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Understanding the impacts of overexploitation on the Salento aquifer: A Comprehensive review through well data analysis

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A B S T R A C T

The Salento aquifer located in the Salento Peninsula in Southern Italy plays a vital role in supporting various sectors like agriculture, economy, and tourism. However, the aquifer has faced escalating challenges from rising water abstraction, falling piezometric levels, and saltwater intrusion for decades. This comprehensive review identifies the varied drivers of increased water abstraction like intensified agricultural activities and expanding tourism, through well data analysis, geological and hydrogeological studies, alongside evaluations of land use patterns, water consumption trends, and meteorological records. The study compares the findings of previous research, which have consistently shown a downward trend in the piezometric levels of the aquifer over several decades, confirming that this decline persists to the present day. The analysis of new and historical well data is combined with existing studies to explore the complex interactions between climate change and human impacts on the aquifer, providing general recommendations for sustainable aquifer management.

1. Introduction

The issue of water availability has emerged as a significant challenge for many countries due to various human activities, including industrial and agricultural expansion, urban development, population growth, rising tourism, and the impacts of climate change. These factors have led to noticeable shifts in both the quantity and quality of groundwater, with harmful effects on public health [35].

Groundwater systems along coastlines, known as coastal aquifers, span the transition from terrestrial to marine environments. These critical zones are where geological, hydrological, and oceanographic systems converge. Coastal aquifers provide freshwater to more than one billion people who live along the coast and interact with coastal hazards and coastal ecosystems alike. In the twenty-first century, projected climate change and human population growth will dramatically affect coastal aquifers [60]. Challenges such as saltwater intrusion, intensified by the extraction of groundwater and the rise in sea levels, will compromise both the quality and availability of freshwater from these sources. The coastal karst aquifer composed of soluble rocks like limestone, is vulnerable to tides and sea waves as seawater infiltrates porous rocks, affecting the quality of freshwater resources within the aquifer [45]. Moreover, land use changes related to farming, industrial activities, and urban expansion will further influence the sustainability of groundwater in coastal regions [61]. These aquifers are threatened by groundwater pollution, and this trend is expected to continue in the future due to the increasingly intense and unplanned anthropogenic activities and water exploitation under the climate change impacts [35]. Human activities easily disrupt the balance of the coastal aquifer system, leading to environmental degradation. Seawater intrusion, in particular, is a global concern intensified by excessive groundwater extraction, rising sea levels, climate changes, and alterations in coastal land use. Of these factors, groundwater pumping stands out as a key contributor to the extent and severity of seawater intrusion. Consequently, the salinization of groundwater can directly result from the overexploitation of aquifers, accentuating the challenges posed by seawater intrusion [62]

The scientific community has recognized the assessment and mapping of aquifers' vulnerability to pollution and related risks as to the most effective prevention tools for groundwater protection and management strategies [35,36]. Various approaches have been employed to understand the behavior of coastal aquifers and their response to hydrologic and human-induced stresses, aiming for sustainable groundwater management. Geochemical methods, including electrical conductivity and chloride concentration measurements, are used to detect seawater contamination [46,58]. Some studies combine hydrogeochemical, isotopic, statistical, and GIS approaches to analyze groundwater composition. Remote sensing and geophysical methods aid

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in subsurface exploration for coastal environment characterization [39,31,62]. Numerical models are utilized to predict groundwater evolution under different stress scenarios European and national regulations advocate for modeling tools to assess coastal aquifer status and predict saltwater intrusion due to overexploitation and climate change [6,18,23,26,61].

Coastal aquifers play a crucial role in meeting irrigation and domestic water needs in Italy, especially in the Puglia region which is located in Southeastern Italy [17]. The Puglia region, like much of the Mediterranean region, faces significant challenges due to climate change, particularly desertification. These changes threaten the local economy, especially agriculture, and may lead to migration from regions experiencing severe water scarcity [3]. In Puglia, the total water resources are estimated at around 570 million cubic meters (Mcm) per year, sourced 28 % from springs, 50 % from reservoirs, and the remaining 22 % from groundwater. A significant portion (443 Mcm/year) is imported from other regions, while the rest is extracted from about 90,000 registered wells in the area [22]. Despite the massive import of water, the Puglia groundwater supply barely meets 20 % of the local demand for drinking water [7].

Groundwater in Puglia is affected by two major types of human-related pollution: salt contamination which spreads over large portions of land thus reducing the availability of good quality water; and chemical-physical and biological pollution which is mainly confined to urban areas. In the early 1990s, urban contamination aroused great attention following the continuous use of subsoil for wastewater collection. This is especially relevant to the health, environmental, and economic emergency that hit the area in 1994 (cholera epidemic) [14]

The Puglia region is characterized by a diversity of aquifers, including the Gargano, Murge, Salento, Miocene, Tavoliere, Arco Ionioco Tarantino, Piana Brindisi, Serre Salentine, Saccione, Fortore, and Ofante [3,55]. Within these, the Salento aquifer is further subdivided into various groundwater bodies:

1. Coastal Salento
2. Central-northern Salento
3. Central-southern Salento
4. Miocene central-southern Salento
5. Miocene central-eastern Salento
6. Salento Leccese northern
7. Salento Leccese coastal Adriatic
8. Salento Leccese central
9. Salento Leccese south-western

For the purpose of this review, a generalized approach will be taken, referring to the Salento aquifer as a unified water body within the Altamura limestone unit. Known as one of the largest and most significant aquifers in Italy, the Salento aquifer plays a important role in maintaining the hydrological balance for ecosystems and coastal wetlands and preserving the biodiversity of the region [25]. The aquifer recharges by precipitation and natural groundwater flow from Murge Hills [25], serving domestic, industrial, and agricultural needs. However, its karstic nature makes it vulnerable to saltwater intrusion through rock openings [19]. The Salento region heavily relies on groundwater for agricultural and drinking water supply, as indicated by the significant number of wells in the peninsula, based on surveys conducted by the 'Genio Civile' Department of Regione Puglia. In this region, more than 80 % of the water used for drinking purposes is obtained from groundwater [43].

Water demand has risen due to population growth, a surge in regional tourism in the past few years, and various human activities in Salento. Tourism contributes to increased water use, involving activities such as personal hygiene, leisure pursuits, food production, and maintenance of accommodation facilities [44]. Regarding agriculture, the Salento aquifer is of primary importance for the cultivation of olive trees, vineyards, and seasonal crops, which are the key sectors of the local economy since the Salento peninsula, is characterized by limited surface water resources [25]. These crops, characterized by a constant demand for water, benefit from the supply provided by the aquifer, which makes it possible to sustain agricultural production and preserve its quality.

Over the past decades, the aquifer has experienced a continuous reduction in groundwater volume due to overexploitation, leading to saltwater intrusion as confirmed by several studies [7–18,24,25,35,36,39,45,52].

The intensification of agricultural production has led to soil degradation and salinization of groundwater in some areas of Salento. This can trigger the process of desertification phenomena. Furthermore, the observed climatic variations tend to expand arid zones, intensify drought events, and increase erosive effects from rainfall [2]. Over abstraction of groundwater is one of the main reasons for the decreasing quantity, driven by demographic development and increasing human activities in the area. As water demands continue to rise, the aquifer is being exploited at a rate that far surpasses its natural recharge capacity. Another concern is the increasing salinity which is linked to the intrusion of seawater into the groundwater, where the freshwater from the aquifer interacts with salty seawater [10,13,34,38]. The excessive withdrawal of freshwater from the aquifer intensifies the intrusion of seawater, exposing not only the availability of potable water but also impacting agricultural practices that rely on adequate freshwater resources [18,39].

The notable variability of the salt content in time and space, as well as the general increase in salinity over the last twenty years, show that the risk of qualitative degradation due to saline contamination of the underground water resources of Salento must not be underestimated. The predominant cause of the worsening of salinity is the total lack of correct planning and management of underground water resources, currently subject to extensive overexploitation, aimed at satisfying an uncontrolled and unsustainable growing demand for natural resources [47].

There has been a concerning rise in marine water intrusion in numerous wells utilized by the Acquedotto Pugliese (AQP) for potable water extraction. This issue has been linked to the progressive reduction in average annual rainfall over the past fifty years. Additionally, the pollution of groundwater due to the disposal of domestic waste is particularly significant in Salento. This is because many of the wells used for drawing drinking water are situated close to sites where municipal waste is directly discharged underground. This proximity raises concerns about the potential contamination of the water supply [35].

Research by Cotecchia et al., in 1998 and 2002 [7,11] highlights the issue of metal pollution in several southern regions largely due to widespread industrial and commercial activities. The Salento Peninsula faces serious pollution including organic, bacteriological elements, and toxic metals like lead, creating health risks in the region. A decrease in the overall water quality poses further challenges to the region's ecological balance and economic activities dependent on clean water sources [24].

The issue of desertification is growing in various regions of Italy, particularly in areas like Salento. [28]. The risk of desertification appears large as the Salento aquifer's declining health could disrupt the balance of the local ecosystem and lead to soil degradation. This situation is currently threatened by climate change, which is leading to an increase in groundwater exploitation as in other areas characterized by a high level of urbanization and low natural availability of water resources [2,20,32,33].

This article offers a comprehensive analysis by integrating both recent and historical well data with past studies, aiming to understand the principal factors behind the rise in water extraction in the Salento and their effects on both the water table and salinity patterns. By analyzing and comparing available data with earlier studies, the article seeks to track variations over different periods. Additionally, the impact of human activities, such as the expansion of tourism and the intensification of agriculture, on the equilibrium of the aquifer is assessed. The incorporation of current data in this review helps highlight existing data gaps in the region and lays out recommendations for future work leaning toward the sustainable management of the aquifer. This comprehensive approach not only reveals the underlying causes of hydrological changes but also underscores the importance of integrated water resource management in facing the challenges of overexploitation and environmental sustainability.

2. Geology and hydrogeology

The Salento Peninsula is located in the southeastern part of the Puglia region (Southern Italy) and extends from Ionian to Adriatic Sea (Fig. 1a). The peninsula covers 2760 km^2, and its limits roughly coincide with those of Lecce Province [24]. Geologically, the Salento peninsula belongs to the Apulian carbonate platform that is composed of a well-bedded succession of Jurassic-Cretaceous carbonate rocks, with a thickness varying from about 3–5 km. The basement of the Salento Peninsula is composed of limestone and dolomitic limestone of Cretaceous age, which outcrop in large areas [17] (Fig. 1a). The Salento area represents a complex hydrogeological environment and is characterized by two aquifers. The first, which is the shallower one, is composed of sediments from the Plio-Pleistocene, containing one or more underground water bodies. The second aquifer is deeper and consists of Mesozoic carbonate formations. This aquifer is highly permeable.

