Article

A Steady-State Model to Simulate Groundwater Flow in Unconfined Aquifer

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Featured Application: The topic developed in this paper can be useful for the optimization and the management of groundwater, particularly for aquifers drained by powerful springs tapped by aqueduct companies for water supply. Caposele spring catchment can be considered a sample aquifer from scientific point of view, given its hydraulic and hydrogeological features, widely studied and investigated over the time, representing an important source of water for many village of southern Italy. Different scenarios proposed for aquifer modelling offer to stakeholders a tool to pinpoint accurate strategies to safeguard water resources from contamination and climatic change which threaten it.

Abstract: The hydraulic and hydrogeological features of the Caposele aquifer have been investigated by using a numerical groundwater flow model. In particular, groundwater flow simulations were performed for a multilayered, unconfined aquifer in steady-state conditions for different thicknesses of the aquifer's saturated zone. The Caposele groundwater model was carried out starting from a generic model drained by a unique spring outlet in accordance with the geo-hydrological features of the study area. The conceptual model was built considering hydrogeological features of spring catchment, and was then implemented with the MODFLOW numerical code. A combined 2D-3D approach was adopted, and the model was calibrated on borehole data available for the time period 2012–2019. Different thicknesses of the aquifer were set, and a reliable relationship was found between the hydraulic head, saturated zone and hydraulic conductivity of the aquifer. Using the MODPATH package, the mean travel time (Darcian) of groundwater was computed for five different scenarios, corresponding to the model's depths; the analysis that was performed shows that the travel time is higher for a greater and lower for a smaller thickness of the aquifer's saturated zone, respectively. The Caposele aquifer model was zoned in different sectors, named flow pipe areas, that play different roles in groundwater recharge-discharge processes. A vector analysis was also carried out in order to highlight the ascendant flow near the spring zone.

Keywords: groundwater modelling; unconfined aquifer; steady state condition; hydraulic head; laminar flow; flow net; Darcian travel time; Caposele spring; Southern Italy

1. Introduction

The assessment of groundwater circulation in natural media, which are complex and irregular systems, needs specific hydraulic, hydrogeological and geometric assumptions and simplifications; this assessment can be carried out by resorting to aquifer modelling techniques, based on the use of different geo-informatics tools that allow for the proposition of possible scenarios of groundwater flow.

The investigation of karst aquifers is not easy to carry out due to the complexity and heterogeneity of such natural systems, where groundwater circulation occurs through a well-structured net of cave and conduits [1]. The groundwater modelling in karst aquifers in southern Italy relies on some assumptions which represent the benchmark for the design of the conceptual model. In particular, the methodology followed using the MODFLOW numerical code implementation relies on the Darcy law and laminar conditions of the flow expressed by the Reynolds number, only applicable to the matrix domain of the aquifer. As the karst system is characterized by extreme types of porosity, connected to the presence of voids of different sizes, from the matrix to the conduit/cave systems [2], the Darcy law can be applied to the flow system into the matrix portion, whereas it becomes hardly achievable in aquifers that are strongly fractured and affected by a highly developed net of conduits/shafts, which need different approaches. Among different numerical codes, the tool which better simulates the groundwater flow for the saturated zone, at a regional and subregional scale [3], is the MODFLOW numerical code [4–6], which allows one to assess the flow path, calibrating the simulated hydraulic parameters on the observed data.

Several authors focused on groundwater flow modelling to simulate the aquifer behavior and provide forecast scenarios, through different mathematical and statistical approaches [7–9]. However, groundwater models are affected by an uncertainty degree, because they represent a simplification of natural and complex hydrogeological systems. Teutsch [10] proposed a model to simulate the flow within an aquifer that was moderately karstified, for a catchment area of the Swabian Alb, considering a porous-equivalent medium (EPM model).

For Barton springs (Texas), which belong to a high karstified aquifer, a regional groundwater model has been proposed by Scanlon et al. [11]. Huntton [12] highlights that the EPM hydraulic approach is suitable if we analyze the regional groundwater flow but that it is not taken into account to examine the hydraulic and hydrogeological aspects at the local scale and near the spring zone. Halihan and Wicks [13] focused on the effect of the karst/shaft conduit net on the karst aquifer response, proposing a discrete fracture model (DF), assuming that the flow occurs mainly in the conduit net and that no water exchange between the shaft net and aquifer matrix occurs.

