Abstract

The Canale Reale River is an effluent-fed river located nearby the city of Brindisi, on the south-eastern side of the Apulia Region, in Italy. Four wastewater treatment plants discharge within the river a wastewater volume which contributes for about 16.5% of the annual volume of channel drainage (i.e., 3.82 Mm^3 out of 23.02 Mm^3 distributed along its path, about 50 km) and that partially feeds the Torre Guaceto protected wetland, along the Adriatic coast. Within a complex geological setting, the Canale Reale River flows throughout different lithologies, which reflect in different streambed hydraulic conductivity values. The aim of the study was to investigate the transmission losses occurring between the ephemeral watercourse and the underlying aquifers and to estimate the volume infiltrating which in this specific study case identify with treated wastewater discharge. By adopting the Reach Length Water Balance method, the estimation of a spatially average value of the riverbed's infiltration rate applicable to the whole river course was investigated, as well as Potential Transmission Losses (TL_P) from the river to the underlying groundwater systems. Combining the estimated TL_P values and the Flow Duration Curve (FDC), it was possible to draw the Transmission Loss Duration Curves (TLDCs) and to estimate the water volume infiltrating during an average hydrological year, equal to 6.25 Mm^3, 61% of which consist in treated wastewater. The obtained outcomes confirm that the practice of increasing the river flow rates with effluents can be considered a sustainable management tool for both surface and groundwater resources, since in the first case, the riverbed periods of zero-flow are reduced with potential improvements to the river's ecological sustainability and in the second case, relevant increasing of groundwater recharge is possible.

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Silvia Brigida

Transmission losses through effluent-fed ephemeral streams: a case study from the Canale Reale River (Brindisi)

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LIBERATORIA PER L'ARCHIVIAZIONE DELLA TESI DI DOTTORATO

Al Magnifico Rettore
del Politecnico di Bari

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Infiltrazione nel sottosuolo di acque reflue trattate attraverso corsi d'acqua effimeri: caso studio del Canale Reale (Brindisi)

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EXTENDED ABSTRACT (eng)

Climate change and anthropogenic pressures are the main drivers affecting the sustainability of freshwater resources, worldwide, in term of hydrological cycle.
Rising in temperature and droughts events, have a deep negative impact on the amount of water infiltration and hence groundwater recharge; moreover, the reduction in precipitation forecasted by climate-change models will intensify this process, leading furthermore to a dramatic shift from hydrological perennial regimes to ephemeral.
Population growth imposes an additional stress on water resources, especially groundwater, often overexploited for irrigation purposes, meanwhile urbanization processes move together with the tendency to produce waste and therefore the need to build-up new wastewater treatment plants. In many urban environments, discharging treated wastewater from wastewater treatment plants into surface water bodies represents a water resource and ecosystem services management tool to tackle different environmental issues. Although this practice may raise some concerns among people but also scientific community, about possible sanitary and ecological side-effects, as well as the impairment of water quality of receiving streams, the reuse of treated effluent is crucial to support ecosystem quality and urban amenities, to contribute to the environmental baseflow of ephemeral streams and to enhance groundwater recharge processes, especially in semi-arid and arid regions. In arid environments these *effluent-fed streams* are likely to become crucial for guaranteeing a vital equilibrium in the hydrological cycle since aquifer recharge through ephemeral streambeds is believed to be a major source of groundwater storage and replenishment. Groundwater recharge processes are enhanced by transmission losses that preferentially occur trough *losing reaches* along the streambed, which create a connection between the river and the underling aquifer. Interactions between surface and ground water bodies are extremely complex since several factors may affect the infiltration rate, such as spatial distribution of streambed sediments and hydraulic properties. Owing to the peculiar nature of ephemeral rivers, they often flow within ungauged basin, leading to a significant lack of in situ hydrological data, such as precipitation, streamflow, and evaporation time series.

Furthermore, not all the methods proposed in the scientific literature for estimating transmission losses in perennial streams can be applied to ephemeral ones, although they can provide some *proxy* for measuring groundwater recharge from hydraulically connected surface water bodies. The study case is the ideal framework in which all these natural features and hydrological issues converge. The Canale Reale River is an *effluent-fed river* located nearby the city of Brindisi, on the south-eastern side of the Apulia Region, in Italy. Four wastewater treatment plants discharge within the river a wastewater volume which contributes for about 16.5% of the annual volume of channel drainage (i.e., 3.82 Mm^3 out of 23.02 Mm^3 distributed along its path, about 50 km) and that partially feeds the Torre Guaceto protected wetland, along the Adriatic coast. Within a complex geological setting, the Canale Reale River flows throughout different lithologies, which reflect in different streambed hydraulic conductivity values.

The aim of the study was to investigate the transmission losses occurring between the ephemeral watercourse and the underlying aquifers and to estimate the volume infiltrating which in this specific study case identify with treated wastewater discharge.

By adopting the *Reach Length Water Balance* method, the estimation of a spatially average value of the riverbed's infiltration rate applicable to the whole river course was investigated, as well as Potential Transmission Losses (TL_P) from the river to the underlying groundwater systems. Combining the estimated TL_P values and the Flow Duration Curve (FDC), it was possible to draw the Transmission Loss Duration Curves (TLDCs) and finally, to estimate the water volume infiltrating during an average hydrological year, equal to 6.25 Mm^3, 61% of which consist in treated wastewater. The obtained outcomes confirm that the practice of increasing the river flow rates with effluents can be considered a sustainable management tool for both surface and groundwater resources, since in the first case, this allow to reduce the riverbed periods of zero-flow, with potential improvements to the river's ecological sustainability and in the second case, relevant increasing of groundwater recharge is possible.

key words: ephemeral rivers; effluent-fed rivers; surface-groundwater interactions; Reach Length Water Balance method; sustainable water resource management; climate change.

EXTENDED ABSTRACT (ita)

I cambiamenti climatici e le pressioni antropiche rappresentano la più importante minaccia alla sostenibilità delle risorse idriche, in termini di ciclo idrologico, a livello globale. Secondo recenti modelli climatici, un incremento delle temperature e la riduzione delle precipitazioni, a seguito di eventi siccitosi sempre più frequenti, avranno un profondo impatto sia sui volumi delle acque che si infiltrano nel sottosuolo per la ricarica della falda, sia sui corsi d'acqua superficiali, che subiranno un passaggio da regimi idrologici perenni a regimi effimeri. L'incremento demografico impone un ulteriore stress alle risorse idriche, soprattutto sotterranee, spesso eccessivamente sfruttate per scopi irrigui, mentre i processi di urbanizzazione sono determinanti nella produzione crescente di rifiuti, che rendono necessaria la realizzazione di nuovi impianti di depurazione. In molti ambienti urbani, l'immissione di acque reflue trattate nei corpi idrici superficiali, costituisce uno strumento di gestione delle risorse idriche e dei servizi ecosistemici, indispensabile per fronteggiare diverse problematiche ambientali. Sebbene questa pratica possa destare alcune preoccupazioni su possibili effetti collaterali sanitari ed ecologici, nonché sul deterioramento della qualità dell'acqua dei corsi d'acqua riceventi, il recupero degli effluenti trattati è indispensabile per garantire il minimo flusso vitale di corsi d'acqua effimeri, per supportare la qualità degli ecosistemi che li caratterizzano, ed inoltre per contribuire ai processi di ricarica delle acque sotterranee, specialmente nelle regioni semi-aride e aride. In queste aree, caratterizzate da precipitazioni sporadiche e intense, i processi di ricarica degli acquiferi, avvengono attraverso processi di infiltrazione lungo tratti disperdenti degli alvei fluviali di corsi d'acqua effimeri che hanno origine in seguito agli eventi piovosi. Questi processi vengono definiti *transmission losses*, e rappresentano un potenziale volume di ricarica dell'acquifero. Le interazioni tra corpi idrici superficiali effimeri e corpi idrici sotterranei, infatti, sono estremamente complesse poiché diversi fattori possono condizionare i processi di infiltrazione, e di conseguenza di ricarica, tra cui le caratteristiche geologiche del sottosuolo e la distribuzione spaziale delle litologie. Inoltre, i fiumi effimeri, a causa della loro natura peculiare, ricadono all'interno di bacini non strumentati, per cui molte informazioni idrologiche spesso non sono disponibili. Nella letteratura scientifica relativa alla idrologia dei corsi d'acqua perenni, molteplici metodi possono essere applicati per stimare le *transmission losses*, tuttavia non tutti i metodi possono essere applicati ai corsi d'acqua effimeri.

Il caso di studio rappresenta il contesto ideale in cui convergono tutti questi aspetti idrologici e problematiche idrologiche e che permette di indagare i processi di infiltrazione che avvengono attraverso il Canale Reale, e la falda acquifera sottostante, considerando le differenti litologie con relativi differenti coefficienti di permeabilità attraverso cui il corso d'acqua scorre. Il Canale Reale è situato nei pressi della città di Brindisi, sul versante sud-orientale della Regione Puglia, in Italia, ed è alimentato da effluenti provenienti da quattro impianti di depurazione, per un volume complessivo di acque reflue che contribuisce per circa il 16,5% al volume annuo del canale e che corrisponde a 3.82 Mm^3 su 23.02 Mm^3 distribuiti lungo circa 50 km di corso.

Adottando il metodo Reach Length Water Balance è stata calcolata la stima di un valore medio del tasso di infiltrazione dell'alveo applicabile all'intero corso fluviale, nonché delle Potential Transmission Loss (TL_P). Combinando i valori stimati di TL_P e la Flow duration curve (FDC), è stato possibile tracciare le Transmission Loss Duration Curves (TLDCs) e, infine, stimare il volume d'acqua che si infiltra nel sottosuolo, durante un anno idrologico medio, pari a 6.25 Mm^3, e di cui il 61% è rappresentato dalle acque reflue trattate. Considerando i risultati ottenuti, l'immissione in alveo di effluenti trattati può essere considerato uno strumento sostenibile di gestione sia delle risorse idriche superficiali, in quanto verrebbero ridotti i periodi di portata nulla, contribuendo anche alla sostenibilità della biodiversità degli ecosistemi fluviali, sia delle risorse idriche sotterranee, poiché rappresenta un potenziamento dei processi di ricarica.

key words: corsi d'acqua effimeri; corsi d'acqua alimentati da effluenti; interazioni tra corpi idrici superficiali e sotterranei; Metodo "Reach Length Water Balance"; gestione sostenibile della risorsa idrica; cambiamenti climatici.

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INTRODUCTION

The availability of fresh water worldwide, represents an actual issue of great concern which firstly reflects in the effective poorness of this resource. Fresh water is an extremely rare resource on Earth, as to be defined the '*blue gold*' for its unique value: less than 3 % of the water distributed on the Earth is fresh water, of which about one third is readily available for human use, while the remaining 97 % is composed of salt water (https://www.usbr.gov/mp/arwec/water-facts-ww-water-sup.html).

Freshwater availability is also threatened by the huge amount of water required for human needs and for the global economic development. It is estimated that about 70% of the world's freshwater is used by farmers for fields irrigation and by 2050, groundwater extractions will grow significantly, with an increase estimated equal to 1.100 km^3 per year, or 39%, to meet global water demand in response to the demographic growth, estimated by 2050 between 9.4 to 10.2 billion people (https://www.unwater.org/publications/world-water-development-report-2018).

In addition, global water demand for different purposes related to non-agricultural use, mainly represented by industrial field and domestic use, will increase by 20% to 30% by 2050, up to 5.500 to 6.000 km^3 per year (Wada et al. 2014).

Finally, by 2050, up to 79% of catchments affected by groundwater pumping will have reached or surpassed the ecological limits of streamflow (de Graaf et al. 2019).

Although the highest load on freshwater availability is chiefly related to groundwater withdrawals for human welfare, climate change imposes an important additional stress on water resources, being responsible of a very concrete risk of depletion volumes of renewable freshwater resources in the future, affecting groundwater storage reservoirs (Taylor et al. 2013; Cuthbert et al. 2019; Wu et al. 2020; Epting et al. 2021).

Groundwater is considered a renewable resource, depending on near-surface hydrological processes and therefore by the hydrological cycle. Climate variability in temperature and rainfall patterns, may affects quantity and quality of groundwater resources, by the alteration of the hydrological cycle.

Future severe droughts forecasted by climate-change models (Ukkola et al. 2020), fostered by rising temperatures, prevent adequate soil moisture and therefore increasing in evaporation rates, reducing the amounts of water that infiltrate underground to replenish groundwater storage.

Moreover, the reduction in precipitation followed by drought events, intensifies this process, considering that by the 2050 in many areas of the world, is projected a dramatic shifts from perennial to intermittent hydrological flow regimes (Döll and Schmied 2012) and nowadays, ephemeral rivers are recognised to be widespread worldwide, crossing different zones and geographic settings, ranging from small to large in size (Datry et al. 2017; Messager et al. 2021).

Increasing in temperature and scarcity of precipitation events, are climatic conditions extremely diffuse worldwide, but particularly felt in arid and semi-arid environments, as well as the Mediterranean region, considered the warmest region in the world (Navarra and Tubiana 2013; Vurro et al. 2013; Ouhamdouch et al. 2019; Bahir et al. 2020).

The reduction in precipitation or, in some cases, the occurrence of heavy rainfall, long dry periods and consequent high evapotranspiration rates, often do not allow the natural recharge of aquifer (Doglioni and Simeone 2019; Bahir et al. 2020; Analy and Laftouhi 2021). This is a very crucial aspect, because in dry areas, the major source of groundwater recharge is represented by infiltration processes which generally occur through the new-born of ephemeral streambed, only after seasonal flood events (Sorman and Abdulrazzak 1993; Abdulrazzak 1995; Shentsis and Rosenthal 2003; Scanlon et al. 2006; Dahan et al. 2008; Cuthbert et al. 2016; Herrera et al. 2018).

The lack or the presence of very few surface water (SW) bodies, most of them sometimes originate in other countries, force populations living in arid areas to rely on fragile, and sometimes non-renewable aquifers, whose waters are employed mainly in agricultural sector but also for household, municipal and industrial activities (Wada et al. 2010; 2014), giving birth to a dramatic competition among different water-use sectors.

To reduce the gap between water demand and supply for industrial and agricultural needs, because of the rapid economic development coupled with population growth and large agricultural sector expansion, government and local authorities have been forced to rely on non-conventional water resources.

Among these, the conjunctive use of SW and groundwater (GW) bodies (Pulido-Bosch et al. 2020; Ahmed et al. 2021), desalinization plants and the reuse of treated wastewater as secondary sources for the irrigation of agriculture crops (Contreras et al. 2021) and finally aquifer recharge (Manzoor and Sato, 2016; Tabatabaei et al. 2020; Shawaqfah et al. 2021).

Some virtuous examples of water recycling and reuse have developed since 1980s in Tunisia, Jordan, Israel, and Cyprus island, where the reuse of reclaimed water has been considered as a fundamental and strategic action in the planning and management of both water and wastewater sector, while irrigating agricultural crops with recycled wastewater has been practiced in arid and semi-arid regions and is rapidly getting popular in the countries of the Arab Regions. In this perspective, the reuse of treated wastewater represents a social challenge, since urbanization processes move together with the tendency to produce waste and therefore the need to build-up new wastewater treatment plants, leading to an increase of effluent discharge into streams (Teklehaimanot et al. 2015), and represents a reliable economic resource, as arid regions are projected to increase and to have a deep impact on population (Spinoni et al. 2021).

Reusing treated wastewater represents an environmental issue, because of the multiple several kind of risks involved which are mainly related to sanitary and healthy aspects, therefore need to be managed in an appropriate way.

A recent study carried on the assessment of the distribution of wastewaters at a global scale, shows that 1.2 million kilometres of the global river network collects wastewater input from upstream wastewater treatment plants (WWTPs), of which more than 90.000 km are downstream of WWTPs that offer only primary treatment (Ehalt Macedo et al. 2022).

Give a second chance to treated wastewater is a challenging issue since the beginning of the century, because of the necessity to guarantee adequate treatment processes and reduce ecological and quality impairments on receiving streams (Brooks et al. 2006; Garcia and Pargament 2015).

Besides the agriculture implication and advantages in reusing wastewater for economic purposes, discharging treated wastewater from municipal wastewater treatment plants into the hydrographic network is nowadays observed in many urbanized contexts, with different intended use and social benefits (Bixio et al. 2008).

Recycled wastewater is effectively considered as an ecosystem-management tool, especially in semi-arid and arid regions used to support ecosystem quality and urban amenities, to provide drinking water supplies (Karakurt et al. 2019), to restore environmental baseflow of ephemeral rivers that otherwise could not exist (Bischel et al. 2013; Lawrence et al. 2014; Luthy et al. 2015; Hamdhani et al. 2020), to fight seawater intrusion (Zaccaria et al. 2016; Frollini et al. 2022;) and to enhance groundwater recharge processes (Asano and Cotruvo 2004; Asano 2006; Fournier et al. 2016).

Owing to the several issues exposed above, in many arid areas effluent-fed streams are likely to become crucial for guaranteeing a vital equilibrium in the hydrological cycle. In these environments, is asserted to be that aquifer recharge through ephemeral streambeds is believed to be a major source of groundwater recharge, which is unfortunately threatened by rainfall variability, a typical feature of arid areas enhanced by climate changes. Combining both aspect, the aquifer recharge that occurs naturally through streambeds infiltration after flood events in arid areas on one hand, and on the other hand, the chance of restoring a natural flow by replacing it with reclaimed water, to cope with water scarcity and climate changes effects, is a challenging issue because of the complexity affecting the interaction between surface and groundwater systems.

Since these actions move towards an integrated and sustainable water management, the interaction processes that involves both SW and GW bodies need to be conceptualized from a multidisciplinary perspective, as well as the comprehension of all the variables that may affect the volume of water transmission losses along a watercourse, intended to replenish the underlying aquifer through riverbed losing processes. This is particularly important, since, although surface river system interacts with groundwater system in all landscapes (Acuña et al. 2014; Dvory et al. 2018; Kaletová et al. 2019; Blackburn et al. 2021), giving birth to different hydrological settings, SW and GW bodies have always generally considered as two separated physical systems.

Nevertheless, in the last decades, scientific research has emphasized the necessity of considering them as parts of a whole more complex system where discharge-recharge fluxes occur at their interface (*hyporheic zone*) controlling also chemical and biological processes to the stream ecosystem (Winter et al. 1998; Woessner 2000; Sophocleous 2002; Mojarrad et al. 2019).

In general, many factors can control the amount of transmission losses along a watercourse. Besides topographic and climate patterns, the streambed morphology and lithology, the heterogeneous distribution of hydraulic conductivity of the riverbed, the related vertical permeability, the depth to groundwater table, and the quality of the flowing water are binding factors of such infiltration phenomena (Kalbus et al. 2009; Beetle-Moorcroft et al. 2021; Bourke et al. 2021).

This implies different infiltration processes or losses condition that allow to identify gaining reaches and loosing reaches along the same river (Chen et al. 2013).

From a perspective of sustainable water management in dryland areas, these interactions become more complicated when considering ephemeral streams, strongly depending on precipitation events characterised by flow variations in both space and time (McCallum et al. 2013; Quichimbo et al. 2020) and generally characterised by ungauged basins.

In fact, further complexity in the hydrological characterization of non-perennial streams, comes from the fact that they are mainly located in ungauged basins in most cases worldwide (Shanafield et al. 2021),with a significant lack of in situ hydrological data, such as precipitation, streamflow, and evaporation time series (Hrachowitz et al. 2013; van Emmerik et al. 2015).

Taking into account all the factors affecting recharge processes in ephemeral streams, methods capable of estimating transmission losses or quantifying loss rates from ephemeral losing streams are useful as they can provide some proxy for measuring GW recharge from hydraulically connected SW bodies.

Although they range from simple to complex approaches, not all the method proposed in the scientific literature for estimating transmission losses in perennial streams can

be applied to ephemeral streams (de Vries and Simmers 2002; Scanlon et al. 2002; Goodrich et al. 2004; Shanafield and Cook 2014).
Nevertheless, many efforts have been done to address the research in understanding the dynamics of these peculiar stream typical of arid areas and to develop also new methods more suitable for estimating channel infiltration (Gallo et al. 2020; Mujere et al. 2022; di Ciacca et al. 2023), even in ungauged catchments (Sivapalan et al. 2003; Passarella et al. 2022).

Among the simpler methods to provide estimates of flow transmission losses, this research project refers to the Reach Length Water Balance (RLWB) method (Shanafield and Cook 2014).The RLWB method has been applied and tested along two stretches of the Canale Reale River, the most significant important Salento water course in the southern part of the Apulia region. The river originates from some innermost springs nearby Villa Castelli municipality and before reaching the Adriatic Sea, it crosses the Brindisi plain to finally flowing within the Torre Guaceto wetland.

As many other rivers flowing in the Apulia region, it is characterized by an ephemeral regime owing to the presence of a karst morphology, a distinctive feature of the whole region which recognizes into widespread outcroppings of carbonate rocks (Parise 2011), inherited by complex and ancient geodynamic events which involved the Apulian platform since Cretaceous (Funiciello et al. 1991; Mindszenty et al.1995). A scarce and a very slight shaped hydrography distinguishes the karst Apulian landscape from other types of geomorphological settings. Despite these features, karst hydrology exerted an important control in the past in favouring human settlements in the region (Parise 2009). As a consequence of this, along many ephemeral rivers, especially in the area between the Murge and the Salento, reclamation works and many hydraulic regulation interventions, modified or even deleted not only the main morphological features the karst environment, but also the hydrographic original asset of these rivers. Nowadays, artificial channels replace the original surface hydrography and in many cases, as for the Canale Reale River, they are used to collect both urban and industrial discharges (Delle Rose and Parise 2010; Pisano et al. 2022).

Wastewater discharge practice has been occurring for decades, with increasing discharge rates for 20 years and actually, it collects, for more than half of its length, about 50 km, the treated effluents from WWTPs of the municipalities of Francavilla Fontana, Ceglie Messapica, Latiano, and partly from the Carovigno one, for an overall volume discharge of about $1.83 \cdot 10^3$ m^3/d.

Owing to the complexity of the study case, the methodological approach has been applied by adopting some fundamental and general assumptions, which refers in the study case, to the hydrogeological and geological framework in which the river falls within and the kind of interaction that occur between the river and the underlying aquifer.

The first assumption refers to a supposed hydraulic connection between the Canale Reale River and both the shallow and deep aquifers, supported by the geological and the structural asset of the study area, strongly depending on the types of lithology crossed by the river along its path. The RLWB method, based on the mass conservation principle, allows for approximating the flow rate exchanged along a river reach bounded by two defined cross-sections as the difference between the discharge measurements at the two sections.