Based on previous research [37–42] the study area reveals a sequence of lithostratigraphic formations, organized chronologically from the oldest to the most recent:

1. The Altamura limestone, made of fractured, karst sediments dating back to the Cretaceous and deposited after periodic emergences of the Apulian platform
2. The Galatone unit, made of thin layers of compact limestone dating back to the Oligocene, overlies Cretaceous limestones with interbedded residual deposits
3. The Miocene unit, which includes different lithologies made of calcarenites and marly limestones
4. The Pliocene unit, which includes different lithologies made of breccias and calcareous conglomerates. The Miocene and Pliocene units were deposited during a period when the region was submerged by seawater
5. The Gravina calcarenites, dating back to Lower Pleistocene
6. The Subappennine clays, dating back to the Middle Pleistocene. These last two units were deposited during a further period of submersion which affected a portion of the peninsula
7. The Terrace deposits, made of sands and silty sands deposited after repeated lifting and lowering of the mean sea level.

The oldest hydrostratigraphic unit (Calcare di Altamura – Altamura limestone) hosts the deep aquifer of the peninsula and consists of fractured limestone and dolomitic limestone, dating back to the Cretaceous and the Oligocene. This hydrostratigraphic unit reaches about 5600 m in depth below the ground surface [1], while its top varies from 250 m above the mean sea level on the northwestern side of the area, to 200 m below the mean sea level near Lecce (Fig. 1b), to 100 m below the mean sea level near Brindisi and down to 250 m below the mean sea level near Taranto. The interface between freshwater and saltwater lies inside this

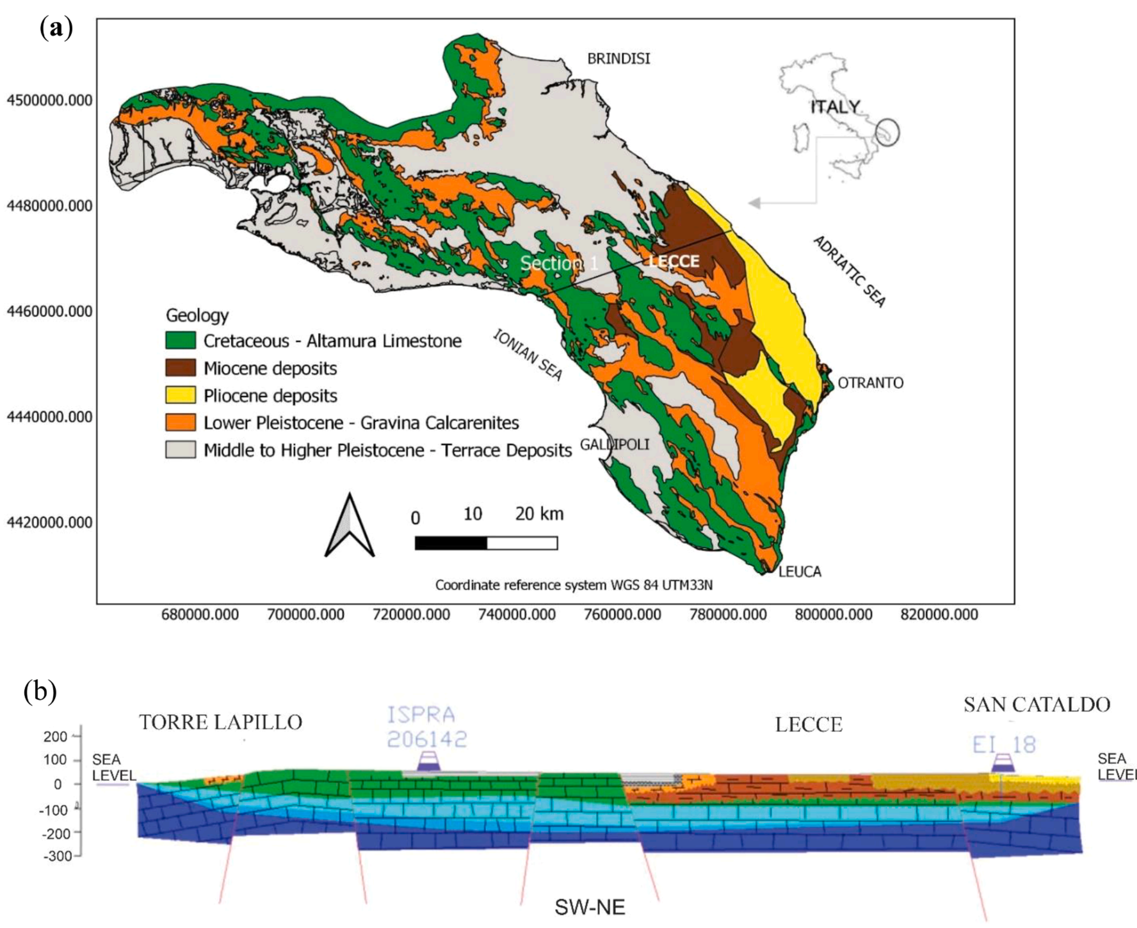

Fig. 1. **(a)** Plan-view Lithological Map of the Salento Peninsula; **(b)** Hydrostratigraphic Cross-Section along the Profile Indicated in Fig. 1(a). The fill colors for geological units are consistent between both figures. In Fig. 1b, dark blue represents the seawater zone, while light blue indicates the freshwater zone.

unit and extends inland [17]. The aquifer takes the shape of a lens floating above saltwater, with maximum thickness in the center of the peninsula [18]. Moreover, the deep aquifer is mostly phreatic (free surface) in the central-western part of the region, while the top of the Altamura limestone stands at hundreds of meters below medium sea level in the eastern portion, where the aquifer is mainly confined. According to the previous groundwater model of the Salento aquifer [17] the thickness of the aquifer reaches its maximum in the center of the Peninsula while it decreases towards the coastline. Below Lecce the thickness of the aquifer changes 10 to 40 m while going south it increases up to 160 m.

3. Materials and methods

The database of the Laboratory of Applied Geophysics, Georesources, and Territorial Diagnostics of the University of Salento has data from 1040 wells that contain geology data. This data provided valuable information regarding the geological characteristics of the study area, including subsurface rock formations, sedimentary layers, their top and bottom information, and structural features. Furthermore, within the dataset, a subset of 170 wells contains piezometric head data measured between 1954 and 2018 in different periods.

In addition, “Acquedotto Pugliese (AQP)”, an organization responsible for the water supply in the region, provided data from 38 wells, with the most recent measurements taken between 2021 and 2023. This information has proven fundamental in the assessment of groundwater levels and salinity trends over the past three years. A subset of 8 wells from the historical database and a set of 4 wells from AQP were chosen for detailed analysis due to their complete information on salinity and piezometric head from the same periods.

To assess water consumption patterns for drinking and agricultural purposes, data was collected from multiple sources, including Regione Puglia, AQP, the Italian National Institute of Statistics (ISTAT), and the Italian Institute for Environmental Protection and Research (ISPRA). Data on land use, statistics of tourism, and population figures were obtained from reports provided by ISTAT and Regione Puglia. These datasets allowed for an understanding of the spatial distribution of land uses, identification of areas with high tourism activity, and assessment of population density trends.

Fig. 2 provides a visual representation of the spatial distribution of the well data.

The data interpretation, encompassing water usage patterns, land use distribution, tourism statistics, population trends, and meteorological variables, including annual rainfall, was carried out systematically. This approach aimed to extract visual materials representing geological characteristics, piezometric head, salinity, and their interrelationships. The kriging method in Surfer was utilized to extract visual materials from well data for piezometric head analysis. Interpolated contour lines of piezometric data from 170 wells are represented in Fig. 6. Comparisons were conducted between available salinity and piezometric data, utilizing Python and the Matplotlib libraries for their visualization.

4. Causes and drivers of increasing water abstraction

4.1. Water consumption for drinking purposes

Withdrawals from the Salento aquifer is mainly due to agricultural uses: on the other hand, the extractions for industrial purposes mainly affect the shallow aquifer. The water consumption for drinking purposes in Puglia varies significantly across the region, influenced by factors such as water infrastructure, territory appeal (for agriculture, tourism, work, study, and health), population demographics, and socio-economic dynamics. The estimated water abstraction for drinking purposes in 2009, sourced from Regione Puglia, amounted to a total of 120.9 million cubic meters per year (m^3/year), while for 2020, this number increased to 166,4 million cubic meters [30]. Between 2015 and 2019, the Puglia region experienced a significant increase in the extraction of groundwater for production purposes. This represents a considerable percentage change and indicates a notable expansion in the usage of groundwater for various industrial or commercial activities within the region.

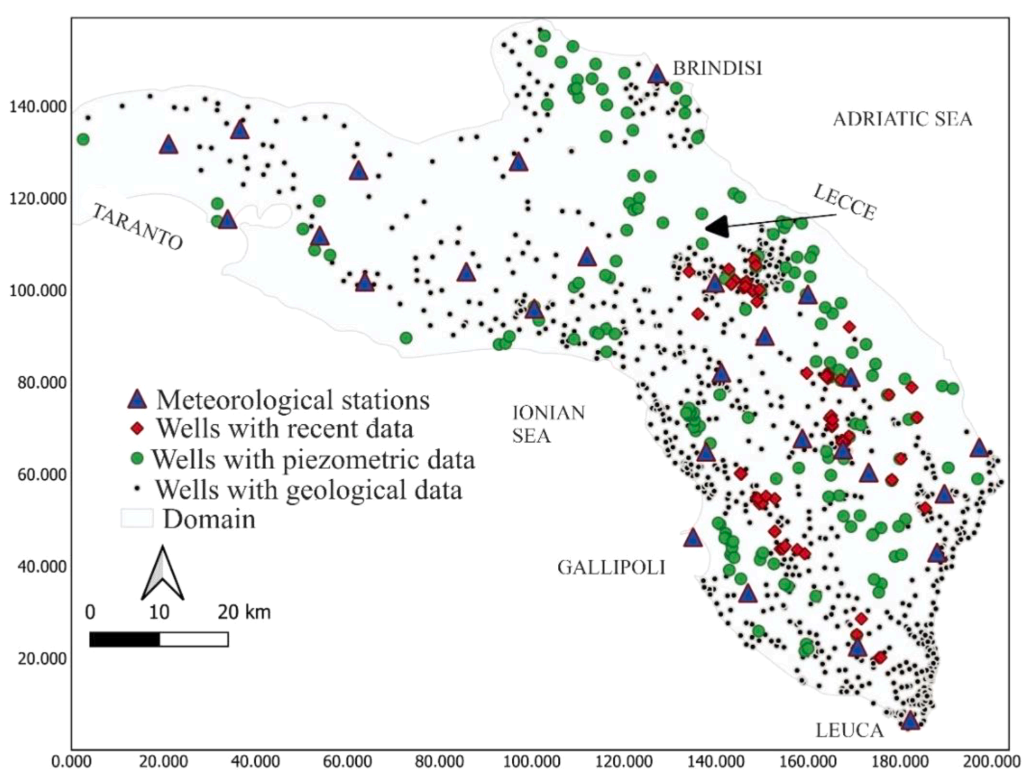

Fig. 2. Geographical distribution of wells and meteorological stations.

