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Assessing Transmission Losses through Ephemeral Streams: A Methodological Approach Based on the Infiltration of Treated Effluents Released into Streams

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Abstract: Climate change and anthropogenic pressures are the main drivers of the quantitative and qualitative depletion of water bodies, worldwide. Nowadays, in many urban areas, discharging effluents from wastewater treatment plants (WWTPs) into surface water bodies is a management solution to face the problem of water scarcity and sustain environmental flows. Although this practice can cause some concerns in public opinion about possible ecological side-effects and impairment of quality on receiving streams, it is an important contribution to the environmental baseflow of ephemeral streams, but also to groundwater recharge, especially during dry seasons, and in semi-arid and arid regions. This latter occurs through losing reaches along the streambed, though many factors may affect the infiltration rate, such as spatial distribution of streambed sediments and bedrock or the presence of channel lining. Moving from such premises, this study focuses on the Canale Reale River, an effluent-fed stream located nearby the city of Brindisi on the south-eastern side of the Apulia Region, in Italy. The Canale Reale flows through the Torre Guaceto protected wetland, located along the Adriatic coast. It collects effluents from four WWTPs with wastewater contributing for about 16.5% of the annual volume of channel drainage (i.e., 3.82 Mm^3 out of 23.02 Mm^3 along its 50 km long course). Within the framework of a complex geological setting, the Canale Reale River crosses different lithologies, which implies different streambed infiltration conditions. Using the Reach Length Water Balance method (RLWB), the transmission losses between the watercourse and the underlying aquifers were investigated. Particularly, the method allowed for the estimation of a spatially-average value of the riverbed's infiltration rate applicable to the whole river course as well as the minimum, average, and maximum 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) allowed for the inferring of the Transmission Loss Duration Curves (TLDC). Finally, the water volume infiltrating during an average hydrological year was estimated to be 6.25 Mm^3, 61% of which was due to treated wastewater discharge. The results obtained confirm that the practice of increasing the river flow rates with WWTP effluents reduces the dry riverbed periods, with potential improvements to the river's ecological sustainability and relevant enhancement of groundwater recharge.

Keywords: surface-groundwater interactions; effluent-fed river; Reach Length Water Balance method

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Citation: 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*, 3758. https://doi.org/10.3390/w14223758

Academic Editor: Daniel Kurtzman

Received: 4 October 2022
Accepted: 17 November 2022
Published: 18 November 2022

1. Introduction

In the global context of climate change and the growing population, water resources are threatened by overexploitation, especially in Mediterranean arid and semi-arid regions leading to negative environmental impacts [1,2]. In these regions, to compensate for surface water (SW) scarcity, the population largely relies on groundwater resources, especially for drinking purposes and irrigation. Nevertheless, changing climate conditions bringing more intense rainfall, prolonged dry periods, and higher evapotranspiration rates, are expected to reduce the natural recharge of the aquifer [3,4] which instead generally occurs only during high flow periods along ephemeral streams [5–8].

In such a context, the necessity of safeguarding water resources in both quantitative and qualitative terms is an urgent issue. This has driven communities to adopt smart and environmental-friendly solutions, such as high-performance wastewater treatment plants, especially in urban and industrialized districts [9]. In particular, the reuse of treated wastewater is one of the foreseen options, though it has been a challenging matter since the beginning of the century [10–12], with the continuous advancement of water treatment technologies to avoid ecological and sanitary impairments of recipient waterbodies [13–15].

Nowadays, discharging treated wastewater in the hydrographic networks through losing streams is frequently considered a useful water management practice, especially in coastal semi-arid and arid regions, to enhance groundwater recharge and to fight seawater intrusion [16,17]. Moreover, climate change scenarios depict increasing drought periods associated with an increasing groundwater shortage and a change of river flow regimes from perennial to intermittent conditions in arid and semiarid areas [18,19]. In such environments, treated wastewater allows for supporting ecosystem survival, restoring the baseflow of ephemeral watercourses, and supplying potable water in some cases [20–25]. Properly treated effluents, which nowadays represent an alternative source of freshwater, are likely to become crucial for guaranteeing a vital equilibrium in the hydrological cycle. All these actions move towards the integrated and sustainable management of both SW and groundwater (GW) bodies.

Consequently, interactions between SW and GW bodies need to be conceptualized and understood from a multidisciplinary perspective. Although these systems have been often considered as two separated physical systems, in the last decades, research has emphasized the necessity of considering them as parts of a whole complex system where discharge-recharge fluxes occurring at their interface (hyporheic zone) also drive chemical and biological processes relevant to the stream ecosystem [26–29].

In general, many factors can affect the amount of transmission losses along a watercourse. In addition to topographic and climate patterns, even the streambed morphology and lithology, the related vertical permeability, the depth to the groundwater table, and the quality of the flowing water are binding factors of such infiltration phenomena [30–33]. This implies different infiltration or loss conditions that allow for the identification of gaining and losing reaches along the same river [34].

From a perspective of sustainable water management in dryland areas, the comprehension of these interactions becomes more complicated when considering ephemeral streams, strongly depending on precipitation events characterized by flow variations in both space and time [35,36] and generally characterized by ungauged basins.

Further complexity in the hydrological characterization of non-perennial streams [37] comes from the fact that they are located in ungauged basins in the majority of cases worldwide, with a significant lack of in situ hydrological data, such as precipitation, streamflow, and evaporation time series [38,39]. Taking into account all the factors affecting recharge processes in ephemeral streams, methods capable of estimating transmission losses from ephemeral losing streams are useful as they can provide some proxy for measuring unconfined GW recharge from hydraulically connected SW.

Not all the methods proposed in the scientific literature for estimating transmission losses in perennial streams can be applied to ephemeral streams [40–42]. Nevertheless, many efforts have been taken to understand the dynamics of these streams, typical of arid areas, and develop more methods suitable for estimating channel infiltration [43–45], even in ungauged catchments [46,47].

Among such methods, this work refers to the Reach Length Water Balance (RLWB) [44]. Assuming SW and GW are hydraulically connected, 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 at the two sections.

This paper proposes a novel methodology that contributes to the comprehension of hydrological processes in dryland environments through the characterization of streamflow transmission losses in ephemeral rivers. In doing this the authors used the wastewater discharge effluents with known hydraulic features to undertake empirical riverbed infiltration tests, extrapolate transmission losses all through the channel bed, and consequently evaluate the overall water balance. Generally speaking, 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 [48].

The proposed approach has been applied and tested along two stretches of the Canale Reale River, an effluent-fed, ephemeral watercourse in the Apulia region (Southern Italy), to estimate the transmission loss of treated wastewater, coming from three wastewater treatment plants (WWTPs).

Table 1 reports a list of the abbreviations and definitions used in the paper.

Table 1. List of abbreviation used in the paper reported alphabetically.

Abbrev.	Definition	Abbrev.	Definition
B_C	Avg. wetted width of the whole channel	L_C	Length of the whole channel
B_w	Avg. wetted width of cross section	L_w	Wetted length of the channel
Ca	Town of Carovigno	MAR	Managed Aquifer Recharge
CM	Town of Ceglie Messapica	Q_{ww}	Daily discharge rates
CoG	Calcarenite of Gravina	RLWB	Reach Length Water Balance method
E_w	Evaporation rate	SW	Surface Water
FDC	Flow Duration Curve	TLDC	Transmission Loss Duration Curves
FF	Town of Francavilla Fontana	TL_P	Potential transmission losses
GW	Groundwater	TMDs	Terraced Marine Deposits
K_{RB}	Averaged hydraulic conductivity	WFD	Water Framework Directive
La	Town of Latiano	WWTP	Wastewater Treatment Plant

The paper is organized starting with Section 2 dedicated to an overview of the study area and its geological setting, also presenting the knowledge base of the interaction between surface water and groundwater. A sub-section is dedicated to the adopted methodology based on the RLWB method, which include details on the data retrieval and computational steps. The application of the proposed methodology is summarized in Section 3 followed by the results section (Section 4) and conclusions (Section 5).