Another important condition to be considered is that Canale Reale River, despite its ephemeral nature, is characterized by the presence of a baseflow thanks to the constant effluent discharged into the river, with known hydraulic features.

This allows to undertake empirical riverbed infiltration tests, extrapolate transmission losses along the riverbed and then evaluate the overall water balance.

The occurrence of stable flow conditions due to wastewater discharges makes RLWB a suitable method for estimating riverbed transmission losses, and can be considered a simple, reliable, and repeatable method to be used in different flow regimes over the seasons, especially for carrying out measurement campaigns along ungauged river stations, as for the case of Canale Reale River.

A recent attempt of assessing hydrodynamic features of the Canale Reale River was done by Passarella et al. (2022) by means of an affordable and reliable measurement technique, based on beamforming applied on video sensing.

The purpose of the research study topic consists in proposing a novel methodology that contributes to the comprehension of hydrological processes in dryland environments through the characterization of streamflow transmission losses in ephemeral rivers. This innovative approach will help to bypass several technical and objective limitations which effectively does not allow to really understand the hydrological behaviour of ephemeral rivers, by considering the increasing tendency of ephemeral flow regimes, due to climate change effects. In addition, ephemeral rivers have been underestimated in hydrological studies, if compared to perennial rivers, although more exposed to different stressors and being less protected than the latter.

This study is also addressed in understanding the complex processes controlling the spatial patterns and temporal dynamics of groundwater–surface water interactions, in a karst-dominated landscape, nowadays still poorly explored and understood, as a consequence first of a scarce awareness of these processes as well as the lack of knowledge and experience related to appropriate measurement and analysis approaches (Lewandowski et al. 2020).

The possibility to manage alternative resources such as wastewater for the replenishment of aquifers, certainly represents one of the most important contemporary challenge and it represents a strategic solution that should be undertaken, especially in arid and semiarid landscapes, the most affected by water shortage. In fact, such a technical enhancement has been proved being an effective contribution to the in-channel Managed Aquifer Recharge (MAR) practice in arid and semi-arid regions (Standen et al. 2020).

Finally, this study and the project INTERACTION in which it has been developed, would like to encourage the dialogue between scientific community and policy makers, to find sustainable management practice useful to face the challenges driven by climate changes effects and anthropogenic pressures, emphasizing that many efforts still need to be done, especially considering the fragile environment such as karst that characterizes the whole Apulia region.

1.1 Motivation for the study

The Canale Reale River is the longest river of the Salento peninsula and, to date, the unique effluent-fed river of the whole Apulian region. Wastewater discharge practice has been allowed for decades, with increasing discharge rates, and therefore, the Canale Reale River has been considered by local communities as an artificial channel used to collect wastewater discharge and often used as a discharge for different types of waste, despite the waters flowing into the river feed the protected wetland located inside the Natural State Reserve of Torre Guaceto.

As many rivers flowing through the Brindisi plain, the Canale Reale River has undergone hydraulics regulations since the first half of the last century (Mainardi 2017), which have deeply modified its hydraulic behaviour and consequently, its natural characteristics, which reflect in the presence of concrete banks along some stretches of the river and along the riverbed itself. The development of an intensive agriculture activity through the Brindisi plain and in proximity of the Canale Reale catchment basin, as well as the anthropic transformation occurred through the years, have contributed to deprive the river of its natural morphological continuity and to further reduce its although but limited naturalness.

Furthermore, the loss of some specific areas belonging to the fluvial environment has caused a collateral loss of the original ecological function and the impoverishment of the ecosystem services supported by the river, the natural recharge processes of aquifer and the guarantee of a good water quality.

Nowadays, as a consequences of all these aspects, the Canale Reale River has been classified as a temporary flow regime of ephemeral-intermittent type and a heavily modified river. The discharge of treated effluents along its course, compensate someway its ephemeral path, allowing the presence of a very low basal flow through all the year. Despite the actual conditions and all the pressures affecting nowadays the river, the Canale Reale River was once a used as secondary way of communication between the Adriatic Sea and the hinterland. Its presence enhanced the development, in the early Middle Ages, of some Basilian monk’s communities, which established their settlements just along this river, using some caves dug as a place for carry on their monastic life, e.g. the rupestrian church of San Biagio in San Vito dei Normanni and the Crypt of San Giovanni in Latiano (Semeraro Herrmann 1982; Chionna 2001).

Indeed, for centuries, the springs which fed the Canale Reale river have represented an important source of water supply for farming and for the cultivation of local crops, especially wheat, so that it was once called as “Fonte dei Grani”, and as a confirm of this, the church built nearby the source is indeed dedicated to Santa Maria dei Grani. Nowadays the spring, which position is not easily accessible and not well visible, is known as “Sorgente di Strabone” in honour of the Greek historian and geographer Strabone, which wrote about the importance of this spring and the river in his manuscript “Geography”. Going back in time, the primary and ancient name of the Canale Reale River was “Pactius” or “Ausonius”, mentioned by Plinio il Vecchio in his “Naturalis Historia”.

These are very few, but important historical information which allow to think that in the past, water flowing inside this river was more copious than the water volumes flowing nowadays into the stream, as well as its undoubtful ecosystem and economic value.

Recently, a local awareness has been raised among local communities and other stakeholders, towards this peculiar river and its catchment basin, which has led to the development of the “Contratto di Fiume” (River Contract) in July 2021.

This represents a novelty in Apulia region, because this document is the first official contract signed in the whole Apulia region and even in Southern Italy, regarding an ephemeral river. Among the stakeholders involved in the project, the University Polytechnic of Bari, the Puglia Region, the Water Research Institute of the National Research Council (IRSA-CNR) and other local institutions, such as the “Consorzio di Torre Guaceto, are present. The River Contract is a tool used for identifying a series of strategic and planned actions for the environmental requalification of the watercourse, the restoration of its naturalistic and ecological properties, but also the socio-economic and environmental potentiality, through the knowledge of the territory and its critical issues, contributing to local development.

All these actions comply with the requirements of the Water Framework Directive (WFD) 2000/60/EC, which recognizes the river basin as the main physical and socio-economic domain for implementing systemic policies for supporting a sustainable management of both surface and groundwater resources(https://www.eea.europa.eu/policy-documents/water-framework-directive-wfd-2000).

Referring to this last aspect, even though effluent discharge practice has been allowed for years, there is still a poor awareness about the environmental potential of this practise, not only locally but also at regional and national scale. Nowadays in fact, in many urbanized environment, wastewater effluent streams support ecosystem services, aquatic habitats, and urban facilities, and are considered as an essential resource and a tool for ecosystems and water resources management, in response to climate changes effect.

The case study hence, represents the ideal framework where to test the concrete possibility of reusing wastewater treated effluent discharging into the Canal Reale River as an aquifer recharge management tool, starting from the comprehension of the complex hydrological interactions that occur between the river and the underlying aquifer, within a catchment basin missing of monitoring system devices and which could be used as a virtuous example to raise the local and later regional awareness about the need to adopt some management tools to deal with water scarcity issues which, in our case study, affect the Brindisi plain.

The research project finds its primary motivation in the necessity to tackle this urgent issue which involves all areas most exposed to climate changes variability, including the Mediterranean and Southern Italian regions.

This necessity is also strengthened by the fact that Apulian landscape, because of its geological, geomorphologic and hydrogeological karst heritage, can be considered a fragile environment with a correlated high vulnerability (White 1988; North et al. 2009; Parise 2010; Pisano et al. 2022). Despite the lack of a visible and consistent surface hydrography, Apulia region is furrowed by many ephemeral rivers (Cristino et al. 2015) and during rainfall, extreme events floods involving wide areas may occur (Carrozzo et al. 2003; Parise 2003; Mossa 2007; Delle Rose et al. 2020). In these occasions, moreover, water runoff infiltrates quickly underground through the intricate network of fractures and karstic conduits typical of karst environments and contaminants can easily reach the aquifer (Delle Rose and Parise 2010). This last issue should be also taken into account, since most of the socio-economic and anthropic needs depend on the Apulian groundwater resources hosted in the deep Mesozoic carbonate aquifer.

Finally, the choice of the pilot area part of the research activities proposed in this research work, were developed within the INTERACTION project, (Integrated Assessment of Climate Impacts on Ecosystem Functions and Productivity of Critical-Zone Eco-Hydrology) awarded by the Belmont Forum, in the framework of the call for a Collaborative Research Action (CRA) on the theme "Towards Sustainability of Soils and Groundwater for Society and supported by the Belmont Forum (Earth System Science and Environmental Technologies Department of the National Research Council of Italy) Grant (https://belmontforum.org/projects?fwp_project_call=soils2020).

1.2 Aim of the research study

To pursue the objective of promoting the use of treated effluents to enhance groundwater recharge is necessary to quantify the transmission losses and therefore streambed recharge. This implies a more focused comprehension of the various components of the local water budget as well as their relative magnitudes.

In our study case two apparently divergent hydrological situations coexist: although the Canale Reale River is classified as an ephemeral river characterized by a seasonal flow regime, the presence of a stable baseflow through the whole year, and especially during summertime, where rainfall events are rare, is guaranteed by the discharge of effluents, with known hydraulic features, at four different locations along the channel length.

However, the absence of flowing water in some stretches along the river, following a field survey and later supported by satellite images, has been observed.

This evidence has pushed to better understand the role of the components involved in interactions between the river and the underlying aquifer, starting from the geological context in which the river flows, then focusing on a smaller scale, on the distribution of streambed permeabilities along the flow pathways, according to the main lithologies outcropping in the area.

The spatial and vertical distribution of lithologies across the riverbed, in fact, exerts an important control in the direction of the flows between SW and GW bodies, as well as allows to distinguish different hydrological behaviour between *losing stretches* from *gaining stretches*, along the same river, according to the depth occurring between riverbed and aquifer and therefore to the table water fluctuations.

A further goal of the study project was to test if the RLWB method can be considered a reliable method for approximating the flow rate exchanged along a river reach bounded by two cross-sections, as the difference between the discharge measurements at the two sections, by assuming SW and GW hydraulically connected.

Finally, the assessment of the water rates that could infiltrate underground is fundamental to understand if these volumes can really enhance in-channel groundwater recharge, with an undoubtful advantage for the availability of both surface and groundwater resources, in a region that lacks significant surface water bodies and depend on groundwater resources.

In conclusion, the research study aims to improve the current level of knowledge on the main components involved in the riverbed recharge processes in the study area and provide scientific outcomes for answer to the main research questions and the knowledge gaps that affect the study area.

Resuming, the aim of the study if addressed to:

1. understand the nature of the hydrologic connection between the river channel and the underlying aquifer, defining gaining reaches or losing reaches and in the last case, losing disconnected or connected river from the aquifer, through the definition of the hydrological conductivity values of the principal geological formation outcropping in the study area and crossed by the river;
2. undertake empirical riverbed infiltration tests, extrapolate transmission losses all through the channel bed, and consequently evaluate the overall water balance, by adopting the RLWB method;
3. define the role of the effluent discharged by wastewater plants into the river in the local water budget, with respect to total basin recharge in the study area and with transmission losses;

4. support and give a further contribution to the body of literature on artificial groundwater recharge by using wastewater, considering the lack of knowledge about this issue;
5. answer to the main knowledge gaps and research questions to support actions and plans useful for a sustainable water management of both Canale Reale River and the underlying aquifer;
6. encourage the dialogue between scientific community and policy makers to support sustainable water management of treated effluents.

1.3 General approach

Before focusing on the topic of understanding the interaction processes between surface and groundwater, the initial approach to the research project was to collect all the information available in scientific literature referred to the study area.

A fair number of scientific articles have been retrieved, not recent but nonetheless detailed and focused both on the area of the Brindisi plain and its criticalities, and on the interactions between the two surface and deep aquifer systems that characterize the study area; marginally information has been found about the nature of the watercourse, the origins of which are still not entirely clear.

Following the scientific bibliographic consultation, it was also possible to draw a picture of the geological characteristics of the area in which the watercourse falls and important information relating to the geological and structural structure of the area was retrieved by reading the bibliographic sources of study, which create a particular unique configuration in the geology of the Apulia Region, and which justify the hydrogeological characteristics of the same area.

Alongside the reconstruction of the geological and hydrogeological structure of the area, all the few information relating to the stratigraphy was found from a database of wells dating back to the 1980s, during the construction of the regional groundwater network.

The hydrological features of the Canale Reale River, aligns with the geological, and geomorphological features of the Apulia region, mainly in Gargano, Murge and Salento peninsula.

The Canale Reale River, as many ephemeral rivers, generally can be recognizable during or after flood events, while may experience long dry periods during summer season, so they follow a strong seasonality. These rivers represent a distinctive feature of the Apulian landscape, and worldwide, these rivers are collected into Intermittent Rivers and Ephemeral streams (IRES) classification. For this reason, a wide body of literature was explored, to improve the knowledge about their origin and genesis and therefore the hydrology of non-perennial rivers. The same approach was moreover adopted to better understand the processes interactions between groundwater and surface water bodies that play a fundamental role in the hydrologic budgets inside a watershed as well all the multiple factors that drive these, from broader to smaller scale.

Finally, part of research study was addressed to existing rewies related to the methods proposed for quantifying ephemeral and intermittent stream infiltration and aquifer recharge.

The general approach adopted, can be therefore synthesised, and divided into the following sections:

Study area

i. review of the existing literature referred to the Canale Reale River and the Torre Guaceto wetland;

ii. collecting of all geological, stratigraphical, and hydrogeological information necessary to define the frame of the study area;

iii. collection of territorial datasets relating to the distribution of wells in the area (Sit-Puglia website);

iv. collection of pertinent hydrogeological data field from local and regional monitoring campaigns (quali-quantitative information of water sampled from the wells located nearby the area of interest);

v. elaboration of vector data formats and elaboration within the GIS environment.

Hydrology of non-perennial rivers

i. definition of IRES; review of existing literature concerning hydrology of non-perennial rivers, in terms of streamflow generation processes, water losses, and variability in flow.

Interaction between SW-GW bodies:

i. review of existing literature related to the streambed heterogeneity on the distribution of groundwater discharge;

ii. background on streambed infiltration, with a focus on the use of treated effluent for environmental flow and enhance groundwater recharge processes;

Methodology

i. review of existing literature about the methods adopted for quantifying loss rates in losing streams;

ii. identification of the Canale Reale River stretch more suitable for the application of the chosen method, by matching geological information of the study area and the hydrological features of the river;

iii. application of a rainfall-runoff modelling to the case study, to assess volumes infiltration along the Canale Real River occurring through an average hydrological year.

CHAPTER 2. NON-PERENNIAL RIVERS: HYDROLOGIC ASPECTS AND METHODOLOGIES FOR EVALUATING TRANSMISSION LOSSES

Intermittent rivers and ephemeral streams (IRES) represent more than half of the global river network and contrary to what is believed, non-perennial rivers are not only typical of arid and semi-arid areas but are widespread worldwide (Fig.2.1) and occur across all types of latitudes and climates on earth, such as temperate, tropical humid, boreal, and even alpine areas (Datry et al. 2014; Fritz et al. 2017; Skoulikidis et al. 2017; Messager et al. 2021).

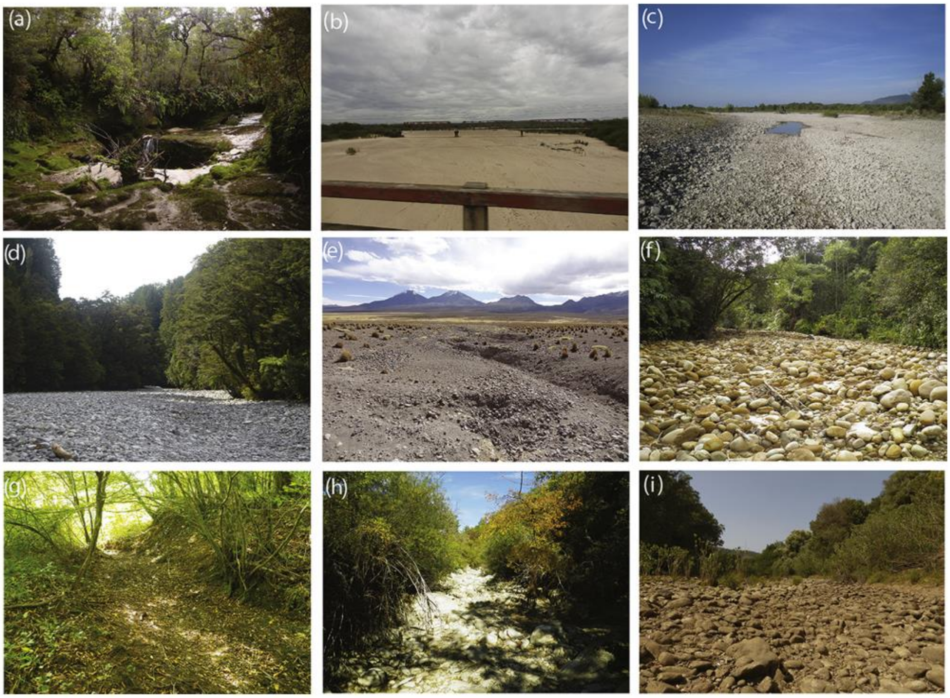

Fig.2.1- Different types of IRES from across the world: (a) unnamed karstic stream, West Coast, South Island, New Zealand, (b) Río Seco, Chaco, Bolivia, (c) Asse River, Provence, France, (d) unnamed gravel-bed stream, West Coast, South Island, New Zealand, (e) unnamed stream, Altiplano, Bolivia, (f) Chaki Mayu, Amazonia, Bolivia, (g) Clauge, Jura, France, (h) Calavon, Provence, France, and (i) Río Hozgarganta, Andalucía, Spain (Datry et al. 2017)

Besides their natural occurrence, the widespread presence of these rivers has increased as a direct consequence of climate changes. In fact, owing to prolonged dry periods with low rainfalls, many perennial rivers are gradually becoming intermittent or have experienced longer dry periods or have been characterized by the absence of a baseflow inside the channel. On the other hand, warmer temperatures during winter season, especially in artic areas such as Siberia and parts of Canada and Alaska, have been crucial for some ephemeral rivers which have naturally turned their flow regimes from ephemeral into perennial one (Döll and Schmied 2012).

Climate change scenarios predict an expansion of non-perennial rivers worldwide, which can be already considered the most widespread flowing-water ecosystem in the world (Döll and Schmied 2012; Datry et al. 2014; Messager et al. 2021). Given the multitude of natural settings that support non-perennial flow, is not surprising the diversified terminology used in scientific literature referring to this peculiar kind of watercourses, as well as a wide range of regional names (Datry et al. 2017; Busch et al. 2020).

To bypass the necessity to strictly classify the hydrological behaviour of a non-perennial river, the acronym IRES has been introduced to group all the “intermittent rivers and ephemeral streams”, whose flowing water cease to flow and/or dry completely at some point along their course, in time and space (Larned et al. 2010; Datry et al. 2017; Busch et al. 2020). Despite their wide geographical distribution and although research items have been generally more focused on their biodiversity and ecology and in a marginal way to their hydrological behaviour, only in the past two decades, a blooming interest for IRES have emerged.

These unique eco-hydrological systems in fact, despite the natural variability of their flow regimes and the presence of different hydrological phases characterizing their flow regime (dry, wet, flowing..), play a key-role in supporting the biodiversity of rivers at network scale, give shelter to aquatic and riparian ecosystems (Katz et al. 2012; Datry et al. 2014; Stubbington et al. 2017) as well provide many ecosystem services, such as flood regulation, transport of biota, materials and nutrients and also allows hydrological connection between perennial river reaches with the aquifer, enhancing groundwater recharge (Acuña et al. 2014; Dvori et al. 2018; Kaletova et al. 2019; Blackburn et al. 2021).

Despite their valuable biological support, there are still very few attempts aimed to quantify the important ecosystem services that these rivers provide to societies; at the same time, a positive perception of IRES from local communities or government still lacks, which unfortunately strongly influence the level of care and the management rules applied to IRES, more exposed to different stressors being less protected than perennial rivers (Leigh et al. 2019; Rodríguez-Lozano et al. 2020). As an example, in the United States and France, non-perennial rivers have been removed from maps and legislations (Marshall et al. 2018)and this is a clear signal of the low consideration of the value and the importance given to these rivers and the non-adequate management they should deserve.

The scarce consideration and negative approach toward IRES, comes alongside the fact that non perennial rivers have been overlooked in hydrological studies, if compared to perennial rivers hydrology literature (Acuña et al. 2014; Fritz et al. 2017; Messager et al. 2021) and the early scientific information about the hydrology of non-perennial rivers have been provided by the ecologists, used as a frame to depict the ecological and biological aspects of these rivers. It follows that a wide scientific literature about the ecology and biology of these rivers is available (Poff et al. 1997; Kennard et al. 2010; Arthington et al. 2014), whistle there is a lack of a global overview about the hydrology of non-perennial rivers.

This aspect is also justified by some other technical factors: many streamflow gaging stations are preferentially located on perennial rivers worldwide (de Girolamo et al. 2015; Eng et al. 2016)while most of ephemeral rivers lacks gauging station, and this poses a limit to collect hydrological quantitative data useful to describe and characterize these systems in time and along the watercourse (Costigan et al. 2017; Borg Galea et al. 2019; Sauquet et al. 2019).

Moreover, not all the most common methods used for monitoring hydrological regimes of rivers are always suitable for monitoring non-perennial systems, because these methods should be representative of physical and hydrological processes that generally belongs to or are dominant in perennial systems (Shanafield and Cook 2014; Gutiérrez-Jurado et al. 2019) rather than non-perennial ones.

In addition, hydrological studies of IRES focus mostly on how to classify nonperennial hydrological systems (Fritz et al. 2013; Beaufort et al. 2017; Carreau, and Sauquet 2019; Kaplan et al. 2019) rather than investigate the processes following intermittence or that origin intermittence flows (Costigan et al. 2017; Zimmer and McGlynn 2017; Lovill et al. 2018; Ward et al. 2018).

2.1 Hydrology of non-perennial rivers

Intermittence can be considered a typical distinctive feature of flow regimes of IRES. Under natural conditions, flow intermittence can be driven by many single different processes or by the combinations of more processes, that is climate drivers, which predominate in semiarid and arid regions, where intermittency is largely driven by low precipitation and high rates of direct evapotranspiration through plants, the water source and catchment basin but also physical and geological channel features (e.g., width, lithology and therefore riverbed permeability). In karstic regions, IRES generally flow intermittently in response to fluctuating groundwater discharge (Bonacci et al. 2019) but, in case of prolonged or intense rainfall, the network of conduits and fractures is not always able to collect large amounts of water, and therefore, floods events occur (Parise 2003; Martinotti et al. 2017). Intermittence can also be a consequence of human activities, which in many cases has turned perennial streams and rivers into IRES, with a consequent lengthening of the duration and extent of the *zero-flow* periods (Zimmer et al. 2020).Streamflow intermittence, which leads to the cessation of the flow, at a certain time and space, has a very important impact on what is defined as *hydrological connectivity.* The hydrological connectivity is defined as the “water-mediated transfer of matter, energy, or organisms within and/or between elements of the hydrologic cycle”(Pringle 2003). Although hydrological connectivity occurs in all flowing systems, in IRES this complex process has a very great influence on the physical, chemical, and biological processes.