On a daily basis, Italy withdraws 25 million cubic meters of water, which averages to 419 liters per resident, as reported by the ISTAT [30] on December 10, 2020. The total amount of potable water withdrawn in Italy, encompassing domestic, public, commercial, industrial, and agricultural usage within the municipal network, stands at 9.2 billion cubic meters. Comparing water consumption regionally, Puglia's average daily water consumption per inhabitant in 2020 is recorded at 155 liters. Despite efforts to manage water consumption, Puglia still faces challenges in meeting the water demand within its borders. The region's internal water sources only provide 116 liters of water per person per day, significantly lower than the actual daily usage of 277 liters per person. As a result, Puglia relies on external sources, potentially neighboring regions, to bridge this gap and ensure an adequate supply of drinking water for its population. In the year 2020, the total billed water for domestic civil use in Lecce, a provincial capital/metropolitan city, amounted to thousands of cubic meters. On average, each inhabitant consumed approximately 189 liters per day [30].

4.2. Water loss

Regions in Southern Italy, in particular, Basilicata and Puglia emerging as the most affected areas, experiencing alarmingly high rates of water losses from their municipal drinking water distribution networks. Puglia reports a considerable water loss of 59 %. In the year 2020, the municipal drinking water distribution network in Lecce City supplied a significant amount of water into its distribution network, reaching a total of 8479 m^3/day per kilometer of the network. This volume represented the supply of water from the city's water sources, including reservoirs, groundwater, and other water supply systems. For authorized uses, which encompassed all legitimate purposes for water consumption within the city, Lecce delivered a total of 6857 m^3/day per kilometer of the distribution network. In 2020, Lecce experienced minimal water loss, a rare positive note in the broader context of water management challenges. However, comprehensive data for other periods is unavailable. From an ecological perspective, the significance of

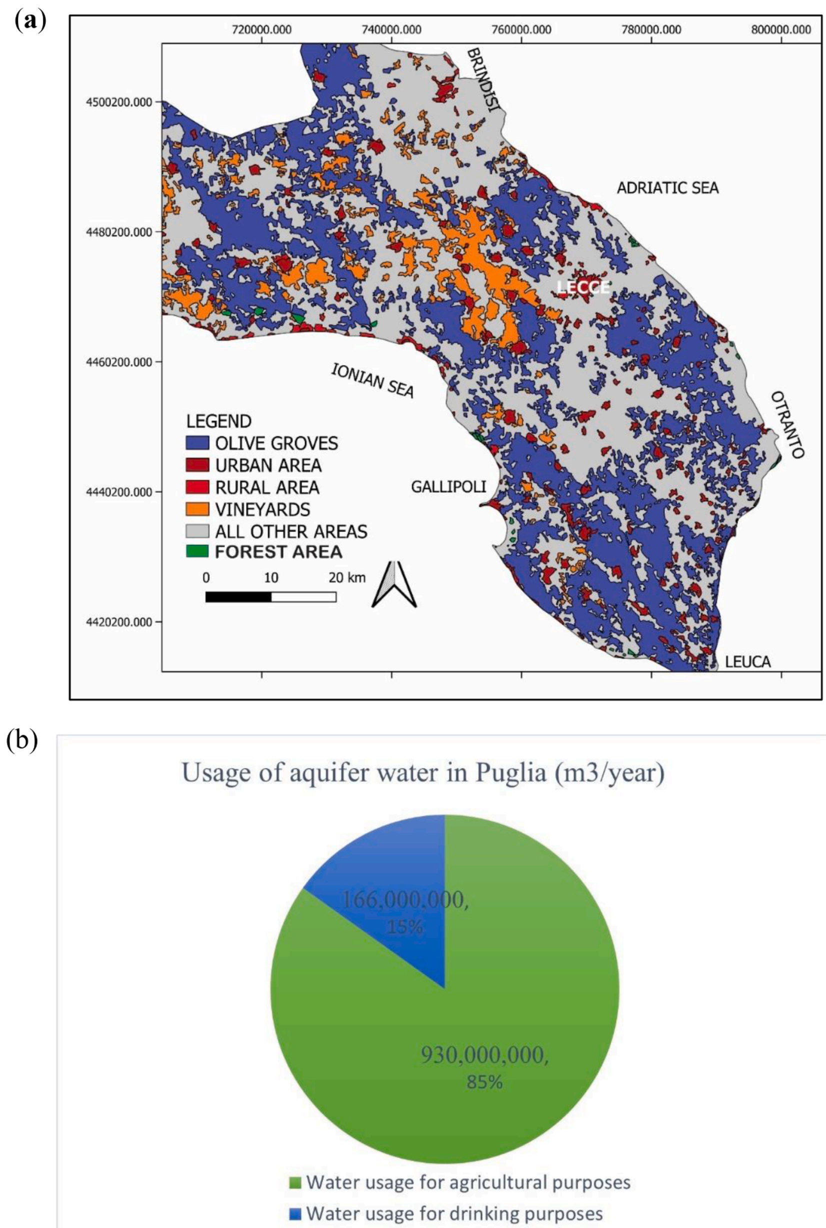

Fig. 3. (a) Simplified Land Use Map of Salento (Modified after SIT Puglia 2011) [57] (b) The distribution of aquifer water usage in Puglia.

minimizing water loss cannot be underestimated, as it increases pressure on the limited water resources in the area [55].

4.3. Water use for Agricultural purposes

Puglia's rural area covers 19,541 square kilometers, with 1.3 million hectares dedicated to agriculture. This scenic region boasts 65.8 percent of its land covered with forests and other wooded areas, spanning 0.2 million hectares. According to Regione Puglia wine yards, agricultural crops, and olive trees are the major irrigated crops, constituting about 80 % of the total irrigated area with the irrigation network of Puglia. The primary sector, especially irrigated agriculture (vines, vegetables, etc.), has a significant impact on Puglia's water availability shortage. Water abstraction for irrigation is based on the land use map of the SIT (Territorial Information System) Puglia from 2011 (Fig. 3a). This yields a total abstraction for irrigation equal to 930 $\times$ 10^6 m^3 /year [54] (Fig. 3b).

According to data from Regione Puglia - Department of Genio Civile, there were 18,474 authorized wells in Puglia between 1980 and 1999, with 15,302 of them intended for agricultural use, particularly irrigation. However, it is suspected that the number of illegal wells far exceeds the authorized ones. It has been estimated that in certain regions, there could be around 10 illegal wells for every authorized well. Applying this ratio to the entire region, it is likely that Puglia has approximately 100,000 private wells, primarily (about 80 %) utilized for irrigation purposes. Unfortunately, there is a lack of specific data on the volumes of water withdrawn, the pump capacities, and the corresponding irrigated areas. Some information on the maximum flow rates and well depths can be obtained from the Territorial Information System (SIT) of the Irrigation Authority. However, this archive only covers 16,707 wells, of which 15,302 are used for irrigation.

4.4. Effects of Tourism on water consumption

Over the past five years, the tourism sector in Apulia has experienced strong growth. Global arrivals have increased by more than 30 %, with 4.2 million arrivals, including 1.2 million foreigners. Fig. 4a represents a 70 % increase since 2015. The ISTAT 2020 [29,30] report indicates that the summer months, especially August, experience a significant surge in tourist activity [30]. During the 2022 summer season, Puglia saw over two million arrivals and more than ten million tourist stays. From January to October 2022, there were 3902,400 arrivals and 14,956,400 overnight stays, marking a slight decline of −1 % in arrivals but a positive trend of +1 % in overnight stays compared to the same period in 2019 [57].

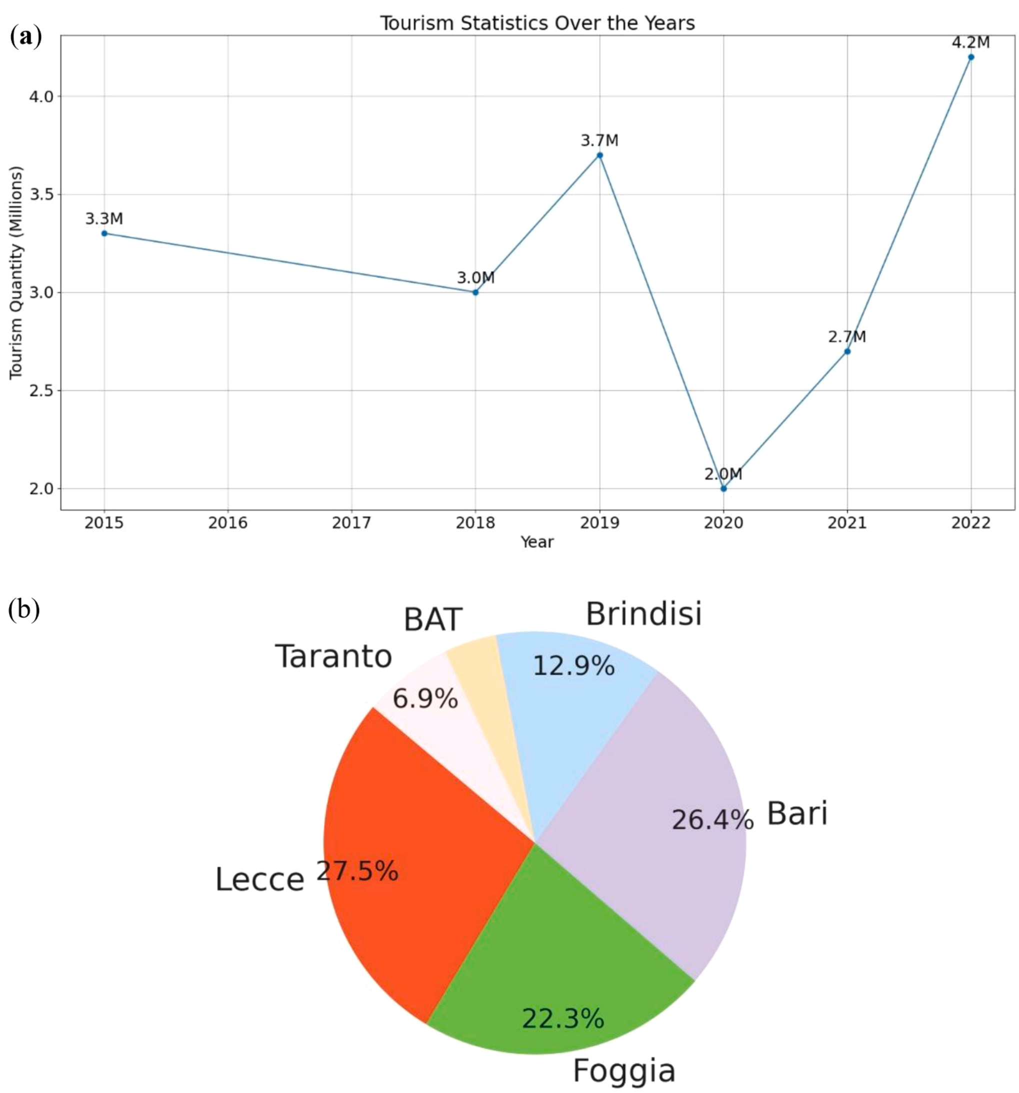

Fig. 4. (**a**) Total arrivals in Puglia (**b**) Distribution of arrivals in Puglia in 2022 [29].