2. Materials and Methods

2.1. Study Area

The study area is located in the south-eastern part of the Apulia region (Southern Italy), in a morphologically flat area known as Brindisi Plain (Figure 1) and characterized by a typical dry sub-humid, Mediterranean climate [49].

The local hydrography is mainly represented by a few ephemeral SW bodies, often regulated within artificial channels that generally cross the plain almost perpendicularly to the Adriatic coast and feed some coastal wetlands characterized by typical Mediterranean shrubs.

Owing to the flat morphology of the area and to the relatively low permeability of the sediments that diffusely outcrop near the coast, since the beginning of the 18th century, many reclamation operations have been carried out to drain the marsh areas as an antimalarial measure. This made possible the development of very diversified and intensive agriculture from inland towards the Adriatic Sea, consisting of olives, grapes, and vegetable crops.

Due to the extension of its catchment basin (approximately 210 km_2) and its length (about 50 km), the Canale Reale River represents the most significant watercourse in southern Apulia. It originates from springs nearby Villa Castelli municipality and crosses the territories of different towns, collecting the treated effluents from WWTPs of the municipalities of Francavilla Fontana (FF), Ceglie Messapica (CM), Latiano (La), and partly from Carovigno (Ca) (Figure 1), with a total discharge of 18.3×10^3 m^3/d. Wastewater discharge practice has been allowed for decades, with increasing discharge rates, so that the Canale Reale River can be considered a wastewater-effluent-fed stream. Due to these anthropogenic disturbances, it is classified as a heavily modified river with a temporary flow regime of ephemeral-intermittent type, according to the Water Framework Directive (WFD) of the European Union [50].

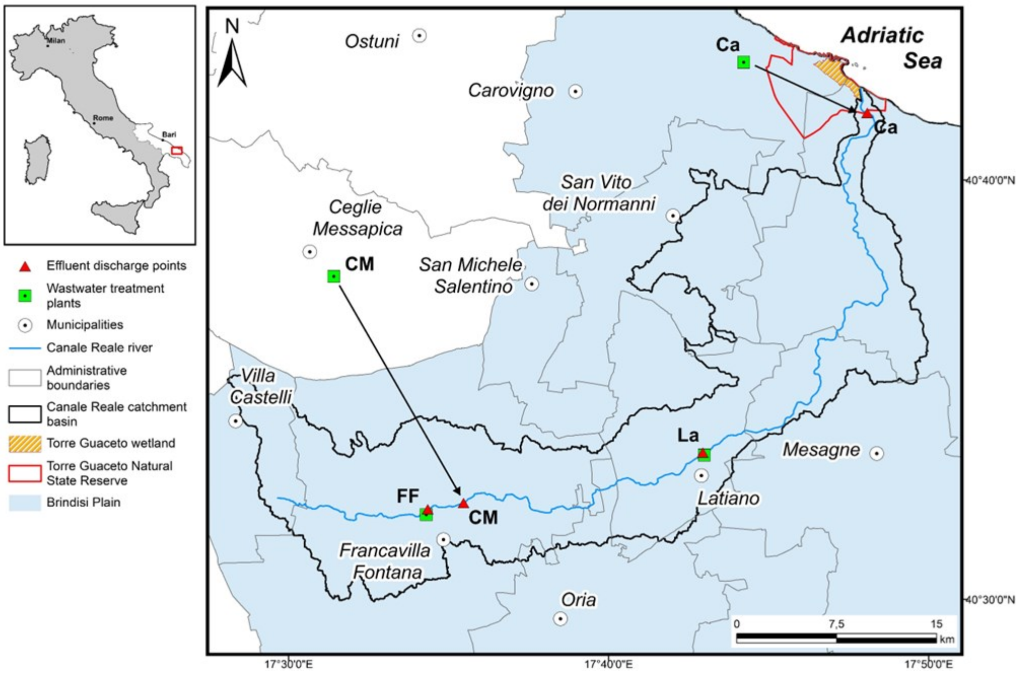

Figure 1. The geographical setting of the study area and distribution of the effluent discharge points along the Canale Reale River.

Nevertheless, the high value of the river ecosystem and naturalistic traits tracing back to its ancient perennial character cannot be denied, also for the presence of the Natural State Reserve of Torre Guaceto at the river mouth, a coastal salty marsh extended for 10 km^2 with 3.50×10^5 m^3 water volume belonging to the list of Ramsar wetlands of international importance.

Recently, an environmental management plan, focusing on the Canale Reale and its catchment basin, has been undertaken by local authorities, to identify a series of integrated actions for the restoration of the watercourse through the adoption of the River Contract approach. These actions comply with the requirements of the WFD, which recognizes the river basin as the main physical and socio-economic domain for implementing systemic policies for the requalification and sustainable management of SW and GW resources. Within the River Contract, establishing an effective hydrological monitoring network is the most urgent action to be implemented mainly considering that qualitative and quantitative information on this watercourse is scarce or even missing both in space and in time. Only periodic monitoring of some physicochemical and biological parameters has been carried out by the Regional Environmental Agency at the closure section of the Canale Reale River, revealing a poor ecological and chemical state, in the last decade. A recent attempt of assessing the hydrodynamic features of the Canale Reale River was conducted by Passarella et al. [51] using an affordable and reliable measurement technique, based on beamforming applied on streamflow video sensing.

The presence of dry channel stretches has been observed all along the warm seasons, especially in the downstream half of the river course, and this feature is typical of losing streams and deep groundwater tables, thus deserving specific attention in the hydrogeological characterization.

2.2. Geological and Hydrogeological Setting

The study area falls within an important transition zone, known as 'Soglia Messapica' (Messapian Threshold), between two structural domains: the Murgia Plateau and the Salento peninsula. The Messapian Threshold is a tectonically disturbed area that has undergone multiple geodynamic and tectonic events involving the carbonate basement. Hence, it results as displaced in a series of blocks bounded by normal sub-vertical faults, predominantly oriented E-W and NNW-SSE [52]. Particularly, the tectonic setup strongly affects the path of the Canale Reale River, which rotates from the W-E direction in the first part of its path to S-N in the middle and final part, thus following the main direction of the pre-existing buried faults system [53].

An exhaustive description of the geological setup concerning the study area can be found in Ciaranfi et al. [54]. Following this study, the stratigraphic succession can be schematized, from bottom to top, as follows:

- Limestone of Altamura (Cretaceous), forming the carbonate basement, made up of calcareous and calcareous–dolomitic rocks, widely outcropping in the western part of the study area;
- Calcarenite of Gravina (upper Pliocene–lower Pleistocene), consisting of calcarenite sediments having 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) made of clay and sandy clay;
- Terraced Marine Deposits (middle-upper Pleistocene) characterized by considerable variations of facies but generally made up of yellow sands and a base level of marly clays, and outcropping in the eastern part of the study area with a thickness not exceeding 10–20 m;
- Alluvial, marshes, and coastal deposits (Holocene) with a small thickness and limited extension [55] (Figure 2).