Panagopoulos [14] simulated the groundwater flow in the Trifilia karst aquifer, Greece, providing different scenarios and using MODFLOW both in the steady state and for transient conditions. Hill [8] proposed a simplified approach for groundwater modelling because all models in natural systems are simplifications; then, the number of parameters considered to build the model is the primary measure of its simplicity or complexity.

Several groundwater models refer to regional groundwater flow [15], which better depicts the groundwater flow from the recharge area to the discharge zone, describing further the flow pattern in a hierarchically nested composite basin. The groundwater flow theory was widely proposed by Toth [15] and other hydrogeologists and karst hydrogeologists; the theory was physically and mathematically demonstrated. Successively, the theory was applied considering specific tools which allow for the automation of the groundwater flow conceptual model. Just as for other tools [16], the MODFLOW numerical code that was used to characterize groundwater flow also allowed for the further enrichment of knowledge on groundwater behavior through the design of a specific model in which the calibration phase assumes a crucial role because it is preparatory for the following steps of aquifer modelling.

Karst aquifers are mainly characterized by a dual system due to the presence of different flowpaths, including (i) a quick flow in karst conduits and channels, and (ii) a slow flow in the matrix and micro fracture network [17]; then, the use of the CFP (Conduit Flow Process) package is strongly recommended for highly karstified aquifers.

However, some karst systems behave as porous-media that is hydraulically homogeneous, which allows one to apply the physical and hydraulic basics of the Darcy law, considering laminar flow conditions. In particular, the Caposele aquifer highlights a behavior that is more similar to the porous-equivalent medium [18] than to the karst medium, allowing for the simulation of the aquifer, assuming specific conditions for the hydraulic model. In this study, a hydraulic model was built

using the MODFLOW numerical code for a generic aquifer that was completely drained by a unique spring outlet, after which the simulation was also extended to the Caposele aquifer (southern Italy), where different flow simulation tools were used, taking into account the hydraulic and hydrogeological features of the spring catchment.

The model that was designed allowed for the estimation of the Darcian travel time of groundwater into the saturated zone and the geometry of the groundwater flow path, using the MODPATH package, providing different scenarios of the groundwater level. In particular, the role of the thickness of the aquifer's saturated zone on the flow net distribution was discussed; a general ascendant flow feeding the spring was also inferred in analyzing a cross-section near the discharge area.

2. Materials and Methods

The groundwater flow was simulated for an unconfined aquifer in a steady-state condition, focusing on the saturated aquifer zone according to the Darcy law [19], through which the filtration velocity, v , can be expressed by Equation (1):

$$v = -K \times \frac{\partial h}{\partial s} = -K \times i \quad (1)$$

where K is the hydraulic conductivity of the medium, and i is the hydraulic gradient, expressed as the ratio between the hydraulic head difference, ∂h , and the spatial coordinate of the filtration direction, ∂s . As the Darcian velocity is generally not available but can be estimated, the aim of mathematical-physical models is properly to assess the hydraulic head for different scenarios and stress conditions. Considering an incompressible fluid, combining the mass conservation law with the Darcy equation, a partial derivative equation was obtained, describing the flow yield of groundwater in a steady state condition [20,21]:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) = W \quad (2)$$

By using Equation (2), the water extracted for the volume unit from the porous medium (W) based on the coordinate of the filtration direction, ∂x , ∂y , ∂z , can be estimated, considering the principal component of the hydraulic conductivity tensors K_{xx} , K_{yy} and K_{zz} , aligned with the x-, y-, and z-axes [22].

The hydraulic approach developed in order to analyze and model groundwater was described for a generic aquifer totally drained by a unique spring outlet, and was then applied to the Caposele spring catchment. The general model can be considered a benchmark that is then applicable to aquifers with the same hydraulic and hydrogeological properties as for the study area.

The MODFLOW numerical code was used, simulating groundwater flow in the saturated zone of the aquifer, based on the conceptual model designed for the study area [4]; then, the code was implemented through the graphic user interface PROCESSING MODFLOW 5.3, which simplified the calculation code. The MODPATH package [23] allows one to calculate the particle paths and travel times of the particle trajectory in order to define the flow net, using a semi-analytical algorithm to draw the water particle.