It is remarkable that in 2020, the tourism sector faced a minimum due to pandemic-related restrictions, which significantly impacted global travel and tourism activities. However, right after this period, a resurgence in tourism numbers is observed, indicating a robust recovery. Compared to 2021, arrivals and overnight stays in 2022 experienced significant growth, with +26 % and +12 % respectively. In 2022, foreign tourist arrivals and attendance surpassed pre-pandemic levels by 7 % and 11 % respectively [29,53]. Foggia and Lecce emerged as key provinces with a predominant focus on seaside tourism (Fig. 4b), driving a peak in tourist flows. However, an in-depth analysis reveals a significant environmental impact in the province of Lecce, particularly due to the concentration of arrivals (27.5 %) and stays (30.9%) in the summer months. The Province of Lecce, spanning 279,907 square kilometers, boasts a population of 795,134. In fact, for every resident, 1.35 tourists are arriving in Lecce, highlighting the city's tourist appeal. Furthermore, each tourist who arrives in Lecce tends to stay overnight, and some even stay for multiple nights. This is evidenced by the fact that the number of overnight stays by tourists exceeds the city's population by a factor of six. All these elements combined point towards a vibrant tourism industry, where Lecce holds a prominent position in the regional tourism market of Puglia.

Hotels and resorts play a crucial role in water consumption. These establishments utilize water for various purposes, such as showers, toilets, kitchens, laundry, swimming pools, cooling, and irrigation. The average water consumption rates for hotels and resorts can range from 84 to 2000 liters per tourist per day, with some establishments consuming as much as 3423 liters per bedroom per day. Factors like irrigated gardens and swimming pools contribute significantly to water usage, with rural areas generally having higher water demands than urban areas and high-rise hotels and campsites consuming less water than luxurious five-star hotels [28]. In 2018, the surveyed tourist movement at the national level consumed 4 liters of potable water per capita daily. This represented a growth from 3.7 to 4 liters per capita between 2015 and 2018, indicating an increasing demand for water resources [28]. As tourist arrivals surge during the hot season, water scarcity becomes a concern for both the natural environment and agricultural needs. This demand for water resources is quantified by comparing the daily per capita consumption of water for residents with the equivalent population, which considers tourist presences spread throughout the year.

5. Problems

5.1. Rainfall scarcity

Decreasing precipitation directly impacts groundwater recharge processes, resulting in diminished aquifer storage, particularly when rainfall constitutes the primary source of aquifer replenishment. This phenomenon is especially critical in scenarios where continuous pumping activities prevail, leading to an imbalance between the rates of aquifer recharge and water extraction.

In Italy, particularly certain southern regions have been identified as at risk of becoming dry, mainly during the summer months. During this time, temperatures often increase above 30 °C, sometimes reaching 40 °C, while rainfall becomes scarce or nonexistent for extended periods. This has led to a P/EPT (Precipitation/Evapotranspiration) ratio in these areas ranging between 0.2 and 0.5 [32,33]. Low and declining rainfall levels in Southern Italy, with varying situations among different stations pose significant challenges for the recharge of groundwater resources and agricultural activities in the medium to long term. This problem has become a pressing concern in Salento, particularly during the autumn and winter seasons, leading to water supply challenges for agriculture and other sectors [9,50].

Previous studies analyzed long-term data from rain gauge stations in Puglia to establish a non-empirical aridity index, calculating summer periods of consecutive dry days and using extreme event statistics to correlate these sequences with aridity levels. The findings indicate that in Salento, periods exceeding 50 consecutive days of summer drought are frequent, occurring once every 2 years in Gallipoli, every 3.1 years in Otranto and Taranto, highlighting the significant thermal and water stress affecting the region's vegetation during summer [32,33].

A significant downward trend in annual rainfall, affecting 97 % of Southern Italy from 1921 to 2001, has been observed, which adversely affects the sustainability of groundwater resources [48].

Data from Salento over 40 years of the period show annual precipitation ranging between 600 and 800 mm. The line plot in Fig. 5 shows variations in annual rainfall for Lecce, Brindisi, and Taranto between the years 1980 and 2021. Lecce experienced its highest rainfall after the drought period, in 2002 with a precipitation of 958.8 mm/year. On the contrary, 2020 was notably drier, registering the lowest rainfall. On average, Lecce received approximately 630.6 mm/year of rainfall between 1980 and 2021. While the rainfall patterns for Brindisi and Taranto show their unique trends, it's evident that all three cities have years where rainfall is scarcer and others where it is more abundant.

There have been several studies on rainfall scarcity and drought periods in Salento [2,4,5,21,48]. Based on the research by Alfio et al. [1] precipitation in Salento is about 638 mm/year (concerning the period 1951–2002), where 60 % is lost due to evapotranspiration, 118 mm/year represents the runoff, 34 mm/year the irrigation and only 132 mm/year recharge the aquifer.

Balacco et al. [4] focused on Salento's karst coastal aquifer droughts (1949–2011). They linked meteorological and groundwater droughts, finding decreased groundwater levels at four monitoring wells due to "recharge droughts" and overexploitation, more than climate change.

Doglioni and Simeone's [21] temperature analysis detected changing daily peaks, impacting groundwater. During a 1987–1994 drought, the water level in Salento's coastal karst aquifer dropped significantly, exposing vulnerability to groundwater depletion and slow recovery from saltwater intrusion. Climate change and human factors intensify groundwater stress. Despite climate change's role, human-induced groundwater exploitation's lack of control, identified by various authors, remains the primary issue.

According to the results of previous models, the main aquifer in the study area is recharged primarily through rain infiltration and inflow from the adjacent "Murge" hills [25,17]. According to Polemio et al. [48], the data from 2002 indicated a concerning decrease in groundwater levels across southern Italy caused by the droughts since 1980 and 2000–2002. This trend continued into 2003 in areas like Murgia and Salento, despite over a year of increasing rainfall, suggesting a lasting impact of the drought on groundwater resources. This indicates that the recovery of groundwater resources from drought conditions is slow and may not immediately respond to subsequent increases in rainfall.

The synthesis of meteorological data and prior studies underscores a continuing decline in precipitation within the Salento region, which consequentially impairs the recharge of the aquifer, heavily reliant on rain infiltration and flow from the adjacent Murge hills.

5.2. Decreasing piezometric level

The declining piezometric levels in Salento have been a persistent issue for many decades, intensified by the increasing water demand and the impacts of climate change. Several studies focused on interpreting and modeling the changes in aquifer patterns due to overexploitation in Salento. For example, Margiotta and Negri [39] characterized the aquifer by monitoring various parameters such as piezometric level, salinity, pH, dissolved oxygen, and the volume of freshwater using geophysical surveys such as electrical tomography and induced polarization. The surveys conducted from 1987 to 2003 in Salento revealed a 0.50 m decline in the piezometric level, leading to a nearly 20-meter reduction in the freshwater aquifer thickness. This change in thickness is calculated through the Ghyben-Herzberg approximation, a method used for estimating the relationship between freshwater and saltwater in

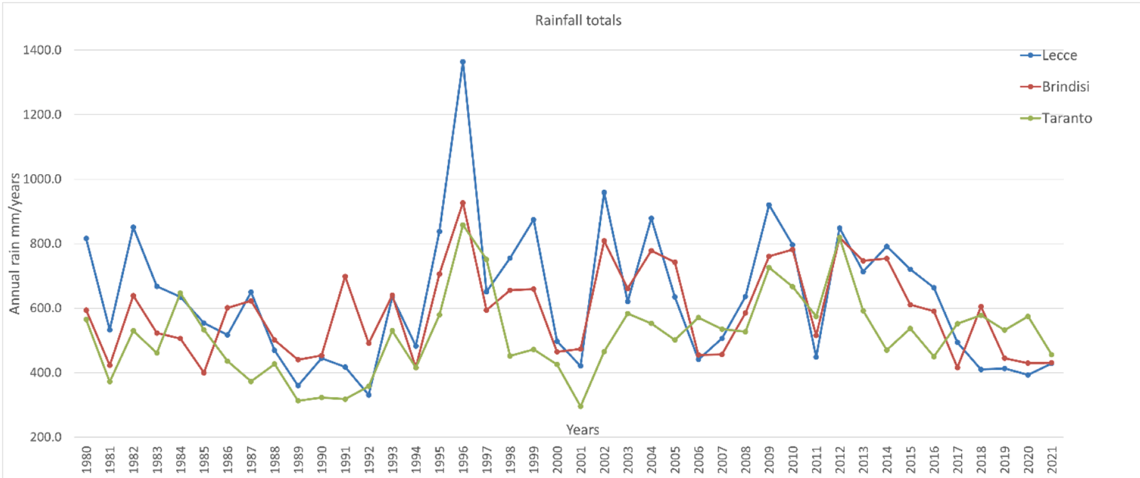

Fig. 5. Rainfall Totals for Lecce, Brindisi, and Taranto from 1980 to 2021.

coastal aquifers. Applying the Ghyben-Herzberg approximation, which suggests multiplying the piezometric head by a factor of 40 to estimate the freshwater aquifer thickness, yields a theoretical thickness of 20 m (Thickness of freshwater = 0.5 × 40 = 20 m). While this approximation serves as a useful guideline, it is important to note that its accuracy can vary [51].

The numerical model by Giudici et al. [25], which was later expanded upon by De Filippis et al. [17] involved an in-depth investigation of the hydro stratigraphic setup in areas with saltwater-saturated deep aquifers. They conducted a sensitivity analysis to identify crucial parameters in their numerical model and developed two scenarios to quantify piezometric head changes in response to decreased rainfall and increased abstraction. The results of both scenarios predicted a lowering of the piezometric head in the central part of the Salento Peninsula.

Romanazzi et al. [56] further contributed to the study by developing a 3D density-dependent flow model for the southern part of the peninsula under transient conditions. They created three scenarios covering different periods: 1930–1979, 1980–1989, and 1990–1999. These scenarios indicated a decrease in the piezometric head of up to 2.5 m from the 1930s to the 1990s. Fig. 6 illustrates contour lines of piezometric head values extracted from well data obtained in 1954, primarily covering the years between 1987 and 2018, across various intervals. Due to the absence of continuous monitoring data, it is not possible to observe the temporal fluctuations of the piezometric head within this period. The data points that are available were collected irregularly during the years 1954, 1987, 2003, and 2018. The measurements were taken while the water level remained static. In 2003, the sampling was intentionally carried out in May, marking the conclusion of the wet period when the aquifer undergoes recharge, and in September, after the dry summer characterized by low precipitation in Salento. This timing was chosen to evaluate the influence of seasonal rainfall variations on the levels of the piezometric head.

