finite-difference Ground-water Flow Model*. Open-File Report 90-392 [Report] = Open-File Report 90-392. - Reston, Virginia : U.S. Geological Survey, 1990. - p. 49.
- Harbaugh, A.W. (2005) - *MODFLOW-2005, the U.S. Geological Survey modular ground-water model—the Ground-Water Flow Process*: U.S. Geological Survey Techniques and Methods, book 6, chap. A16, variously paged, accessed June 27, 2017, at <https://pubs.usgs.gov/tm/2005/tm6A16/>.
- Harris R. (2003) - *Pompeii*; Mondadori: Milan, Italy, 2003; ISBN 978-88-04-49650-2.
- Hartmann A. (2018) - *Experiences in calibrating and evaluating lumped karst hydrological models*. Geol. Soc. Lond. Spec. Publ., 466, 331-340, <https://doi.org/10.1144/SP466.18>.
- Hartmann A., Goldscheider N., Wagener T., Lange J. & Weiler M. (2014)- *Karst water resources in a changing world: Review of hydrological modeling approaches*. Rev. Geophys., 52, 218-242, <https://doi.org/10.1002/2013RG000443>.
- Hartmann, A., Weiler, M., Wagener, T., Lange, J., Kralik, M., Humer, F., Mizyed, N., Rimmer, A., Barberá, J. A., Andreo, B., Butscher, C., and Huggenberger, P. (2013) – Process-based karst modelling to relate hydrodynamic and hydrochemical characteristics to system properties, Hydrol. Earth Syst. Sci., 17, 3305–3321, <https://doi.org/10.5194/hess-17-3305-2013>
- Healy R. W., Cook P. G. (2002) - *Using groundwater levels to estimate recharge*. Hydrogeology Journal, 10(1), 91–109. <https://doi.org/10.1007/s10040-001-0178-0>
- Healy RW (2010) - *Estimating Groundwater Recharge*. Cambridge University Press; 2010.
- Hock R. (1999) - *A distributed temperature-index ice- and snowmelt model including potential direct solar radiation*. J. Glaciol., 45, 101-111, <https://doi.org/10.3189/S0022143000003087>
- Hodge T.A. (1992) - *Roman Aqueducts & Water Supply*; Duckworth: London, UK, 1992.
- Hoffman G., Kummer S., Marquez R. (2019) - *Valdivia Machego, M. The Roman Eifel Aqueduct: Archaeoseismological Evidence for Neotectonic Movement at the Transition of the*

Eifel to the Lower Rhine Embayment. Int. J. Earth Sci. **2019**, 108, 2349–2360.
<https://doi.org/10.1007/s00531-019-01766-y>

Hofierka J., Gallay M., Bandura P., Šašak J. (2018) - *Identification of Karst Sinkholes in a Forested Karst Landscape Using Airborne Laser Scanning Data and Water Flow Analysis*. Geomorphology **2018**, 308, 265–277.

Hughes J.D., Langevin C.D., Banta, E.R. (2017) - *Documentation for the MODFLOW 6 framework*: U.S. Geological Survey Techniques and Methods, book 6, chap. A57, 36 p., accessed August 4, 2017, at <https://doi.org/10.3133/tm6A57>

Hunt Randall J. [et al.] (2010) - *Using the cloud to replenish parched groundwater modeling efforts*. Rapid Communication for Ground Water, doi: 10.1111/j.1745-6584.2010.00699 [Journal] // Ground Water. - [s.l.] : Ground Water, 2010. - 3 : Vol. 48. - pp. 360-365.

Iannace A., Frijia G., Galluccio L., & Parente M. (2014) - *Facies and early dolomitization in upper Albian shal- low-water carbonates of the southern Apennines (Italy): paleotectonic and paleoclimatic implications*. Facies, 60, 169–194.

Iasiello I.M. (2007) - *Samnium: assetti e trasformazioni di una provincia tardoantica* “*Samnium: structures and transformations of a province late antique*”. Edipuglia, p. 59

Incoronato A., Nardi G., Ortolani F. (1978) - *Assetto Strutturale Dei Massicci Carbonatici Della Campania Meridionale. Implicazioni Idrogeologiche*. Rend. Accad. Sci. Fis. E Mat. Della Soc. Naz. Sci. Lett. E Arti Napoli **1978**, 45, 479–493.

Ippolito F., D’argenio B., Pescatore T., Scandone, P. (1973) - *Unità stratigrafico-strutturali e schema tettonico dell’Appennino meridionale*. Trad. from «The guidebook of Italy», 134–155. Petroleum Exploration Society of Libia. Ist. Geol. Geof. Univ., pubbl. n.s., 15, Napoli.

Ippolito F., Ortolani F., Russo M. (1973) - *Struttura Marginale Tirrenica Dell’Appennino Campano: Reinterpretazione Di Dati Di Antiche Ricerche Di Idrocarburi*. Mem Soc Geol It **1973**, 12, 227–249.

Isernia E. (1895) - *Istoria della città di Benevento, dalla sua origine fino al 1894* “*History of the city of Benevento, from its origins until 1894*”. Vol. 1-3. Benevento. Stabilimento Tipografico A. D’Alessandro e Figlio.

ISPRA (2009) - *Carta Geologica d’Italia alla scala 1:50.000. Foglio 432 Benevento*. <https://www.isprambiente.gov.it/Media/carg/>. Accessed 1 November 2023

ISPRA (2021) – *Carta Geologica d'Italia alla scala 1:50.000, F. 419 San Giorgio La Molara*. Available on line: <http://www.isprambiente.gov.it/Media/carg/419SANGIORGIOLAMOLARA/Foglio.html> (accessed on 15 December 2021).

ISPRA. (2017) - *Geological maps of Italy, scale 1:50,000. Sheets 405, 407, 419, 431, 432, 433, 446–447, 448, 449, 450, 451, 464, 465, 466, 467, 468, 484, 485, 486, 489, 502, 503, 504, 505, 519, 520, 521*. Retrieved from [http:// www.isprambiente.gov.it/Media/carg/campania.html](http://www.isprambiente.gov.it/Media/carg/campania.html)

ISTAT (2023) - *Bilancio demografico mensile anno 2023 (dati provvisori)* “Monthly demographic balance for the year 2023 (provisional data)”, su demo.istat.it, ISTAT, 18 dicembre 2023. URL consultato il 22 dicembre 2023.

Jeannin P.-Y. (2001) - *Modeling flow in phreatic and epiphreatic karst conduits in the Holloch cave (Muotatal, Switzerland)*: v. 37, p. 191–200.

Johannowsky W. (1983) - *L'attività archeologica nella provincia di Salerno, Avellino e Benevento* “Archaeological activity in the province of Salerno, Avellino and Benevento”. Pratola Serra. Atti del XXII Convegno di Studi sulla Magna Grecia, Taranto, p. 437.

Keenan Jones D. (2010a) - *The Aqua Augusta. Regional Water Supply in Roman and Late Antique Campania*; Department of Ancient History, Faculty of Arts, Macquarie University: Sydney, Australia, 2010.