Hydrological connectivity occurs through three spatial dimensions, longitudinal, lateral, and vertical and is primarily controlled by the interactions between flow regime (e.g., duration, magnitude, frequency and timing of streamflow) and fluvial geomorphology (e.g., channel and floodplain shape, size, gradient, sediment composition, and location along the network).

However, this biological and physical process appear to be more complex because of the interaction of other important drivers (Fig.2.2) that operates at a landscape scale including climatic conditions, timing and amounts of precipitation and evaporation, but also tectonic activity (e.g., fault lines, volcanism), the underlying lithology and geology and finally the *hydrogeological features* which control gains and losses dynamics along the channel (Tooth and Nanson 2011).

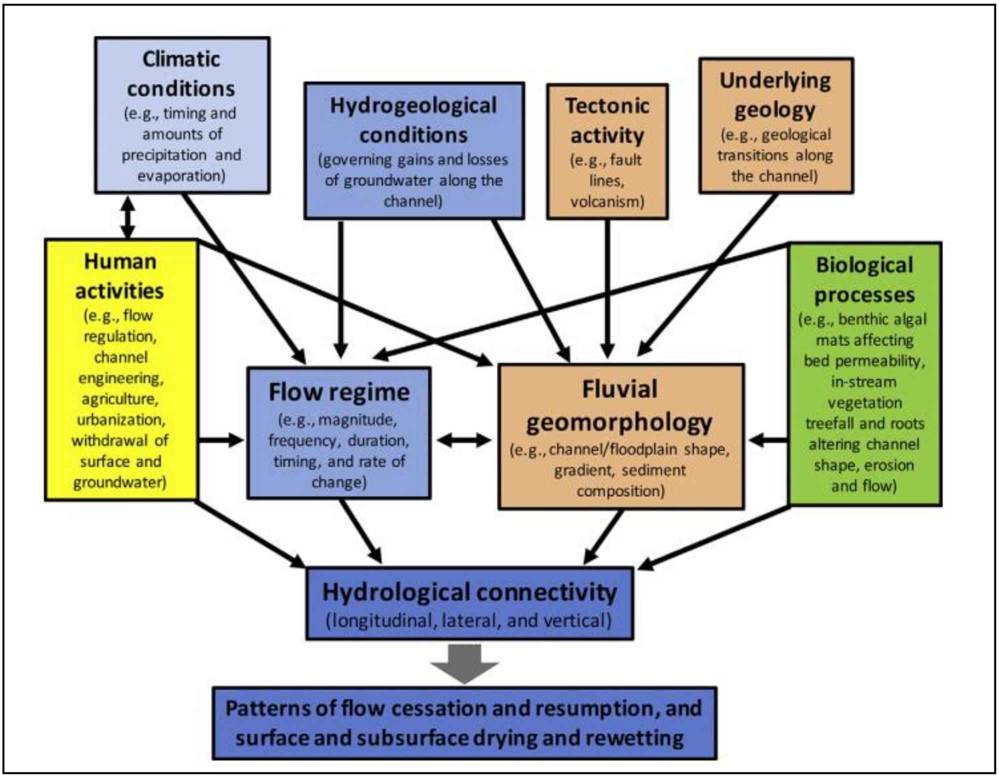

Fig.2.2 - Interactions among different factors affecting hydrological connectivity in ephemeral streams, along the three dimension, longitudinal, lateral, and vertical (Boulton et al. 2017).

Along longitudinal dimension, the cessation of surface flow prevents and reduces the downstream transport of sediments and biota (Rolls et al. 2012) instead laterally, it happens that aquatic communities living on the floodplain and along the riparian zone strictly linked to the main channel experience isolation when the water level drops (Paetzold et al. 2006). Finally, vertical hydrological connectivity is largely determined by patchiness of rainfall-runoff than by groundwater inputs, and most of the exchange of water between the surface channel and the shallow saturated sediments below (i.e., *hyporheic zone,* White 1993), ceases when surface flow stops, leading to a reduced oxygenation of the hyporheic zone (Datry et al. 2014; Boulton et al. 2017).

Vertical hydrological connectivity certainly represents the most important hydrological dimension when refer to the interaction between surface and subsurface water bodies and the related hydrological processes.

Vertical hydrological connectivity governs the behaviour in many IRES as a function of the water table fluctuations. Along its length, a channel can alternate between *gaining* and *losing* in response to temporal fluctuations in water table elevation as well as longitudinal variations in geology, topography, substrate and other conditioning factors (Cardenas 2009). It follows that, along a specific reach in a river network, the direction of vertical flow may change, according to fluctuations in the elevation of the water table (e.g., in response to precipitation or evapotranspiration).

Generally, a stream is defined as losing or influent (Fig.2.3) when streamflow is not connected with groundwater, by a unsaturated zone, on the contrary is defined gaining whereas groundwater enters the channel (Winter et al. 1998) (Fig. 2.3 B).

Generally, a great number of non-perennial rivers are considered losing rivers for much or all of the year. The dynamics of losing and gaining exchanges in many IRES as a function of the water table fluctuations, control the cycles of surface flow cessation, drying, rewetting, and flow resumption. While surface runoff usually triggers rewetting and streamflow in upland zones, rising groundwater levels in response to recharge by precipitation often is responsible of rewetting conditions along the channel, which therefore behaves as a gaining channels. This occurs especially in IRES with shallow water tables or in extremely permeable catchments. When water tables stations below the channel (Fig.2.3 A), surface flows and water levels decline, resulting in prolonged losing conditions after the cessation of the surface flow and finally, leading to dry surface and subsurface (Larned et al. 2011).

The recognized alternation of gaining and losing conditions along a streamflow is used by many hydrologists (Gordon et al. 2004) to stand out hydrological differences among IRES. Ephemeral streams generally lie above the water table and are constantly losing, intermittent rivers fluctuate between gaining and losing conditions, and finally, perennial systems are considered predominantly gaining (Fig.2.3 C).

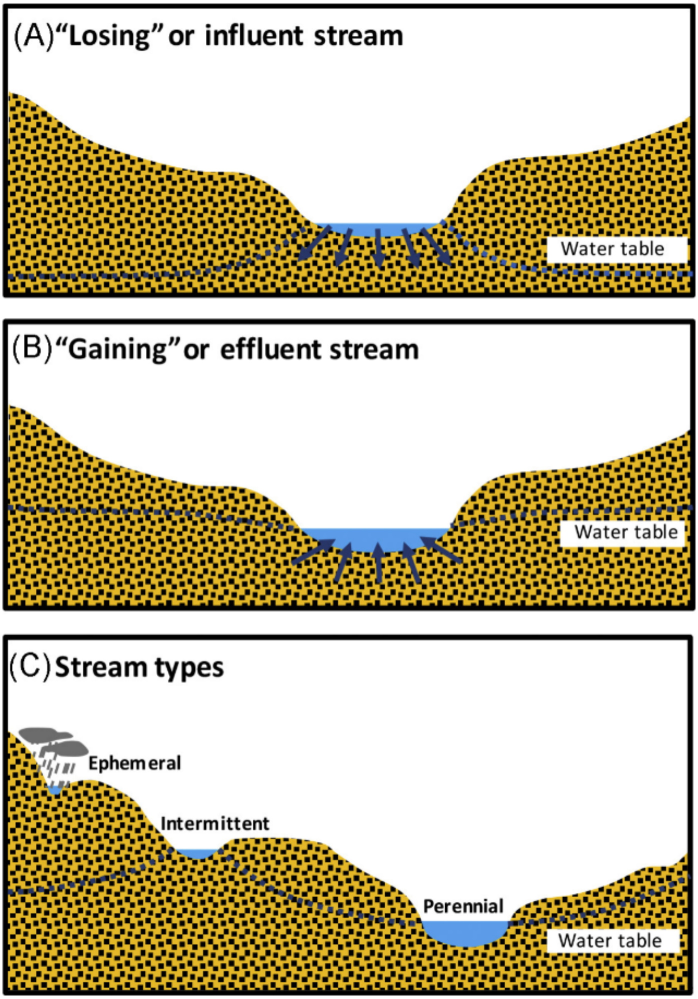

Fig.2.3 – Different hydrological behaviour between losing or influent streams (A), gaining or effluent streams (B) and between ephemeral, intermittent and perennial streams (Boulton et al. 2017).

2.2 Interaction between surface and groundwater bodies

SW and GW bodies have been generally always considered as two separated physical systems (Winter et al. 1998). Only in recent times, a growing awareness of the importance of the exchanges happening at the interface between SW and GW bodies, supported also by new regulations introduced by the EU Water Framework Directive (WFD), has pushed the scientific community to change this simplified perspective of GW–SW interactions, and to consider them as a coupled complex system, where discharge-recharge fluxes and biological functions occur at their interface, known as *hyporheic zone* (Winter et al. 1998; Woessner 2000; Sophocleous 2002; Fleckenstein et al. 2010).

Interactions between SW and GW bodies play a fundamental role in the hydrologic budgets inside a watershed and for this reason it is necessary to understand the processes that occur between them and the factors which may control hydrological interactions and therefore, the water fluxes and the recharge processes to benefit the groundwater reservoir.

Many factors govern the interaction between SW and GW bodies, from broader to smaller scale and these elements control the rate of transmission losses along a watercourse. Transmission loss is defined as the infiltration of surface water into the streambed and is mainly driven by hydraulic gradients between the regional water table and the riverbed (Wheater et al. 2010).

The rate of transmission loss is driven by both the streambed characteristics (e.g., hydraulic conductivity and moisture content) and the geology (Quichimbo et al. 2020). Thanks to transmission losses to groundwater storage beneath the channel bed, these losing streams contribute substantially to aquifer recharge in many areas, because the water collected and stored within the alluvium can be considered as a precious water resource for local communities (Pacheco-Guerrero et al. 2017).

Owing to the complexity of these hydrological exchanges, it is necessary to recall the effects of what Tóth (1970) defines the “*hydrogeologic environment*” on the groundwater flow systems, in which many factors concur to define SW and GW interactions. The effects of topography, in which the watershed and the river lies upon and geomorphologic features at different spatial scales, are responsible of variabilities of water exchange across the groundwater-surface water interface (Kasahara and Wondzell 2003; Cardenas 2009); the geometry and position of the stream channel within the alluvial plain (Woessner 2000), the distribution of the main lithologies that cross the river and the magnitude of hydraulic conductivities of the sediments composing the channel. Interaction between GW and SW is not only controlled by natural factors, but also affected by climate and human activities, with a heavy load in arid and semi-arid areas (Saha et al. 2018).

Among the aforementioned factors, at a smaller scale, the spatial distribution of lithologies (Kalbus et al. 2009; Beetle-Moorcroft et al. 2021) and therefore the hydraulic conductivity and streambed permeabilities along the river path, reflect into a highly variations in space and time at different scales of groundwater fluxes at the interface between aquifers and streams (Ellis et al. 2007; Krause et al. 2007).

The spatial distribution of lithologies across the riverbed, in fact, exerts an important control in the direction of the flows between SW and GW bodies, because streambed sediments can range over more than eight orders of magnitude, and locally this range maybe cover more than two orders of magnitude (Calver 2001). This is a further element allowing to distinguish a losing reach of the river from a gaining one.

Although the comparisons of the hydraulic conductivity of streambeds for losing and gaining streams are not yet well documented, a study has shown how flow direction along which stream and groundwater exchanges occur, operates a selection of the streambed sediments and therefore a shift in hydraulic conductivity patterns (Chen et al. 2013).

In gaining reaches, flow from groundwater moves upward in the vertical direction beneath the water–sediment interface, through streambed sediments. This upward movement operates a sorting of fine particles in the upper part of the streambed: the water flow in pores suspends the fine particles and brings them upwards into streams, where currents wash away the fine materials. This winnowing process operates a selection of the sediments composing the streambed, leaving coarser materials in streambeds, following a higher hydraulic conductivity in shallower parts of streambeds (Song et al. 2007; Chen 2011) and a decrease with the depth.

Conversely, in losing reaches, fine particles are brought by downward movement of water to benefit of groundwater, partially silting the pores of coarser sediment (Chen et al. 2013). As a result, in losing reaches, streambed hydraulic conductivity is the smallest near the water–sediment interface and increases with depth; in gaining streams, streambed hydraulic conductivity is likely the greatest near the water–sediment interface and decreases with depth, hence the hydraulic conductivity becomes larger in the top layer of streambeds (Dong et al. 2012). These flux directions can impact hydraulic conductivity values to depths of greater than 5 m (Chen et al. 2013).

Besides the geological and lithological characteristics of streambed (permeability, hydraulic conductivity) also precipitation events and seasonal patterns may have an influence on the positioning of the water table inside the aquifer thereby inducing changes in flow direction as well as having a control on the stream stage to the adjacent groundwater level (Sophocleous 2002).

In gaining reaches, the elevation of the groundwater table is higher than the elevation of the stream stage. Conversely, in losing reaches the elevation of the groundwater table is lower than the elevation of the stream stage.

Losing streams can be classified as either ‘*connected to’* or ‘*disconnected from*’ the underlying aquifer (Fig. 2.4). In the first case, water infiltrates directly from the stream into the groundwater, because of the absence of an unsaturated zone underneath the stream, and when stream levels rise higher than adjacent ground-water levels, a bank storage condition occur (Winter et al.1998).

Disconnected streams are generally typical of arid regions, where the water table fluctuates several meters below the streambed, also in response to intense groundwater pumping. Disconnected stream systems also develop if a layer of lower permeability, a ‘*clogging layer’*, lies below the streambed, due to natural process of fine sedimentation during low flow periods. Downward shifts in water tables in response to seasonal fluctuations and human activities can cause flow intermittence in streams, so they can turn from connected to disconnected along their length and can also change over time.

The determination of water fluxes between groundwater and surface water represents still a challenge in hydrology field, due to distribution of heterogeneities and the problem of integrating measurements at various scales (Sophocleous 2002).

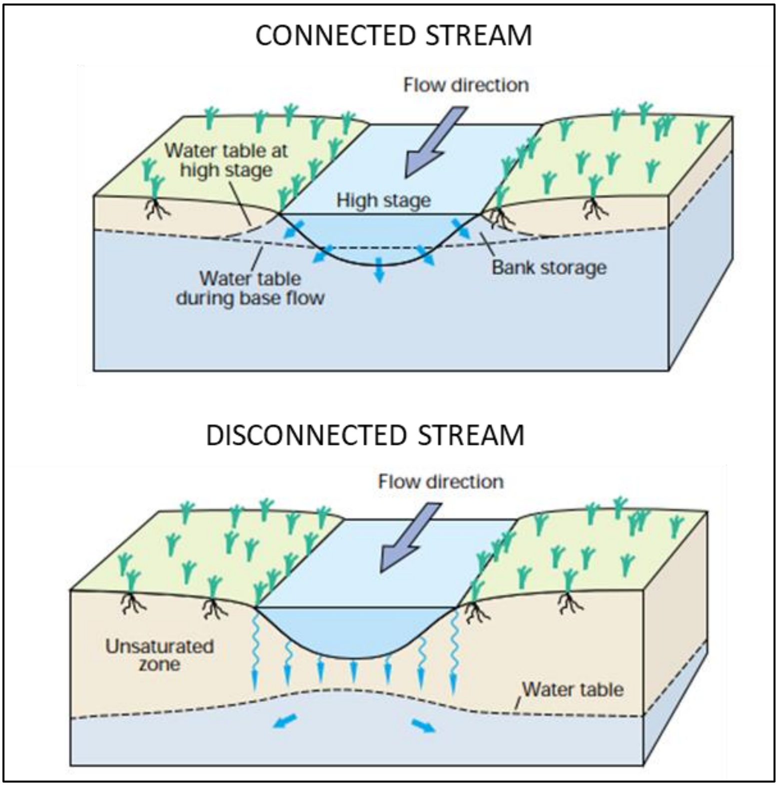

Fig.2.4 - Different flow regimes behaviour between stream and aquifer: in a losing connected system, the stream and the aquifer are linked; in losing disconnected streams, an unsaturated zone separates the stream from the groundwater (Winter et al. 1998).

2.3 Background on streambed infiltration

Aquifer recharge processes occur naturally, thanks to rainfall contribution and following runoff infiltration processes. During and after flow events, infiltration and percolation processes into the unsaturated alluvium ensures the presence of a huge volume of water that generally is stored in the channel alluvium between runoff events (Costa et al. 2013; Mpala et al. 2016; Rodríguez-Burgueño et al. 2017).

Thanks to transmission losses to groundwater storage beneath the channel bed, the water collected and stored within the alluvium can be considered as an alternative source and, in some cases, the unique source, to provide water supply for food production or for consumptive use, during dry periods (Costigan et al. 2017).

This is the main reason for which, in many arid areas across the globe, such as America, Africa or eastern drylands, ephemeral streambeds play a fundamental role in facilitating groundwater recharge aquifer through transmission losses (Gallo et al. 2020; Wekesa et al. 2020).

Ephemeral streamflow that cross the arid and semi-arid Southwest US, for example in Arizona, represent for the communities, a key component of the local water cycle, necessary for agriculture and for groundwater recharge.

They occur after summer precipitation known as the North American Monsoon, and along their channels made with sandy and coarse-grained soils, transmission losses and very huge infiltration occur, with subsequent recharge processes (Coes and Pool 2005).

In some countries of the Sub-Saharan Africa, such as Namibia or Kenya, ephemeral rivers are the starting point to carry on studies about water flow behaviour and storage potential for purposes of supporting water resources development and ecological sustainability and water resource potential as alternative water sources for local communities (Botes et al. 2003; Wekesa et al. 2020).

Although these phenomena are generally driven naturally, in some cases it is necessary to rely on alternative water resources to cope with water emergencies, such as enhance aquifer level recharge, limit salinization issues or control aquifer water quality, especially in areas affected by constant water scarcity.

Water scarcity is a crucial issue deeply felt in arid and semiarid areas, owing to the dramatic effects of the climate changes, but is also an argument of great global concern for the combination of multiple stressors. For all these reasons, water recycling practices and reuse, as well as the addition of treated wastewater to streams, are becoming a more widespread technique in response to urban populations grow and increasing irrigation demands. The development of new wastewater treatment plants is a direct consequence of urban increasing population and their needs worldwide, and for this reason, the discharge of effluent into streams will increase.

Streams receiving effluent are generally called effluent-fed, but the ratio between the percentage of effluent discharged and the natural streamflow, allows to define different types of effluent fed river: effluent-dependent (100% effluent during baseflow, Du et al. 2014), effluent-dominated (>50% effluent, Boyle and Fraleigh 2003) and effluent-impacted (<50% effluent, Schultz et al. 2010). Effluent-fed streams are widespread worldwide and can be found in many different climate zones and geographic settings with different size and extension (Fig.2.5).

A recent global review, mainly focused on the ecological aspects of wastewater discharge has highlighted that widespread technique is frequently adopted in many countries, with a higher percentage in the U.S.A. and Europe (Hamdhani et al. 2020).

Fig.2.5 - Some examples of fed-effluent rivers: (a) Rio de Flag, Arizona, U.S.A.; (b) Fountain Creek, Colorado, U.S.A.; (c) Los Angeles River, California, U.S.A.; (d) Rio San Miguel, Spain; (e) Boulder Creek, Colorado, U.S.A.; (f) Salt River, Arizona, U.S.A.. Photo credits: Michael Bogan (a, c, e), Bonita Bogan (b), Nuria Cid (d), Hamdhani (f).(Hamdami et al. 2020)

In the US Southwest, many examples of effluent-dominated rivers can be found in urbanized watersheds, among which the Santa Ana River in southern California, the Trinity in Texas, the South Platte in Colorado, and the Chattahoochee that cross both Alabama and Georgia states. All these rivers, once characterized by intermittent flow, are now perennially dominated by municipal effluent discharges, with a series of economic, environmental, and social benefits that ranges from supporting ecosystem services, creating habitat, and providing urban amenities, improve water quality and support water reuse, and not for least, support base-flow of non-perennial rivers(Brooks et al. 2006; Luthy et al. 2015).

The end uses of this treated effluent include agricultural and urban irrigation (Tabatabaei et al. 2020), groundwater recharge (Dillon et al. 2006; Fournier et al. 2016; Shawaqfah et al. 2021), direct potable reuse (Leverenz et al. 2011), and direct discharge into streams or oceans (Brooks et al. 2006).

Another case study of urbanized fed effluent river is represented by Israel's Yarqon River which flows through Tel Aviv city and is a historically perennial stream that is now sustained by wastewater-effluent discharges.

Despite this growing trend, many uncertainties about the impacts of effluent on receiving streams are still not solved, and probably include a complex mixture of ecosystem subsidies and stressors (Aristi et al. 2015). Improved understanding of effluent-fed streams could also help provide motivation for managers and the public to better protect these systems.

2.4 A review of methods used for evaluating transmission losses and groundwater recharge in ephemeral streams

One of the most important and relevant aspect regarding ephemeral streams, is related to the possibility to quantify the volumes of water that effectively reach the aquifer and can be considered the recharge rate into the water cycle.

However, before assessing the recharge rate, which is the final target in a sustainable management of water perspective, it is fundamental to understand and having, were possible, as much more accurate information on the magnitude and patterns of transmission losses, especially in ephemeral streams, owing to the extremely variability of their flow regimes, especially in drylands, which represent a unique environmental settings having the potential to amplify these losses.

Quantifying the rate of recharge passes through the estimation of transmission losses (or infiltration rate) through streambed; however, this seems to be extremely complicated by the presence and the interaction of several factors which make difficult to measure this recharge. A confirm to this, in the scientific literature very few studies have quantified recharge rate and this aspect remains a considerable research challenge (Schoener 2016; Mujere et al. 2022). In addition, most of the method proposed in the review literature are addressed to estimate groundwater recharge in perennial streams and most of them are not suitable or cannot be applied for ephemeral streams (de Vries and Simmers 2002; Scanlon et al. 2002; Goodrich et al. 2004; Shanafield and Cook 2014).

Taking account of all the factors that may affect recharge processes in ephemeral streams, methods that estimate transmission loss or quantifying loss rates from losing streams, can be considered as a proxy for measuring groundwater recharge and range from simple to complex approaches.