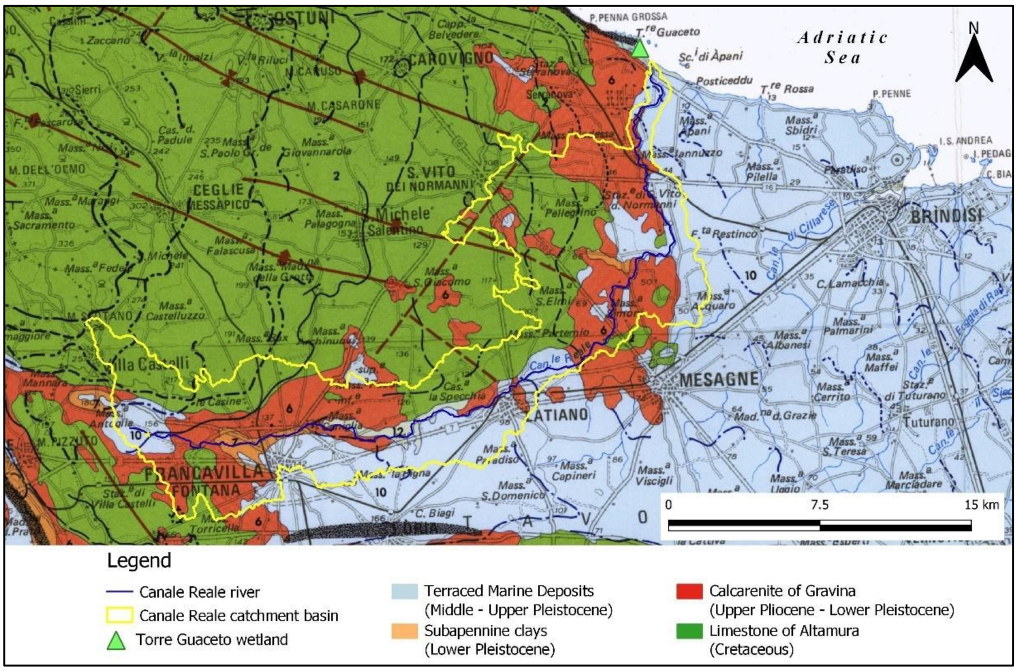

Figure 2. Geological map with a focus on the main formations outcropping in the Canale Reale catchment basin.

The above-described stratigraphic and structural setting reflects the presence of two distinct aquifer structures, the deep aquifer hosted in the Cretaceous carbonate rocks succession and the shallow local porous aquifer, corresponding to sand-calcarenite levels of Terraced Marine Deposits [56].

The shallow aquifer, still intensively used for local irrigation needs, is only recharged by rainwater. When maximum recharge conditions are reached, excess water is drained into the rivers, canals, and topographically depressed areas. It is moderately or not at all affected by seawater intrusion while severe nitrate contamination is highlighted [57].

The deep carbonate aquifer is characterized by a marked anisotropy that strongly controls the groundwater circulation conditions. The structural setup, combined with the presence of karst systems at different stages of evolution, results in an extreme spatial variation in hydraulic conductivity and other hydrogeological parameters.

Due to this feature, and the presence of Subapennine clays locally covering the Mesozoic bedrock, groundwater flows both under confined and unconfined conditions and emerges, particularly, along the wetland, area of Torre Guaceto through submarine and subaerial springs along the coast [58]. The deep aquifer is mainly recharged by rainfalls that infiltrate the innermost part of the Murgia Plateau. 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 [59,60].

The increasing amount of water-demanding crops in this area over the last 50 years has determined a significant anthropogenic impact on deep groundwater resources in either quantitative or qualitative terms. Indeed, localized phenomena of saline contamination both along the coastal aquifer and into the inner part of the Brindisi plain have been recognized [57]. Although the shallow and deep aquifers are physically separated by the impermeable formation named Subapennine clays, the temperature distribution within the deeper one suggests that a hydraulic connection exists between them. This is likely due to the over 3000 irrigation wells, improperly drilled along the Brindisi plain, but also to significant structural discontinuities involving the impermeable layer [57,61].

2.3. SW-GW Interaction

The geology and the structural setting of the study area allow supposing the hydraulic connection between the Canale Reale River and both the shallow and deep aquifers, depending on the lithology crossed by the river in its different stretches (Figure 2). Indeed, the Canale Reale Riverbed almost 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 roles played by the two aforementioned formations. Figure 3 shows a schematic cross-section of the Canale Reale River, which illustrates the different interactions between SW and GW. Particularly, when the Canale Reale crosses the CoG, which is not an aquifer formation, it behaves as a losing disconnected stream where the water infiltrates into the thick vadose zone, finally feeding the deep carbonate aquifer (left bank in Figure 3). On the contrary, the TMDs host a shallow aquifer due to the presence of a basal clay layer. Therefore, when the Canale Reale River crosses them, it can alternatively play the role of gaining or losing stream, depending on the seasonal fluctuations of the water table (right bank in Figure 3).

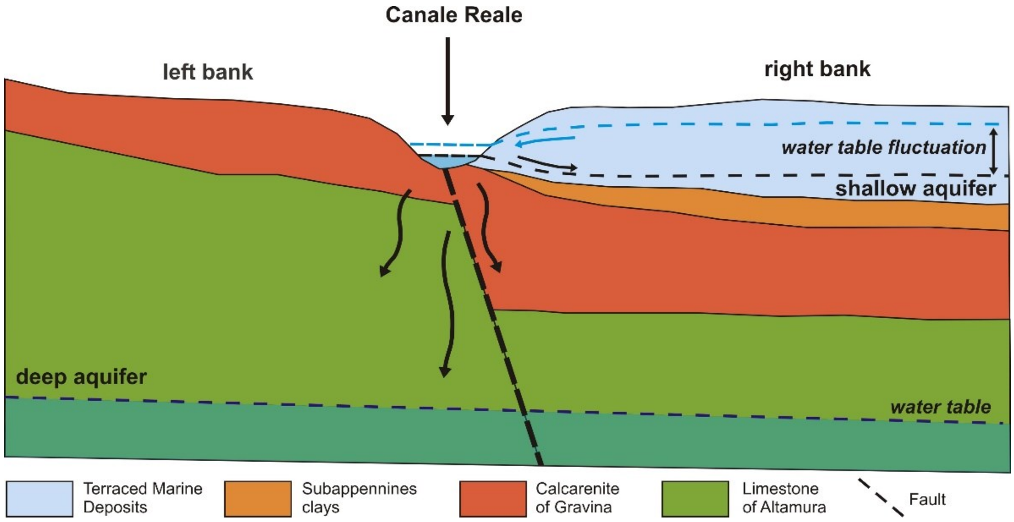

Figure 3. Schematic cross-section of Canale Reale River showing the different types of interaction between SW and GW: on the left side is the case of a losing stream, on the right one is the case of a gaining stream that can turn into a losing stream, and vice versa, according to water table fluctuations.

According to the literature, the hydraulic conductivity of the TMDs ranges from 10^{-5} m/s to 10^{-8} m/s and partially overlaps the CoG range, which in turn varies from 10^{-4} m/s to 10^{-6} m/s [57,62–64]. The largest variability towards the lower values of the TMDs hydraulic conductivity is related to the variable clay content. At the same time, the presence of karst forms in the CoG can locally increase its hydraulic conductivity values.

2.4. Methodology

The approach adopted in this study is based on the RLWB method in which differential discharge measurements between an upstream and a downstream cross-section along a surface watercourse are used to empirically quantify the streambed infiltration [65,66].

The streamflow differencing method has been generally used for estimating transmission losses in perennial streams, characterized by a stable flow condition that easily allows for measuring the difference between upstream and downstream flow [44]. On the contrary, ephemeral streams are characterized by non-stable flow conditions, and loss rate estimation is determined by measuring the flow rate between the upstream and downstream stations across the entire flow event [67]. In our case study, the Canale Reale River is classified as an ephemeral river characterized by a seasonal flow regime, in which the presence of a stable low flow condition in the summer season is guaranteed by treated wastewater discharged at four different locations along the channel length (Figure 1).

Therefore, the proposed methodology is based on the use of WWTPs discharge to characterize the riverbed infiltration during the dry season, when the natural river flow is negligible. This methodology has been applied according to the following steps:

1. Preliminary steps
   - Retrieval of the daily discharge rates from the existing WWTPs, namely Q_{ww} (m^3/s), and the location of the discharge points, and a survey of the geometry of the cross-sections along the river;
   - Detection of wetted channel portions downstream of the discharge points using high-resolution aerial images during the dry season to identify the average wetted width of channel cross-section B_w (m) and the wetted length of the channel L_w (m);
2. Computational steps
   - 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:

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

where q is the specific infiltration rate of water through a unit horizontal surface of the channel (m/s), K is the saturated hydraulic conductivity (m/s) in the vertical direction z, dh/dz is the hydraulic gradient (m/m), which is expressed with i as a short-hand notation.