Keenan-Jones D., Motta D., Garcia M.H., Sivaguru M., Perillo M., Shosted R.K., Fouke B.W. (2022) - *Travertine crystal growth ripples record the hydraulic history of ancient Rome's Anio Novus aqueduct*. Scientific Reports, 12. <https://doi.org/10.1038/s41598-022-05158-2>

Keenan-Jones, D. (2010b) - *The Aqua Augusta and the Control of Water Resources in the Bay of Naples*. In Proceedings of the Australasian Society for Classical Studies Conference 31, Perth, Australia, 2 February 2010b.

Kirn L., Mudarra M., Andreo B. & Hartmann A. (2017) – *Improved assessment of groundwater recharge in a Mediterranean karst region: Andalusia, Spain*. P. Renard & Bertrand C. (Eds), Eurokarst 2016, Neuchatel, Advances in Karst Science. DOI: 10.1007/978-3-319-45465-8_13.

Klimchouk A. (2000) - *The Formation of Epikarst and Its Role in Vadose Speleogenesis*. In *Speleogenesis: Evolution of Karst Aquifers*; National Speleological Society: Huntsville, AL, USA, 2000.

- Klimchouk A.B. (2007) - *Hypogene Speleogenesis: Hydrogeological and Morphogenetic Perspective*; Special paper/National Cave and Karst Research Institute; National Cave and Karst Research Inst: Carlsbad, NM, USA, 2007; ISBN 978-0-9795422-0-6.
- Klingseisen B., Metternicht G., Paulus G. (2008) - *Geomorphometric Landscape Analysis Using a Semi-Automated GIS-Approach*. Environ. Model. Softw. **2008**, 23, 109–121.
- Kovacic G. (2010) - Hydrogeological study of the Malenščica karst spring (SW Slovenia) by means of a time series analysis. Acta carsologica 39 (2).
- Kovács A., and Stevanović Z. (2023) - *A Combined Stochastic–Analytical Method for the Assessment of Climate Change Impact on Spring Discharge*: Water, v. 15, p. 629, doi:10.3390/w15040629.
- Kovacs A., Perrochet P., Darabos E., Lenart L., Szucs P. (2015) – *Well hydrograph analysis for the characterization of flow dynamics and conduit network geometry in a karst aquifer*, Bükk Mountains, Hungary. J. Hydrol., 530: 484-499. <http://dx.doi.org/10.1016/j.jhydrol.2015.09.058>
- Kozar M.D., McCoy K.J., Weary D.J., Field M.S., Pierce H.A., Schill W.B., Joung, J.A. (2007) - *Geohydrology and Water Quality of the Leetown Area*, West Virginia; U.S. Geological Survey Open-file Report; U.S. Geological Survey: Raystown, WV, USA, 2007.
- Kresic N. (2023) – *Hydrogeology 101*. Introduction to Groundwater Science and Engineering. Blue Ridge Press LLC.
- Kumar C.P. (2015) – *Modelling of Groundwater Flow and Data Requirements*. International Journal of Modern Science and Engineering Technology. Vol., 2, 2, pp. 18-27. ISSN 2349-3755.
- Langevin C.D., Hughes J.D., Banta E.R., Niswonger G., Panday S. & Provost A.M. (2017) – *Documentation for the MODFLOW 6 Groundwater Flow Model*. U.S. Department of the Interior. U.S. Geological Survey.
- Langevin C.D., Thorne D.T., Jr. and Dausman A.M. (2007) - *SEAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport*: U.S. Geological Survey Techniques and Methods Book 6, Chapter A22, 39 p. [Report]. - Reston, Virginia : U.S. Geological Survey, 2007.
- Lehmann P., Stauffer F., Hinz C., Dury O., Fluhler H. (1998) - *Effect of hysteresis on water flow in a sand column with a fluctuating capillary fringe*. J. Contam. Hydrol. 33, 81e100. [http://dx.doi.org/10.1016/S0169-7722\(98\)00066-7](http://dx.doi.org/10.1016/S0169-7722(98)00066-7).

Leone G, Pagnozzi M, Catani V, Ventafridda G, Esposito L, Fiorillo F (2020) - *A hundred years of Caposele spring discharge measurements: trends and statistics for understanding water resource availability under climate change*. Stoch Environ Res Risk Assess. <https://doi.org/10.1007/s00477-020-01908-8>

Leone G., Catani V., Pagnozzi M., Ginolfi M., Testa G., Esposito L., Fiorillo F. (2022) - *Hydrological Features of Matese Karst Massif, Focused on Endorheic Areas, Dolines and Hydroelectric Exploitation*. J. Maps **2022**, 19, 2144497.

Leone G., Ginolfi M., Esposito L., Fiorillo F. (2024) - *Relationships between River and Groundwater Flow in an Alluvial Plain by Time Series Analysis and Numerical Modeling*. Water Resources Management <https://doi.org/10.1007/s11269-024-03795-y>

Leone G., Hervé J., Esposito L., Ginolfi M., Ventafridda G., Fiorillo F. (2025) - *Daily Spring Discharge of a Diffuse-Flow Karst System Predicted by a Lumped Modeling Approach*. F. Fiorillo et al. (eds.), Eurokarst 2024, Advances in Karst Science, https://doi.org/10.1007/978-3-031-84338-9_6

Leone G., Jourde H., Ginolfi M., Esposito L., Ventafridda G. & Fiorillo F. (2026) - *Modeling the recharge-discharge processes of the Caposele karst spring (Cervialto massif, southern Apennine)*. Rend. Online Soc. Geol. It., 68, XX-XX, <https://doi.org/10.3301/ROL.2026.02>

Leone G., Pagnozzi M., Catani V., Testa G., Esposito L., Fiorillo F. (2019) - *Hydrogeology of the Karst Area of the Grassano and Telesse Springs [Idrogeologia dell'Area Carsica delle Sorgenti di Grassano e di Telesse]*. Acque Sotterranee - Italian Journal of Groundwater (2019) - AS31- 415: 63 – 68. DOI: 10.7343/as-2019-415.

Lettieri P. (1862) - *Studi Sull'Acquedotto Claudio e Progetto per Rifornire Di Acqua Potabile La Città di Napoli*; Manfredi, Napoli, Italy, 1862.

Libertini G., De Feo G., Miccio B. (2014) - *The Augustan Aqueduct in the Context of Road System and Urbanization of the Served Territory in Southern Italy*. In Proceedings of the IWA Regional Symposium on Water, Wastewater and Environment, Patras, Greece, 22 March 2014.

Libertini G., Miccio B., Leone N., de Feo G. (2016) - *The Augustan Aqueduct of Capua and Its Historical Evolution*. Water Supply **2016**, 17, 1653–1662. <https://doi.org/10.2166/ws.2017.050>.

Lin HT, Ke KY, Tan YC, Wu SC, Hsu G, Chen PC, Fang ST (2013) - *Estimating pumping rates and identifying potential recharge zones for Groundwater Management in Multi-aquifers System*. Water Resour Manage 27:3293–3306. <https://doi.org/10.1007/s11269-013-0347-7>

Linsey R.K., Kohler M.A., Paulhus J.L.H. (1982) – *Hydrology for Engineers*. McGraw-Hill, New York.