In a recent outstanding review, Shanafield (2014) proposes a review of seven methods for quantifying ephemeral and intermittent stream infiltration and aquifer recharge. Each of the described methods has different purposes that ranges from the parameter measured (infiltration, transmission loss, or recharge), spatial and temporal ranges, and advantages and limitations. Methods can be grouped into three main clusters and for the purpose, the first five methods are mainly used for detecting transmission losses. The first group of methods is more focused on the monitoring of infiltration and transmission losses through the riverbed and have a punctual application. The methods are the following three and are briefly described.

Controlled infiltration experiments

Controlled experiments are generally carried out in dry channels and provide a quantification of infiltration rates during flood events by using some instrument such as infiltrometer or permeameter for measurement at a certain location within the streambed. A column of constant head above the streambed allows to directly measure the rate of infiltration, from which soil properties such as sorptivity and field saturated hydraulic conductivity can be calculated.

Although this method provides estimating some streambed hydraulic properties, several studies has highlighted that the hydraulic properties or infiltration rates measured during controlled infiltration experiments may not always be indicative of reach-scale infiltration rates during flood events (Dahan et al. 2007).

Monitoring variations in water content

This method estimates the infiltration rate from an ongoing wetting front after a wetting event (streamflow). Therefore, it can be applied only to ephemeral or intermittent streams because the formation of a wetting front and consequently a streambed partially saturated is required.

Water fluxes variations through the sediments are derived by some information about change in stored water in the vadose zone (i.e., changes in moisture content) and the velocity of the wetting front through the soil. This technique is generally considered the most suitable for determining ephemeral stream recharge (Dowman et al. 2003). However, field application of waterfront methos in ephemeral streams are very rare. In addition, although measurements of water content allow to calculate vertical infiltration rates, once the streambed sediments at the measurement depth are saturated, changes in flux cannot be determined from water content so that the technique cannot capture late infiltration resulting from long flood events which may be significant in replenishing continuous natural losses from storage such as percolation and transmission flows (Dahan et al. 2008).

Heat as a tracer of water movement

This method is based on the transmission of a transient temperature signal which propagates through the streambed at various depths, to determine recharge through ephemeral channels.

While during periods of streamflow, both conductive and convective processes are present, allowing percolation characteristics beneath the streambed to be evaluated (Constantz and Thomas 1997) and infiltration rates to be calculated, when no flow occur, this signal is propagated only through conduction.

To date, the application of temperature as a tracer of ephemeral stream recharge has generally been used to identify the length and/or depth of infiltration rates within the river rather than quantifying the actual recharge. In some cases, the method has been applied to differentiate gaining, losing or dry conditions along some ephemeral streams in the southwestern USA (Moore 2007).

The second group of methods describe how to measure the streamflow during flow events and allow to estimate either transmission losses or streambed infiltration covering a large spatial distance, that can also reach tens of kilometres between river distance (Lane et al.1971; Pool 2005; Rodríguez-Burgueño et al. 2017). The methods are the *Floodwave front tracking,* hereinafter briefly described, and the *Reach length water balance method,* which will be extensively described in chapter 4.

Floodwave front tracking

By adopting this method, it is possible to track the advancement of a floodwave down an ephemeral or intermittent stream channel based on the velocity and variations in velocity. To estimate water velocity and modeling floodwave progression in ephemeral streams, different equations are used, ranging from the simpler Muskingum–Cunge method (Cunge 1969) that generally does not require input data, to the full Saint–Venant equations, which combine the momentum and continuity equations.

These models found a good application in cases of long duration flow events, allowing to estimate recharge rates under long-time flow conditions or as drying occurs and are suitable for covering a wide spatial range. For example, Niswonger et al. (2008) estimated hydraulic conductivities and identified areas of high transmission loss over 43 and 11 km of an intermittent and an ephemeral stream channel, respectively.

Unlike the other methods, the third group collects two methods which are addressed to estimate groundwater recharge rather than streambed infiltration, by monitoring groundwater storage evolution in the alluvium before, during and after flow events (Sorman et al. 1997). These methods include Groundwater mounding and Groundwater dating methods.

Groundwater mounding

The application of this method needs some assumption to be taken into account, among which, a homogeneous and isotropic behaviour of the aquifer (Sorman et al.1997), a uniformity in the geological properties in the longitudinal direction (Goodrich et al. 2004), and a percolation occurring beneath the stream downwards to the water table. Another common assumption for this method is that of Dupuit flow, which can lead to errors in groundwater level calculations when the observation well is very close to, or beneath the stream (Brunner et al. 2009; 2011). All these assumptions can lead to uncertainties in estimated fluxes of at least ±50%.

However, this method can be considered useful for estimating actual recharge instead of infiltration, since the response of the formation of a groundwater mound to changes in streamflow can be used to calculate changes in the volume of groundwater storage, and therefore infiltrated stream water that has recharged the aquifer.

Groundwater dating

The last technique relies on the use of environmental tracers to estimate groundwater age (or residence time) over timescales ranging from days to thousands of years (Cook and Böhlke 2000). This method provides information on actual groundwater recharge rates, rather than infiltration rates.

The groundwater velocity in a losing stream in response to flood events can be determined from measurements of groundwater age derived from environmental tracers. For the purpose, many affordable tracer methods have been used, among which radon (Bertin and Bourg 1994), tritium (Geyh et al. 1995), 3H/3He (Massmann et al. 2009), and carbon-14 (Fulton 2012), the last one providing information on long-term fluxes. The choice of tracer will depend upon the likely rate of recharge and the distance of the available bores from the river.

The application of this method, in some cases, makes difficult to distinguish between indirect and punctual recharge resulting from transmission losses from the contribution of diffuse recharge to the river-bed storage. Although uncertainties in estimating groundwater age (and hence flow velocity) are often relatively small (approximately 10%), uncertainties in aquifer thickness and porosity can lead to uncertainties in fluxes on the order of ±50%.

CHAPTER 3. STUDY AREA

3.1 Location of the study area

The study area is in the south-eastern part of Apulia region (Southern Italy), in a morphologically flat area known as Brindisi Plain (Fig.3.1). Since the beginning of the 18th century, owing to the flat morphology of the area and to the relatively low permeability of the sediments that diffusely characterize the plain near the coast, many reclamation operations were carried out to drain the marsh areas in order to prevent flooding and also to reduce epidemiologic concern related to malaria outbreaks (Mainardi 1998; 2017; Margiotta and Parise 2019). This made possible in the following years, the development of a diversified and intensive agriculture from inland towards the Adriatic Sea, which mainly consists in olives, vineyards, and vegetables crops. Few ephemeral SW bodies, often regulated within artificial channels, cross the plain perpendicularly to the Adriatic coast and feed several conservation wetland areas characterized by typical Mediterranean vegetation.

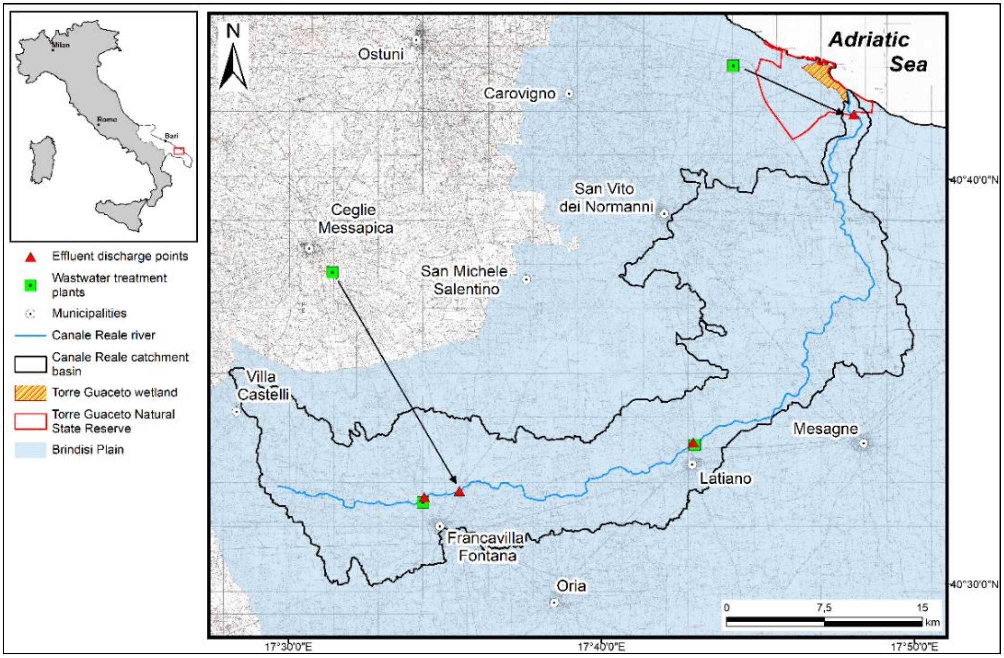

Fig.3.1 - Geographical setting of the study area, with the relative distribution of the effluent discharge points along the Canale Reale River (Passarella et al. 2022).

The Canale Reale River represents the most significant watercourse in the southern Apulia, owing to the extension of its catchment basin (approximately 210.00 Km^2) and its length (about 50 km).

It originates from some innermost springs nearby Villa Castelli municipality, located at about 150 m a.m.s.l., nowadays hidden by a dense reed and recognizable only thanks to the presence of a touristic road sign which reports the title of “Sorgente di Strabone” (Fig. 3.2).

Fig.3 2. - Reeds and road sign in correspondence of the Canale Reale springs (Photo made by the author, 2021).

The Canale Reale River crosses the territories of different towns, collecting the treated effluents from the wastewater treatment plants (WWTPs) of the municipalities of Ceglie

Messapica, Francavilla Fontana, Latiano, and partly from the Carovigno WWTP with a total discharge of $18.3 \cdot 10^3$ m^3/d.

Since wastewater discharge practice has been allowed for decades along the river, with increasing discharge rates in the last 20 years, the Canale Reale River can be defined as an *effluent-fed river.*

Although it has been classified as a heavily modified river with a temporary flow regime of ephemeral-intermittent type, according to the WFD (Id. ITF-R16-14417EF7T), the Canale Reale River is locally appreciates for its high eco-systemic and naturalistic value: it flows within the Torre Guaceto Marine Protected Area, which extends for 2.200 ha, before reaching the Adriatic Sea, and partially feeds a salt marsh of $3.50 \cdot 10^5$ m^3 volume together with groundwater springs (Fig.3.3).The Marine area and the Natural Area (1.100 ha) for a length of 8 km of natural coast, established by the Italian Minister of Environment, define the Natural State Reserve of Torre Guaceto, which is safeguarded by Ramsar Convention as site no. 215[1] .

3.2 Canale Reale River - wetland interaction

The Canale Reale before reaching the Adriatic Sea, flows into the protected marine area, south of Zone A, a zone forbidden for tourism as it holds the highest protection. Within the marine reserve, the Canale Reale River feeds with its freshwater, a salt marsh area which extend for about 119.41 ha. Both the mean depth and the mean volume of the salt marsh are variable depending on seasonal water input which varies from summer to winter season. This is justified by the fact that the study area is characterized by a Mediterranean-type climate, with meteorologically stable summers and unstable winters and precipitation pattern characterize by a strong seasonality.

During summer season, the mean depth is about 20 centimetres, while an increase up to 40-45 centimetres during winter has been registered; the mean volume of the salt marsh has been estimated approximately equal to $3.49 \cdot 10^5$ m^3, and it follows that the system does not hold the hydraulic equilibrium during the year.

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[1] (https://www.ramsar.org/wetland/italy).

Fig.3.3 - A salty marsh, partially fed by the water collected by the Canale Reale River, into the Natural State Reserve of Torre Guaceto. (Picture made by the author, 2022)

Besides precipitations, the wetland receives a diffuse and diversified water input: freshwater coming from the Canale Reale, and also brackish water from the groundwater springs contribute to the water budget of the wetland area. On the contrary, tidal variations registered in sea levels in the area does not affect the hydrological budget of the Torre Guaceto marsh, being very low to the presence of shallow coastal dunes which limits tidal effects.

Even though the Torre Guaceto salt marsh ecosystem is fed by the Canale Reale watershed, to date the Canale Reale is physically separated from the marshy ecosystem by the presence of some concrete dykes and at the mouth section, by a concrete riverbed (Pomes et al. 2005), as can be seen in some pictures taken during a field survey (Fig.3.4).

Fig.3.4 - Some pictures of the mouth of the Canale Reale River ending into the Natural State Reserve of Torre Guaceto. (Pictures made by the author, 2022)

According to LOICZ budget method to calculate the water balance of the Torre Guaceto wetland, it emerges that the main contribute comes from freshwater marsh; however, also a discrete marine input occurred via groundwater as a saltwater infiltration has been confirmed by water sampling and analyses demonstrating salinity values varying between 5.8 and 13.3 psu (Practical Salinity Unit) (Pomes et al. 2005).

Nevertheless, an increasing of groundwater extraction through the wells spread through the Brindisi plain and close to the Torre Guaceto area since 1950, may be considered responsible of this marine infiltration through the years as well as an increasing of salinity of the wetland area, with a consequent alteration of the local biodiversity and wetland equilibrium. All these aspects highlight the complexity of this hydrological system that involves both the Canale Reale River and the effluent collected and the Torre Guaceto wetland.

3.3. Climate

The study area is characterized by a typical Mediterranean climate, with mild temperatures and an overall precipitation volumes of about 600 mm/year. During summer season, temperatures often exceed 40° C and rainfall maybe missing even for two or three consecutive months; winter season, instead, is characterized by scarce and irregular rainfall, while temperatures are mild and usually exceeding 10°C (Lo Presti et l. 2010; Passarella et al. 2017a; Passarella et al. 2017b; Maggi et al. 2018; Passarella et al. 2020). In Figure 3.5 some elements of the hydrological balance related to study area, have been plotted, covering a spatial range of the last 20 years. For the purpose, precipitation and temperature data were downloaded from the Hydrological Annals published by the Apulian Civil Protection (https://protezionecivile.puglia.it/), while effective precipitation and the potential evapotranspiration (PET) were assessed based on Brouwer and Heibloem (1986) and the Hargreaves formula (Hargreaves and Samani 1982), respectively. For its strategic position, in the central part of the area, the monthly measured total and estimated effective precipitation are plotted together with the estimated monthly potential evapotranspiration to the weather station of Latiano. The PET values have been estimated constantly around 1000 mm/year.

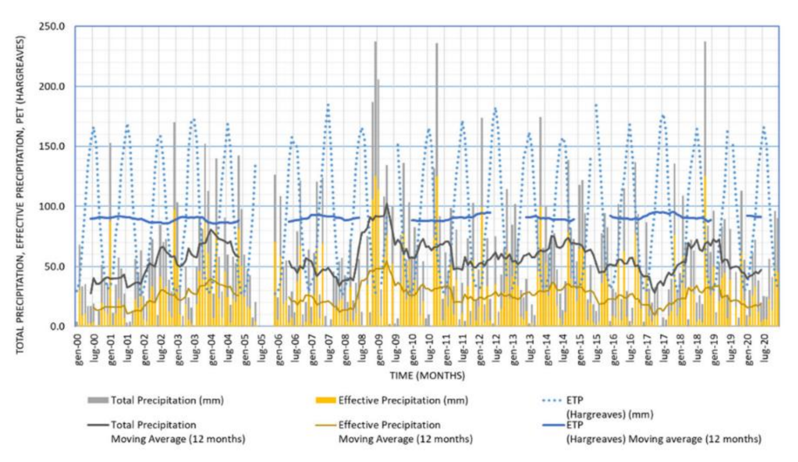

Fig.3.5 - Monthly elements of the hydrological balance in the area under investigation. (Passarella et al. 2022).

3.4 Main local environmental issues

The study area depicts a very particular geological and environmental context, in which several elements interact and create a unique ecosystem.

For this reason, the environmental critical issues mainly linked to the human activities, have a very deep impact, and involves all natural elements, being connected to each other. The main problem is represented by the qualitative and quantitative degradation of groundwater resources, which in turn causes a serious impact that mainly affects the groundwater resources.

Since 1970, the Brindisi plain including almost all the areas close to the Canale Reale towards the Adriatic Sea has been suited to a hydro-intensive cultivation of olive trees, vines and vegetables, especially artichokes, thanks to its flat morphology and a fertile availability of land, following the reclamation works of the marshes.

This led to an increase in water uptakes for irrigation purposes, with a significant impact on the availability of the local groundwater resources, especially those hosted in the deep aquifer, which represent the most precious resource of the entire region and of the Salento peninsula (Cotecchia 2014). Furthermore, the huge and prolonged withdrawals for irrigation purposes, affect the natural chemical- physical composition of groundwater resources, inducing localized phenomena of seawater intrusion along the coast that in some cases even pushes into the hinterland of Brindisi, as a consequence of the imbalance between fresh groundwater and salt water (Zaccaria et al. 2016).

This issue is also worsened by the effects of climatic changes that affect semi-arid Mediterranean coastal region, among which the study area, which reflect into alternance of intense rainfall events and dry periods characterized by high evapotranspiration rates. These climatic patterns, in turns, do not enhance the recharge of local aquifer (Doglioni and Simeone 2019), neither allows the flow continuity of those few surface water bodies, generally limited to ephemeral flows. As a consequence of these phenomena, soils are often irrigated with brackish water causing an impoverishment and a progressive soils salinization; in addition, high evapotranspiration rates, soil characteristics and improper water management practices, (e.g., improper irrigation), limit water drainage through soils, and cause salt accumulation in the upper layers.

Another pressure of anthropogenic origin is represented by the treated wastewater discharged by four wastewater plants directly into the Canale Reale River. This practice has increased during the last 20 years and nowadays the Canale Reale River is fed mainly by these traded affluent for all year. One of the main issue related to the use of this practice as an alternative disposal of treated municipal water, is related to the chemical characteristic of discharged water. Evidence of streambed infiltration during the dry season, particularly in the downstream half of the river course, allows to suppose a possible connection between surface water and groundwater. Therefore, the quality of the water that may infiltrates and reach the aquifer, if not properly treated, may cause contamination of groundwater sources, although these practices may be useful to contrasting sea water intrusion, by acting as an underground freshwater barrier.

3.5. Geological and hydrogeological setting

The study area extends between two structural domains, the Murgia Plateau and the Salento peninsula within an important transition zone, known as ‘Soglia Messapica’ (Messapian Threshold). It consists in a tectonically disturbed area that has experienced multiple geodynamic and tectonic events involving the carbonate basement that, hence, results displaced in a series of blocks by means of normal sub-vertical faults, predominantly oriented E-W and NNW-SSE (Tozzi 1993). Particularly, the path of the Canale Reale River follows the tectonic setup as well as the main direction of pre-existing buried faults system, and this evidence is confirmed by a rotation from the W-E direction in the first part of its path to N-S in the middle and final part (Guerricchio and Zezza 1982).

In accordance with Ciaranfi et al. (1988), the geological setup concerning the study area, is made up of five main formations, with different spatial extension, (Fig.3.6) described, from bottom to top, as follows:

- Limestone of Altamura (Cretaceous), composing the regional carbonate basement, is mainly made up of calcareous and calcareous–dolomitic rocks; this formation widely outcrops in the western part of the study area;
- Calcarenite of Gravina (upper Pliocene–lower Pleistocene), composed by calcarenite sediments with a variable cementation degree, outcropping in the central part of the study area, with a thickness not exceeding 20-30 m;
- Subapennine clays (lower Pleistocene) constituted by clay and sandy clay, outcropping sporadically in the study area;
- Terraced Marine Deposits (middle-upper Pleistocene) characterized by considerable variations of facies, generally made up of poorly cemented calcarenites and fine calcareous sands and a base level of marly clays. These deposits outcrop in the eastern part of the study area with a thickness not exceeding 10-20 m and are located at different heights (terraces);
- Alluvial, marshes and coastal deposits (Holocene) with few thickness and limited extension (Spizzico et al. 2005).

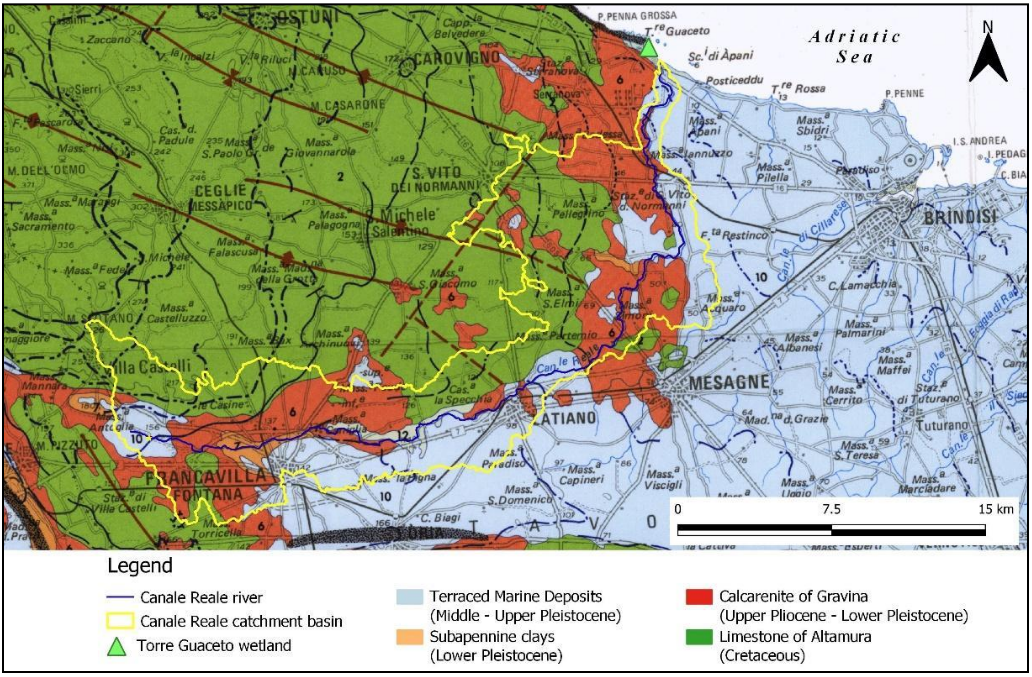

Fig.3.6 - Geological map with a focus on the main formations outcropping in the Canale Reale catchment basin based on Ciaranfi et al. 1988 (Passarella et al. 2022).

According to the structural and geological setting, and the lithological composition of the main formations outcropping in the area, two different aquifer structures can be identified: a deep carbonate aquifer hosted in the permeable Cretaceous carbonate rocks succession and a shallow local porous aquifer, recognizable in the Terraced Marine Deposits (TDMs), supported at the base by the impermeable clayey level (Maggiore and Pagliarulo 2004).