For those sites with thick unsaturated zones, where the effects of groundwater mounding will generally be small, the infiltration rate can be approximated by the Green-Ampt equation [68] where the gradient will not typically be reduced by infiltration from the channel and will be approximately equal to 1.0 (reported in the literature as unit gradient approximation).

- Under deep groundwater table conditions, the evaluation of spatially averaged hydraulic conductivity K_{RB} (m/s) of a dry riverbed stretch receiving some wastewater effluent with known characteristics can be derived from the water balance (i.e., RLWB method):

$$K_{RB} = \frac{Q_{ww}}{L_w \times B_w} - E_w \tag{2}$$

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.

- Extension of the riverbed hydraulic conductivity to the whole channel length (L_C) and evaluation of the riverbed potential transmission loss TL_P $\left(\mathrm{m}^3/\mathrm{s}\right)$:

$$TL_P = K_{RB} \times L_C \times B_C \tag{3}$$

where B_C is the average width of the whole considered channel.

3. Postprocessing step

Finally, the estimated riverbed potential transmission loss has been suitably used as a component of a water balance to integrate a rainfall-runoff model application recently developed over the same study area [69]. Indeed, as for most similar cases, this model application neglected the contribution of the runoff re-infiltration along the losing riverbed stretch, which is a common condition during the dry season.

3. Case Study

In the scientific literature, the RLWB method applications to ephemeral watercourses usually refer to concurrent measurements of the streamflow during flow events. In the case at hand, an adaptation of the standard RLWB method has been proposed. 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 corresponding to the central part of the considered water course from the most upstream outlet point to the last downstream wet cross-section.

Based on the above assumption, considering the summer month of July 2021, the average daily discharge rates at the above-mentioned outlet points range from 0.02 $\left(\mathrm{m}^3/\mathrm{s}\right)$ to 0.051 $\left(\mathrm{m}^3/\mathrm{s}\right)$ (Table 1).

At the same time, supported by Google Earth images and high-resolution dry period orthophotos provided by the Apulia Region web-GIS, it was possible to distinguish wet and dry reaches within the riverbed along the considered 20 km river stretch. Figure 4 shows magnified orthophotos of three river portions characterized by different flow characteristics and channel vegetation.

Figure 4. Orthophoto frames of three different channel portions: (**a**) flowing water filling the entire cross-section of the riverbed nearby the effluent outlet; (**b**) flourishing riparian vegetation indicating a wet riverbed; (**c**) transition from a wet to a dry streambed condition suggested by a colour change from vivid green to light brown.

In particular, Figure 4a,b refers to wet river conditions evidenced by water within the riverbed or rich riparian vegetation. On the contrary, Figure 4c shows the transition from a wet to a dry condition marked by different riverbed colours. Thus, the visual survey of the Canale Reale River during summertime has allowed us to verify that:

(i) the riverbed is virtually dry from the upstream spring (S) until the first effluent discharge location of the treatment plant of FF;

(ii) a first wet stretch is visible from the discharge location of FF downstream for about 10.9 km (stretch #1 in Figure 5). Given the short distance between the FF and CM discharge points, in the following computational steps, they have been treated as a unique location, positioned in FF and delivering a total effluent discharge equal to the sum of the two;

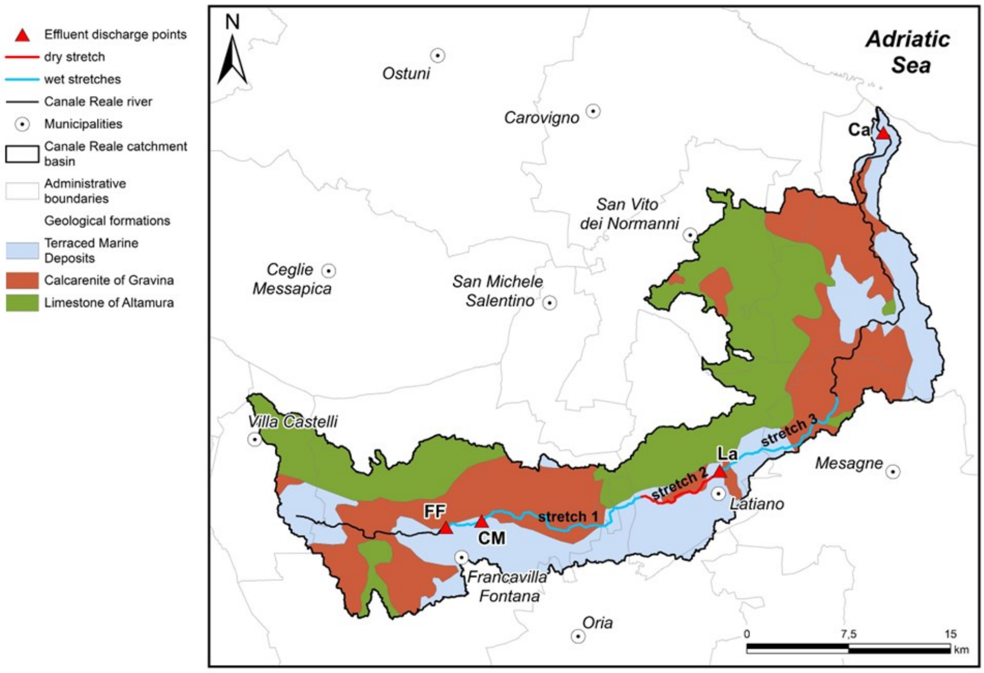

Figure 5. Distribution of wet and dry stretches along the Canale Reale River after the visual survey.

(iii) a second dry stretch, about 4.4 km long, follows stretch #1, down to the La discharge location (stretch #2 in Figure 5);

(iv) a new wet stretch of 7.2 km, fed by the La effluent is then visible (stretch #3 in Figure 5).

(v) the riverbed turns into dry conditions from the ending section of stretch #3 until the Ca effluent discharge point, located a few hundred meters upstream from the river outlet. Given the short distance of such a discharge point from the river outlet and the concrete sealing of the channel bottom, the released flow quickly runs to the sea making the potential transmission losses almost negligible.

Based on the physical system defined above, the proposed methodology allowed for the estimation of a range of potential transmission loss values to be assigned to the whole Canale Reale River bed.

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.

In particular, the average Flow Duration Curves (FDCs), obtained by a daily rain-fall-runoff model application for the period 2005–2021 [69], have been combined with the above estimated potential transmission losses. This final step enabled us to make some inferences about the significance of the WWTP outflows' contribution to the scarce natural river discharge as well as about the river's potential contribution to the groundwater recharge.

The next section reports a detailed description of the results of these methodological steps.

4. Results and Discussion

Coherently with the computational steps of the proposed methodology, and neglecting the evaporation loss in Equation (2), two values of K_{RB} have been first calculated, one per river wet stretch. Table 2 reports the values of K_{RB} besides the position and flow rates of the four WTTPs' discharges into the Canale Reale River, as well as the values of the parameters used in Equation (2).

Table 2. Relevant distances of wastewater treatment plants (WWTPs) discharge points from the river outlet, flow rates, and channel features used for the estimation of average riverbed hydraulic conductivity. FF = Francavilla Fontana; CM = Ceglie Messapica; La = Latiano; Ca = Carovigno. L_w = length of the downstream wet stretch; B_w = mean width of the downstream wet stretch. (*) Given the short distance between the FF and CM effluent discharge location, they have been treated as a unique point, positioned in FF, with a total effluent discharge equal to the sum of the two.