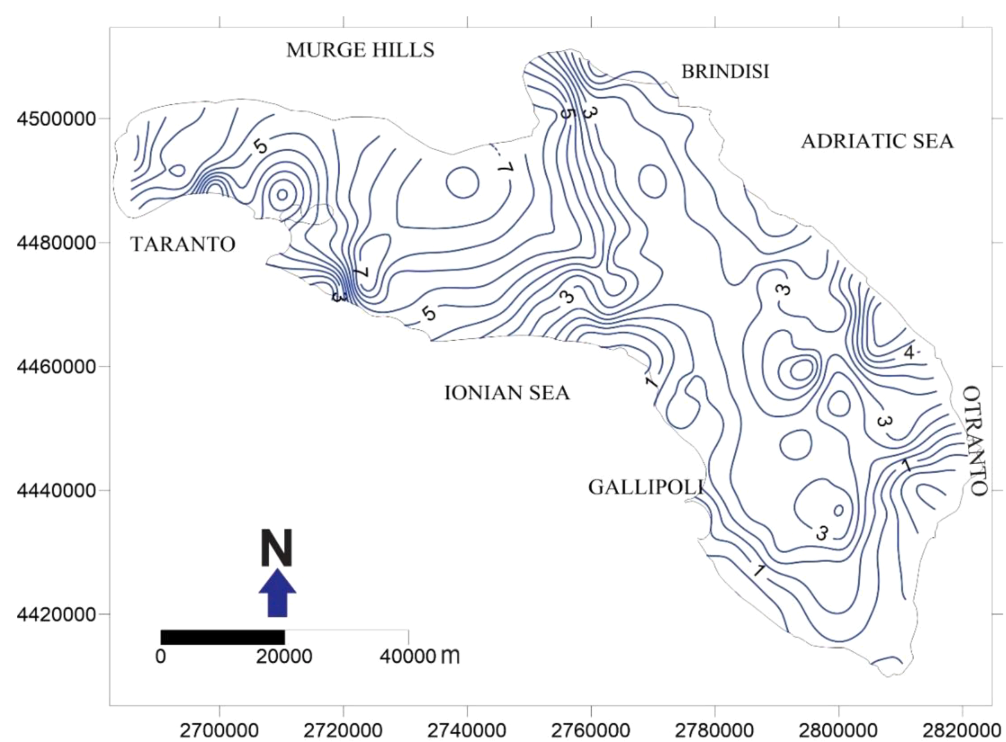

Fig. 6. Contour map of piezometric head over the study area (contour spacing 0.5 m) **(b)** Rainfall Totals for Lecce, Brindisi, and Taranto from 1980 to 2021.

The deep aquifer in the Salento Peninsula is generally characterized by a lens shape floating above saltwater, with a maximum thickness in the central region except in a local area immediately north of Otranto [25,17]. Due to its karstic nature, the aquifer exhibits high permeability, resulting in piezometric head levels ranging between mean sea level (at the coastline) and about 4 m above mean sea level [17]. The highest piezometric head levels are near Murge Hills and Taranto (0.5 - 8 range), indicating the rich availability of groundwater in these areas (Fig. 6). Heading south, levels decrease with lower terrain. Water naturally moves from high to low hydraulic head areas, showing north-to-south groundwater flow. Coastal areas also exhibit natural flow to the sea. Lecce, Otranto, Taranto, and Murge hills have tightly packed contours, implying fast groundwater flow. Central and western zones feature wider-spaced contours, signaling slower flow.

This paragraph focuses on a few wells near Lecce that provided reliable information for piezometric head interpretation. Fig. 7a illustrates the location of the analyzed wells and Fig. 7b shows the change in piezometric heads and salinity values measured in June 1987, May and September 2003, and September 2018. The depth of the measurements was not deep enough to provide information about the transition zone. The observed average decrease in piezometric head was about 0.50 m. There was a gradual, though not particularly significant, lowering of the piezometric level in the wells between the years 1987 and 2003, followed by a period of stability with similar values observed from 2003 to 2018 (Fig. 7b). This stability observed could depend on potential recharge resulting from a slight increase in rainfall between 2003 and 2018, when compared to the rainfall totals recorded between 1987 and 2003 (Fig. 5), or a decrease in use for agricultural purposes, although this is the least recognized assumption. To understand these patterns more comprehensively, continuous monitoring data is essential.

Analyzing the impact of the dry and wet seasons in 2003, measurements indicated that the piezometric head in wells number 28 and 32 experienced a decline from May, following the wet period, to September, after the drier months (Fig. 7b).

The change in the piezometric head for wells 26, 28, 31, 32, 33, 36, 37, and 40 is summarized in the Table 1:

The piezometric level, on average, decreased from 1987 to 2003 by approximately 0.38 m. The total average change from 1987 to 2018 decreased by about 0.32 m. Despite the overall decreasing trend in piezometric heads among the wells from 1987 to 2018, well number 32 turned from this pattern, showing a minor increase.

Comparing the findings with the previous work conducted by Polemio et al. in 2011 [49] on the same area reveals a consistent pattern of declining piezometric levels in the Salento aquifer, extending the observed trend to the present day. Polemio et al. [49] reconstructed the piezometric surface for various years up to 2010 and also noted a

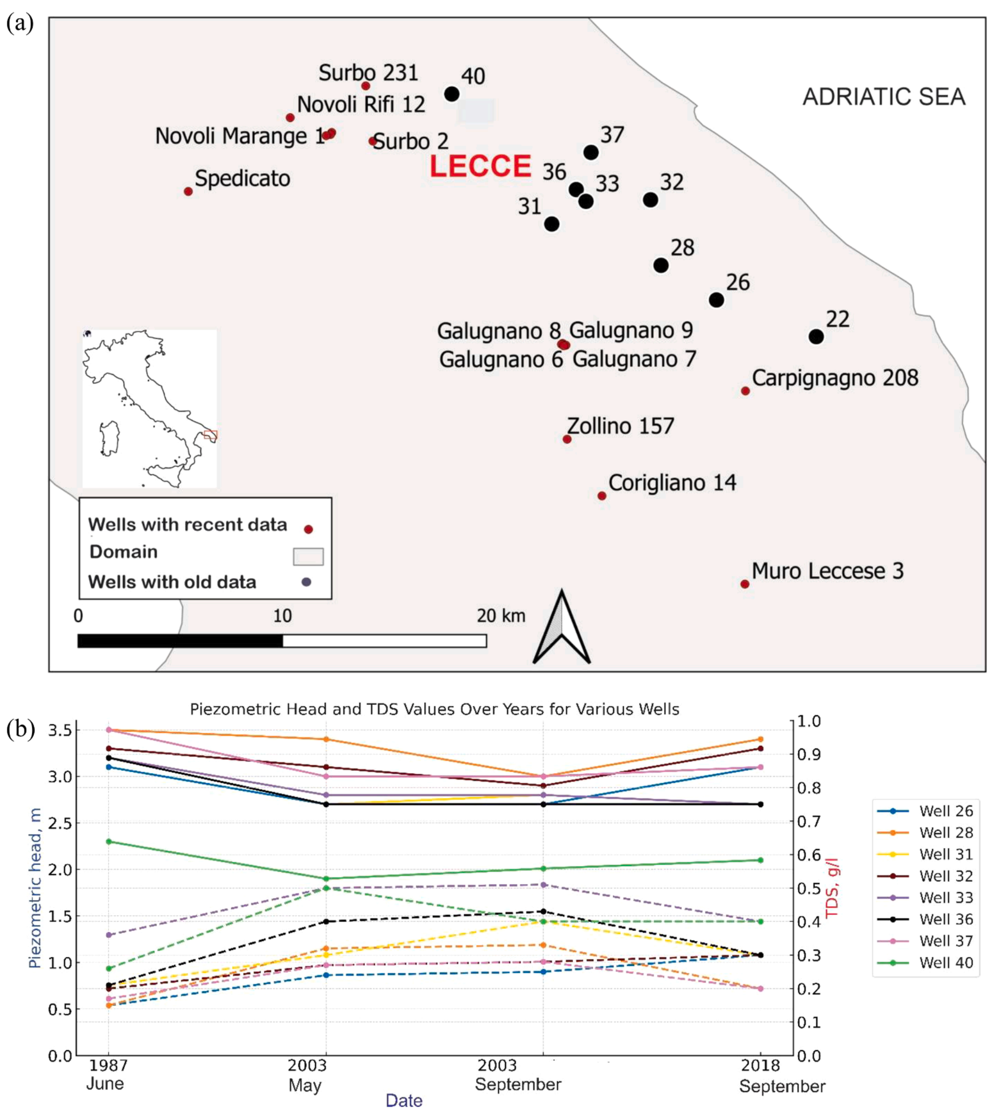

Fig. 7. (**a**) Geographical distribution of analyzed wells (**b**) Piezometric Head (Solid Lines) and Salinity Values (Dashed Lines) over time.

Table 1
Change in Piezometric head for each well. For the location of the wells see Fig. 7a

Well Number	Change 1987–2003	Change 2003–2018	Total Change 1987–2018
26	−0.40	+0.30	−0.10
28	−0.10	0.00	−0.10
31	−0.45	−0.08	−0.53
32	−0.40	+0.45	+0.05
33	−0.45	−0.04	−0.49
36	−0.46	−0.02	−0.48
37	−0.50	+0.14	−0.36
40	−0.40	+0.10	−0.30

decrease in the piezometric head with some fluctuations, such as a stabilization in 1996 attributed to a particularly wet year. The study calculated the average piezometric variation for each interval since 1930. The average decline was found to be 0.165 m in 1976, 0.20 m in 1996, 0.876 m in 2003, and 0.397 m in 2010. The research underscored the influence of both climatic changes and aquifer withdrawals on the flow rates of coastal springs, marking them as critical points in the aquifer's hydrological cycle. Well number 32, included in this study, showed a decreasing trend in Polemio's findings between 1973 and 2010, contrasting with the minor increase observed in this research from 1987 to 2018.

This comparison underlines the continuing decrease in the piezometric head within the Salento aquifer, emphasizing the persistent challenge of managing groundwater resources among varying climatic conditions and extraction rates. Overall, the consistent downward trend underscores the need for sustained monitoring and adaptive management strategies to mitigate the impacts of declining groundwater levels in the region.

5.3. Rising salinity

The phenomenon of salt contamination in Apulian groundwater, flowing through karstic limestones and overlaying intruded seawater, has been extensively studied for decades [10,13,16]. Currently, there is a well-established link between the rise in salt contamination and the decline in piezometric levels, attributed to either excessive groundwater extraction or a decrease in rainfall [16]. Studies conducted in Salento indicate an increase in salinization within the aquifer, with higher salinity levels observed near the Adriatic coast compared to the Ionian coast.