The shallow aquifer extends without continuity, following the morphology of the area, and generally deepening moving from the inland parts of the area to the coast. It is supplied by a direct recharge from rainwater and when maximum recharge conditions occur, exceeding water are drained into the rivers, canals, and topographically depressed areas. Despite its limited extension, this aquifer is still intensively used for local irrigation purposes, as confirmed by the severe nitrate contamination highlighted in Spizzico et al. (2006) and does not suffer at all the effects of the seawater intrusion.

The deep carbonate aquifer shows a very marked anisotropy that strongly affect the groundwater circulation conditions, due to the combination of the structural setup and the presence of karst systems at different stages of evolution (Grassi 1983).
It results an extreme variable degree and spatial variation of hydraulic conductivity and other hydrogeologic parameters.
According to this feature, and the presence of Subapennine clays which locally cover Mesozoic bedrock, groundwater generally flows both under unconfined and confined condition, this latter generally is recognized along the coastal area, where carbonate rocks deepen up to 70 meters below sea level. Particularly, along the wetland area of Torre Guaceto, water emerges through submarine and subaerial springs along the coast (Sciannamblo et al. 1994), due to a mixing between waters flowing in both deep and shallow aquifers. The deep aquifer is mainly recharged by rainfalls that infiltrate the innermost part of the Murgia Plateau, as also confirmed by the use of heat as an environmental tracer in local studies (Cotecchia et al. 1978). Groundwater floats on intruded seawater and flows towards both the Adriatic coastline and the north-west sector of the Salento, through the Soglia Messapica, where a gradual increase in aquifer permeability occurs (Cotecchia 1979; Cotecchia et al. 2005).

In the study area, the increasing of water withdrawals for irrigation needs over the last 50 years caused a severe anthropogenic impact on deep groundwater resources both in quantitative and in qualitative terms. Besides a poor availability of groundwater resources, localized phenomena of saline contamination both along the coastal aquifer and the inner part of the Brindisi plain have been recognized (Spizzico et al. 2006). In addition, although the shallow and deep aquifers are not communicating because of the presence of the impermeable formation, a hydraulic connection exists between them, which can be attributable to the over 3.000 irrigation wells, improperly drilled along the Brindisi plain, but also to significant structural discontinuities, such as faults and tectonic fractures involving the impermeable layer (Cotecchia 1979;

Sciannamblo et al. 1994; Ricchetti and Polemio 1996; Cotecchia et al. 2005; Spizzico et al. 2006).

3.6 Available data from GW monitoring networks and hydrogeological data set

One of the major difficulties encountered in this study project was that of the discontinuity of information dating back to the origin of the regional system monitoring network. From the old first effort to create a reliable monitoring groundwater network in the 1995, where the first groundwater network was effectively established, many modifications have been done, until 2015 (Barca et al. 2015).

The first monitoring network operating on a regional scale was developed following a severe period of drought that affected Apulia region in the late 1980s, with the aim to evaluate the quantitative and qualitative status of the Apulian groundwater.

The extended period of drought caused a huge increase in water extraction from aquifers, and to face the progressive degradation of groundwater resources, in 1991, the "Project for the enlargement of the hydrographic and qualitative control of aquifers network of the Apulia region" was carried on.

The project aimed at an enlargement and updating of the hydro - metrographic of the previous regional network (Bari Irrigation Authority) with the establishment of 107 wells monitoring (47 newly built wells and 70 already existing, before 1991) and 7 mareographic monitoring stations. The aim was not only to guarantee a continuous monitoring of the chemical-physical parameters of groundwater, i.e., pH, temperature, electrical conductivity, oxygen potential reduction and dissolved oxygen, but also to rely on a suitable instrument for the management of groundwater resources in real time.

All the data recorded in continuous monitoring, by automatic recording equipment fixed in specific checking points, were collected into data storage centres, managed by a “Territorial Information System” (SIT-Puglia), to know, in real time, the quantitative and qualitative status of the underground water resources (Colucci et al. 1998)

In the whole Apulian region, hydrogeological, geochemical and geophysical investigations were later carried out from 1995 to 1997, on all sampled water from the regional

well network and on some of the main coastal springs. In particular, periodic multiparametric profiles and chemical-physical analysis were performed on water samples.
At the end of the 90, after the development of the informative network, because of insufficient budget to support the project, the regional network was abandoned. As the first regional groundwater monitoring network was effectively established in 1995, from 1995 to 2022 the monitoring of some specific parameters such as quantitative information (groundwater level) or qualitative (Ph, temperature,) were unfortunately discontinuously measured, although nowadays, the regional groundwater dataset consists of about 4000 measured values of the main hydrogeochemical parameters. As for qualitative groundwater monitoring network, it consists of 341 wells and 20 springs distributed almost uniformly over the regional territory (Fig.3.7).

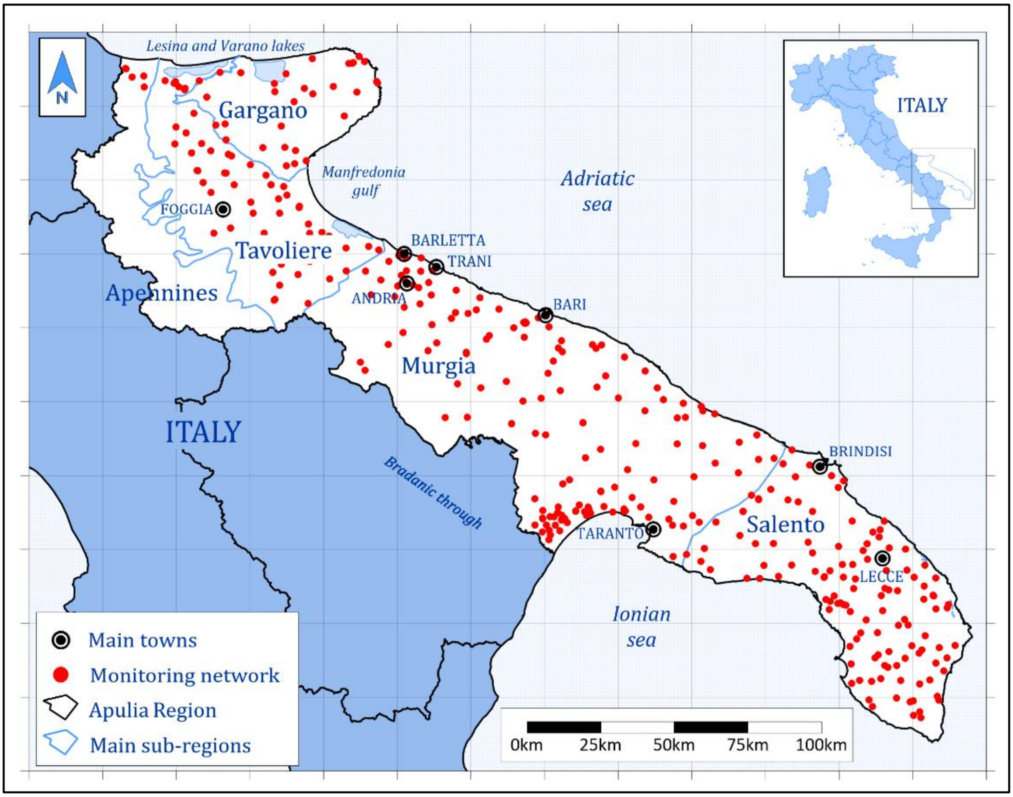

Fig.3.7 - Map of the Apulia region, showing the main geographical sub-regional areas (Gargano, Tavoliere, Murgia and Salento) and the regional groundwater monitoring network.

Qualitative and quantitative information have been retrieved from different monitoring network campaigns, to build up a quali-quantitative database composed of total of 169 wells falling within or nearby the study area. Specifically, the “Tiziano” monitoring network covering a period of four year, from 2007 to 2011; the “Maggiore” monitoring network for the period 2016-2108 and the Irrigation development agency (EIPLI) for the period 1995-1997. The data collected from 1995 to 1997 are available at the Sit-Puglia website.

Other qualitative and quantitative information which have been used for the development of the quali-quantitative database, have been taken by some specific research project carried on by the IRSA-CNR, such as the research project “VIOLA” on the assessment of background levels in the groundwater bodies of the Apulia Region (Masciale et al. 2021; Frollini et al. 2022) or literature (Spizzico et al. 2006).

Groundwater monitoring data and stratigraphic information, related to more than 65 wells, dating back to the period from the 1950s to the 1970s (when the wells-drilling operations took place), have been retrieved in old regional archives and technical literature (Cotecchia 1955; Grassi 1973). Detailed information is available only for data collected after 2000. From this date on, official monitoring protocols and field forms indicate the physical parameters (pH, Eh, EC, temperature and DO) have been measured onsite by a multiparametric probe. All the data collected from monitoring network and from scientific and technical literature, concerning both qualitative and quantitative information, have been organized within the database and elaborated.

The effective number of wells on which monitoring campaign was carried out is 169 and their distribution within the study area and the catchment basin of the Canale Reale River, can be observed in Fig.3.8, according to the main information retrieved from monitoring campaigns or technical literature.

However, in many cases, the same well has been detected in different monitoring campaigns and through different years, so for the same well, different measures of the quantitative information, i.e., the groundwater level, or qualitative information, i.e., TDS, Ion Chlorine, Ph, were made.

As a consequence, more than one measure, both quantitative and qualitative, corresponds to the same well and finally the database counts a total of 269 records. For example, the graph in Fig.3.9 shows the number of wells coming from the different monitoring network, as described before, from 1950 to 2020: even the number of wells detect is 169, for the reason explained before, the total number of wells is 214.

The graphical elaboration points out the discontinuity of the quali-quantitative measurements, in particular, two temporal gaps can be distinguished, one from 1971 to 1981 and one from 1983 to 1994, where either qualitative or quantitative data have been collected. For a better visualization of the data, the years without any useful information were not used in the final graphical elaboration.

In addition, there is not always a perfect match between the data: for the same well, the quantitative information is available, despite the qualitative one.

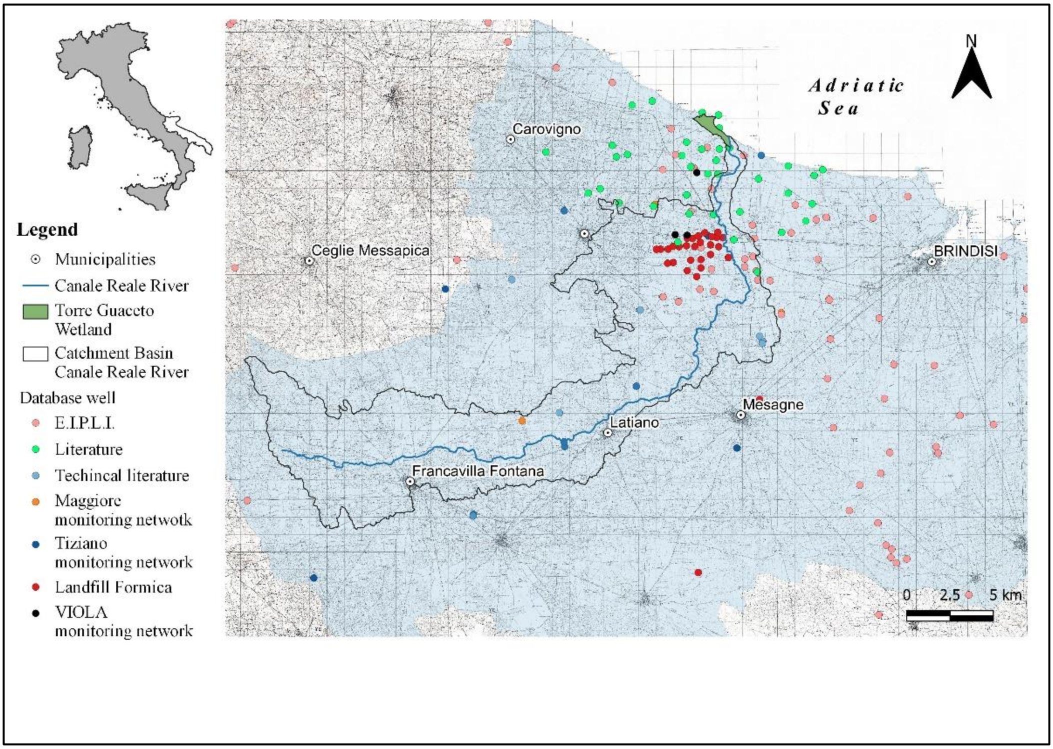

Fig.3.8 – Distribution of the 169 wells according to the main information retrieved from monitoring campaigns or technical literature.

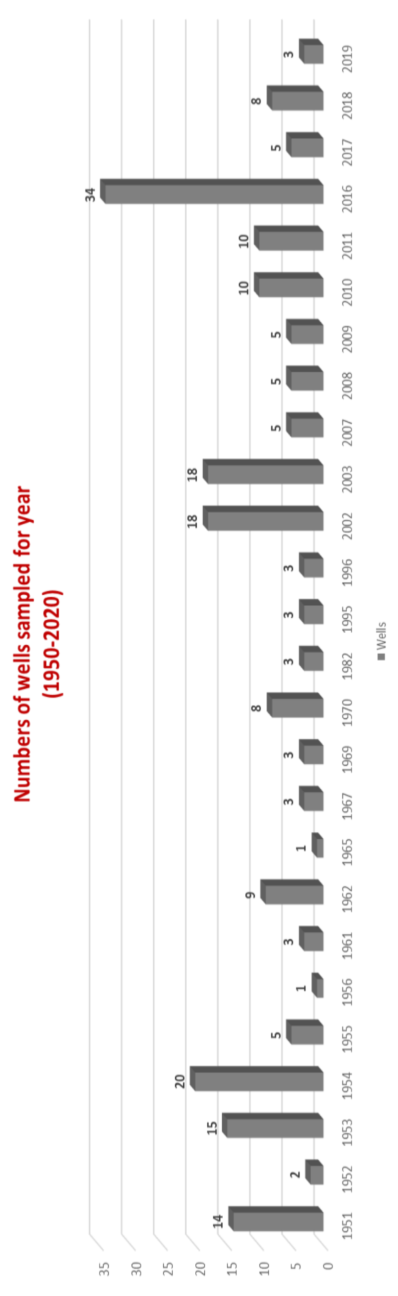

Fig.3.9 - Graphical elaboration of the wells collected in the qualitative and quantitative database.

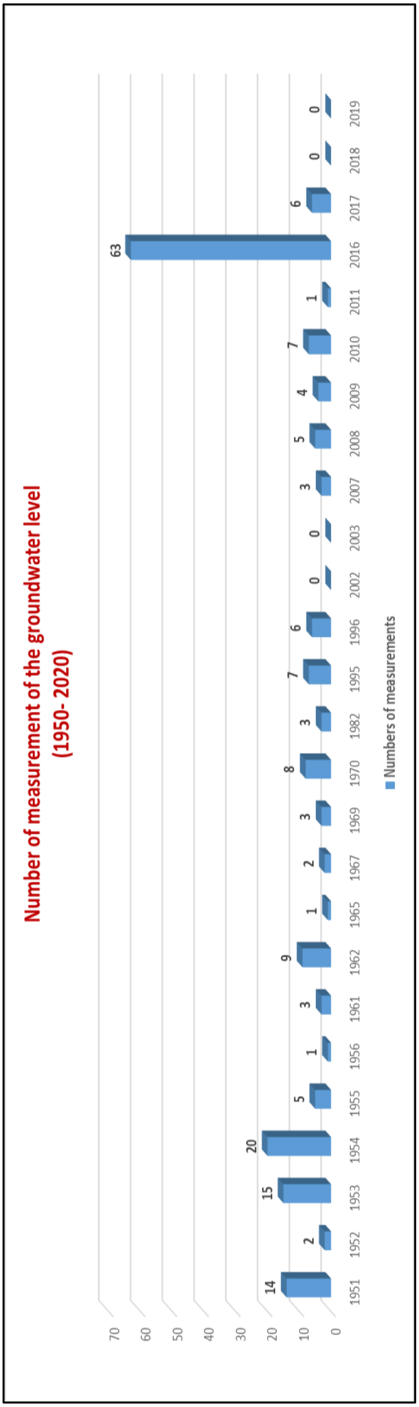

Fig.3.10 - Number of measurement of the groundwater level below surface ground, from 1950 to 2020.

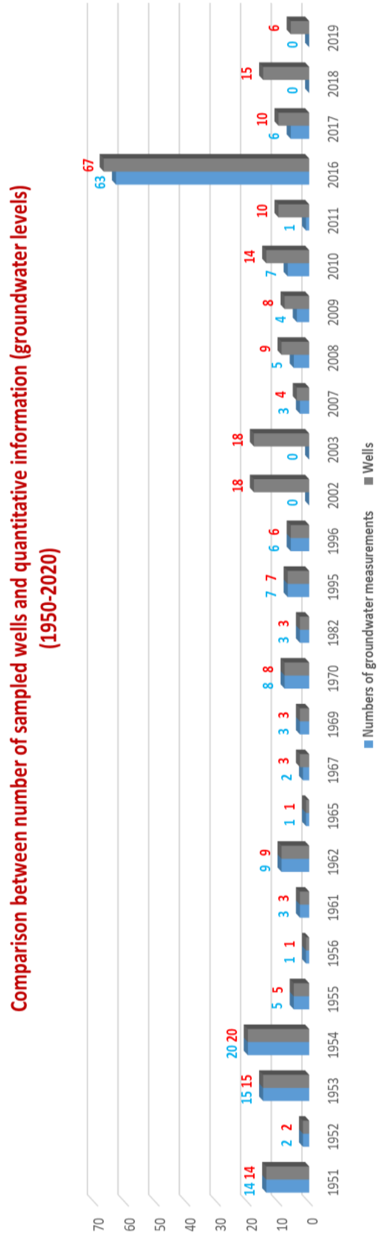

Fig.3.11 – Comparison between the number of wells composing the database and the quantitative information.

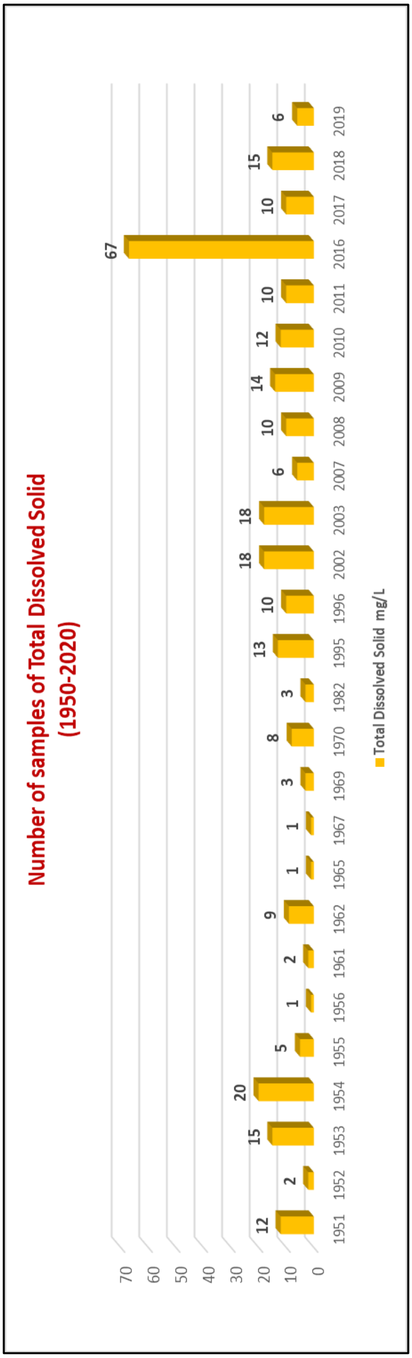

Fig. 3.12 - Number of measurement of samples related to TDS from 1950 to 2020.

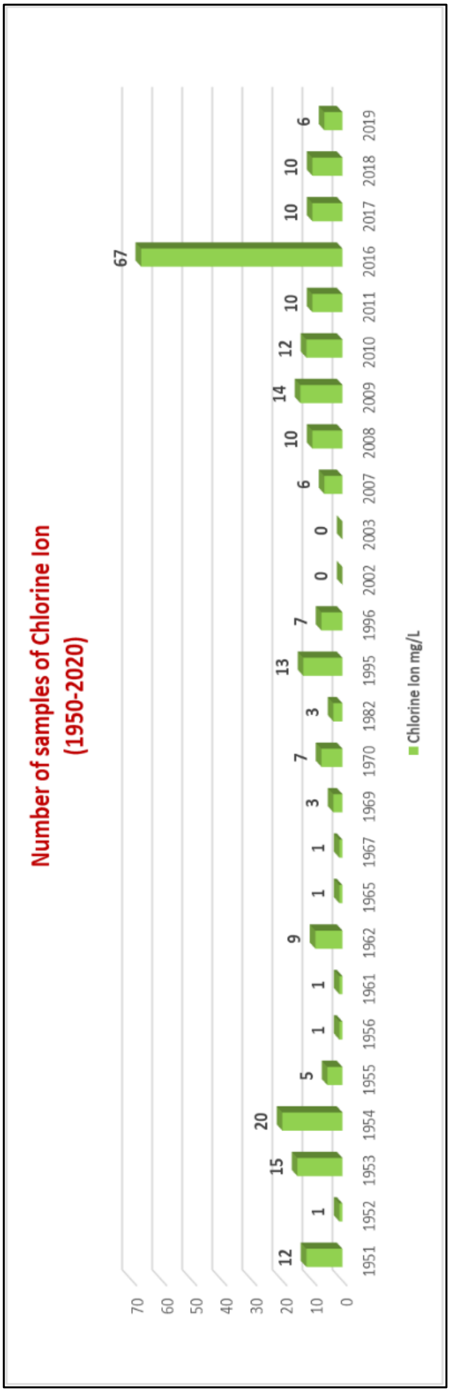

Fig.3.13 - Number of measurement of samples related to Chlorine Ion from 1950 to 2020.