Lorenz W., Libertini G., Miccio B., Leone N., De Feo G. (2016) - *Prominent Features of the Augustan Aqueduct in the Naples Bay Area*. In Proceedings of the 4th IWA International Symposium on Water and Wastewater Technologies in Ancient Civilizations, Coimbra, Portugal, 17–19 September 2016.

Lorenzi V., Sbarbati C., Banzato F., Lacchini A. & Petitta M. (2022) – *Recharge assessment of the Gran Sasso aquifer (Central Italy): time-variable infiltration and influence of snow cover extension*. Journal of Hydrology, regional studies 41 101090. <https://doi.org/j.ejrh.2022.101090>

Magliulo P, Bozzi F, Leone G, Fiorillo F, Leone N, Russo F, Valente A (2021) - *Channel adjustments over 140 years in response to extreme floods and land-use change, Tammaro River, southern Italy*. Geomorphology 383. <https://doi.org/10.1016/j.geomorph.2021.107715>

Magliulo P, Sessa S, Cusano A, Beatrice M, Giannini A, Russo F (2022) - *Assessing the morphological quality of Calore River*. Geographies 2(3):354–378. <https://doi.org/10.3390/geographies2030023>

Magliulo P., Bozzi F., Leone G., Fiorillo F., Leone N., Russo F., Valente, A. (2021) - *Channel adjustments over 140 years in response to extreme floods and land-use changing, Tammaro River, southern Italy*. Geomorphology, 383, 107715. <https://doi.org/10.1016/j.geomorph.2021.107715>

Maiuri A. (1928) - *Ercolano. I Nuovi Scavi (1927–1958)*; Istituto poligrafico dello Stato, Libreria della Stato: Rome, Italy, 1958.

Malinverno A., Ryan W. B. F. (1986) - *Extension in the tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere*. Tectonics, 5, 227–245.

Mangin A. (1975) - *Contribution a l'étude hydrodynamique des aquifères karstique*. PhD thesis. University of Dijon, France.

Marin A.I., Martin Rodriguez J.F., Barbera J.A., Fernandez-Ortega J., Mudarra M., Sanchez D., Andreo B. (2021) - *Groundwater Vulnerability to Pollution in Karst Aquifers, Considering Key Challenges and Considerations: Application to the Ubrique Springs in Southern Spain*. Hydrogeol. J. **2021**, 29, 379–396.

Marín AI (2009) - *Los Sistemas de Información Geográfica aplicados a la evaluación de recursos hídricos y a la vulnerabilidad a la contaminación de acuíferos carbonatados: caso de la Alta Cadena (Provincia de Málaga) [The Geographic Information Systems applied to the evaluation of groundwater resources and to the vulnerability to the contamination of carbonate aquifers: the case example of the Alta Cadena aquifer (Malaga province)]*. PhD Thesis, University of Malaga, Spain, 131 pp

Mariniello A. (1988) - *Il Tracciato Dell'Acquedotto Augusteo Nel Tratto Napoli-Miseno*. Club Alpino Ital. Sez. Napoli **1988**, 3, 34–36.

Marti A., Folch A., Costa A. (2016) - *Reconstructing the Plinian and Co-Ignimbrite Sources of Large Volcanic Eruptions: A Novel Approach for the Campanian Ignimbrite*. Sci. Rep. **2016**, 6, 21220. <https://doi.org/10.1038/srep21220>

Martínez-Santos P, Pedretti D, Martínez-Alfaro PE, Conde M, Casado M (2010) - *Modelling the effects of Groundwater-based urban supply in Low-Permeability aquifers: application to the Madrid Aquifer, Spain*. Water Resour Manage 24:4613–4638. <https://doi.org/10.1007/s11269-010-9682-0>

Matsui S., Sorrentino L., Sakai S., Shimizu Y., Iorio V. (2009) - *La Provenienza Dell'acqua Potabile Dell'antica Pompei: Un'ipotesi Basata Sull'analisi Chimica Dei Residui Calcarei Degli Impianti Idrici*. J. Fasti Online **2009**. Available online: <https://www.fastionline.org/s/folder/item/96799> (accessed on 08 November 2025).

Mayaud C., Gabrovšek F., Blatnik M., Kogovšek B., Petrič M., Ravbar, N. (2019) - *Understanding Flooding in Poljes: A Modelling Perspective*. J. Hydrol. **2019**, 575, 874–889, doi:10.1016/j.jhydrol.2019.04.092.

Mazarini L. (1823) - *Mappa originale della città di Benevento “Original map of the city of Benevento”*. Roma. Archivio di Stato.

Mazzilli N., Guinot V., Jourde H., Lecoq N., Labat D., Arfib B., Baudement C., Danquigny C., Dal Soglio L. & Bertin D. (2019) - *KarstMod: A modelling platform for rainfall-discharge analysis and modelling dedicated to karst systems*. Environ. Model. Softw., 122, 103927, <https://doi.org/10.1016/j.envsoft.2017.03.015>

Mazzilli N., Sivellev V., Jourde H. & Bertin D. (2022) - *KarstMod User Guide (version 3.0, 2022/05)*. User Guide.

- Mazzoli S., Ascione A., Candela S., Iannace A., Megna A., Santini S., Vitale, S. (2013) - *Subduction and continental collision events in the southern Apennines: Constraints from two crustal cross-sections*: Rendiconti online della Società Geologica Italiana, v. 25, p. 78–84, <https://doi.org/10.3301/ROL.2013.07>
- McDonald, M. C. and A. W. Harbaugh (1988) - *MODFLOW, A modular three-dimensional finite difference ground-water flow model*, U. S. Geological Survey, Open-file report 83-875, Chapter A1.
- Melluso L., Morra V., Guarino V., de Gennaro R., Franciosi L., Grifa, C. (2014) - *The crystallization of shoshonitic to peralkaline trachyphonolitic magmas in a H₂O–Cl–F-rich environment at Ischia (Italy), with implications for the feeder system of the Campania plain volcanoes*. Lithos, 210–211, 242–259.
- Meomartini A. (1889) - *The monuments and works of art of the city of Benevento*. de Martini typography, Benevento.
- Miccio B., Potenza, U. (1994) - *Gli Acquedotti Di Napoli*; Tip. Gaeta.; A.M.A.N—Azienda Municipalizzata Acquedotto di Napoli: Napoli, Italy, 1994.
- Milić M., Jeftenić G., Stipić D., Budinski L. (2023) - *Mathematical Modeling of Groundwater Flow: A Case Study of Foundation Piles in the Vicinity of Danube River*. Appl. Sci. **2023**, 13, 13277. <https://doi.org/10.3390/app132413277>
- Milia A., Valente A., Cavuoto G., Torrente M. M. (2017) - *Miocene progressive forearc extension in the central Mediterranean*. Tectonophysics, 710-711, 232–248.
- Moreno-Gomez M., Liedl R., Stefan C. A. (2019) - *New GIS-Based Model for Karst Dolines Mapping Using LiDAR; Application of a Multidepth Threshold Approach in the Yucatan Karst, Mexico*. Remote Sens. **2019**, 11, 1147.
- Morretta, S. (1990) - *L'Acquedotto Augusteo Di Serino (Av)*. Geoarcheologia **1990**, 2, 57–89.
- Mostardini F. and Merlini S. (1986) – *Appennino centro-meridionale: Sezioni geologiche e proposta di modello strutturale*: Memorie della Società Geologica Italiana, v. 35, p. 177–202.
- Mudarra M., Hartmann A. & Andreo B. (2019) - *Combining experimental methods and modeling to quantify the complex recharge behavior of karst aquifers*. Water Resources Research, 55, 1384–1404. <https://doi.org/10.1029/2017WR021819>