The study by Cotecchia [10] examines fluctuations in the transition zone of Salento aquifer which are typically due to natural recharge and depletion cycles. However, an imbalance between precipitation and the lowering of the piezometric surface is observed in different areas. In some cases, changes in the transition zone are linked to nearby water withdrawals. Salt content showed a significant increase in some wells in Southern parts of Salento, with logs showing an expanded transition zone and a notable decrease in freshwater depth.

According to the research by [16] Cotecchia and Polemio and a subsequent similar study conducted by [47] Polemio et al. in 2006, the spatiotemporal evolution of salinity is important to assess marine intrusion phenomena. These studies established a threshold salinity level of 0.5 g/l and they identified three distinct categories based on vulnerability to seawater intrusion: areas with low vulnerability where salinity remains below 0.5 g/l, regions highly vulnerable with salinity consistently exceeding this threshold, and areas with variable vulnerability where the extent of salt degradation is largely influenced by the management of water discharge. The findings consistently showed that the coastal areas of Salento exhibited salinity levels exceeding this threshold. In contrast, the central areas of Salento displayed variability in salinity over time (slightly lower or higher than 0.5 g/l). This indicates that coastal areas have been vulnerable to seawater intrusion for several decades, underlining a longstanding environmental challenge in Salento.

Over the last three decades, not only the Salento aquifer but also other aquifers in Puglia, especially in Tavoliere and Murgia, have witnessed a notable decline in piezometric levels, leading to groundwater degradation. In Salento, while the decline is gradual, the naturally low piezometric levels make it vulnerable to salt pollution and seawater intrusion. The study highlights an alarming trend of saltwater intrusion coupled with a steady deterioration in the quality and increasing salinity of groundwater in Apulia Polemio et al. [48].

The research conducted by Margiotta and Negri [39] highlighted significant shifts in Total Dissolved Solids (TDS) levels in several wells, with wells 27, 28, 37, and 40 showing an increase in TDS values ranging from 0.2 to 0.5 g/l since 1987. Fig. 7b presents a detailed examination of the same wells which reveals a gradual increase in average salinity of samples from 0.21 g/l in 1987 to 0.28 g/l in 2003, reaching 0.31 g/l by 2018. This progression confirms a consistent rise in salinity levels over the period under review. The analysis of individual wells in this study reflects the general trend identified by Margiotta and Negri, although with some discrepancies in the extent of change across different wells (Fig. 7b). When examining individual wells, similar trends were observed in all wells from 1987 to 2003, although the exact values varied. The well that recorded the highest salinity in 2018 was Well Number 40, while the lowest was observed in Well Number 28. Not all wells experienced an upward trend. For example, salinity in Well Number 37 decreased between 1987 and 2003, and Well Numbers 36 and 33 saw a decline between 2003 and 2018.

Table 2 shows differences in change of salinity for each well from 1987 to 2003, 2003 to 2018, and total change. Positive values represent an increase in salinity, while negative values in blue signify a decrease. If we take into consideration minor changes in salinity, the salinity in Well N 26 increased by 0.09 g/l from 1987 to 2003. It further rose by 0.06 g/l from 2003 to 2018. Cumulatively, over the entire period from 1987 to 2018, salinity augmented by 0.15 g/l.

In conclusion, while all these wells experienced an increase in salinity, Wells 26 and 40 witnessed a notably higher increase than the average, making them of potential concern. Conversely, Wells 28, 37, and 33 had relatively minor increases in salinity, notably less than the average change across all wells.

Looking at the recent data provided by AQP, (Fig. 8 and Table 3) the salinity of water, measured in grams per liter (g/l), in various wells was observed over three consecutive years: 2021, 2022, and 2023. In 2021, AQP collected 4–5 samples from each well during various months, while in 2022 and 2023, the sampling increased to over 7 samples per well. Some wells have samples from each month in 2022 (Fig. 8). The average salinity for each year was calculated from available samples taken in different months throughout the year (Table 3). During the three years, wells "Muro Leccese 3″, "Corigliano 14″, and "Carpignano 208″ consistently showed the lowest salinity at 0.4 g/l, while "Surbo 2″ and "Surbo 231″ reached the peak at 1 g/l (Table 3). Notably, wells like "Zollino 157″, "Novoli Rifi 12″, "Galugnano 7″, "Galugnano 6″, "Muro Leccese 3″, "Corigliano 14″, "Carpignano 208″, "Novoli Marange 1″, "Novoli Marange

Table 2
Differences in salinity levels. Negative values show a decrease in salinity.

Well Number	Change from 1987 to 2003 (g/l)	Change from 2003 to 2018 (g/l)	Total Change from 1987 to 2018 (g/l)
26	0.09	0.06	0.15
28	0.04	0.01	0.05
37	−0.02	0.05	0.03
22	0.05	0.07	0.12
32	0.06	0.04	0.10
31	0.09	0.00	0.09
36	0.11	−0.02	0.09
40	0.07	0.07	0.14
33	0.11	−0.07	0.04

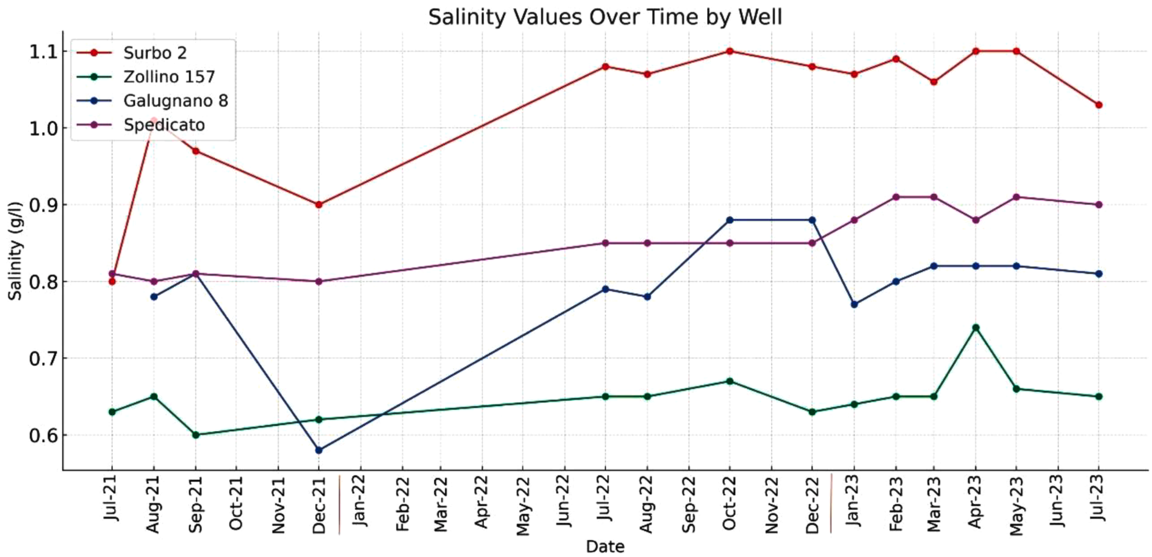

Fig. 8. Salinity values over time in different wells. Values show samples taken in different months.

Table 3
Average salinity levels (g/l) of samples in 2021, 2022 and 2023 in AQP wells.

Well Number	Average salinity 2021 (g/l)	Average salinity 2022 (g/l)	Average salinity 2023 (g/l)
Surbo 2	0.9	1.0	1.0
Zollino 157	0.6	0.6	0.6
Novoli Rifi 12	0.9	0.9	0.9
Galugnano 9	0.9	0.8	0.9
Galugnano 8	0.7	0.8	0.8
Galugnano 7	0.9	0.9	0.9
Galugnano 6	0.8	0.8	0.8
Muro Leccese 3	0.4	0.4	0.4
Corigliano 14	0.4	0.4	0.4
Carpignagno 208	0.4	0.4	0.4
Spedicato	0.8	0.8	0.9
Novoli Marange 3	0.8	0.8	0.8
Novoli Marange 2	0.7	0.7	0.7
Novoli Marange 1	0.7	0.7	0.7
Surbo 231	0.8	1.0	1.0

2″, and "Novoli Marange 3″ maintained stable salinity levels from 2021 to 2023.

Fig. 8 presents salinity values from four wells, illustrating variations based on samples taken during selected months. Comparing changes over time, all four wells showed an increase from 2021 to 2023. The salinity levels in "Surbo 2″ appeared to increase more during the warmer months (July and August) and decrease or stabilize during colder months (December through February). This pattern could be attributed to increased evaporation rates during warmer months, which concentrate salts in the water, thus raising salinity. Conversely, colder months might see reduced evapotranspiration, more rainfall, or increased aquifer recharge, which could stabilize the salinity levels. The well is located in the north of Lecce and is labeled as a discharge well by AQP. As a discharge well, "Surbo 2″ might be subject to varying levels of water extraction and discharge activities throughout the year. During periods of high-water extraction, the well might draw in more saline water or wastewater from surrounding areas or layers, leading to increased salinity levels. Conversely, during periods of reduced extraction or increased recharge, the salinity might decrease. In the plot, "Zollino 157″, "Galugnano 8″, and "Spedicato" demonstrated minor fluctuations in salinity values; however, month-to-month variations reveal a trend of increasing salinity levels over the observed period.

In summary, in terms of magnitude, an increase of 0.1 or 0.15 g/l over three years can be seen as relatively minor, especially if the absolute values remain within acceptable limits for their intended uses. However, context matters:

- If the water is primarily used for drinking, typical salinity standards are much stricter. The World Health Organization (WHO) suggests that the taste of water becomes noticeably salty at around 0.2 g/l. In this context, while the values from our data are below this threshold, the upward trend might warrant monitoring and investigation.
- If the water is used for irrigation, different crops have varying salinity tolerance levels. In general, a salinity level of 1 g/l can be harmful to sensitive crops, so the wells are approaching this threshold, especially Surbo 2.
- For industrial or other uses, the acceptable salinity would depend on specific requirements.

6. Conclusions

This review synthesizes existing literature to understand the long-standing issue of aquifer overexploitation in the region, dating back several decades. Previous studies consistently show a drop in piezometric levels and an increase in salinity gradient, mainly due to increased water extraction. The escalation of these conditions is further influenced by increased tourism, intensified agricultural practices, and prolonged drought episodes.

The integration of meteorological data with previous research highlights a persistent decrease in rainfall over the Salento region, leading to a negative impact on the aquifer's recharge balance, which depends significantly on rainwater infiltration and the inflow from the neighboring Murge hills. Meteorological data indicate that the driest months in Salento are during summer, coinciding with the peak tourist season as shown by tourism statistics. This results in an increased water demand during a period when the aquifer's natural recharge is at its lowest.

Analytical observations from well data validate a diminution in piezometric head alongside an increase in salinity across a majority of wells, inclusive of recent datasets.

The scientific literature and planning tools indicate two significant problems in the Salento aquifer: a decline in available water resources attributed to a high density of pumping wells observed over so many years and an increasing salinity of groundwater connected to the first aspect. As the water levels continue to diminish, seawater intrusion plays an increasingly significant role in further elevating the salinity levels, compounding the challenges faced by the aquifer system.