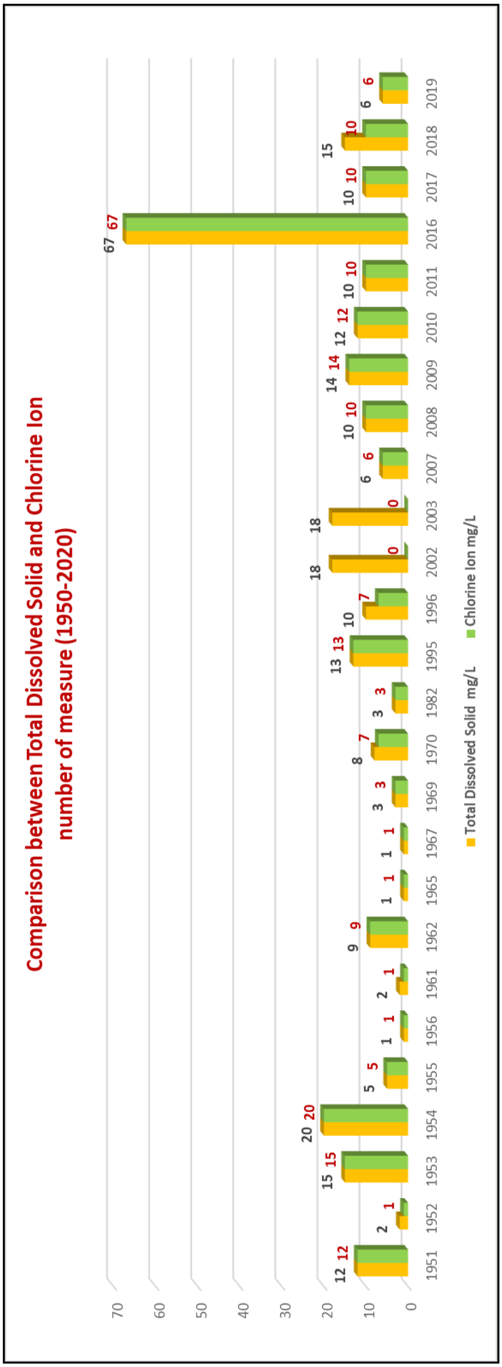

Fig.3.14 – Comparison between the two chemical parameters, TDS and Chlorine ion in relation to the number of measurements.

As in the cases of two physical parameters, TDS and Ione Chlorine were chosen as indicative of salinization of groundwater. Since the measurements refer to a very long-time interval, the sampling and analytical methods could have likely changed over time and for these parameters, and therefore some analytical correction were applied to the data.

In Fig.3.14 two parameters were compared, once more to stress the non-homogeneity of the data, is also compared to the number of wells. Among the 169 wells analysed, only 19 wells with qualitative measures and 3 with quantitative ones can be identified in the study area or close to it, belonging to the regional groundwater monitoring network. The huge and unique database about stratigraphical information of the drilled wells trough the Brindisi Plain, refers to a paper dataset dating back to the 1950, long before a reliable regional network was developed in Apulia region.

The data collected for the study area, together with some climate information, are summarized in Table 3.1.

Table 3.1 - Summary of the GW datasets available for the study area.

Description	Variables	Type	Time	Notes
Climate records	Temperature and precipitation	Microsoft Excel files	From 1950 (monthly, daily)	10 stations
Regional Groundwater monitoring network	Water table	Microsoft Excel files	1995-2018 (generally seasonal but discontinuous over the years)	3 wells
	Salinity, basic geochemistry, basic pollutants	Microsoft Excel files		19 wells
	Logs of temperature and Electric conductivity in wells	Microsoft Excel files	1995-2011	3 wells
VIOLA monitoring network	Basic geochemistry and isotopes	Microsoft Excel files	2019-2021 (4 seasonal sampling)	3 wells

Other surveys by CNR-IRSA	Water table	Microsoft Excel files	July 2016– Dec 2016	29 wells
	Basic geochemistry	Microsoft Excel files	July 2016	29 wells
SW quality	Basic pollutants as required by the WFD	PDF	From 2005 (annual)	Available upon request to the Regional Environmental Protection Agency (ARPA)
SW intensive campaign	Basis pollutant at wastewater discharge points	Microsoft Excel files	2021 (ongoing)	Available upon request to the Regional Environmental Protection Agency (ARPA)
GW observations from scientific literature	Water table, basic pollutants and geochemistry	Microsoft Excel files	1951-1994	Data rescue by Brigida
Spatial maps	Water table, aquifer geometries, isohaline	ESRI Shape files and PDF	Various	-
Spatial maps	Land-use, Land-cover	ESRI Shape files and PDF	Various	TBD
GW exploitation	Estimated annual withdrawal	Raster		Crop modelled results available from previous studies. Unit in mm/y
Geological stratigraphic information	Lithology	ESRI Shape files and PDF	From 1950	About 65 wells

3.7. Surface - groundwater interaction along the Canale Reale River

According to the geological description in paragraph 3.5 and depending on the lithology crossed by the river along its path in different stretches (Fig.3.15), a hydraulic connection between the Canale Reale River and both the shallow and deep aquifers, can be supposed. Referring to the lithologies described in paragraph 3.5, Fig.3.6, two different lithologies are mainly involved in hydraulic and infiltration processes. Indeed, the Canale Reale riverbed roughly lies on the western edge of the Terraced Marine Deposits (TMDs) crossing both these latter deposits and the Calcarenite of Gravina (CoG) along its course. Therefore, different types of interaction between SW and GW can be identified according to the different hydrogeological role played by the two formations. In Figure 3.15 a schematic cross-section of the Canale Reale River shows the differences between a gaining reach from a losing one.

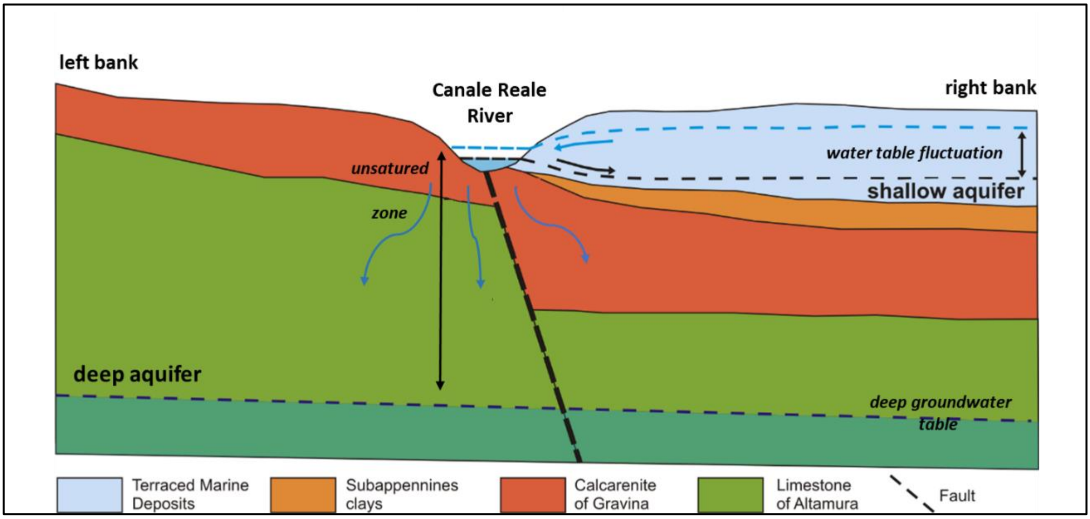

Fig.3.15 - Schematic cross-section of Canale Reale River in which showing the different types of interaction between SW and GW: on the left side is the case of a losing disconnected stream, on the right one is the case of a gaining stream that can turn into losing stream and vice versa, according to water table fluctuations (based on Portoghese et al. 2022b).

When the Canale Reale River crosses the CoG, which is not an aquifer formation, it behaves as a losing disconnected stream, and in correspondence of this reach, water infiltrates into the underlying unsaturated zone, long before reaching the deep carbonate aquifer (left bank in Fig.3.15). Referring to Fig. 3.15, the unsaturated zone falls within the CoG formation and partially within the Limestone of Altamura formation (LoA). In this hydrogeological condition, according to the thickness of the CoG formation reported in literature, about 30 metres (Ciaranfi et al. 1988; Margiotta et al. 2010), water infiltrating through CoG formation may reach the deep carbonate aquifer with a delayed time with respect to infiltration time. Hence, recharge processes may be very slow, or locally, the hydraulic conductivity values could be fostered by the presence of karst elements or fractures in LoA but also in CoG formation (Bossio et al.1987). The presence of dry channel stretches observed along the Canale Reale River, especially in the downstream half of the river course and during all the warm seasons, is evidence of this type of interaction between disconnected losing streams and deep groundwater tables, as in the case study.

Referring to Fig.3.15, right bank, a different hydraulic interaction between the Canale Reale River and the underlying aquifer can be described. The TMDs host a shallow aquifer supported by a basal clay layer. When the Canale Reale River crosses TMDs formation, it can alternatively behave as a gaining or losing stream, depending on the seasonal fluctuations of the water table. The river gains water through the riverbed when the water table within the shallow aquifer is higher than water level inside the riverbed; otherwise, it loses water to the surface aquifer, when the water table is lower than water level inside the riverbed. When this last condition occur, the surface aquifer is recharged and this allows the surface aquifer to be still exploited for agricultural purposes, although its limited thickness.

It follows that the infiltration processes and therefore recharge processes occurring in both aquifers, are strongly influenced by the lithology and also by the stratigraphic correlation between the geological formations, which in turns, as already described in paragraph 2.2, can affect hydraulic conductivity values.

The hydraulic conductivity of the TMDs ranges from 10^{-5} m/s to 10^{-8} m/s and the largest variability towards lower values of TMDs hydraulic conductivity is a function of the variable clay content. These values can be comparable and partially overlapping the CoG range, which in turn varies from 10^{-4} m/s to 10^{-6} m/s (Andriani and Walsh 2003; Spizzico et al. 2006; Turturro et al. 2020), and in this case, the presence of karst form in the CoG can locally increase its hydraulic conductivity values.

3.8 On field measurements

Surface water discharges can be measured in two different ways, directly or indirectly. The direct method needs a practical gauging measurement, and specifically, the manual placement of a current meter, at specific depth and width intervals across the stream cross-section. The current meter provides a velocity measurement, and the stream velocities obtained are then averaged over the distance between approximately twenty measurement points dividing the cross-section, according to the width of the channel. Vertical variations in velocity are averaged by measuring velocities at depths of 0.6 x depth of water below the surface (Dobriyal et al. 2017). Indirect discharge measurements, instead, require the development of a "rating curve" for a specific stream section, which should be not variant in time. Once the rating curve is obtained, a unique relationship between stream stage and stream discharge at that site is provided and the stage-discharge relationship can be used to estimate discharge from stage measurements at a single location.

A weakness point for the Canale Reale River basin is the total lack of a stable hydrological monitoring system and the hydrological data, hence the possibility to draw rating curves. In addition, many stretches of the river are made with concrete banks, while some other preserve their naturality.

In our case study, considering the total lack of flow measurement stations along the Canale Reale River, on-field flow measurements were carried out on 27 July 2021. For the purpose, a direct method was used on three gauging cross-sections, identified along the downstream half of the river, as Section A, downstream the Ceglie Messapica WWTP discharge point, and the other two sections, named Section B1 and B2, to the downstream reach of the Carovigno WWTP discharge point.

Since B1 and B2 were only 8 meters from each other and the channel geometry was quite regular, them were considered as one section, named as Section B. The two cross sections A and B are located less than 100 meters downstream from the Ceglie Messapica and Carovigno WWTP effluent discharge points, respectively. The location of both sections is reported in Fig. 3.16.

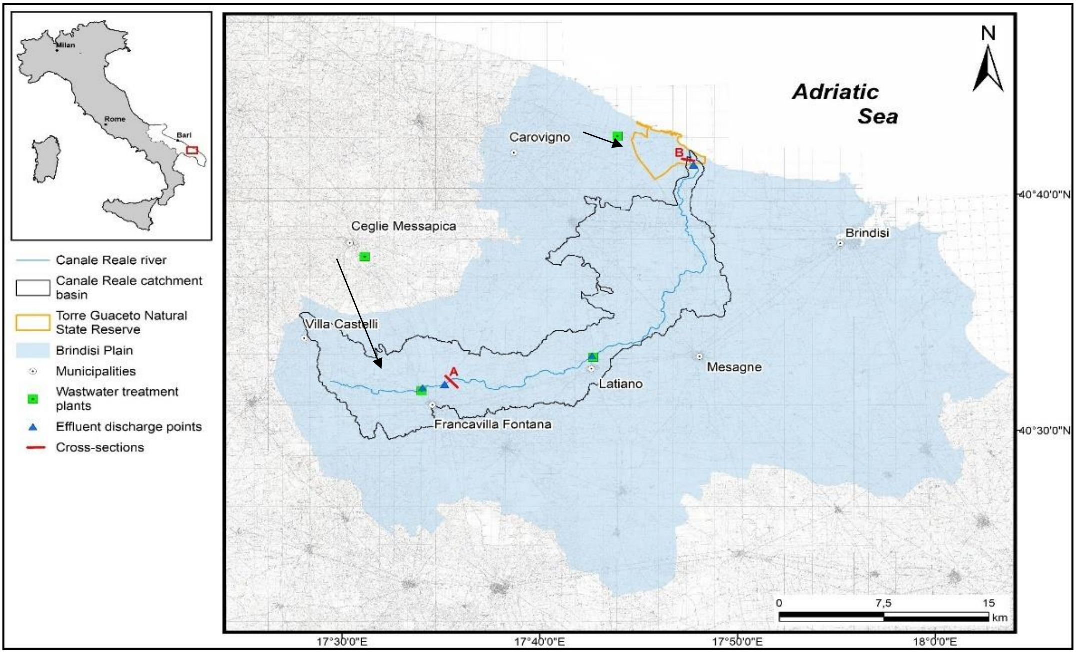

Fig.3.16 - Location of the flow measurements cross sections A and B (B1 and B2).

A recent attempt to assess hydrodynamic features of the Canale Reale River was done by Passarella et al. (2022) by means of an affordable measurement technique, based on beamforming applied on video sensing which was compared with two more reliable standard measurement methods that is the current meters method (CM method) and the float method (F method). In recent literature, a detailed comparison of the different flow measurements methods that can be applied on field, is described in Dobriyal et al. (2017). Among the methods proposed, velocity-area methods, based on the principle of the continuity of fluid flow, and specifically, the Current meter (CM method) and the Float method (F method), were suitable for the assessment of the water flow rate of the three cross sections. In addition, the reconstruction of the channel geometry riverbed characteristics, comply with both CM and F method request, and for the purpose the width of the channel and the bottom depth from the water level were measured along the three specific cross sections of the Canale Reale riverbed. Moving from the right to left bank with a space step of 10 cm, the width of the channel and the bottom depth from the water level were measured, so that the stream channel cross-section results divided in a finite number of vertical segments (i). The resulting cross-sectional profiles are shown in Fig. 3.17, except for B2 profile, distant 8 meters from B1 section but with a comparable shape to the B1 section, owing to the more regular channel geometry in the specific surveyed reach.

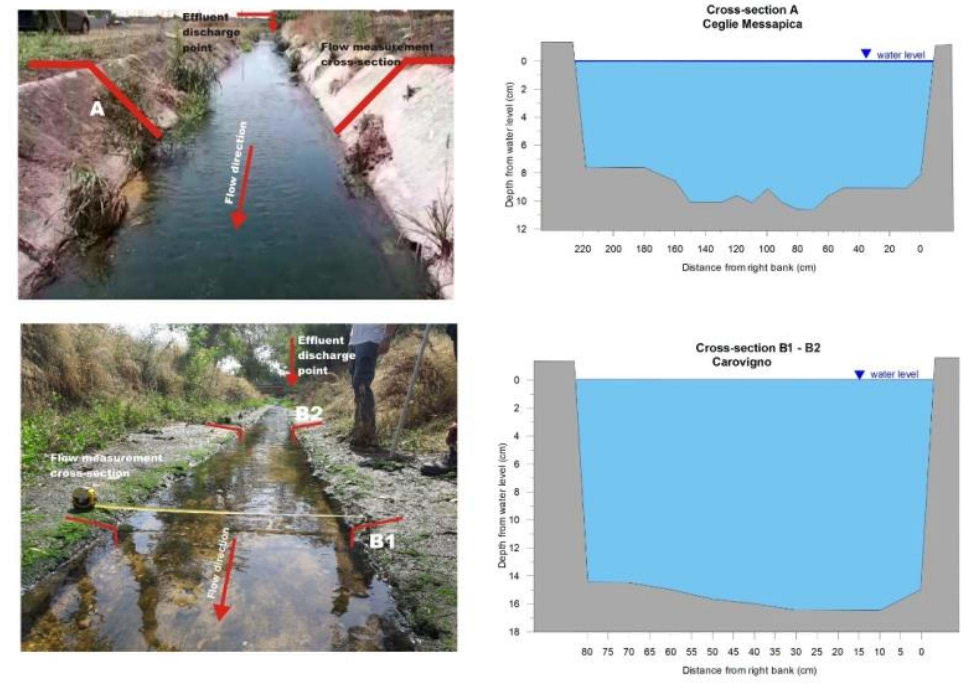

Fig.3.17 - Flow measurement along the two cross-sections of Ceglie Messapica (A) and Carovigno (B) (Passarella et al.2022).

By applying the quadratic corrective coefficient (F) (WMO, 2008), the average sectional velocity (Vm) was calculated and finally, the transit flow rate (Q) was obtained by multiplying the latter by the average area (Am) between the upstream and the downstream sections.

It is necessary to point out that while conducting the flow measurements along section A, Ceglie Messapica wastewater plant was stopped for maintenance, so the flow was very low if compared to the average volumes discharged in the month of July.

CM method required punctual speed measurements, and for the purpose, a Miniwater ®20 water-flow velocity meter was used. Starting from the right riverbank and moving to the opposite one with a step of 10 cm, velocity measurements were recorded at a depth equal to the 60% of the water level, with the aim to approximate the average velocity (Vmi) for each (i) segment. The sum of the product obtained by multiplying each segment area (Ai) with the relative average velocity (Vmi). Herschy (2008) defines the total transit flow rate (Q). The results obtained are summarized in Table 3.3.

Table 3.3 - Values of the transit flow rate (Q) measured in the cross-sections (nd = not determined).

On - site Direct Measures			
Cross-Section	**Wet Area (m^2)**	**CM Method (L/s)**	**F Method (L/s)**
A	0.20	93.74	104
B	0.14	33.90	nd

Referring to the Q values obtained and reported in Table 3.3, it results an overestimation by about 11% of the water flow rate obtained with the F method compared to the CM one, in accordance with a recent work by Portoghese et al. (2020). This relative error can be considered acceptable if compared to the more rigorous but much more time-consuming CM method, especially in conditions in which the repeatability of measurements in different periods of the hydrological year is required or where the absence of a several gauging cross-sections along the water course does not allow to collect useful data.

In supporting this last issue, the study carried on by Passarella et al. (2022) shows promising outcomes to build, in future, an effective monitoring system capable of carrying out measurements along the channel, repeatable for different seasonal flow regimes to provide accurate and reliable quantitative monitoring of a surface water body.

CHAPTER 4. FIELD STUDY AND APPLIED METHODOLOGY

4.1 Reach length water balance method (RLWB)

As described in paragraph 2.4, different methods, inherited by the hydrology of perennial rivers can be applied to estimate transmission losses infiltration or groundwater recharge through ephemeral and intermittent streambeds.

The RLWB method allows to empirically quantify the streambed infiltration and is used to estimate transmission losses in perennial streams, characterised by a stable flow regime. On the contrary, ephemeral streams are characterised by non-stable flow conditions, and by applying this method, loss rate estimation is determined by measuring the flow rate from the upstream and downstream stations across the whole flow event (Abdulrazzak 1995). Hence, flow should be measured automatically, using rating curves that correlate flow depth to discharge rate. Nevertheless, because streamflow in ephemeral streams occur after flash flood events which are difficult to predict, this measure cannot be detected easily. This aspect is fostered by the fact that many ephemeral rivers are not equipped with gauging stations; in addition, floods events may induce significant scouring and deposition processes in the streambeds with consequent alteration in streambed geometry and subsequent inaccuracies in gauging stations and rating curves (Constantz and Thomas 1997). Furthermore, ephemeral streams typically develop far from population centers, and the unpredictable nature of flood events makes extremely complex to take manual readings to calibrate rating curves. It is not uncommon to apply this method to stream reaches with a length ranging between 4 and 30 km: owing to the relatively high error associated with streamflow measurements, upstream and downstream gauging stations must be spaced far enough so that the error is not greater than the transmission loss. In many cases, calculation of transmission losses in these long reaches is difficult, because of the water input coming from tributaries between gauging stations, and generally they are poorly gauged. Alternatively, relationships between transmission losses and other hydraulic parameters (e.g., channel width) can be established, and this can allow extrapolation of results of ungauged channel reaches (Walters 1990).

Another parameter which results difficult to estimate is the evaporation, including soil evaporation, especially if river spreads out across a flood plain: it follows that relatively small errors in estimate evaporation loss can induce to large errors in estimated infiltration rates.

To bypass some of these objective difficulties, especially those related to the absence of gauging stations along ephemeral streams, to rely on the use of a digital modern technique may represents a useful solutions. By coupling gauged flow measurements with satellite imagery to determine streambed geometry and river dynamics between stream gauges, Costa et al. (2012) were able to estimate relationships between input flow and transmission losses for 60 km of the Middle Jaguaribe River in Brazil. Walter et al. (2012) instead, used digital orthophoto quadrangles (DOQs) and Systeme Probatoire de l'Observation de la Terre (SPOT) images to estimate indirectly channel width and depth at several cross-sections and finally, by using Manning's equation, to distinguish which areas of the stream reach had highest loss rates.

Recently, an alternative method for non-perennial rivers consists in replacing the downstream gauging location by visual assessments of the wetted river reaches by the support of satellite images (Portoghese et al. 2022b; di Ciacca et al. 2023). The transmission losses are then calculated as the flow gauged at the upstream location divided by the wetted river length.

4.2 Methodology applied to the case study of the Canale Reale River

Among the simpler method suitable for the assessment of transmission losses along the Canale Reale River, the RLWB method was chosen to calculate a spatially average value of the riverbed's infiltration rate.

Although the methodology is well known and generally widely used to concurrent upstream and downstream measurements during flow events, in the specific case of the Canale Reale River, given the negligible natural baseflow, the streamflow measurements have been replaced by the known average daily discharge of treated wastewater released at three consecutive outlets along an approximately 20 km river stretch, and which refers, from upstream to downstream, to the Francavilla Fontana, Ceglie Messapica and Latiano WWTPs (see Fig.3.1). The innovative application of this method consists in using wastewater discharge effluents with known hydraulic features to undertake empirical riverbed infiltration tests, extrapolate transmission losses occurring all through the channel bed, and consequently evaluate the overall water balance. The proposed methodology has been applied during the dry season, when the natural river flow can be neglected and the effective volumes of the treated effluent discharging, can be taken into account. Based on the above assumption, considering the summer month of July 2021, during which on site flow measurements were carried on, the average daily discharge rates at the three outlet points range from 0.02 to 0.051 m^3/s (Table 4.1).

Besides onsite measurements and the evaluation of the average flow discharging on Canale River, the study has been also supported by Google Earth images and high-resolution dry period orthophotos provided by Apulia Region GIS.