WTTP	Distance from the River Outlet	Average Q_{ww} (July)	Average Q_{ww} (July)	L_w	B_w	K_{RB} (Equation (2))
	(km)	(m^3/d)	(m^3/s)	(m)	(m)	(m^3/s)
FF (*)	42.5	4326	0.050	10,900	2.5	3.72×10^{-6}
CM (*)	40.3	4439	0.051		2.5	
La	26.5	1737	0.020	7180	2.5	1.12×10^{-6}
Ca	1.3	7795	0.090	1300	2.5	-

The estimated K_{RB} values are in agreement with the range of values proposed in the literature (see Section 2.3). Particularly, the higher value obtained for stretch #1 is consistent considering that this latter river portion predominantly crosses the CoG formation. Even being of the same order of magnitude, a slightly lower value of K_{RB} has been estimated for stretch #3, where the river equally crosses both the TMD and CoG formations.

Moving to the next computational step, the maximum, average, and minimum TL_P values have been estimated as spatially averaged K_{RB} along the whole river, based on Equation (3).

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.

Conversely, the average TL_P value has been calculated by weighting K_{RB1} and K_{RB3} over to the respective river stretch length. Table 3 reports the resulting TL_P values ranging from 1.19×10^{-1} m^3/s to 3.95×10^{-1} m^3/s while the average TL_P value is 2.23×10^{-1} m^3/s.

Table 3. Estimated minimum, average and maximum values of the potential transmission losses (TL_P) along the Canale Reale River.

	K_{RB}	River Sector Length	TL_P
	(m/s)	(m)	(m^3/s)
minimum	$K_{RB3} = 1.12 \times 10^{-6}$	42,500	1.19×10^{-1}
average	$K_{RB3} = 1.12 \times 10^{-6}$	16,000	2.23×10^{-1}
	$K_{RB1} = 3.72 \times 10^{-6}$	26,500	
maximum	$K_{RB1} = 3.72 \times 10^{-6}$	42,500	3.95×10^{-1}

The range of estimated TL_P values can be seen as the uncertainty related to the initial assumptions of the proposed method. Considering the average TL_P and the related uncertainty in the water balance estimation should provide a range of possible infiltrating water volumes.

Such a task has been carried out by overlapping the estimated TL_P to the FDCs of the Canale Reale River, obtained by rainfall-runoff modelling [69] (Figure 6). This allowed for assessing a sort of Transmission Loss Duration Curves (TLDC) indicating the infiltration during an average hydrological year. In particular, Figure 6 shows two river flow scenarios: scenario #1, which considers only the natural flow due to the rainfall-runoff processes (Figure 6a), and scenario #2, where the discharge from the WWTPs has been added to the natural flow (Figure 6b). This allowed us to approximately establish how much and for how long the infiltration actually takes place during an average hydrological year along the whole river course in both scenarios.

The two scenarios differently perform during an average year in terms of both river flow duration and transmission losses. In particular, the FDC curves of scenario #1 (blue line in Figure 6a) indicate that the river is wet between 120 and 225 days per year, depending on the different TL_P values. On the contrary, the same curve of scenario #2 (Figure 6b) evidences a wet riverbed for a period from 150 to the whole year, with streamflow never lower than 0.121 m^3/s. In other words, such results prove the WWTPs treated discharges guarantee a wet riverbed during the whole year, strongly supporting the water-dependent habitat along the river banks.

Figure 6 also shows the estimated TLDCs. 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 2. The two plots in Figure 6 reveal that as long as the TLDCs lie below the corresponding FDCs, the river flow rate guarantees a constant transmission loss equal to the TL_P value. However, in such a condition, part of the flow rate continues to run into the riverbed. As soon as the TLDC crosses the FDC, the river bed becomes dry, since the flow rate fully infiltrates with a decreasing rate of less than TL_P.

The timing of such a circumstance change based on the considered scenario and TL_P value. So, considering the maximum estimated TL_P value in scenario #1, the river flow rate guarantees at the same time a transmission loss equal to TL_P and a residual discharge at the river mouth for about 120 days. Otherwise, considering the minimum TL_P value in scenario #2, the transmission loss, even being relatively small, is guaranteed during the whole year, together with a residual flow rate at the river mouth.

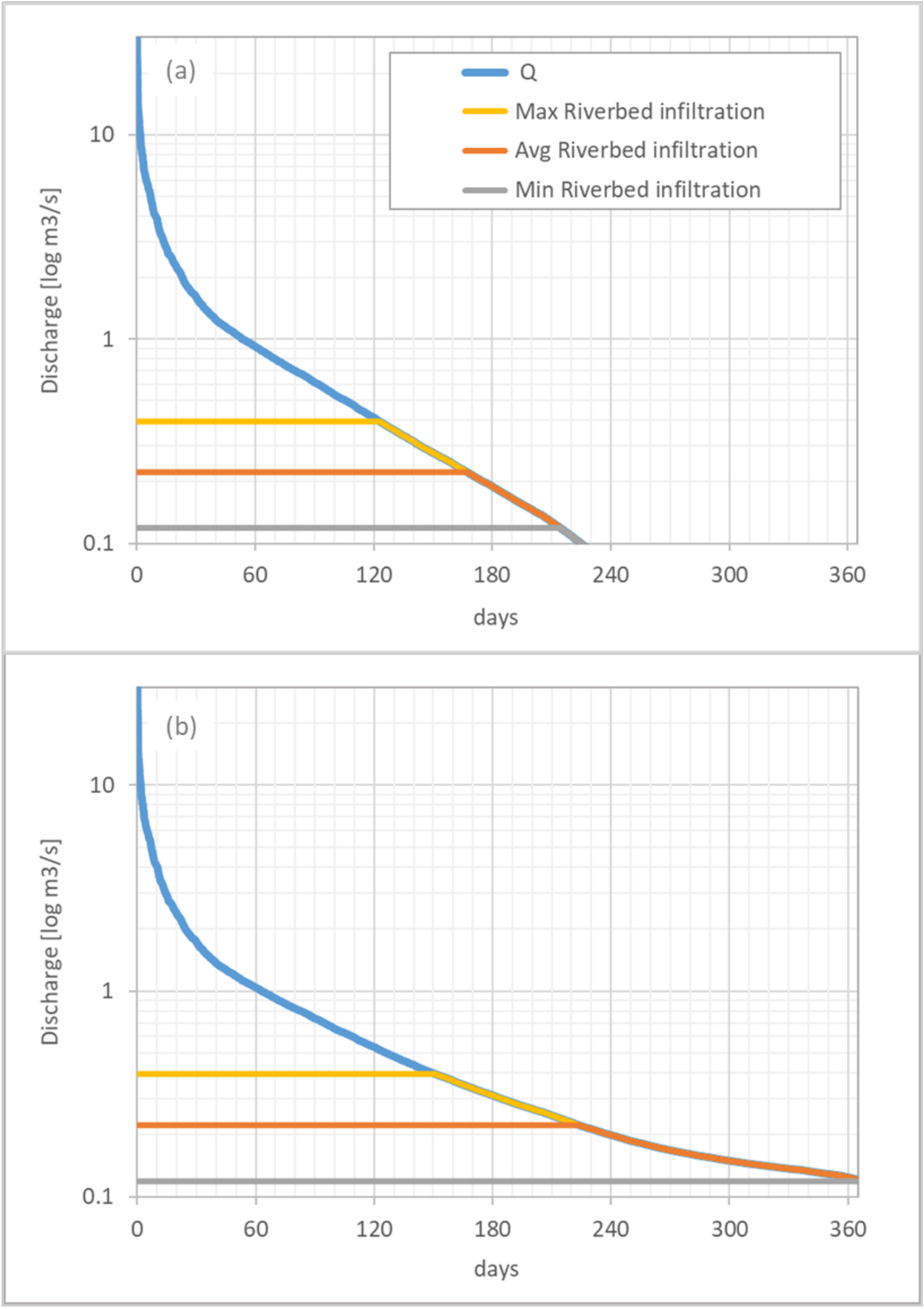

Figure 6. Flow (blue line) and transmission loss duration curves (yellow, orange and grey) of the Canale Reale River. (**a**) scenario #1: Q = simulated rainfall-runoff, (**b**) scenario #2: Q = daily discharge from the four WWTPs outlets summed to the simulated rainfall-runoff.