Discussion and recommendations

The Salento aquifer is currently facing significant environmental challenges. The region has endured droughts that impact agriculture, competing with domestic, industrial, and ecological water needs. The equilibrium between the recharge and discharge of the Salento aquifer is disrupted, compounding desertification. The region faces "medium sensitive" to "very sensitive" desertification risks as per estimates from ISPRA [28].

With limited rainfall and rising demand due to tourism and population growth, excessive water extraction worsens aquifer depletion. Agriculture, particularly the cultivation of olive trees and vineyards, remains a major consumer of aquifer water. The intensive irrigation practices required for these crops contribute significantly to the depletion of the aquifer. The pumping from both legal and illegal wells further compounds this issue, as unregulated water extraction undermines efforts to maintain a sustainable water balance. Tourism, especially in coastal areas like Lecce, places additional demands on the aquifer. The influx of tourists during peak seasons increases water consumption, driven by the needs of hotels, resorts, and other tourist facilities. This surge in water usage during the summer months aligns with a period of lower rainfall, creating a storm for water scarcity.

The observed decline in piezometric levels and increasing salinity in the Salento aquifer underscores the gradual degradation of water quality in the region. As the water table declines, it results in a consequential reduction of the aquifer's thickness. This alteration in the aquifer structure creates a conducive environment for saline water intrusion from adjacent coasts, compromising water quality and availability. In addition to these issues, some researchers have verified that water from certain wells in Salento is contaminated with metals, rendering them unfit for consumption.

These challenges necessitate comprehensive management: sustainable water use, efficient farming, anti-desertification measures, and exploring desalination and rainwater harvesting. Striking a balance between economic development, especially in tourism, and environmental preservation is crucial. However, there is potential for positive change through the rational and efficient use of water resources in agriculture. Combining this with environmentally friendly agricultural practices, such as erosion and desertification mitigation and protection of vegetation cover and soil productivity, can reduce land degradation processes. Integrating environmentally sustainable agricultural practices, including measures to mitigate erosion and desertification, along with the protection of vegetation cover and soil productivity, can significantly curtail land degradation.

Among decreasing rainfall and expanding urban areas, especially in cities such as Lecce where impermeable surfaces prevent rainwater from infiltration into the ground, Managed Aquifer Recharge (MAR) stands out as a crucial approach to support aquifer balance. Infiltration ponds, specifically designed to facilitate the percolation of rainwater through the urban substrate into the aquifer, present a viable solution for cities struggling with the dual challenges of water scarcity and dry climate. The International Groundwater Resources Assessment Centre's MAR portal [27] indicates that such practices are widespread in countries like the Netherlands, Belgium, and parts of France and Germany, underscoring their effectiveness in diverse hydrogeological settings. Within Italy, a total of eleven MAR sites is documented, of which only one is situated in the Salento region. Given the challenges of decreasing rainfall and impermeable surfaces in big cities the adoption of MAR techniques, particularly the establishment of more infiltration ponds, becomes imperative in Salento's urban locales to ensure the aquifer's sustainable replenishment and balance.

Another MAR technique includes the reuse of treated wastewater, which is injected into wells to support aquifer recharge, a practice essential for enhancing sustainability. Research done by De Filippis et al., in 2019 [18] evaluated the effects of injecting treated wastewater from a treatment plant located in Lecce into the aquifer. This innovative approach was explored to increase the aquifer's piezometric head, which is essentially the pressure level in the aquifer, measured as the piezometric head would rise in a well. The simulation results from the MAR experiment showed a promising increase in the piezometric head of up to 12 cm at the locations of the injection wells. This is significant because even a modest rise in the groundwater level can substantially reduce the vulnerability of the aquifer to saltwater intrusion by creating a hydraulic barrier that prevents or slows down the inland movement of saltwater. Moreover, the model predicted that the progression of the saltwater intrusion front would retreat by approximately 1 kilometer at the injection sites. This progression is crucial for the sustainability of groundwater resources in coastal areas, as it implies a reduction in the risk of salinization of freshwater resources, which is a major concern for both drinking water supplies and agricultural irrigation.

The positive outcomes of the MAR experiment highlight its potential as an effective tool in coastal groundwater management strategies. It suggests that treated wastewater, often considered a waste product, can be repurposed to enhance groundwater resources, and protect them from degradation. Additionally, the MAR approach aligns with broader environmental sustainability goals by promoting the reuse of water and protecting freshwater resources from salinization.

Complementarily, the integration of Afforestation and Green Infrastructure within urban and peri-urban landscapes stands as a critical adjunct to MAR efforts. Salento's limited forest coverage and the limited green infrastructure within its cities, especially Lecce, intensify the thermal and hydrological impacts of urbanization. The establishment of trees and vegetative systems not only serves as a natural filtration mechanism, improving groundwater quality but also enhances aquifer recharge by mitigating surface runoff. Moreover, vegetative cover plays a crucial role in moderating urban heat through evapotranspiration, contributing to a more temperate microclimate while indirectly promoting rainfall generation. Strategic investments in green infrastructure - encompassing artificial wetlands, vegetative buffers, and the expansion of urban and peri-urban forests can significantly improve the adverse effects of urbanization on the hydrological cycle. By fostering a symbiotic relationship between urban development and the natural environment, these initiatives can ensure the long-term resilience and sustainability of Salento's aquifer systems.

Furthermore, the development of advanced numerical models for the Salento aquifer is critical for accurately estimating aquifer storage capacities and forecasting potential future scenarios. Evidence from research underscores the value of numerical models in the effective management of aquifers, particularly those at risk. For instance, in some valleys in California, United States America, where agriculture heavily relies on groundwater, the development of various groundwater models (e.g., the Butte Valley groundwater model, San Joaquin Basin groundwater model, and Owens Valley groundwater model) has been instrumental [6,23,59,61]. These models have facilitated climate change analyses and future scenario predictions, taking into account variations in rainfall and extraction rates, especially in the context of decreased precipitation and lowering groundwater levels over the past two decades.

Calibration of numerical models with recent, observed data is crucial to enhance their accuracy and reliability. While historical studies reference monitoring systems dating back to the 1990s, there is a conspicuous lack of updated monitoring data in Salento. Therefore, a modern, continuous monitoring system is necessary for Salento, which should also include the monitoring of seawater intrusion, to ensure the aquifer's sustainable management and protection against over-exploitation and environmental changes. Continuous, data-driven assessments are vital for developing adaptive management strategies responsive to the dynamic conditions of the aquifer.

It's important to acknowledge that despite the analyses conducted from the available data, they only provide a fundamental representation of the potential situations within the complex environment of the karstic Salento aquifer. This complexity makes it challenging to capture and describe the aquifer's full range of characteristics and behaviors accurately.

In conclusion, the sustainable management of water resources is not just a technical challenge but also a societal one. The strategies outlined above provide a multifaceted approach to address the pressing issue of water abstraction. By integrating technological solutions, agricultural reforms, public awareness campaigns, and regulatory measures, we can open the way for a more resilient and sustainable water future. The health of the Salento aquifer is linked to the well-being of our communities, economies, and ecosystems.

CRediT authorship contribution statement

Lala Mammadova: Conceptualization, Data curation, Software, Validation, Visualization, Writing – original draft. **Sergio Negri:** Methodology, Resources, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

[1] Agip, Temperature sotterranee, F.lli Brugora: Segrate (1977). Italian.
[2] M.R. Alfio, G. Balacco, A. Parisi, V. Totaro, M.D. Fidelibus, Drought index as indicator of salinization of the salento aquifer (Southern Italy), Water. (Basel) 12 (7) (2020).
[3] ARPA Puglia. Monitoraggio Corpi Idrici Sotterranei (CISott). https://www.arpa.puglia.it/pagina2939_acque-sotterranee.html [accessed February 2024].
[4] G. Balacco, M.R. Alfio, M.D. Fidelibus, Groundwater drought analysis under data scarcity: the case of the salento aquifer (Italy), Sustainability. 14 (2) (2022) 707.
[5] G. Balacco, M.R. Alfio, A. Parisi, A. Panagopoulos, M.D. Fidelibus, Application of short time series analysis for the hydrodynamic characterization of a coastal karst aquifer: the Salento aquifer (Southern Italy), J. Hydroinformatics 24 (2) (2022) 420.
[6] Butte Valley FINAL Groundwater Sustainability Plan (2021). https://www.co.siskiyou.ca.us/naturalresources/page/butte-valley-final-groundwater-sustainability-plan [accessed February 2024].
[7] V. Cotecchia, M. Polemio, The hydrogeological survey of Apulian groundwater (Southern Italy): salinization, pollution, and over-abstraction, in: H Wheater, C Kirby (Eds.), In: Hydrology in a Changing Environment 3, Wiley, Exeter, United Kingdom, 1998, pp. 129–136.
[8] V. Cotecchia, MEDIT - Rivista di economia, agricoltura e ambiente, Strategie progettuali e gestionali delle risorse idriche 2 (1990) 40–55.
[9] V. Cotecchia, D. Casarano, M. Polemio, Characterization of rainfall trend and drought periods in Southern Italy from 1821 to 2001, in: Conference Paper. 1st Italian-Russian Workshop "New Trends in Hydrology, Rende (CS), Italy, 2004.
[10] V. Cotecchia, Studi e ricerche sulle acque sotterranee e sull'intrusione marina in Puglia (Penisola Salentina), Quaderni dell'Istituto di Ricerca sulle Acque 20 (1977) 103–107. Italian.
[11] V. Cotecchia, M. Daurù, P.P Limoni, D. Mitolo, M. Polemio, Sotterranee Acque, La valutazione della vulnerabilità integrata degli acquiferi, La sperimentazione nell'area campione di Corigliano in Salento 77 (2002) 9–20.
[12] V. Cotecchia, M. Daurù, P.P. Limoni, M. Polemio, M. Spizzico, T. Tadolini, Atti della giornata mondiale dell'acqua Acque sotterranee: risorsa invisibile, Il controllo idro-chimico fisico della falda idrica carbonatica Murgiano-Salentina (Puglia) (1998).
[13] V. Cotecchia, D. Grassi, M. Polemio, Carbonate aquifers in Apulia and seawater intrusion, Giornale di Geologia Applicata 1 (2005) 219–231.
[14] V. Cotecchia, M. Polemio, Dimensione Ricerca, Area di Ricerca CNR, Bari, L'inquinamento salino e la salvaguardia delle acque sotterranee pugliesi mediante il monitoraggio idrogeologico continuo (1997).
[15] V. Cotecchia, Polemio, The hydrogeological survey of Apulian groundwater (Southern Italy): salinization, pollution, and over-abstraction, in: H. Wheater, C. Kirby (Eds.), The hydrogeological survey of Apulian groundwater (Southern Italy): salinization, pollution, and over-abstraction, M. Hydrology Chang. Environ. 3 (1998) 129–136. Eds.
[16] V. Cotecchia, M. Polemio, Salinization and pollution of main Apulian aquifers (Southern Italy), in: Conference paper. International Conference on Water Management, Salinity and Pollution Control towards Sustainable Irrigation in the Mediterranean Region, Valenzano (Bari), Italy, January 1997.
[17] G. De Filippis, M. Giudici, S. Margiotta, F. Mazzone, S. Negri, C. Vassena, Numerical modeling of the groundwater flow in the fractured and karst aquifer of the Salento peninsula (Southern Italy), Acque Sotterranee Ital. J. Groundwater 2 (1) (2013) 17–28.
[18] G. De Filippis, S. Margiotta, C. Branca, S.L. Negri, A modeling approach for assessing the hydrogeological equilibrium of the karst, coastal aquifer of the Salento Peninsula (Southeastern Italy): evaluating the effects of a MAR facility for wastewater reuse, Geofluids (2019).
[19] M. Delle Rose, M. De Marco, A. Federico, C. Fidelibus, G. Internò, W. Orgiato, A. Piscazzi, Studio preliminare sul rischio di desertificazione nel territorio carsico di Lecce, Atti II convegno Il carsismo nell'area mediterranea (2003). Italian.
[20] A. Dipace, G. Baldassare, Aree sensibili alla desertificazione nel Tavoliere di Puglia, Giornale di Geologia Applicata 2 (2005) 203–209. Italian.
[21] A. Doglioni, V. Simeone, The influence of climatic changes on aquifers of Salento area – south Italy, in: In Proceedings of the EGU General Assembly 2010, Vienna, Austria, 08 April 2010, p. 10358, 03–.
[22] ENEA, & Regione Puglia. (2008). Piano di azione locale PAL per la lotta alla Siccità e alla Desertificazione della Regione Puglia.
[23] Evaluation of the hydrologic system and selected water-management alternatives in the owens valley, California (2017). https://ca.water.usgs.gov/projects/owens/report/conclusions.html [accessed February 2024].
[24] M. Fidelibus, A. Pulido-Bosch, Groundwater temperature as an indicator of the vulnerability of karst coastal aquifers, Geosciences. (Basel) 9 (1) (2019) 23.
[25] M. Giudici, S. Margiotta, F. Mazzone, S. Negri, C. Vassena, Modelling hydrostratigraphy and groundwater flow of a fractured and karst aquifer in a Mediterranean basin (Salento peninsula, southeastern Italy), Environ. Earth Sci. 67 (7) (2012) 1891–1907.
[26] Q. Guo, et al., Experiment and numerical simulation of seawater intrusion under the influences of tidal fluctuation and groundwater exploitation in coastal multilayered aquifers, Geofluids (2019) 2316271. Article ID.
[27] International groundwater resources assessment centre. Managed Aquifer Recharge Portal. Available at: https://ggis.un-igrac.org/view/marportal/[accessed February 2024].
[28] ISPRA Institute for Environmental Protection and Research, Indicatori Ambientali (September 2023) available at: https://www.isprambiente.gov.it/it/banche-dati/banche-dati-folder/indicatori-ambientali [accessed].
[29] ISTAT. Puglia Tourism. Spot Sistema Puglia per l'Osservatorio turistico 2022. available at: https://dati.puglia.it/ckan/dataset/movimento-turistico [accessed September 2023].
[30] ISTAT. Rapporto Annuale - La Situazione Del Paese 2020. Available at: https://www.istat.it/it/archivio/244848 [accessed September 2023].
[31] L. Jarlan, S. Khabba, S. Er-Raki, et al., Remote sensing of water resources in semi-arid Mediterranean areas: the joint international laboratory TREMA, Int. J. Remote Sens. 36 (19–20) (2015) 4879–4917.