- Mylopoulos N, Mylopoulos Y, Veranis N, Tolikas D (2007) - *Groundwater modeling and management in a complex lake-aquifer system*. Water Resour Manage 21:469–494. <https://doi.org/10.1007/s11269-006-9025-3>
- Nanou E.A., Perdikaris K., Tserolas P. & Zagana E. (2024) – *Recharge assessment in Greek karst systems: methodological considerations and implications*. In Water, 16, 568. <https://doi.org/10.3390/w16040568>
- Nash J.E. & Sutcliffe J.V. (1970) - *River flow forecasting through conceptual models part I - A discussion of principles*. J. Hydrol., 10, 282-290, [https://doi.org/10.1016/0022-1694\(70\)90255-6](https://doi.org/10.1016/0022-1694(70)90255-6).
- Nazari S., Kruse J.L., Moosdorf N. (2025) – *Spatiotemporal dynamics of global rain-fed groundwater recharge from 2001 to 2020*. J. Hydrol. <https://doi.org/10.1016/j.hydrol.2024.132490>
- Nicotera P. (1953) - *Studi di Geologia Applicata su Talune Sorgenti del Sannio*. Mem. Note Dell'istituto Geol. Appl. **1953**, 5, 1–60. (In Italian)
- Nicotera P. (1959) – *Rilevamento ed indagini geologiche per la captazione delle sorgenti di Sorbo Serpico (Avellino)*. Mem. e Note Ist. Geol. Appl., 7, Napoli.
- Nicotera P. and Aquino S. (1995) – *Una captazione “sui generis” per la sorgente Baiardo del massiccio del Terminio (Campania)*. Rivista Italiana Geotecnica, 1/95.
- Nimmo J.R., Horowitz C., Mitchell L. (2015) – *Discrete storm-water-table fluctuation method to estimate episodic recharge*. Groundwater, Vol. 53, 2: 282-292. DOI: 10.1111/gwat.12177
- Nisio S. (2008) – *I sinkholes: problemi terminologici, meccanismi genetici, classificazione*. In S.Nisio(Ed.), I fenomeni naturali di sinkhole nelle aree di pianura italiane (pp. 17–32). GEDAsrl.
- Niswonger Richard G., Panday Sorab and Ibaraki Motomu (2011) - *MODFLOW-NWT, A Newton formulation for MODFLOW-2005*: U.S. Geological Survey Techniques and Methods 6-A37, 44 p. [Report]. - Reston, Virginia : U.S. Geological Survey, 2011.
- O’Callaghan J.F., Mark D.M. (1984) - *The Extraction of Drainage Networks from Digital Elevation Data*. Comput. Vis. Graph. Image Process. **1984**, 28, 323–344.

- Omar PJ, Gaur S, Dwivedi SB, Dikshit PKS (2020) - *A Modular Three-Dimensional scenario-based Numerical Modelling of Groundwater Flow*. <https://doi.org/10.1007/s11269-020-02538-z>. Water Resour Manage
- Orsi G., D'Antonio M., De Vita A., Gallo G. (1992) - *The Neapolitan Yellow Tuff, a Large-Magnitude Trachytic Phreatoplinian Eruption: Eruptive Dynamics, Magma Withdrawal and Caldera Collapse*. J. Volcanol. Geotherm. Res. **1992**, 53, 257–287. [https://doi.org/10.1016/0377-0273\(92\)90086-S](https://doi.org/10.1016/0377-0273(92)90086-S)
- Ortloff C.R. (2021) - *Roman Hydraulic Engineering: The Pont Du Gard Aqueduct and Nemausus (Nîmes) Castellum*. Water **2021**, 13, 54. <https://doi.org/10.3390/w13010054>
- Ortolani F., Aprile F. (1985) - *Principali Caratteristiche Stratigrafiche e Strutturali Dei Depositi Superficiali Della Piana Campana*. Boll. Della Soc. Geol. Ital. **1985**, 104, 195–206.
- Pagnozzi M, Coletta G, Leone G, Catani V, Esposito L, Fiorillo F (2020) - *A Steady-State Model to Simulate Groundwater Flow in Unconfined Aquifer*. App Sci 10, 2708. doi:10.3390/app10082708
- Pagnozzi M., Fiorillo F., Esposito L., Leone G. (2019) - *Hydrological Features of Endorheic Areas in Southern Italy*. Ital. J. Eng. Geol. Environ. **2019**, 85–91. <https://doi.org/10.4408/IJEGE.2019-01.S-14>
- Palmer A.N. (1991) - *Origin and Morphology of Limestone Caves*. Geol. Soc. Am. Bull. **1991**, 103, 1–21.
- Panday S., Langevin C.D., Niswonger R.G., Ibaraki, Motomu, Hughes, J.D. (2013) - *MODFLOWUSG version 1—An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation*: U.S. Geological Survey Techniques and Methods, book 6, chap. A45, 66 p., accessed June 27, 2017, at <https://pubs.usgs.gov/tm/06/a45/>.
- Parajuli A., Nadeau D.F., Anctil F., Schilling O.S., Jutras S. (2020) - *Does Data Availability Constrain Temperature-Index Snow Models? A Case Study in a Humid Boreal Forest*. Water 12, 2284. <https://doi.org/10.3390/w12082284>
- Pasquale N. (1916) – *Storia di Volturara Irpina*. A cura di Edmondo Marra.
- Passchier C.W., Schram W.D. (2004) - *Roman Aqueducts. An Introduction*. 2004. Available online: <http://www.cs.uu.nl/wilke/introduction/index.html> (accessed on 08 November 2025)

Patacca E., Scandone P. (2007) - *Geology of the Southern Apennines*. Ital. J. Geosci. **2007**, 7, 75–112.

Patacca E., Scandone P. (2014) - *Il contributo degli studi stratigrafici di superficie e sottosuolo alla conoscenza dell'Appennino Campano-Lucano*, in Atti del 1° Congresso dell'Ordine dei Geologi di Basilicata, Ordine Geologi Basilicata, ed., Potenza, Ordine Geologi Basilicata, p. 97–153, <https://www.geologibasilicata.it/Comunicazione/Atti-Congresso-2012/11-Sessione/Etta-Patacca-e-Paolo-Scandone>.

Peduto A. (1992) - *S. Giovanni di Pratola Serra. Archeologia e storia nel ducato longobardo di Benevento* “*S. Giovanni di Pratola Serra. Archeology and history in Lombard duchy of Benevento*”. Salerno.

Pescatori Colucci G. (1996) - *L'acquedotto di Serino: Fontis Augustei Aquaeductus* “*The Serino aqueduct: Fontis Augustei Aquaeductus*”. Storia Illustrata di Avellino e dell'Irpinia, I, Pratola Serra, 129-142.