A yearly-based assessment of the river water balance has been finally carried out for both the proposed scenarios. The total water volume drained by the Canale Reale River resulted equal to 19.20 Mm^3/yr and 23.02 Mm^3/yr for scenarios #1 and #2, respectively. Consequently, by difference, the related 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 4).

Table 4. 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.

	Transmission Losses $(\mathbf{Mm^3/yr})$					
	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

In particular, the first row of Table 3 shows the total volumes of transmission losses through the channel. As expected, these values point out that the infiltrated flow rates for scenario #2 are always larger 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 $\mathrm{Mm}^3/\mathrm{yr}$ to about 2.5 Mm^3/yr. Practically, this result confirms that the increasing river flow rates due to WWTP discharge potentially improve, not only the river's ecological sustainability by reducing the dry riverbed periods, but it also contributes to enhanced groundwater recharge.

5. Conclusions

Streamflow transmission losses through ephemeral streams are believed to be a major source of groundwater recharge mainly in arid areas. Although this phenomenon results in a flow rate reduction at the river mouth, it can produce doubtless advantages for the underground reservoir. Several studies proved that the discharge of treated effluents into surface watercourses contributes to satisfactorily preserving the environmental baseflow in the river while guaranteeing a good groundwater recharge rate through losing stream infiltration. Determining how to quantify the SW-GW balance the RLWB method, based on measured time-series of flow rates at two river cross-sections, is often referred to in the literature. Unfortunately, ephemeral water streams often lack gauging sections and the only available information often consists of sporadic and erratic on-site measures.

In this paper, an original approach to evaluate the transmission loss from surface water has been proposed based on an adaptation of the RLWB method and aimed at overcoming the lack of structured river flow monitoring in ephemeral watercourses. The proposed method has been applied and tested on the Canale Reale River case study, an ungauged, ephemeral watercourse, located in south-eastern Italy. The method application, moving from a visual survey of the summer season's airborne images of the river when the flow rate is only due to treated wastewater effluents discharged at different river locations, allowed for identifying wet and dry stretches along its course.

Assuming that the entire treated effluent flow rate filtrates through the wet stretch riverbed allowed for the estimation of a range of vertical hydraulic conductivities along the river and then the related potential transmission losses values. The Canale Reale River resulted then characterized by a vertical hydraulic conductivity ranging from about 1.12×10^{-6} m/s to 3.72×10^{-6} m/s, and a potential transmission loss from about 1.19×10^{-1} m^3/s to 3.95×10^{-1} m^3/s.

Combining the TL_P with the flow duration curves of the Canale Reale River, some transmission loss duration curves have been assessed describing the temporal regime of the streamflow transmission losses. Two scenarios have been considered for flow duration curves: the first considers only a natural flow rate within the river, whilst the second refers to the more favourable case of natural flow integrated by the WTTPs' discharge into the riverbed.

Finally, the method allowed for the estimation of the average annual volumes of riverbed transmission losses per scenario, equal to 4.46 $\mathrm{Mm}^3/\mathrm{yr}$ and 6.25 $\mathrm{Mm}^3/\mathrm{yr}$, respectively, and the contribution of both natural flow rates within the river and treated effluents discharged into it.

In conclusion, the proposed method performs well in characterizing the "losing stream" conditions in ephemeral, ungauged watercourses allowing for estimating the transmission losses and the related timing during an average hydrologic year.

Further development of this study will address quantitative and qualitative issues related to:

(i) using WWTP's treated effluents for improving the environmental status of ephemeral surface watercourses;

(ii) refining the proposed methodology to improve the assessment of the net groundwater recharge;

(iii) evaluating the suitable use of WTTP's treated effluents as an "in-channel MAR" tool for groundwater replenishment and seawater intrusion contrast;

(iv) improving the method reliability by introducing uncertainty analysis.

Author Contributions: Conceptualization, R.M., I.P. and G.P.; methodology, R.M., I.P. and G.P.; investigation, R.M., S.B., I.P. and G.P.; data curation I.P., R.M., S.B. and G.P.; writing—original draft preparation, R.M., S.B., I.P. and G.P.; writing—review and editing, R.M., I.P. and G.P.; visualization, R.M. and G.P.; supervision, G.P.; funding acquisition, G.P. All authors have read and agreed to the published version of the manuscript.

Funding: Part of the research activities proposed in this paper were developed within the INTERACTION project, 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 through a Belmont Forum (Earth System Science and Environmental Technologies Department of the National Research Council of Italy) grant (Belmont forum-CNR: B55F21001250007) (https://belmontforum.org/projects?fwp_project_call=soils2020, accessed on 8 February 2022).

Acknowledgments: The authors warmly thank the Management Consortium of Torre Guaceto and, in particular, the President, Rocco Malatesta, and the Scientific Director Sandro Cicolella, which kindly hosted the CNR team and allowed the research activity within the Marine Protected Area and the Natural State Reserve of Torre Guaceto (Italy).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Xanke, J.; Liesch, T. Quantification and possible causes of declining groundwater resources in the Euro-Mediterranean region from 2003 to 2020. *Hydrogeol. J.* **2022**, *30*, 379–400. [CrossRef]
2. Wada, Y.; Wisser, D.; Bierkens, M.F.P. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. *Earth Syst. Dynam.* **2014**, *5*, 15–40. [CrossRef]
3. Doglioni, A.; Simeone, V. Effects of Climatic Changes on Groundwater Availability in a Semi-arid Mediterranean Region. In *IAEG/AEG Annual Meeting Proceedings*; Shakoor, A., Cato, K., Eds.; Springer: Cham, Switzerland; San Francisco, CA, USA, 2018; Volume 4, pp. 105–110.
4. Analy, M.; Laftouhi, N.E. Groundwater Depletion in an Urban Environment under Semiarid Climate and Persistent Drought–City of Marrakesh (Morocco). *Water* **2021**, *13*, 3253. [CrossRef]
5. Sorman, A.U.; Abdulrazzak, M.J. Infiltration-recharge through wadi beds in arid regions. *Hydrol. Sci. J.* **1993**, *38*, 173–186. [CrossRef]
6. Farran, M.M.; Al-Amri, N.; Elfeki, A.M. Aquifer recharge from flash floods in the arid environment: A mass balance approach at the catchment scale. *Hydrol. Process.* **2021**, *35*, e14318. [CrossRef]
7. Hajhouji, Y.; Fakir, Y.; Gascoin, S.; Simonneaux, V.; Chehbouni, A. Dynamics of groundwater recharge near a semi-arid Mediterranean intermittent stream under wet and normal climate conditions. *J. Arid Land.* **2022**, *14*, 739–752. [CrossRef]
8. Herrera, C.; Gamboa, C.; Custodio, E.; Jordan, T.; Godfrey, L.; Jódar, J.; Luque, J.A.; Vargas, J.; Sáez, A. Groundwater origin and recharge in the hyperarid Cordillera de la Costa, Atacama Desert, northern Chile. *Sci. Total Environ.* **2018**, *624*, 114–132. [CrossRef]
9. Teklehaimanot, G.Z.; Kamika, I.; Coetzee, M.A.A.; Momba, M.N. Population Growth and Its Impact on the Design Capacity and Performance of the Wastewater Treatment Plants in Sedibeng and Soshanguve, South Africa. *Environ. Manag.* **2015**, *56*, 984–997. [CrossRef]