This was justified by the fact that, along the river path, although the continuous volume discharged into the river, it has been observed that in some stretches there was no visible flow. This led to investigate the situation by using visual orthophoto imaging, to determine which stretches of the river represented dry or wet conditions. It was hence possible to distinguish wet and dry reaches within the riverbed along the considered 20 km river stretch, and three river portions characterized by different vegetation landscapes were observed (Fig. 4.1).

Figures 4.1a and 4.1b refer to wet river conditions evidenced by water within the riverbed or rich riparian vegetation. On the contrary, Fig. 4c shows the transition from a wet to a dry condition marked by different riverbed colours.

Fig. 4.1 – Orthophoto frames of three different channel portions: (a) flowing water filling the whole cross-section of the riverbed close to the effluent outlet; (b)presence of riparian vegetation indicating a wet stretch; (c) chromatic variation from green to brown suggest a transition from a wet to a dry streambed (Portoghese at al.2022b).

Thus, the visual survey of the Canale Reale River during summer season has allowed us to verify that:

i. the riverbed can be assumed virtually dry from the upstream spring (S) up to the first effluent discharge corresponding to the WWTP of FF;
ii. the first wet stretch is clearly visible within the riverbed, in correspondence of discharge point of FF for about 10.9 km (stretch #1 in Fig. 4.2); given that the distance between the FF and CM discharge points is about 2 km, in the following computational steps, both discharge points have been considered as a unique discharge point, positioned in FF and discharging a total effluent volume given by the sum of the two;
iii. a second dry stretch, about 4.4 km long, follows stretch #1 where the water disappears, before to the La discharge location (stretch #2 in Fig. 4.2);
iv. a new wet stretch of 7.2 km, fed by the effluent coming from the La WWTP (stretch #3 in Fig. 4.2) can be recognized;
v. the riverbed shifts once more to dry conditions from the ending section of stretch #3 until the final Ca effluent discharge point, located a few hundred meters upstream from the river outlet. Since the short distance occurring between this final discharge point and the river outlet and owing to the presence of concrete sealing of the riverbed, potential transmission losses can be considered almost negligible.

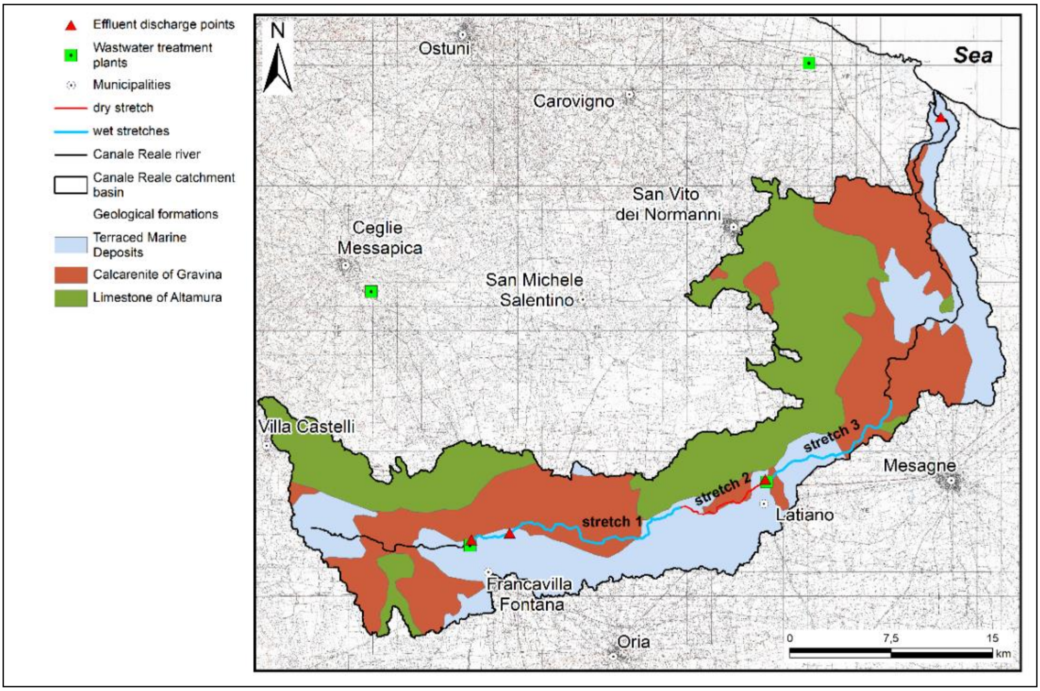

Fig. 4.2 – Distribution of wet and dry stretches along the Canale Reale River after the visual survey, overlapped to the main outcropping lithologies (Portoghese et al. 2022b).

The first part of the research study can be therefore synthesized in two preliminary steps:

- Survey of the geometry of the cross-sections along the river; detection of the discharge points and relative retrieval of the daily mean discharge rates Q_{ww} (m^3/s).
- Detection of wetted reaches located downstream of the discharge points to identify the average wetted width of channel cross section B_w (m) and the wetted length of the channel L_w (m), by using high-resolution aerial images during the dry season.

The RLWB, based on the mass conservation principle, allows for approximating the flow rate exchanged along a river reach bounded by two cross-sections as the difference between the discharge measurements detected at the two same sections. Before applying the method, and describing the following computational steps, is necessary to point out that SW and GW are supposed to be hydraulically connected and that vertical hydraulic conductivity values need to be estimated, as well as the role of evapotranspiration needs to be considered.

The assessment of the nature of the hydrologic connection between the surface water body and the underlying aquifer, requires some information regarding the degree of saturation and the vertical hydraulic gradient beneath the river. In addition it is necessary also to consider that, variable wetted surface areas within the stream respond to variable discharges. These fluctuating wetted areas have a very deep impact on the volume of water which is lost to evaporation during the day; instead, to wide fluctuations in wetted stream surface area correspond large changes in the channel surface area for infiltrating water.

Darcy’s Law (Equation 1) describes the movement of water from a higher energy state to a lower energy state through a saturated soil. Based on Darcy’s law, the infiltration rate at the local scale can be estimated by multiplying the saturated hydraulic conductivity with the hydraulic gradient which describes the driving forces (i.e., gravity and capillary suction) that cause flow from the wetted channel to groundwater:

$$q = K \cdot \left(\frac{dh}{dz}\right) = K \cdot i \tag{1}$$

where:

q = the specific infiltration rate of water through a unit horizontal surface of the channel [m/s]

K = the saturated hydraulic conductivity in the vertical direction z [m/s]

dh/dz = hydraulic gradient [m/m]

i = adimentional short-hand notation for hydraulic gradient

Additional complications in interpreting transmission loss rates can be related to the hydraulic gradient and how infiltration processes develop, especially when dealing with a disconnected losing stream. For those sites with thick unsaturated zones, where the effects groundwater mounding will generally be small, the infiltration rate can be approximated by the Green-Ampt equation (Chin 2000) where the gradient will not typically be reduced by infiltration from the channel and is approximately equal to 1.0 (reported in the literature as unit gradient approximation). The Green-Ampt theory describes how infiltration processes develop starting from a wetted surface. This theory assumes that water infiltrating underground moves downward as "piston flow". This entails a uniform hydraulic conductivity in the wetted zone and constant pressure head at the wetting front.

Applying Darc''s Law (Equation 1) to this flow system gives:

$$v_i = \frac{K_w\,(H_w + L_f - h_f)}{L_f} \qquad (2)$$

where:

v_i = infiltration rate [m/s]

K_w = hydraulic conductivity of wetted zone [m/s]

H = water depth above soil [m]

L_f= depth of wetting front [m]

h_f= pressure head of water at wetting front [m].

Equation (2) shows that infiltration rates are driven by the depth of water above the soil surface most in early time infiltration, when the depth of the wetting front L_f is still reduced. As L_f increases, the depth of water's influence on infiltration ca be assumed negligible (Bouwer 1986). The Green-Ampt equation (Equation 2) also points out that the initial infiltration rate greatly exceeds K_w[2] when L_f is fewer, but as the infiltration process advances, the infiltration tends to become constant and then equals to K_w.

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[2] This is due to gravity forces such as capillarity effect (sorpitivity)

When the surface – groundwater system is characterized by deep groundwater table conditions, as in the study case, when the Canale Reale River crosses non permeable formation of CoG (paragraph 3.7), the evaluation of spatially averaged hydraulic conductivity K_{RB} (m/s) of a dry riverbed stretch receiving wastewater effluent with known characteristics can be derived from the water balance (i.e., RLWB method):

$$K_{RB} = \frac{Q_{ww}}{L_w \cdot B_w} - E_w \tag{3}$$

assuming wastewater discharge and evaporation rate E_W (m/s) from the water surface to be the only flow components within the channel stretch which is classified as wet based on the inspection of the aerial images and field survey during the dry season.
To evaluate the riverbed potential transmission loss TL_P (m^3/s), the obtained value of the riverbed hydraulic conductivity is assigned to the whole channel length (L_C):

$$TL_P = K_{RB} \cdot L_C \cdot B_C \tag{4}$$

where:

B_C= the average width of the whole considered channel.

Following to the computational steps, and based on the physical system defined above, the proposed methodology provides an estimation of a range of potential transmission loss values which can be assigned to the whole Canale Reale riverbed.

Once estimated riverbed potential transmission loss TL_P, the value obtained has been used as a component of a water balance to integrate a rainfall-runoff model recently developed in the same study area (Portoghese et al. 2022a). In this model, as in many other similar cases, the contribution of the runoff re-infiltration is neglected, since it represents a common condition during the dry season, in particular along the losing riverbed stretch.

Finally, the knowledge of the riverbed potential transmission losses has been exploited for improving the hydrological characterization and the assessment of the water balance components in the study area, throughout a given mean water year. Outcomes will be later described in chapter 5.

4.3 Wastewater effluents

As described in previous chapters, the Canale Reale River is effectively an effluent-fed river, collecting treated effluents discharged from four WWTPs.

If on one hand, the possibility to collect treated effluent to enhance environmental flow and support aquatic ecosystem services, surely represents an alternative and environmental- friendly solution to face water resource scarcity issues, among which the possibility to reuse these reclaimed waters directly into the river or through infiltration basin to enhance groundwater recharge, on the other hand, these solution, cannot ignore the quality of these discharged water and their possible contamination effects. In fact, a potential connection between surface water and groundwater may cause contamination of groundwater sources; furthermore, these practices may also create an underground freshwater barrier contrasting sea water intrusion. This aspect represents a very important issue which generally arises much concern among people or institutional figures, when dealing with reuse of treated wastewater. In the study area, the wastewater discharge practice has increased during the last 20 years owing to increasing local population. The average volumes of the wastewater discharged daily are reported in Table 4.1 as their relative distance from the mouth of the Canale Realer River; the location of the four WWTPs are shown in Fig. 4.3.

As regard the values reported in the Table 4.1, the daily discharged volumes for the Ceglie Messapica and Carovigno WWPTs in the July month show values lower than the average daily discharged.

This can be probably due to a malfunctioning of the wastewater flow meters located nearby the discharge point, or probably, the presence of some algal blooming which may occur during summer season and hence limit the correct detection of the discharged flow.

In both cases, also the distance between the location of the WWTPs and the discharge point along the Canale Reale River, may concurr to reduce the flow, in case of damaged pipeline. Furthermore, probably during summer months the inhabitants of the two municipalities leave for summer holidays and therefore, the load of wastewater destined for the treatment plants decreases significantly.

Table 4.1- Summary features of the wastewater discharge point into the Canale Reale River.

Outlet ID	Distance from river mouth [km]	Average daily discharge [m^3/d]	Range of daily discharges (July 2021) [m^3/d]
Francavilla Fontana	42.5	4326.8	4163.2 ± 1618.9
Ceglie Messapica	40.3	4439.9	1694.1 ± 527.1
Latiano	26.54	1737.4	1254.8 ± 455.6
Carovigno	1.3	7795.3	3458.6 ± 705.8

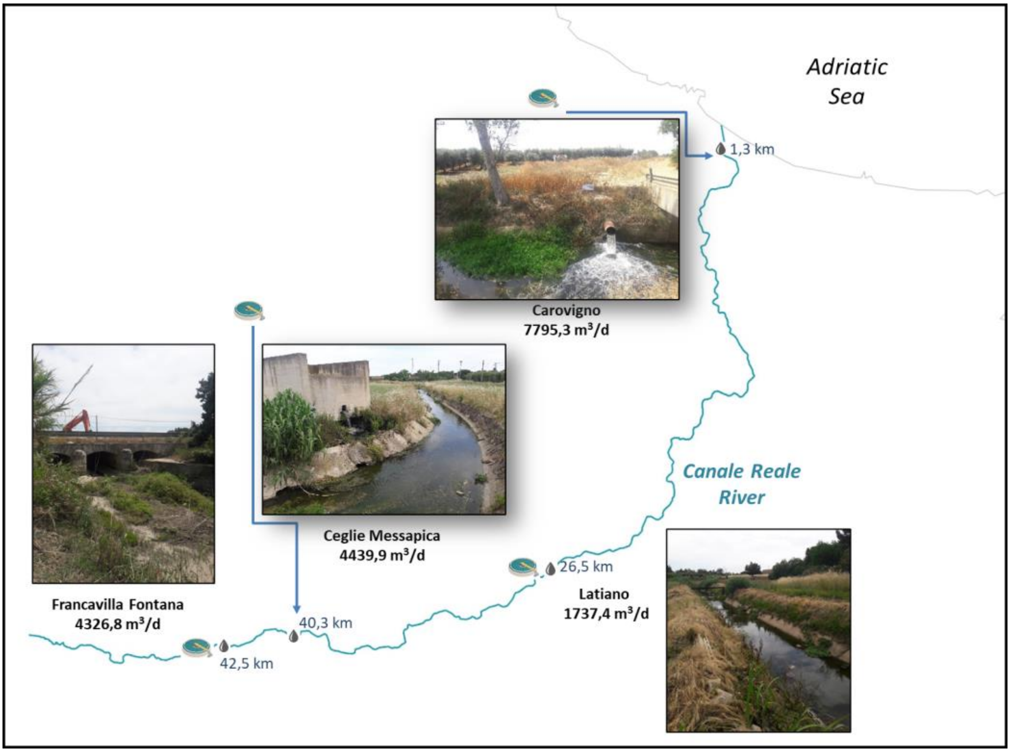

Fig. 4.3- Schematic representation of the location of WWTPs outlets along the Canale Reale River.

As for the WWTPs of Francavilla Fontana, Ceglie Messapica e Latiano, no actions for recycling wastewater have been proposed, while a Regional Decree n. 2083/2016 the Apulia region has allowed the reuse of treated wastewater of the Natural Stare Reserve of Torre Guaceto for irrigation purposes.

In addition, the construction of the submarine pipeline has been financed with FSC funds 2007-2013 APQ, allowing a direct discharge in the Adriatic Sea.

The Regional Environmental Agency (ARPA) is responsible to verify the regularity of the discharge by periodical monitoring of the urban wastewater treatment plants, according to national and regional legislation. The methods and frequency of the checks are established by Legislative Decree no. 152/2006–- Third Part–- Attachment 5, from the Regional Council Resolution n. 1116/2006.

As concern the quality of the water flowing within the Canale Reale River, more recently a periodic monitoring of some physical, chemical and biological parameters was carried out on Canale Reale by Regional Environmental Agency (ARPA) for the assessment of the surface water bodies quality.

This monitoring is limited to some sections, specifically one upstream and one downstream of each wastewater treatment plants and has revealed a bad ecological and chemical state in the last decade, despite the achievement of the national regulatory standards for wastewater treatment plant discharging into surface water characterized by temporary and intermittent streamflow regime (Legislative Decree n. 152, 2006). Basic pollutants are also monitored by ARPA for the classification of the Canale Reale River according to WFD.

As regards the assessment of the water quality of surface water bodies, the last report refers to the monitoring carried out from 2016 to 2018. In 2016, a surveillance monitoring program was conducted, while for the following two years (2017 and 2018), an "Operational monitoring" was carried out in water bodies which did not reach the "Good" quality status after the surveillance phase carried out in 2016. It emerges that, for almost all the water bodies flowing into the Adriatic area, including the Canale Reale River, the average values of dissolved oxygen (both in terms of concentration and saturation) were found to be lower than the annual average of all monitored Apulian water systems. As regards the presence of macronutrients (nitrogen and phosphorus), for total phosphorus, the highest concentrations (annual average values above 1000 μg/l) are found in some water bodies, among which the Canale Reale. Higher levels of macronutrients could be related to the presence of effluents discharged into the river, although them undergo suitable treatment methods. This aspect represents a critical issue and a threat for the aquatic environment since these reclaimed waters are directly discharged first into the Torre Guaceto wetland and later into the Adriatic Sea. An increase of the organic pollutants maybe responsible of eutrophication processes but also causes a significantly alteration of physical and chemical parameters of the brackish water and also groundwater. Indeed, since the Canale Reale River shares these treated water with the underlying shallow aquifer and the deep carbonate aquifer, as pointed out in paragraph 3.7, pollutants may be transported and spread more rapidly, especially through the karst fractured vadose zone, or directly transferred to the surface shallow aquifer, with a higher risk of groundwater contamination.

High values of macronutrients can be also a consequence of the malfunctioning of wastewater treatment facility or caused by extreme weather conditions such as heavy rainfalls or flooding. A recent study estimates that approximately 72% of all WWTPs accidents in Europe is due to a combination of both conditions and, owing to the frequent extreme weather events induced by climate changes, the number of WWTP accidents is expected to increase in the future (Trávníček P et al. 2022).

CHAPTER 5. RESULTS AND DISCUSSION

Before focusing on the research outcomes, a preliminary and necessary important distinction must be highlighted between *infiltration* and *recharge,* since they describe two different hydrological processes.

Infiltration describes the processes by which water flowing moves from a surface water system down through the sediments composing riverbed surface.

Recharge, despite, implies that, once passed through the riverbed, water moves downward from the surface of the streambed to the groundwater table, reaching the aquifer.

In rivers characterized by deep water table for the presence of an unsaturated zone, as in the case of losing disconnected streams, there can be significant delays between infiltration and groundwater recharge (Jolly et al. 1989). It follows that recharge rates can be assumed to be less than infiltration rates.

This assumption can be explained because, owing to the extreme variability of rainfall events in arid areas, between one flood event and the next one an aliquot of the infiltrated water may be lost due to evaporation processes, leading recharge to be very low or equal to zero, once the flow event has ceased.

In addition, infiltration rates lost to evapotranspiration will greatly increase if there are low permeability layers beneath the streambed, which reduce the infiltration rate, as in the case of clogging layers in losing disconnected streams (see paragraph 2.2) (Brunner et al. 2009; 2011). An attempt to explain these processes was done by Shentsis et al. (1999). They found that the evaporative loss was equal to the transmission loss for very small runoff events but was insignificant for larger events. This observation led to assert that evaporation processes can be considered a less relevant component in the estimation of the transmission loss.

In the particular case study, despite the ephemeral hydrology of the Canale Reale River, the discharge of effluent is a constant supply for the river itself, but also for the underlying aquifer. Therefore, the assumption made to neglect the contribution of evapotranspiration, is consistent and applied to both wet river stretches detected along the watercourse, where transmission losses and groundwater recharge are expected.

In particular, for the whole length of the stretch #1 and, and partially for the stretch #3, the Canale Reale River crosses the CoG formation, which represent the vadose zone (or unsaturated zone) separating the streambed from the deep carbonate aquifer, almost thick 20 meters, according to what described in paragraph 3.5.

Along these stretches, the watercourse behaves as a losing disconnected river, where the water infiltrates into the thick vadose zone, before reaching the deep carbonate aquifer.

According to literature, although CoG is not an aquifer, but rather an aquitard, its hydraulic conductivity values should allow possible aquifer recharge processes, although very spanned in time, because of the presence in this case, of a disconnected reach. However, at the same time, the presence of karst forms in the CoG can locally increase its hydraulic conductivity values and reach the aquifer, through preferential pathways.

Nevertheless, streambed infiltration and groundwater recharge processes during extreme flow events is generally very high, (Boas and Mallants 2022) and some studies has asserted that generally, infiltration rates for sewage effluent in ephemeral rivers (i.e., Santa Cruz River) may vary over time in response to natural storm flows, although none has quantified the rate of change in streambed vertical hydraulic conductivities.

Along stretch #3, instead, the Canale Reale River partially crosses the TMDs formation, which hydraulic values refer to a shallow porous aquifer due to the presence of a basal clay layer. Therefore, the river can alternatively play the role of gaining or losing stream, depending on the seasonal fluctuations of the water table.

It follows that, several factors, which describes the complexity of the interactions occurring between surface and groundwater bodies, need to be taken into account, among which a predominant role is played by the lithologies and their relative hydraulic conductivity values, especially in the detection of the range of recharge rates that can be reliably estimated.

In the following paragraphs, all the steps which led to the estimation of the hydraulic conductivity values K_{RB} , the riverbed potential transmission loss TL_P are described and explained. The volumes which may infiltrates underground to replenish the underlying aquifer and finally, a value indicating the infiltration during an average hydrological year by applying a rainfall-runoff model, has been obtained.

5.1 Transmission losses along the Canale Reale River

Based on the assumption made coherently with the computational steps of the proposed methodology and neglecting the evaporation loss contribute in Equation (2), two values of K_{RB} have been calculated, each one per river wet stretch, by applying Equation (3). In Table 5.1 the values of the parameters used in Equation (2) to obtain the K_{RB} values, which refer to each effluent discharge location along the Canale Reale River, are reported. It is important to remind that, owing to the short distance between the FF and CM effluent discharge location, they have been considered as a unique point, positioned in FF, with a total effluent discharge equal to the sum of both.

Table 5.1–- Relevant distances of WWTPs discharge points from the river outlet, flow rates, and channel features used for the estimation of riverbed hydraulic conductivity. FF = Francavilla Fontana; CM = Ceglie Messapica; L = Latiano; C = Carovigno (Portoghese et al. 2022b)

WTTP	***Distance from the river outlet***	***Average Qww (July)***	***Average Qww (July)***	L_w	B_w	K_{RB} ***(Eq.2)***
	(km)	**(m^3/d)**	**(m^3/s)**	**(m)**	**(m)**	**(m/s)**
FF	42.5	4326	0.050	10.900	2.5	$3.72 \cdot 10^{-6}$
CM	40.3	4439	0.051		2.5	
L	26.5	1737	0.020	7180	2.5	$1.12 \cdot 10^{-6}$
C	1.3	7795	0.090	1300	2.5	-

The estimated hydraulic conductivity values K_{RB} summarized in Table 5.1 agree with the range of hydraulic conductivity values proposed in the literature (see paragraph 3.7) related to the main lithologies on which the riverbed lies upon. The higher K_{RB} value obtained for stretch #1 is consistent since it mainly crosses the CoG formation. Comparing the values of K_{RB} estimated for stretch #1 and for stretch #3, although having the same order of magnitude, a slightly lower value has been obtained for stretch#3, as in this portion the river crosses both the TMDs and CoG formations for an almost equal length. Hence, a maximum, average and minimum of the TL_P value has been estimated as spatially averaged K_{RB} along the whole river, according to Equation (4).