Petrella E., Celico F. (2009) - *Heterogeneous aquitard properties in sedimentary successions in the Apennine chain: Case studies in southern Italy*. Hydrol. Process. **2009**, 23, 3365–3371.

Petrone P., De Vita P., Marsiglia P., Allocca P., Coda S., Lepore D., Allocca V. (2024) - *Hydrogeological Conceptual Model and Groundwater Recharge of Avella Mts. Karst Aquifer (Southern Italy): A Literature Review and Update*. J. Hydrol. Reg. Stud. **2024**, 54, 101871. <https://doi.org/10.1016/j.ejrh.2024.101871>

Pezzone M.G. (2008) - *Carlo Buratti. Architettura tardo Barocca tra Roma e Napoli* “*Carlo Buratti. Late Baroque architecture Rome and Naples*”. Alinea. Firenze 2008, 217-221.

Planchon O., Darboux, F. A. (2002) - *Fast, Simple and Versatile Algorithm to Fill the Depressions of Digital Elevation Models*. Catena **2002**, 46, 159–176.

Plinio T.O. (1487) - *Naturalis Historia*; Giovanni da Spira: Venezia, Italy, 77-78 AD, 1487.

Pollock David W. (2016) - *User guide for MODPATH Version 7 -- A particle-tracking model for MODFLOW*: U.S. Geological Survey Open-File Report 2016-1086, 35 p., <http://dx.doi.org/10.3133/ofr20161086>. [Report]. - Reston, Virginia : U.S. Geological Survey, 2016.

Pollock, D. W. (1988) - *Semianalytical computation of path lines for finite difference models*. Ground Water (26)6, 743-750.

Pollock, D.W., (2016) - *Extending the MODPATH algorithm to rectangular unstructured grids: Groundwater*, v. 54, no. 1, p. 121–125.

Powers J.G., Shevenell L. (1999) – *Transmissivity estimates from well Hydrographs in karst and fractured aquifers*. Managed by lockheed martin energy systems, inc. For the United States Department of Energy.

Preziosi G. (2001) - *L'acquedotto di Serino nella storia del territorio "The Serino aqueduct in the history of the area"*. Atti del Convegno di Studi San Gemini, 18-20 ottobre 2000 Abbazia di San Niccolò.

Rea R. (1978) - *L'acquedotto augusteo di Serino, Roma (tesi di laurea non pubblicata) "The Augustan aqueduct of Serino, Rome (degree thesis not published)"*.

Rende P. (2004) - *Storia ed Urbanistica della Benevento romana e medievale attraverso l'uso della fotografia aerea "History and Urban Planning of Roman Benevento e medieval through the use of aerial photography"*. La Provincia KR, 21/2004.

Revellino P, Guerriero L, Mascellaro N, Fiorillo F, Grelle G, Ruzza G, Guadagno FM (2019) - *Multiple effects of Intense Meteorological Events in the Benevento Province, Southern Italy*. Water 1(8). <https://doi.org/10.3390/w11081560>

Richardson L.F. (1910) - *The Approximate Arithmetical Solution by Finite Differences of Physical Problems*, Trans. R. Soc. (London), **A210**, 307–357, 1910

Rossetti, F., Faccenna, C., Goffé, B., Monié, P., Argentieri, A., Funiciello, R., & Mattei, M. (2001) - *Alpine structural and metamorphic signature of the sila piccola massif nappe stack (Calabria, Italy): insights for the tectonic evolution of the Calabrian Arc*. Tectonics, 20, 112–133.

Rotili M. (1958) - *Benevento e la provincia sannitica "Benevento and the Samnite province"*. Roma.

Rotili M. (1986) - *Benevento romana e longobarda "Roman and Lombard Benevento"*. L'immagine urbana, Napoli-Ercolano, 91-62.

Santacroce R. (1987) - *Somma-Vesuvius*, CNR. Quad. La Ric. Sci. **1987**, 8, 10–20.

Santangelo N., Romano P., Ascione A. Russo ermoli, E. (2017) - *Quaternary evolution of the Southern Apennines coastal plains: A review*. Geologica Carpathica, 68, 43–56.

- Santangelo N., Santo A. (1997) - *Endokarst Processes in the Alburni Massif (Campania, Southern Italy): Evolution of Ponors and Hydrogeological Implications*. Z. Fur Geomorphol. **1997**, 41, 229–247.
- Santo A. (1988) - *Alcune Osservazioni Sul Carsismo Ipogeo Dei M. Alburni*. Appennino Meridionale Annu. Club Alpino Ital. Sez. Napoli **1988**, 1, 71–88.
- Santo A. (1993) - *Idrogeologia Dell'area Carsica Di Castelvita (M. Alburni-SA)*. Geol. Appl. Idrogeol. **1993**, 27, 663–673.
- Santo A., Giulivo I., Russo N., Prete S. (2005) - *Grotte e Speleologia Della Campania*; 2005; ISBN 88-88991-32-8.
- Santo A., Liguori M., Aquino S., Galasso M. (1998) - *Problemi Di Geologia Ambientale Nei Polje Appenninici: L'esempio Della Piana Di Forino (Campania)*. Il Quat. Ital. J. Quat. Sci. **1998**, 11, 233–245.
- Sauro U. (2012) - *Closed Depressions in Karst Areas*. In Encyclopedia of Caves; Academic Press: Cambridge, MA, USA, 2012; pp. 140–155.
- Savino E. (2005) - *Campania Tardoantica*; Edipuglia: Bari, Italy, 2005.
- Sbrana A., Cioni R., Marianelli P., Sulpizio R., Andronico D., Pasquini, G. (2020) - *Volcanic evolution of the Somma-Vesuvius Complex (Italy)*. Journal of Maps, 16(2), 137–147. <https://doi.org/10.1080/17445647.2019.1706653>
- Sbrana A., Marianelli P., Pasquini G. (2021) - *The Phlegrean Fields volcanological evolution*. Journal of Maps, 17(2), 557–570. <https://doi.org/10.1080/17445647.2021.1982033>
- Scanlon B. R., Healy R. W., Cook P. G. (2002) - *Choosing appropriate techniques for quantifying groundwater recharge*. Hydrogeology Journal, 10(1), 18–39. <https://doi.org/10.1007/s10040-001-0176-2>
- Scanlon B.R., Mace R.E., Barrett M.E. & Smith B. (2003) - *Can we simulate regional groundwater flow in a karst system using equivalent porous media models? Case study, Barton Springs Edwards aquifer, USA*. J. Hydrol., 276, 137–158, [https://doi.org/10.1016/S0022-1694\(03\)00064-7](https://doi.org/10.1016/S0022-1694(03)00064-7).
- Scarpati C., Cole P., Perrotta A. (1993) - *The Neapolitan Yellow Tuff. A Large Volume Multiphase Eruption from Campi Flegrei, Southern Italy*. Bulletin Vulcanol. **1993**, 55, 343–356.