10. Li, Y.; Liu, M.; Wu, X. Reclaimed Water Reuse for Groundwater Recharge: A Review of Hot Spots and Hot Moments in the Hyporheic Zone. *Water* **2022**, *14*, 1936. [CrossRef]
11. Bixio, D.; Thoeye, C.; Wintgens, T.; Ravazzini, A.; Miska, V.; Muston, M.; Chikurel, A.; Aharoni, D.; Joksimovic, T.; Melin, T. Water reclamation and reuse: Implementation and management issues. *Desalination* **2008**, *218*, 13–23. [CrossRef]
12. Fournier, E.D.; Keller, A.A.; Geyer, R.; Frew, J. Investigating the energy-water usage efficiency of the reuse of treated municipal wastewater for artificial groundwater recharge. *Environ. Sci. Technol.* **2016**, *50*, 2044–2053. [CrossRef]
13. Asano, T.; Cotruvo, J.A. Groundwater recharge with reclaimed municipal wastewater: Health and regulatory considerations. *Water Res.* **2004**, *38*, 1941–1951. [CrossRef]
14. Brooks, B.W.; Riley, T.M.; Taylor, R.D. Water Quality of Effluent-dominated Ecosystems: Ecotoxicological, Hydrological, and Management Considerations. *Hydrobiologia* **2006**, *556*, 365–379. [CrossRef]
15. Hamdhani, H.; Eppehimer, D.E.; Bogan, M.T. Release of treated effluent into streams: A global review of ecological impacts with a consideration of its potential use for environmental flows. *Freshw. Biol.* **2020**, *65*, 1657–1670. [CrossRef]
16. Zaccaria, D.; Passarella, G.; D'Agostino, D.; Giordano, R.; Solis, S.S. Risk Assessment of Aquifer Salinization in a Large-Scale Coastal Irrigation Scheme, Italy. *Clean Soil Air Water* **2016**, *44*, 371–382. [CrossRef]
17. Frollini, E.; Parrone, D.; Ghergo, S.; Masciale, R.; Passarella, G.; Pennisi, M.; Salvadori, M.; Preziosi, E. An integrated approach for investigating the salinity evolution in a Mediterranean coastal karst aquifer. *Water* **2022**, *14*, 1725. [CrossRef]
18. Ukkola, A.M.; De Kauwe, M.G.; Roderick, M.L.; Abramowitz, G.; Pitman, A.J. Robust future changes in meteorological drought in CMIP6 projections despite uncertainty in precipitation. *Geophys. Res. Lett.* **2020**, *47*, e2020GL087820. [CrossRef]
19. de Graaf, I.E.M.; Gleeson, T.; (Rens) van Beek, L.P.H.; Sutanudjaja, E.H.; Bierkens, M.F.P. Environmental flow limits to global groundwater pumping. *Nature* **2019**, *574*, 90–94. [CrossRef]
20. Bischel, H.N.; Lawrence, J.E.; Halaburka, B.J.; Plumlee, M.H.; Bawazir, A.S.; King, J.P.; McCray, J.E.; Resh, V.H.; Luthy, R.G. Renewing urban streams with recycled water for streamflow augmentation: Hydrologic, water quality, and ecosystem services management. *Environ. Eng. Sci.* **2013**, *30*, 455–479. [CrossRef]
21. Lawrence, J.E.; Pavia, C.P.W.; Kaing, S.; Bischel, H.N.; Luthy, R.G.; Resh, V.H. Recycled water for augmenting urban streams in Mediterranean-climate regions: A potential approach for riparian ecosystem enhancement. *Hydrol. Sci. J.* **2014**, *59*, 488–501. [CrossRef]
22. Luthy, R.G.; Sedlak, D.L.; Plumlee, M.H.; Austin, D.; Resh, V.H. Wastewater-effluent-dominated streams as ecosystem-management tools in a drier climate. *Front. Ecol. Environ.* **2015**, *13*, 477–485. [CrossRef]
23. Passarella, G.; Masciale, R.; Sollitto, D.; Caputo, M.C.; Barca, E. Assessment of Groundwater Balance Terms Based on the Cross-Calibration of Two Different Independent Approaches. In *Emerging Issues in Groundwater Resources. Advances in Water Security*; Fares, A., Ed.; Springer: Cham, Switzerland, 2016; pp. 159–186.
24. Passarella, G.; Barca, E.; Sollitto, D.; Masciale, R.; Bruno, D.E. Cross-Calibration of Two Independent Groundwater Balance Models and Evaluation of Unknown Terms: The Case of the Shallow Aquifer of "Tavoliere di Puglia" (South Italy). *Water Resour. Manag.* **2017**, *31*, 327–340. [CrossRef]
25. Karakurt, S.; Schmid, L.; Hübner, U.; Drewes, J.E. Dynamics of wastewater effluent contributions in streams and impacts on drinking water supply via riverbank filtration in Germany—A national reconnaissance. *Environ. Sci. Technol.* **2019**, *53*, 6154–6161. [CrossRef]
26. Valett, H.M.; Reinhold, A.M. Groundwater and Surface Water Interaction. In *Encyclopedia of Inland Waters*; Mehner, T., Tockner, K., Eds.; Elsevier: Oxford, UK, 2022; Volume 3, pp. 348–362.
27. Woessner, W.W. Stream and fluvial plain ground water interactions: Rescaling hydrogeologic thought. *Ground Water* **2000**, *38*, 423–429. [CrossRef]
28. Sophocleous, M. Interactions between groundwater and surface water: The state of the science. *Hydrogeol. J.* **2002**, *10*, 52–67. [CrossRef]
29. Mojarrad, B.B.; Betterle, A.; Singh, T.; Olid, C.; Wörman, A. The Effect of Stream Discharge on Hyporheic Exchange. *Water* **2019**, *11*, 1436. [CrossRef]
30. Kalbus, E.; Schmidt, C.; Molson, J.W.; Reinstorf, F.; Schirmer, M. Influence of aquifer and streambed heterogeneity on the distribution of groundwater discharge. *Hydrol. Earth Syst. Sci.* **2009**, *13*, 69–77. [CrossRef]
31. Beetle-Moorcroft, F.; Shanafield, M.; Singha, K. Exploring conceptual models of infiltration and groundwater recharge on an intermittent river: The role of geologic controls. *J. Hydrol. Reg. Stud.* **2021**, *35*, 100814. [CrossRef]
32. Bourke, S.A.; Degens, B.; Searle, J.; de Castro Tayer, T.; Rothery, J. Geological permeability controls streamflow generation in a remote, ungauged, semi-arid drainage system. *J. Hydrol. Reg. Stud.* **2021**, *38*, 100956. [CrossRef]
33. Xi, H.; Zhang, L.; Feng, Q.; Si, J.; Chang, Z.; Yu, T.; Li, J. The spatial heterogeneity of riverbed saturated permeability coefficient in the lower reaches of the Heihe River Basin, Northwest China. *Hydrol. Process.* **2015**, *29*, 4891–4907. [CrossRef]
34. Chen, X.; Dong, W.; Ou, G.; Wang, Z.; Liu, C. Gaining and losing stream reaches have opposite hydraulic conductivity distribution patterns. *Hydrol. Earth Syst. Sci.* **2013**, *17*, 2569–2579. [CrossRef]
35. McCallum, A.M.; Andersen, M.S.; Rau, G.C.; Larsen, J.R.; Acworth, R.I. River-aquifer interactions in a semiarid environment investigated using point and reach measurements. *Water Resour. Res.* **2014**, *50*, 2815–2829. [CrossRef]
36. Quichimbo, E.A.; Singer, M.B.; Cuthbert, M.O. Characterising groundwater–surface water interactions in idealised ephemeral stream systems. *Hydrol. Process.* **2020**, *34*, 3792–3806. [CrossRef]