[32] G. Ladisa, M. Todorovic, G. Trisorio Liuzzi, A GIS-based approach for desertification risk assessment in Apulia region, SE Italy, Phys. Chem. Earth 49 (2012) 103–113.
[33] Ladisa, M.; Todorovic, G.; Trisorio-Liuzzi, G. Characterization of areas sensitive to desertification in southern italy. new trends in water and environmental engineering for safety and life: eco-compatible solutions for aquatic environments. Capri, Italy, 2002.
[34] H. Maathuis, R.N. Yong, S. Adi, S. Prawiradisastra, Development of Groundwater Management Strategies in the Coastal Region of Jakarta, Indonesia, Saskatchewan Research Council Report R-1250-1-E-96 (1996).
[35] M. Maggiore, P. Pagliarulo, Groundwater vulnerability and pollution sources in the Apulian region (Southern Italy), in: Proceedings of the 2nd Symposium on the Protection of Groundwater from Pollution and Seawater Intrusion, Bari, Italy, 1 October 1999, pp. 9–20, 27 September -.
[36] M. Maggiore, P.Workshop Pagliarulo, Uso e tutela dei corpi idrici sotterranei pugliesi, Circolazione idrica ed equilibri idrogeologici negli acquiferi della Puglia (2002) 13–36.
[37] S. Margiotta, Il contatto formazione di Galatone di Lecce evidenze stratigrafi cosedimentologiche, Atti della Società Toscana di Scienze Naturali 106 (1999) 73–77. Italian.
[38] S. Margiotta, S. Negri, Alla ricercarca dell acqua perduta, Congedo Editore: Galatina (2004). Italian.
[39] S. Margiotta, S. Negri, Geophysical and stratigraphical research into deep groundwater and intruding seawater in the Mediterranean area (the Salento Peninsula, Italy), Nat. Hazards Earth Syst. Sci. 5 (1) (2005) 127–136.
[40] S. Margiotta, G. Richetti, Stratigrafia del depositi oligomiocenici del Salento (Puglia), Boll. Societa Geologia 121 (2002) 243–252. Italian.
[41] S. Margiotta, P. Sansò, The Geological Heritage of Otranto–Leuca Coast (Salento, Italy), Geoheritage 6 (4) (2014) 305–316, https://doi.org/10.1007/s12371-014-0126-8.
[42] S. Margiotta, S. Varola, Nuovi dati geologici e paleontologici su alcuni affioramenti nell territorio di Lecce, Atti della Società Toscana di Scienze Naturali 109 (2004) 1–12. Italian.
[43] C. Masciopinto, R. La Mantia, A. Carducci, B. Casini, A. Calvario, E. Jatta, Unsafe tap water in households supplied from groundwater in the Salento Region of Southern Italy, J. Water. Health 5 (1) (2007) 129–148, https://doi.org/10.2166/wh.2006.054.
[44] F. Mazzoni, S. Alvisi, M. Blokker, G. Buchberger, A. Castelletti, A. Cominola, et al., Investigating the characteristics of residential end uses of water: a worldwide review, Water Res. (2022) 230.
[45] A. Parisi, V. Monno, M.D. Fidelibus, Cascading vulnerability scenarios in the management of groundwater depletion and salinization in semi-arid areas, Int. J. Disaster Risk Reduct. 30 (2018) 292–305.
[46] C. Petalas, N. Lambrakis, Simulation of intense salinization phenomena in coastal aquifers—The case of the coastal aquifers of Thrace, J. Hydrol. (Amst) 324 (1–4) (2006) 51–64.
[47] M. Polemio, P.P. Limoni, L'evoluzione dell'inquinamento salino delle acque sotterranee della Murgia e del Salento, Memorie della Società Geologica Italiana 56 (2001) 327–331.
[48] M. Polemio, D. Casarano, Climate change, drought, and groundwater availability in southern Italy, in: W. Dragoni, B.S. Sukhija (Eds.), Climate Change and Groundwater 288, The Geological Society Special Publications, 2008, pp. 39–51.
[49] M. Polemio, V. Dragone, P.P. Limoni, La disponibilità di acque sotterranee in Puglia negli ultimi 80 anni, CNR IRPI (January 2011), https://doi.org/10.13140/2.1.2555.4727.
[50] M. Polemio, D. Casarano, Climate change, drought and groundwater availability in southern Italy, in: W. Dragoni (Ed.), Climate change, drought and groundwater availability in southern Italy, Climate Change Groundwater 288 (2008) 39–51. Geological Society.
[51] M. Pool, J. Carrera, A correction factor to account for mixing in Ghyben-Herzberg and critical pumping rate approximations of seawater intrusion in coastal aquifers, Water Resour. Res. 47 (2011) W05553.
[52] Regione Puglia, Consumo di suolo (September 2023). Report SNPA n. 32/2022. Available at, https://www.snpambiente.it/2022/07/26/consumo-di-suolo-dinamiche-territoriali-e-servizi-ecosistemici-edizione-2022 [accessed].
[53] Regione Puglia, Rapporti e statistiche Turismo (September 2023). Available at, https://aret.regione.puglia.it/dati-e-ricerche/rapporti-e-statistiche [accessed].
[54] Regione Puglia, Relazione Generale - Piano di Tutela delle Acque (2009). Available at, http://www.sit.puglia.it/portal/portale_pianificazione_regionale/Piano%20di%20Tutella%20delle%20Acque [accessed September 2023].
[55] Regione Puglia. Relazione Generale- Piano di Tutela della Acque 2020. Available at: http://www.sit.puglia.it/portal/portale_pianificazione_regionale/Piano%20di%20Tutella%20delle%20Acque [accessed September 2023].
[56] A. Romanazzi, F. Gentile, M. Polemio, Modelling and management of a Mediterranean karstic coastal aquifer under the effects of seawater intrusion and climate change, Environ. Earth Sci. 74 (1) (2015) 115–128.
[57] SIT Puglia. Risorse dell'Agricoltura. Available at: http://www.sit.puglia.it/portal/portale_http://www.sit.puglia.it/portal/portale_cartografie_tecniche_tematiche/Cartografie%20Tematiche/UDSpianificazione_regionale/Piano%20di%20Tutella%20delle%20Acque [accessed September 2023].
[58] M.A. Somay, Ü. Gemici, Assessment of the salinization process at the coastal area with hydrogeochemical tools and geographical information systems (GIS): selçuk plain, Izmir, Turkey, Water. Air. Soil. Pollut. 201 (1–4) (2009) 55–74.
[59] The Central Valley: San Joaquin Basin. https://ca.water.usgs.gov/projects/central-valley/san-joaquin-basin.html [accessed February 2024].
[60] U.S. Geological Survey, Environmental geochemistry of coastal aquifers, wetlands, and tidal exchange, Woods Hole Coastal Marine Sci. Center (February 2024). https://www.usgs.gov/centers/whcmsc/science/environmental-geochemistry-coastal-aquifers-wetlands-and-tidal-exchange [accessed].
[61] USGS. (2024). Sustainable Groundwater Management in California. Available at: https://ca.water.usgs.gov/sustainable-groundwater-management/california-groundwater-modeling.html [accessed February 2024].
[62] Z. Zhu, Z. Shan, Y. Pang, A. Revil, et al., The transient electromagnetic (TEM) method reveals the role of tectonic faults in seawater intrusion at Zhoushan islands (Hangzhou Bay, China), Eng. Geol. 330 (7) (2024) 107425.