- Šegina E., Benac C., Rubinic J., Knez M. (2018) - *Morphometric Analyses of Dolines—The Problem of Delineation and Calculation of Basic Parameters*. Acta Carsologica **2018**, 47, 23–33.
- Senatore MR, Boscaino M, Pinto F (2019) - *The quaternary geology of the Benevento urban area (southern Italy) for seismic microzonation purposes*. Ital J Geosci 138:66–87. <https://doi.org/10.3301/IJG.2018.27>
- Sgobbo I. (1938) - *L'acquedotto Romano Della Campania: "Fontis Augustei Aqueductus*. Not. Scavi **1938**, 1, 75–95.
- Shevenell L. (1996) – *Analysis of well hydrographs in a karst aquifer: estimates of specific yields and continuum transmissivities*. J. Hydrol, 174: 331-55.
- Sivelle V., Jourde H., Bittner D., Mazzilli N., Tramblay, Y. (2021) - *Assessment of the relative impacts of climate changes and anthropogenic forcing on spring discharge of a Mediterranean karst system*. J. Hydrol. 598, 126396 (2021). <https://doi.org/10.1016/j.jhydrol.2021.126396>
- Sobol I. (1977) - *Uniformly distributed sequences with an additional uniform property*. USSR Comput. Math. Math. Phys. 16, 236e242.
- Stefanovski S., Kokalj Ž., Stepišnik U. (2024) - *Sky-View Factor Enhanced Doline Delineation: A Comparative Methodological Review Based on Case Studies in Slovenia*. Geomorphology **2024**, 465, 109389.
- Strabone (2020) - *Geographia*; Eredi di Aldo Manuzio e Andrea Torresano, Venezia, 23 AD, Strabone, Geographia, Gece Kitaplığı, 30 December 2020; ISBN-10: 6257462649.
- Sürmelihindi G., Passchier, C. (2023) - *Writ in water-Unwritten histories obtained from carbonate deposits in ancient water systems*. Geoarchaeology, 39, 63–88. DOI: 10.1002/gea.21980
- Tadamouri R., Shaban A., Baghdady K. & Soliman M.R. (2024) – *Unveiling novel APLIS model for identifying groundwater recharge zones in semi-arid regions: a case from Lebanon*. Alexandria Engineering Journal 97, 360-375. <https://doi.org/10.1016/j.aej.2024.04.015>
- Terzaghi K, Peck RB, Mesri G (1996) - *Soil mechanics in engineering practice*. John Wiley & Sons. New York.

Texier J, Gonçalves J, Rivière A (2022) - *Numerical Assessment of Groundwater Flowpaths below a streambed in Alluvial Plains impacted by a Pumping Field*. Water 14:1100. <https://doi.org/10.3390/w14071100>

Theis CV (1952) - *The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground water storage*. US Geological Survey, Washington.

Theodossiou N (2016) - *Assessing the impacts of Climate Change on the sustainability of Groundwater aquifers. Application in Moudania Aquifer in N. Greece* Environ Process 3:1045–1061. <https://doi.org/10.1007/s40710-016-0191-x>

Thornthwaite CW, Mather JR (1957) - *Instructions and tables for computing potential evapotranspiration and the water balance*. Publications Climatology 10(3)

Thornthwaite CW. (1948) - *An approach towards a rational classification of climate*. Geography Review 38: 55–94.

Thornthwaite, C. W. and Mather, J. R. (1955) - ‘*The water balance*’, Publications in Climatology, 8, (1).

Tolle Kasteinbein R. (1993) - *L’archeologia dell’acqua: la cultura idraulica del mondo classico* “*The archeology of water: culture hydraulics of the classical world*”. Longanesi Ed., Milan.

Tomay L. (2009) - *Benevento longobarda: dinamiche insediative e processi di trasformazione* “*Lombard Benevento: settlement dynamics and transformation processes*”. In G. D’Henry & C. Lambert (Eds.), *il popolo dei longobardi meridionali (576-1076): Testimonianze storiche e monumentali* (pp. 119-151). Salerno: Gruppo Archeologico Salernitano.

Tomlov J. (2021) - *Observations on the Design and Building of the Roman Segovia Aqueduct*. In *History of Construction Cultures*; Mascarenhas-Mateus, J., Pires, P., Eds.; CRC Press: Boca Raton, FL, USA, 2021; ISBN 978-1-032-00203-3.

Torelli, M.R. (2002) - *Benevento romana, Roma* “*Roman Benevento, Roma*”. L’Erma di Bretschneider.

Tozer, R.S.J., Butler, R.W.H., Corrado, S., Geologiche, S., Tre, R., San, L., and Murialdo, L., (2002) - *Comparing thin- and thick-skinned thrust tectonic models of the Central Apennines, Italy*, in Bertotti, G., Schulmann, K., and Cloetingh, S.A.P.L., eds., *Continental Collision and*

the Tectono-Sedimentary Evolution of Forelands: European Geosciences Union (EGU) Stephan Mueller Special Publication Series 1, p. 181–194, <https://doi.org/10.5194/smsps-1-181-2002>.

Tritz S., Guinot V. & Jourde H. (2011) - *Modelling the behaviour of a karst system catchment using non-linear hysteretic conceptual model*. J. Hydrol., 397, 250-262, <https://doi.org/10.1016/j.jhydrol.2010.12.001>

Troester J., White E.L., White W.B. (1984) - *A Comparison of Sinkhole Depth Frequency Distributions in Temperate and Tropic Karst Regions*; 1984; pp. 65–73.

Tügel F, Houben GJ, Graf T (2016) - *How appropriate is the Thiem equation for describing groundwater flow to actual wells?* Hydrogeol J 24:2093–2101. <https://doi.org/10.1007/s10040-016-1457-0>

Turc L. (1954) – *Le bilan d'eau des sols. Relations entre les précipitations, l'évaporation et l'écoulement*. Annales Agronomiques 5: 491-495.

U.S. Geological Survey (USGS) (2022) - "Groundwater Modeling." Link: <https://ca.water.usgs.gov/projects/central-valley/groundwater-modeling...>

Valente A., Catani V., Esposito L., Leone G., Pagnozzi M., Fiorillo F. (2022) – *Groundwater resources in a complex karst environment involved by wind power farm construction*. Sustainability 2022, 14, 11975. <https://doi.org/10.3390/su141911975>

Valipour M., Ahmed A.T., Antoniou G.R., Sala R., Parise M., Salgot M., Bensi N.S., Angelakis, A.N. (2020) - *Sustainability of Underground Hydro-Technologies: From Ancient to Modern Times and toward the Future*. Sustainability **2020**, 12, 8983. <https://doi.org/10.3390/su12218983>.

Van Essen (2018) – *Product manual*. Diver. Van Essen.

Vegezio (2018) - *Epitoma Rei Militaris*; Nicolaus Ketelaer e Gerardus de Leempt IV-V Century AD, Vegezio. Epitoma Rei Militaris. CreateSpace Independent Publishing Platform. 8 January 2018. ISBN-10: 1983653225.

Verbovšek T., Gabor L. (2019) - *Morphometric Properties of Dolines in Matarsko Podolje, SW Slovenia*. Environ. Earth Sci. **2019**, 78, 396.

Veress M. (2016) - *Covered Karsts*; Springer Geology: Dordrecht, The Netherlands, 2016; ISBN 978-94-017-7516-8.

Vitale S. and Ciarcia S. (2022) – *The dismembering of the Adria platforms following the Late Cretaceous–Eocene abortive rift: A review of the tectono-stratigraphic record in the southern Apennines*: Journal of Geology Review, v. 64, no. 20, p. 2866–2889, <https://doi.org/10.1080/00206814.2021.2004559>.