Precisely, minimum and maximum values have been simply calculated by assuming the K_{RB} values of the stretches #1(K_{RB1}) and #3(K_{RB3}) for the whole river length (i.e., 42.5 km) respectively and the average TL_P value has been calculated by weighting K_{RB1} and K_{RB3} over to the respective river stretch length. This is possible because wet and river stretches crosses both the CoG and the TMDs formations and in addition, the hydraulic conductivity values of both formations are comparable.

The resulting river TL_P values range between $1.19 \cdot 10^{-1}$ m^3/s and $3.95 \cdot 10^{-1}$ m^3/s, and the average TL_P value is $2.23 \cdot 10^{-1}$ m^3/s.

The values obtained by these computational steps are showed in Table 5.2. The range of the estimated TL_P values can be justified by the initial assumptions made by applying the proposed method. It follows that, considering the average TL_P and the related uncertainty in the water balance estimation, a range of possible infiltrating water volumes are expected.

Table 5.2–- Estimated minimum, average, and maximum values of the Infiltration Potential TL_P along the Canale Reale River (Portoghese et al. 2022b)

	K_{RB}	**River sector length**	**T_{LP}**
	(m/s)	***(m)***	***(m³/s)***
minimum	K_{RB3} =1.12E-06	42.500	$1.19 \cdot 10^{-1}$
average	K_{RB3} = 1.12E-06	16.000	$2.23 \cdot 10^{-1}$
	K_{RB1} = 3.72E-06	26.500	
maximum	K_{RB1} =3.72E-06	42.500	$3.95 \cdot 10^{-1}$

For the purpose, a rainfall-runoff modelling applied to the study case, has been used (Portoghese et al. 2022a). The potential infiltrating water volumes have been obtained by overlapping the estimated TL_P to the FDCs of the Canale Reale River, obtained by rainfall-runoff modelling and showed in Fig.5.1). This allowed for assessing a sort of Transmission Loss Duration Curves (TLDC) which gives some information about the infiltration occurring through an average hydrological year.

In particular, in Fig.5.1, two river flow scenarios stand out: in scenario #1, only the natural flow due to the rainfall-runoff processes is taken into account (Figure 5.1a); in scenario #2, the discharge volumes from the WWTPs overlap to the natural flow (Fig. 5.1b). These two different scenarios allow to approximately quantify the infiltration rates and for how long these infiltrations takes place during an average hydrological year along the whole river course.

By observing the FDC curves of scenario #1 (blue line in Fig. 5.1a) it emerges that the river is wet between 120 and 225 days per year, depending on the different TL_P.

Considering the same curve for scenario #2 (Fig. 5.1b), a wet riverbed for a period from 150 days to the whole year can be observed, with streamflow never lower than 0.121 m^3/s.

The two described scenarios different perform during an average year, showing two different but favourable hydrological conditions; the outcomes in fact, confirm that WWTPs treated discharges guarantee a wet riverbed during the whole year, and strongly enhance the water-dependent habitat along the riverbanks, as well as the infiltration losses.

As regard the assessment of transmission losses, in Fig. 5.1 the estimated TLDCs are reported. These curves describe the average (orange line), maximum (yellow), and minimum (grey) estimated channel transmission loss due to the different TL_P values, as reported in Table 5.2.

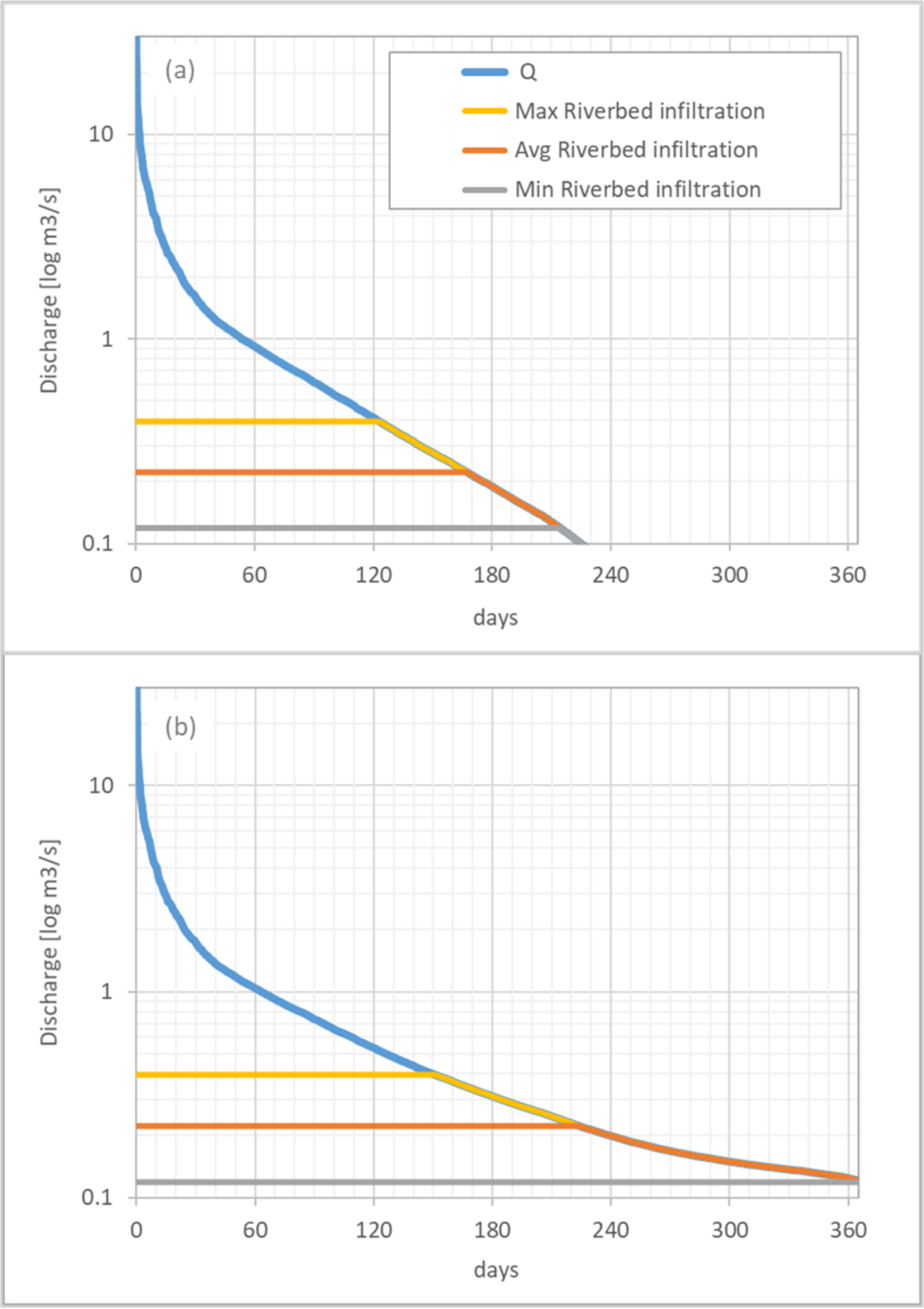

Fig.5.1 - Flow (blue line) and transmission loss duration curves (yellow, orange, and grey) of the Canale Reale River. (a) scenario #1: Q = simulated rainfall-runoff, (b) scenario #2: Q = daily discharge from the four WWTPs outlets summed to the simulated rainfall-runoff. (Portoghese et al. 2022b).

The two plots in Fig.5.1 reveals that if the TLDCs fall below the corresponding FDCs, a constant transmission loss equal to the TL_P value is guaranteed by the river flow rate, although an aliquot of the flow rate continues to run into the riverbed.

As soon as the TLDC crosses the FDC, the riverbed turns to dry conditions, since the flow rate infiltrates with a decreasing rate lower than TL_P.

The timing of this condition depends on both the considered scenario and TL_P value. If considering the maximum estimated TL_P value in scenario #1, the river flow rate allows at the same time a transmission loss equal to TL_P and a residual discharge at the river mouth for about 120 days. In the other scenario, by considering the minimum TL_P value, although relatively low, the transmission loss is guaranteed throughout the year, together with a residual flow at the river mouth.

5.2 Evaluation of riverbed infiltration rates for catchment water balance

In conclusion, a yearly-based assessment of the river water balance has been finally carried out for both the proposed scenarios by considering the TL_P values.

In scenario #1, only the natural flow due to the rainfall-runoff processes was taken into account and the total water volume drained by the Canale Reale River results to be equal to 19.20 Mm^3/yr. Conversely, in scenario #2, the discharge volumes collected from the WWTPs overlap to the natural flow and the overall volume results to be equal to 23.02 Mm^3/yr. It follows that, by difference, the only contribution of the WWTPs' discharge is 3.82 Mm^3/yr. Similarly, the yearly total infiltrated volumes and the related fractions due to the natural flow rate and the WWTPs' discharge, have been estimated for each of the three TL_P values (Table 5.3). In the first row of Table 5.3 the total volumes of transmission losses through the channel are shown. The values obtained point out that the infiltrated flow rates for scenario #2, where the contribution of WWTPs is considered, are always higher than those corresponding in scenario #1. Furthermore, moving from the minimum to the maximum TL_P value, the gap between these values increases from 1.00 Mm^3/yr to about 2.5 Mm^3/yr.

Table 5.3 - Estimated mean annual volumes of riverbed transmission losses for minimum, average, and maximum TL_P values. Fractions attributable to natural flow (i.e., rainfall-runoff) and WWTP discharge, respectively (Portoghese et al. 2022b).

	Transmission losses (Mm^3/year)					
	Minimum TL_P		**Average TL_P**		**Maximum TL_P**	
Scenario	**#1**	**#2**	**#1**	**#2**	**#1**	**#2**
Total annual volume	2.76	3.75	4.46	6.25	6.58	8.97
WWTP's contribution	0.00	3.75	0.00	3.82	0.00	3.82
Natural contribution	2.76	0.00	4.46	2.44	6.58	5.16

These important outcomes allow to make some considerations.

First, although some simplifications and assumptions were made before applying the method proposed, the values obtained support the preliminary thesis according to which, discharges from municipal wastewater treatment plants guarantee a valuable contribution to the Canale Reale River.

This is clearly explained by the values in Table 5.3 where the contribution of WWTPs cannot be neglected, and, wherever natural contribute lacks, for example during prolonged dry periods and absence of rainfall, typically characterizing the summer season, the presence of a baseflow along the Canale Reale River is evident. Furthermore, where favorable conditions for infiltration processes occur along the riverbed, aquifer recharge processes can be hypothesized, although these processes are in any case conditioned by the geological and hydrogeological context that hosts the aquifer underlying the watercourse, as well as the spatial distribution of the lithologies and related hydraulic conductivity values. In the specific case of study, this practice entails a benefit for the watercourse, which reflects in a reduction of the dry riverbed with consequent development and safeguard of the aquatic habitats that populate the riverbanks, but also for the aquifer, thanks to the added water volumes which enhance the recharge of the aquifer.

CONCLUSIONS

The study was carried out with the idea of addressing a not well explored topic concerning the interaction between surface and groundwater bodies and to investigate the dynamics that play a pivotal role in groundwater recharge processes trough transmission losses occurring at the interface of both systems. The decision to undertake the study on the Canale Reale River and the related environmental context, is not accidental, since it is particularly interesting for scientific research purposes. Indeed, the study embraces two core topics: on one hand, the discharge of treated effluents into an ephemeral river, and on the other hand, the interaction between the fed- effluent ephemeral watercourse and the underlying aquifer. These two topics, apparently far from each other, are strictly connected. The research topic, moreover, develops within a broader issue which generates a great concern among scientific community and politicians and focuses the attention on a crucial aspect, not only specific to the study area, but shared by many other areas in the world, suffering water scarcity owing to overexploitation of groundwater resources. In arid landscapes, infiltration processes through ephemeral riverbed are often the dominant source of groundwater replenishment; meanwhile, the discharge of treated effluent into ephemeral watercourses, is likely to be the most suitable solution adopted especially in arid urban environments, where wastewater are used to guarantee baseflow of ephemeral rivers and support the related aquatic and faunal ecosystems. Therefore, natural groundwater recharge processes occurring through ephemeral rivers and recharge processes enhanced by wastewater disposal along riverbed, are two nested arguments since they share the same physical condition, although in two different environmental contexts, natural on one hand and artificial on the other. As in the particular case of the Canale Reale River, both conditions occur. The river, and the underlying aquifer system, are fed by sporadically rainfall events, but, especially during summer season, natural recharge conditions are replaced by the artificial discharge of wastewater along its path and transmission losses, in this specific case, are due to the infiltration of treated wastewater, delivered by four discharge points along the watercourse. Hence, although its ephemeral nature, the Canale Reale River can be considered a river to all effects, even though artificial. This condition has allowed to investigate the hydraulic processes shared by the river and the aquifer system, with the purpose to assess the advantages provided by the practise of discharging wastewater.

The description of the geological characteristics of the area and the identification of the main outcropping lithologies crossed by the river and their relative hydraulic properties, has led to better understand the type of interaction occurring between the Canale Reale River and the aquifer. In fact, according to the different hydrogeological role played by the two main formations crossed, two interactions were detected, and two different types of river were defined. A losing disconnected river in correspondence of more permeable layers, below which the water infiltrates into the wide vadose zone, before reaching the deep carbonate aquifer; a gaining or losing stream, in proximity of a less permeable formation, according to the seasonal fluctuations of the water table. The study outcomes added important information about the hydrology of ephemeral rivers, still poorly understood and often under- represented in hydrological studies, despite perennial ones. In the specific case of the Canale Reale River, although it is the most relevant fed-effluent river of the Salento peninsula, it shares similar geological and hydrogeological features with many other local ephemeral rivers which constitute a distinctive feature of our Apulian landscape. This aspect represents a strong enough motivation to improve the knowledge about the hydrology of non-perennials rivers. Much of the historic understanding of the hydrology of non-perennial rivers derives from field research in arid areas. However, according to recent scientific literature, these rivers are ubiquitous and are no more unique to drylands and cross all kind of landscapes and latitude. In recent years, the scientific understanding of non-perennial river hydrology experienced an increased interest, raising the need to adopt a systemic and holistic approach to bridge the still unsolved knowledge gaps related to these peculiar rivers. The scientific study proposed moves in this direction, trying to answer to the main knowledge gaps that have emerged during the development of the study, supported also by the strategic role played by the Canale Reale River, since it represents the most important watercourse of the Salento peninsula, feeding partially a valuable natural resource, within the Natural State Reserve of Torre Guaceto. In addition, the motivation is strengthened also by the urban context in which the object of the study falls within, and all the environmental issues related to, in particular, the presence of four wastewater discharge points along more than half of its path. Hence, besides the scientific role of the study, the social and environmental impact aspects related to the study case, have been considered. Several study cases reported from literature in the thesis show that the discharge of treated effluents, not only guarantees the environmental baseflow in ephemeral watercourse, but also improves groundwater recharge rate through losing stream infiltration and produce an undoubtful benefit for the underground reservoir, although this phenomenon may cause an impairment of receiving groundwater bodies. In the Apulian region, there is still a scarce perception of the advantages induced by wastewater reuse for enhanced groundwater processes, and without the scientific support, this awareness could be unreachable. This is clearly because the presence of ephemeral rivers in our region is certainly mostly related to the karst morphology of the territory and the activation of the rivers is mainly related to rainfall events. Nowadays, as the Canale Reale River, other regional rivers are fed by urban effluents, although they do not have the same ecological and environmental impact. Nevertheless, according to the climate model change predicting future droughts and reduction in precipitation worldwide, with consequent freshwater resources depletion, probably in a not so far future, new treatment plants could be built up close to dried rivers, to ensure a baseflow and to provide new added water volumes to groundwater benefits, practise already used in many arid areas of the world.

All the useful data collected during the doctoral path, from the geological information to the on-field measurements carried on along the riverbed, have contributed to build up a cross-disciplinary dataset. The geological and hydrogeological information acquired, are not merely qualitative but on the contrary, provide an improved comprehension of the geological influences on non-perennial rivers. Since past literature on non-perennial rivers was merely interested in the ecological aspect of these rivers, only a restricted shallow portion of the streambed was investigated. To date, few studies underline the importance of the geological controls on these rivers, reflecting generally in losing and gaining condition along the same river, as well as the role exerted by the lithologies on which the riverbed lies upon. A better knowledge of these aspects is fundamental to support another important research question, the groundwater recharge processes occurring through ephemeral streambeds, generally ungauged. In the case study, the hydraulic properties of the lithologies lying below the riverbed as well as the detection of the length of the stretches in correspondence of the outcropping formation, led to estimate the potential transmission losses occurring throughout the riverbed by the adaptation of the the Reach Length Water Balance method, and finally to estimate the water volume which can effectively reach and recharge the underlying aquifer. Although the great interest related to this topic, still few studies have carried on a thorough understanding of the recharge processes occurring between streambed and the underlying aquifer. Estimating the volume of recharge, both spatially and temporally, remains a challenge especially because, the knowledge of the mechanisms and drivers of recharge in non-perennial river systems at a broader scale is still limited. Therefore, considering the high diffusion of these types of rivers worldwide, it is difficult if not impossible to transfer the knowledge of the fluvial dynamics of a specific river to another system, since these are very different from each other. In a future perspective of water resource management in climate changes scenarios, all these research questions require significant further attention, with special attention deserved to drylands.

In conclusion, this study represents a first attempt to assess both transmission losses and aquifer recharge related to a fed- effluent ephemeral river and to date, this is the first scientific work dealing with this complex and challenging topic. The study has been carried on by crossing several scientific arguments, addressed to highlight the relevant knowledge gaps and related research questions. The argument discussed reveal the importance of the scientific studies which should pose the basis upon which carry on further development and to provide new knowledge instruments to support decisional actions, bringing together all the scientific knowledge and to encourage the dialogue between scientific community and policy makers to improve sustainable water management. Finally, the theme addressed in the doctoral thesis, follows the direction in which the entire scientific community is moving, looking at the future with great concern respect to global issues of water scarcity, which represent the most important and complex challenge for all mankind, in the contemporary era of climate change.

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CURRICULUM VITAE

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Education

- November 21, 2019 – current: Ph. D. student in the XXXV cycle of the PhD course in Risk and environmental, territorial, and building development at Polytechnic University of Bari. Supervisor: prof. U. Fratino.
- April 2016- September 2019: Post-graduate research at Water Research Institute- Italian National Research Council *(IRSA-CNR)- Bari, for the project "Monitoring models of the water cycle and reconstruction of the geological model".* Scientific responsible*:* dr. V.F. Uricchio.
- May-December 2014: "Master of Expert in Natural and Anthropogenic Risks. Polytechnic University of Bari and University of Bari Aldo Moro.
- December 2013: Master's degree in "Geological and Geophysical science" with 110/110 cum laude at University of Bari Aldo Moro, discussing a thesis on "*Hydrostratigraphic features of the Metaponto coastal plain subsurface".* Supervisor: Prof. M. Tropeano and Prof. F.G. Andriani.
- July 2009: Bachelor's degree in Geological Science at University of Bari Aldo Moro, discussing a thesis on "Assessing permeability coefficient of sand samples having different granulometric composition by experimental tests with a constant load permeameter". Supervisor: Prof. N. Walsh.

Professional experience

- August 2022- current: Research grant at University of Salento – Lecce, for the project:" Hygienic-sanitary aspects of groundwater in relation to wastewater discharge through the soil, and characteristics geological and hydrogeological features". Scientific responsible: Prof. Tiziana Grassi.

- April 2020-July 2022: Research Grant at Water Research Institute- Italian National Research Council (IRSA-CNR)- Bari, for the project “Sustainable management of overexploited aquifers”. Scientific responsible: Eng. Ivan Portoghese, Eng. Giuseppe Passarella.

Skills

Spoken languages	Italian (Mother), English
English Certificate	First Certificate of English (F.C.E.) Preliminary English Test (P.E.T)
Digital	Microsoft Office, Microsoft Word, Microsoft Excel, Microsoft Powerpoint, Basics knowledge in Modeling software, Advanced knowledge in QGis software
Soft skills	Leadership, team working, organizational, communicative, and relational skills, rapid learning, problem solving, curiosity.

Scientific production

1. Portoghese I, **Brigida S**, Masciale R, Passarella G. *Assessing Transmission Losses through Ephemeral Streams: A Methodological Approach Based on the Infiltration of Treated Effluents Released into Streams*. Water. 2022; 14(22):3758. https://doi.org/10.3390/w14223758
2. De Giglio O, Triggiano F, Apollonio F, Pousis C, Calia C, Diella G, Bagordo F, Murgolo S, Grassi T, De Ceglie C, **Brigida S**, La Rosa G, Mancini P, Bonanno Ferraro G, De Donno A, Mascolo G, Caputo MC, Montagna MT. *The Geological Characteristics of the Vadose Zone Influence the Impact of Treated Wastewater on the Groundwater Quality (SCA.Re.S. Project 2019–2020*). Pathogens. 2022; 11(6):677. https://doi.org/10.3390/pathogens11060677
3. Passarella G, Lay-Ekuakille A, Djungha Okitadiowo JP, Masciale R, **Brigida S**, Matarrese R, Portoghese I, Isernia T, Blois L. *An Affordable Streamflow Measurement Technique Based on Delay and Sum Beamforming*. Sensors (Basel). 2022 Apr 7;22(8):2843. doi: 10.3390/s22082843.
4. Montagna, M.T.; De Giglio, O.; Calia, C.; Pousis, C.; Triggiano, F.; Murgolo, S.; De Ceglie, C.; Bagordo, F.; Apollonio, F.; Diella, G.; Narracci, M.; Acquaviva, M.I.; Ferraro, G.B.; Mancini, P.; Veneri, C.; **Brigida, S**.; Grassi, T.; De Donno, A.; Di Iaconi, C.; Caputo, M.C.; Cavallo, R.A.; La Rosa, G.; Mascolo, G. *Microbiological and Chemical Assessment of Wastewater Discharged by Infiltration Trenches in Fractured and Karstified Limestone (SCA.Re.S. Project 2019–2020).* Pathogens 2020, 9,1010. https://doi.org/10.3390/pathogens9121010
5. De Giglio O, Caggiano G, Apollonio F, Marzella A, **Brigida S**, Ranieri E, Lucentini L, Uricchio VF, Montagna MT. 2018. *The aquifer recharge: an overview of the legislative and planning aspect*. Ann Ig 2018; 30: 34-43 doi:10.7416/ai.2018.2193