Figure 1 highlights a plan view (horizontal) of the groundwater model of a generic aquifer (obtained by 3D flow simulation) drained by a unique spring outlet and characterized by a regular shape. The groundwater modelling was carried out simplifying the groundwater framework [24], where physical and hydraulic parameters were mathematically integrated on the vertical plane, as equipotential lines, [25–29]. Figure 1 shows the flow net obtained for an unconfined aquifer, square shape with a 7500 m length of side, grid characterized by 22,500 cells, and with a dimension of 50×50 m; vertically, the model discretization was carried out for a maximum model depth of 2000 m considering two equally sized layers. In accordance with the MODFLOW simulation, a regular flow net was drawn, in which the flow lines converge towards a unique spring outlet.

Figure 1. 2D plan-view (horizontal) groundwater model of a homogenous square-shape aquifer, n.22550 cells, with a single drain (spring outlet). (1) spring; (2) active cell (flow zone); (3) inactive cell (no flow zone); (4) flow net with equipotential and flow lines (blue and red color respectively); (5) section trace.

Assigning specific boundary conditions to the model, the hydraulic head of the spring was considered constant during the flow simulation (*Dirichlet type condition*), and the recharge amount was modulated on the spring discharge (*Neumann type condition*).

In this model, the hydraulic head progressively decreases towards spring; conversely, the slope of the water table progressively increases towards spring. Even if the flow net shape depends on the geometry of the aquifer, the recharge amount and the hydraulic conductivity of the medium rule the maximum hydraulic head in the aquifer, following which the hydraulic head value drops between two consecutive equipotential lines.

Based on the grid shown in Figure 1, the model domain was also analyzed considering cross sections drawn along the entire spring catchment area to highlight the groundwater flow in depth. To analyze the flow in depth, and go over the *Dupuit-Forchheimer conditions* used to build the plan model, a 2D analysis was carried out along a vertical plane. In this case, the boundary conditions fixed to build the general model were taken from the result obtained by the horizontal model.

In particular, the hydraulic head values along the cross-sections of Figure 1 (AS, BS and CS) were imposed into the 2D vertical model to find the geometry of the flow net in depth.

Figure 2 shows the results of the modelling along the vertical cross sections AS, BS and CS, where each different flow pipe is distinguished by different colors, for a total of n.7 flow pipes in this example. The flow net in the vertical plane was obtained using MODPATH package. Of course, the geometry of the flow net and the number of flow pipes depend on the thickness of the aquifer's saturated zone (TSZ), which plays a crucial role in flow paths, as the more thickly saturated zone implies the higher the travel time. The model was also run for different values of the effective porosity n_{eff} considering the range 0.01–0.10 [30]; even if the effective porosity ruled the flow net geometry, in particular the groundwater travel time, no significant differences were found for the considered n_{eff} .

range, representative of these kinds of aquifers; as described in the following sections, the hydraulic conductivity, K , has an important role in controlling the flow net shape.

Figure 2. 2D vertical groundwater model along the cross-section traces AS, BS, and CS of Figure 1. Flow pipes have been drawn with different colors and marked with the relative number. The geometry and size of the cross-section are defined by the depth (h) and length (l) of the grid.

Even if this procedure could be an approximation of a more complex 3D model, it could provide a useful simplification of the flow net geometry both horizontally and vertically, allowing for the further considerations that are described below.

Considering the common flow pipe of different cross-sections (Figure 2), in a plan-view it is possible to extrapolate the origin of flow pipes by interpolation, considering the beginning of the flow line boundaries of each flow pipe. Figure 3 provides a plan-view of the starting path of each flow pipe, which corresponds to zones 1 to 7; this representation has been obtained through a combined use of the GIS-MODFLOW tools, interpolating the flow pipe boundaries on the horizontal plane.

Figure 3. Plan-view of the starting path of the flow pipes (1, 2, 3, 4, 5, 6 and 7 from Figure 2) marked by different colors on the water table, drawn by interpolation from the cross-sections.

In Figure 3, the different zones (from 1 to 7) contribute differently to aquifer discharge: the most distant ones from the spring are also wider, and they are characterized by a deeper flux, whereas the closest to the hydraulic outlet are smaller and are affected by a shallower flux.