Vitale S., Ciarcia S., Mazzoli S., Zaghloul M. N. (2011) - *Tectonic evolution of the ‘Liguride’ accretionary wedge in the Cilento area, southern Italy: a record of early Apennine geodynamics*. Journal of Geodynamics, 51, 25–36.

Vitale S., Ciarcia S. (2018) – *Tectono-stratigraphic setting of Campania region (Southern Italy)*. Journal of Maps, 14 (2), 9-21. <https://doi.org/10.1080/17445647.2018.1424655>

Vitale S., Ciarcia S., Fedele L., Tramparulo, F.D. (2019) - *The Ligurian oceanic successions in southern Italy: The key to decrypting the first orogenic stages of the Southern Apennines–Calabria chain system*: Tectonophysics, v. 750, p. 243–261, <https://doi.org/10.1016/j.tecto.2018.11.010>.

Vitale S., Tramparulo F. D. A., Ciarcia S., Amore F. O., Prinzi E. P., Laiena, F. (2017) - *The northward tectonic transport in the southern Apennines: Examples from the Capri Island and western Sorrento Peninsula (Italy)*. International Journal of Earth Sciences, 106, 97–113.

Vitale S., Zaghloul M.N., El Ouaragli B., Tramparulo F.D., and Ciarcia S. (2015) – *Polyphase deformation of the Dorsale Calcaire complex and the Maghrebien Flysch Basin units in the Jebha area (Central Rif, Morocco): New insights into the Miocene tectonic evolution of the Central Rif belt*: Journal of Geodynamics, v. 90, p. 14–31, <https://doi.org/10.1016/j.jog.2015.07.002>.

Vitale, S., Ciarcia, S. (2013) - *Tectono-stratigraphic and kinematic evolution of the Southern Apennines/Calabria-Peloritani terrane system (Italy)*: Tectonophysics, v. 583, p. 164–182, <https://doi.org/10.1016/j.tecto.2012.11.004>.

Vitruvius (1487) - *De Architectura*; Eucharius Silber: Roma, Italy, 15 AD, 1487.

Waltham T., Bell, F. Culshaw M. (2005) - *Sinkhole and subsidence: Karst and cavernous rocks in engineering and construction*. Springer.

Wang L., Liu H. (2006) - *An Efficient Method for Identifying and Filling Surface Depressions in Digital Elevation Models for Hydrologic Analysis and Modelling*. Int. J. Geogr. Inf. Sci. **2006**, 20, 193–213.

- White W.B. (1988) – *Geomorphology and Hydrology of Karst Terrain*. Oxford Press University: Oxford, UK; 464.
- White WB. (2002) - *Karst hydrology: recent developments and open questions*. Engineering Geology 65: 85–105.
- Wu Q., Deng C., Chen Z. (2016) - *Automated Delineation of Karst Sinkholes from LiDAR-Derived Digital Elevation Models*. Geomorphology **2016**, 266, 1–10.
- Xanke J., Stevanović Z., Liesch T., Kaltenbrunn A., Ravbar N., Jourde H., Andreo B., Barberá, J.A., Goldscheider N. (2024) - *Flooding and Flood Water Storage in Karst Systems of the Mediterranean Region*. Hydrogeol. J. **2024**, 32, 1587–1605, doi:10.1007/s10040-024-02811-0.
- Zarcone G., Petti F.M., Cillari A., Di Stefano P., Guzzetta D., Nicosia U. (2010) - *A possible bridge between Adria and Africa: New palaeobiogeographic and stratigraphic constraints on the Mesozoic palaeogeography of the central Mediterranean area*: Earth-Science Reviews, v. 103, p. 154–162, <https://doi.org/10.1016/j.earscirev.2010.09.005>.
- Zazo A. (1977) - *L'acquedotto del Serino e una vertenza fra Napoli e Benevento nel XVI secolo* “The Serino aqueduct and a dispute between Naples and Benevento in the 16th century”. Samnium, Anno L, n. 3-4, 124-133.
- Zazo A. (1980) - *L'acquedotto settecentesco di Benevento e le rimostranze dell'architetto romano Carlo Buratti* “The eighteenth-century aqueduct of Benevento and the grievances by the Roman architect Carlo Buratti”, Samnium, Anno LIII, 1980, 137-151.
- Zheng C., Wang P. (1999) - *MT3DMS: A modular three-dimensional multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems*; Documentation and User's Guide, Contract Report SERDP-99-1 [Report]. - Vicksburg, MS : U.S. Army Engineer Research and Development Center, 1999.
- Zheng, C. (1990) - *MT3D, a modular three-dimensional transport model*, S.S. Papadopoulos & Associates, Inc., Rockville, Maryland.
- Zhou P, Wang G, Mao H, Liao F, Shi Z, Huang H (2022) - *Numerical modeling for the temporal variations of the water interchange between groundwater and surface water in a regional great lake (Poyang Lake, China)*. J Hydrol 610. <https://doi.org/10.1016/j.jhydrol.2022.127827>
- Zigarelli, D.M. (1979) - *Storia di Benevento* “History of Benevento”. Bologna

Scientific production

Papers

- 1) Leone G., **Ginolfi M.**, Esposito L., Fiorillo F. (2024) - *Relationships between River and Groundwater Flow in an Alluvial Plain by Time Series Analysis and Numerical Modeling*. Vol. 38. <https://doi.org/10.1007/s11269-024-03795-y>
- 2) Leone A.P., Magliulo P., **Ginolfi M.** (2024) – *Fabbisogni idrici aziendali*. Chapter in RINATAA Project Volume, Valorizzazione Bacino dell'Alto Tammaro. Paesaggio agrario e Acqua, Report Finale (in italian).
- 3) Fiorillo, F.; Esposito, L.; **Ginolfi, M.**; Leone, G. (2024) - *New Insights into Turbulent and Laminar Flow Relationships Using Darcy–Weisbach and Poiseuille Laws*. Water 2024, 16, 1452. <https://doi.org/10.3390/w16101452>
- 4) Leone G., **Ginolfi M.**, Esposito L., Fiorillo F. (2024) - *Terzaghi's effective stress principle and hydrological deformation of karst aquifers detected by GNSS measurements*. Italian Journal of Engineering Geology and Environment, Special issue, 1.
- 5) Esposito L., **Ginolfi M.**, Leone G., Fiorillo F. (2024) - *Hydrogeological and historical aspects of the water supply of Benevento city since the Roman times*. Italian Journal of Groundwater-Acque Sotterranee: Special Issue, Groundwater in Cities of Europe.
- 6) Esposito, L., Leone, G., **Ginolfi, M.**, Chenari, S. A., & Fiorillo, F. (2025) - *Mapping of Closed Depressions in Karst Terrains: A GIS-Based Delineation of Endorheic Catchments in the Alburni Massif (Southern Apennine, Italy)*. Hydrology, 12(7), 186. <https://doi.org/10.3390/hydrology12070186>
- 7) Leone G., Hervé J., Esposito L., **Ginolfi M.**, Ventafridda G., Fiorillo F. (2025) - *Daily Spring Discharge of a Diffuse-Flow Karst System Predicted by a Lumped Modeling Approach*. Eurokarst 2024, Springer.
- 8) Esposito L., **Ginolfi M.**, Leone G., Fiorillo F. (2025) - *Geo-hydrological characteristics that contributed to the choice and configuration of the ancient Roman aqueduct Aqua Augusta from Serino springs*. Water, 17, 3342. <https://doi.org/10.3390/w17233342>
- 9) Leone G., Jourde H., **Ginolfi M.**, Esposito L., Ventafridda G. & Fiorillo F. (2026) - *Modeling the recharge-discharge processes of the Caposele karst spring (Cervialto*

massif, southern Apennine). Rend. Online Soc. Geol. It., 68, <https://doi.org/10.3301/ROL.2026.02>