37. Shanafield, M.; Bourke, S.A.; Zimmer, M.A.; Costigan, K.H. An overview of the hydrology of non-perennial rivers and streams. *Wiley Interdiscip. Rev. Water* **2021**, *8*, 1504. [CrossRef]
38. Hrachowitz, M.; Savenije, H.; Blöschl, G.; McDonnell, J.; Sivapalan, M.; Pomeroy, J.; Arheimer, B.; Blume, T.; Clark, M.P.; Ehret, U.; et al. A decade of predictions in ungauged basins (PUB) a review. *Hydrol. Sci. J.* **2013**, *58*, 1198–1255. [CrossRef]
39. van Emmerik, T.; Mulder, G.; Eilander, D.; Piet, M.; Savenije, H. Predicting the ungauged basin: Model validation and realism assessment. *Front. Earth Sci.* **2015**, *3*, 62. [CrossRef]
40. de Vries, J.J.; Simmers, I. Groundwater recharge: An overview of processes and challenges. *Hydrogeol. J.* **2002**, *10*, 5–17. [CrossRef]
41. Scanlon, B.R.; Healy, R.W.; Cook, P.G. Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeol. J.* **2002**, *10*, 18–39. [CrossRef]
42. Fleckenstein, J.H.; Krause, S.; Hannah, D.M.; Boano, F. Groundwater-surface water interactions: New methods and models to improve understanding of processes and dynamics. *Adv. Water Resour.* **2010**, *33*, 1291–1295. [CrossRef]
43. Goodrich, D.C.; Williams, D.G.; Unkrich, C.L.; Hogan, J.F.; Scott, R.L.; Hultine, K.R.; Pool, D.; Coes, A.L.; Miller, S.N. Comparison of Methods to Estimate Ephemeral Channel Recharge, Walnut Gulch, San Pedro River Basin, Arizona. In *Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States*; Phillips, F.M., Hogan, J.F., Scanlon, B., Eds.; American Geophysical Union: Washington, DC, USA, 2004; pp. 77–99.
44. Shanafield, M.; Cook, P.G. Transmission losses, infiltration and groundwater recharge through ephemeral and intermittent streambeds: A review of applied methods. *J. Hydrol.* **2014**, *511*, 518–529. [CrossRef]
45. Mujere, N.; Masocha, M.; Makurira, H.; Mazvimavi, D. Dynamics and scales of transmission losses in dryland river systems: A meta-analysis. *Australas. J. Water Resour.* **2021**, *1*, 227–241. [CrossRef]
46. Sivapalan, M.; Takeuchi, K.; Franks, S.W.; Gupta, V.K.; Karambiri, H.; Lakshmi, V.; Liang, X.; McDonnell, J.J.; Mendiondo, E.M.; O'Connell, P.E.; et al. IAHS Decade on Predictions in Ungauged Basins, 2003–2012: Shaping an exciting future for the hydrological sciences. *Hydrol. Sci. J.* **2003**, *48*, 857–880. [CrossRef]
47. Lay-Ekuakille, A.; Okitadiowo, J.D.; Avoci Ugwiri, M.; Maggi, S.; Masciale, R.; Passarella, G. Video-Sensing Characterization for Hydrodynamic Features: Particle Tracking-Based Algorithm Supported by a Machine Learning Approach. *Sensors* **2021**, *21*, 4197. [CrossRef] [PubMed]
48. Standen, K.; Costa, L.R.D.; Monteiro, J.P. In-Channel Managed Aquifer Recharge: A Review of Current Development Worldwide and Future Potential in Europe. *Water* **2020**, *12*, 3099. [CrossRef]
49. Passarella, G.; Bruno, D.E.; Lay-Ekuakille, A.; Maggi, S.; Masciale, R.; Zaccaria, D. Spatial and temporal classification of coastal regions using bioclimatic indices in a Mediterranean environment. *Sci. Total Environ.* **2020**, *700*, 134415. [CrossRef] [PubMed]
50. European Union. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Open J. Leadersh.* **2000**, *327*, 1–73.
51. Passarella, G.; Lay-Ekuakille, A.; Djungha Okitadiowo, J.P.; Masciale, R.; Brigida, S.; Matarrese, R.; Portoghese, I.; Isernia, T.; Blois, L. An Affordable Streamflow Measurement Technique Based on Delay and Sum Beamforming. *Sensors* **2022**, *22*, 2843. [CrossRef]
52. Tozzi, M. Assetto tettonico dell'avampaese apulo meridionale (Murge meridionali—Salento) sulla base di dati strutturali. *Geol. Romana* **1993**, *29*, 95–111.
53. Guerricchio, A.; Zezza, F. Esempio di mapping da foto aeree da immagini da satellite in zone carsiche: La Penisola Salentina. *Geol. Appl. Ed Idrogeol.* **1982**, *XVII*, 502–527.
54. Ciaranfi, N.; Pieri, P.; Ricchetti, G. Note alla carta geologica delle Murge e del Salento (Puglia centromeridionale). *Mem. Della Soc. Geol. Ital.* **1988**, *41*, 449–460.
55. Spizzico, M.; Lopez, N.; Sciannamblo, D. Analysis of the potential contamination risk of groundwater resources circulating in areas with anthropogenic activities. *Nat. Hazards Earth Syst. Sci.* **2005**, *5*, 109–116. [CrossRef]
56. Maggiore, M.; Pagliarulo, P. Circolazione idrica ed equilibri idrogeologici negli acquiferi della Puglia. *Geol. e Territ.* **2004**, *1*, 13–35.
57. Spizzico, M.; Lopez, N.; Sciannamblo, D.; Tinelli, R. La Piana di Brindisi: Fenomeni di interazione tra le falde idriche sotterranee presenti nell'area. *G. Di Geol. Appl.* **2006**, *3*, 17–24.
58. Sciannamblo, D.; Spizzico, M.; Tadolini, T.; Tinelli, R. Lineamenti idrogeologici della zona umida di Torre Guaceto (BR). *Geol. Romana* **1994**, *30*, 754–760.
59. Cotecchia, V. Salt freshwater relationships in the carbonate formation of Apulia. In *Salinity Problems in Coastal Areas*; Project 5.6 Case study 9.2.3; UNESCO-I.H.P.: Paris, France, 1979.
60. Cotecchia, V.; Grassi, D.; Polemio, M. Carbonate aquifers in Apulia and seawater intrusion. *G. Di Geol. Appl.* **2005**, *1*, 219–231.
61. Ricchetti, E.; Polemio, M. L'acquifero superficiale del territorio di Brindisi: Dati idrogeologici diretti e immagini radar da satellite. *Mem. Della Soc. Geol. Ital.* **1996**, *51*, 1059–1074.
62. Tinelli, R.; Daurù, M. Problemi idrogeologici connessi allo sviluppo urbanistico: L'esempio dell'abitato di Mesagne (Brindisi). *Acque Sotter.* **2002**, *75*, 19–23.
63. Andriani, G.; Walsh, N. Fabric, porosity and water permeability of calcarenites from Apulia (SE Italy) used as building and ornamental stone. *Bull. Eng. Geol. Environ.* **2003**, *62*, 77–84. [CrossRef]
64. Turturro, A.C.; Caputo, M.C.; Perkins, K.S.; Nimmo, J.R. Does the Darcy–Buckingham Law Apply to Flow through Unsaturated Porous Rock? *Water* **2020**, *12*, 2668. [CrossRef]

65. Fuchs, E.H.; King, J.P.; Carroll, K.C. Quantifying disconnection of groundwater from managed-ephemeral surface water during drought and conjunctive agricultural use. *Water Resour. Res.* **2019**, *55*, 5871–5890. [CrossRef]
66. Schwartz, U. Factors affecting channel infiltration of floodwaters in Nahal Zin basin, Negev desert, Israel. *Hydrol. Process.* **2016**, *30*, 3704–3716. [CrossRef]
67. Abdulrazzak, M.J. Losses of flood water from alluvial channels. *Arid Soil Res. Rehabil.* **1995**, *9*, 15–24. [CrossRef]
68. Chin, D.A. *Water Resources Engineering*; Prentice Hall: Hoboken, NJ, USA, 2000.
69. Portoghese, I.; Totaro, V.; Panciera, C.; Iacobellis, V. Calibration of a Large-Scale Water Balance Model in a Semi-Arid Ungauged Catchment of Southern Italy. In Proceedings of the 39th IAHR World Congress, Granada, Spain, 19–24 June 2022.