- 10) Leone G., Abbasi Chenari S., **Ginolfi M.**, Esposito L., Fiorillo F. (2026) - *Long- and short-terms trends in karst groundwater resources using standardized spring discharges and piezometric time series*. Environmental Processes <https://doi.org/10.1007/s40710-026-00825-2>
- 11) Abbasi Chenari S., Leone G., **Ginolfi M.**, Esposito L., Fiorillo F. (2026) - *Flooding of Dragone Plain Polje and its Impacts on the Karst Groundwater Resource (Terminio-Tuoro Massif, southern Apennines, Italy)*. Submitted to Water.

Contributions to National and International Congresses

- 1) Leone G., D'Agostino N., **Ginolfi M.**, Esposito L., Fiorillo F. (2023) - *Hydrological Deformation of the Matese Karst Massif (Southern Italy) recorded by GPS monitoring*. Contribution to XII Congresso Nazionale dei Giovani Ricercatori in Geologia Applicata, Urbino 22th-24th June 2023.
- 2) **Ginolfi M.**, Leone G., Catani V., Pagnozzi M., Testa G., Esposito L., Fiorillo F. (2023) - *Mapping of the Hydrological features of Matese Karst Massif (Southern Italy)*. Contribution to XII Congresso Nazionale dei Giovani Ricercatori in Geologia Applicata, Urbino 22th-24th June 2023.
- 3) Fiorillo F., Cafaro S., Pagnozzi M., Leone G., Lisio S., Esposito L., **Ginolfi M.**, Parise M. (2023) - *Karst Hydrology and Geomorphology of the Alburni Massif (Campania, Italy)*. Contribution to SIMP-SGI-AVI-SOGEI 2023 Congress "The Geoscience Paradigm: resources, risks and future perspectives", 19-21th September 2023, Potenza.
- 4) Leone G., **Ginolfi M.**, Esposito L., Fiorillo F. (2023) - *Terzaghi's effective stress principle and hydrological deformation of karst aquifers detected by GNSS measurements*. Contribution to SIMP-SGI-AVI-SOGEI 2023 Congress "The Geoscience Paradigm: resources, risks and future perspectives", 19-21th September 2023, Potenza.
- 5) **Ginolfi M.**, Leone G., Catani V., Pagnozzi M., Testa G., Esposito L., Fiorillo F. (2024) - *Study of the influence of surface hydrological features in the recharge processes of karst aquifers: the example of the Alburni mountains and of the Matese massif (Southern Apennines)*. Contribution to International Eurokarst Conference, 10-14th June 2024, Rome.

- 6) Leone G., Fiorillo F., Esposito L., **Ginolfi M.**, Hervé J. (2024) - *Analysis and modeling of the complex recharge-discharge relationship of the Caposele karst spring (southern Apennine)*. Contribution to International Eurokarst Conference, 10-14th June 2024, Rome.
- 7) Leone G., Esposito L., **Ginolfi M.**, Fiorillo F. (2024) – *Terzaghi's Effective Stress Principle and Hydrological Deformation of Karst Aquifers Detected by GNSS Measurements*. Contribution to International Eurokarst Conference, 10-14th June 2024, Rome.
- 8) Leone G., **Ginolfi M.**, Esposito L., Fiorillo F. (2024) - *Terzaghi's effective stress principle and hydrological deformation of karst aquifers detected by GNSS measurements*. Contribution to VIII Congresso Nazionale dell'Associazione Italiana di Geologia Applicata e Ambientale, 27-29th June 2024, Naples.
- 9) **Ginolfi M.**, Leone G., Esposito L., Fiorillo F. (2024) - *Relationships between river and groundwater flow in an alluvial plain by time series analysis and numerical modelling: the case of Benevento Plain (southern Italy)*. Contribution to VIII Congresso Nazionale dell'Associazione Italiana di Geologia Applicata e Ambientale, 27-29th June 2024, Naples.
- 10) Leone G., Lisio I.S., **Ginolfi M.**, Esposito L., Parise M., Fiorillo F. (2025) - *Karst Hydrology and Geomorphology of the Matese and Alburni Massifs (southern Italy), Focusing on Dolines and Endorheic Areas*. Contribution to SIMP-SGI-AVI-SOGEI Congress Geology for sustainable management of our planet, 3-5th September 2025, Bari.
- 11) Leone G., **Ginolfi M.**, Esposito L., Fiorillo F. (2025) - *Terzaghi's Effective Stress Principle and Hydrological Deformation of Karst Massifs Detected by GNSS Measurements*. Contribution to SIMP-SGI-AVI-SOGEI Congress Geology for sustainable management of our planet, 3-5th September 2025, Bari.
- 12) Leone G., **Ginolfi M.**, Esposito L., Fiorillo F. (2025) - *Terzaghi's Effective Stress Principle and Hydrological Deformation of Matese Karst Aquifer Detected by GNSS and InSar*. Contribution to FlowPath National Meeting on Hydrogeology, 11-13th June 2025, Turin.
- 13) Esposito L., **Ginolfi M.**, Leone G., Fiorillo F. (2025) - *Historical aspects of the water supply of Benevento town*. Contribution to FlowPath National Meeting on Hydrogeology, 11-13th June 2025, Turin.

- 14) Leone G., Esposito L., **Ginolfi M.**, Fiorillo F. (2025) - *Hydrological and Geomorphological Features of the Karst Area of the Grassano-Telese Springs (southern Apennine, Italy)*. Contribution to Congress Geosciences and the Challenges of the 21st Century, 16-18th September, Padova.

Introduction to Processing MODFLOW X theoretical and practical user guide

The numerical modeling of groundwater resources represents one of the most presently methods with the aim to reach the rational use and the safeguard of water resources. To this purpose, during years, several mathematical models for the water management have been developed.

The usage of these modeling methodologies needs good mathematical and physical skills, and, in some cases, also geological. Also, a huge collection of data regarding the studied aquifers features and the withdrawal amounts from springs and wells are required.

The main aim of this user guide is that to provide a brief overview of usage of mathematical models used for groundwater resources modeling. Then, theory about MODFLOW code, MODPATH software and friendly user-interface Processing MODFLOW X have been described.

After, the interface and functions of user-interface Processing MODFLOW X will be described including also the guided simulation of two cases of groundwater flow modeling considering different scenarios.

At the end, to contextualize the contents of the guide, several examples, from scientific literature, of use of MODFLOW code for safeguard and quality and quantity management of groundwater resources will be reported.

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