The simple zonation of the aquifer shown in Figure 3, considering an isotropic and homogenous aquifer, allowing one to investigate the contribution of different hydraulic sectors to the spring, in terms of the percentage of total discharge and the time that the flow needs to reach the final outlet. In particular, the catchment area zoning in different flow pipes allows one to estimate the different recharge volumes and different contributions to spring discharge (Equation (3)). The contribution to the discharge Q_i of each flow pipe can be expressed by:

$$Q_i = FPA_i \times R \quad (3)$$

where R is the recharge amount, expressed as a length/time, [L/t], imposed as constant on the entire catchment (*Neumann condition*), and FPA_i is a generic flow pipe area. Applying Equation (4), the total amount of the discharge Q_s is computed:

$$Q_s = \sum_{i=1}^{i=n} FPA_i \times R \quad (4)$$

where n is the number of flow pipes. To estimate the travel time along each flow line, and to evaluate the (Darcian) mean travel time to reach the spring, Equations (5) and (6) were applied, considering steady state conditions and the Darcy regime (laminar flow). The time, t_λ , needed between two equipotential lines with length L_λ is:

$$t_\lambda = \frac{L_\lambda}{K \times i_\lambda} \quad (5)$$

and the total time, t_i , estimated along the entire flow line, i , is:

$$t_i = \sum_{\lambda=1}^{\lambda=m} t_{\lambda} \quad (6)$$

where m is the number of equipotential lines along the flow line i . The total time t_i of the flow line i can be assumed constant for a generic flow pipe i , and each flow pipe area of Figure 3 would be characterized by a specific travel time to reach the spring. This simplification allows one to provide the following considerations about the (Darcian) mean travel time of the spring water, t_S , which can be estimated by:

$$t_S = \frac{\sum_{i=1}^{i=n} (Q_i \times t_i)}{Q_S} \quad (7)$$

The actual travel time, t'_S , can be found knowing the effective porosity of the medium, n_{eff} :

$$t'_S = t_S \times n_{eff} \quad (8)$$

The aquifer zoning in flow pipe areas also allows one to estimate the age of the groundwater (Equations (7) and (8)), following which we can assess the older and younger zones of groundwater circulation in the saturated zone of the spring catchment area. The flow pipes assessment leads to zoning the aquifer in different hydraulic sectors, which behave differently in recharge-discharge processes; this approach also allows one to estimate the contribution to spring discharge of each sector, getting a preliminary estimation of groundwater velocity in shallow and deep zones of the aquifer. Particularly, a travel time assessment in aquifers, with the estimation of the groundwater age, is a crucial hydraulic aspect for the modeler; the knowledge of the groundwater age, with its relative hydraulic and physical parameters, allows one to understand several hydrogeological and hydrogeochemical phenomena connected to intrinsic groundwater vulnerability [31] and the specific vulnerability of water bodies to contamination [32,33].

2.1. Geological and Hydrogeological Features

The Caposele spring is fed by the northern sector of the Picentini Mountains (Figure 4), where the Cervialto massif is the highest mountain (1809 m a.s.l.). This area is characterized by high slope angles, connected to Quaternary tectonic uplift, which has caused several fault-scarps in the carbonaceous rocks, actually showing a slope angle around 35°–45°. Locally, a series of limestone and limestone-dolomite (Late Triassic-Miocene) outcrops, characterized by a thickness ranging between 2500 m and 3000 m, are generally extremely faulted and crushed. Along the northern and eastern sectors, these massifs overlap tectonically on the terrigenous and impermeable deposits (Figure 4), constituting argillaceous complexes (Paleocene) and flysch sequences (Miocene).

Figure 4. (a) Italy and study area; (b) relief map with hydrogeological features of the Caposele spring catchment. (1) Slope breccias and debris, pyroclastic, alluvial and lacustrine deposits (Quaternary); (2) argillaceous complex and flysch sequences (Paleogene–Miocene); (3) calcareous-dolomite series (Jurassic–Miocene); (4) Caposele spring; (5) village; (6) mountain peak; (7) elevation (m. a.s.l.); (8) borehole; (9) endorheic areas; and (10) spring catchment.

A more specific geological insight on the outcropping areas can be found in Vitale and Ciarcia [34] and related literature, and in the Geological Map of Italy, 1:50.000 scale (Foglio 450, Sant’Angelo dei Lombardi; Foglio 468, Eboli) provided by Istituto Superiore per la Protezione e la Ricerca Ambientale, ISPRA [35]. Pyroclastic deposits of the Somma-Vesuvius activity cover the Picentini Mountains, with thicknesses of up to several meters along gentle slopes and only a few decimeters along steep slopes.

The pyroclastic cover is generally composed of several irregular, ashy pumiceous layers, intercalated with weathered ash deposits. All these deposits have high water retention values and play an important role in the infiltration of water into the karst substratum. Wide endorheic areas (Figure 4) characterize these mountains, having also an important role in the recharge processes [36–38]. The origin of these endorheic zones is connected to tectonic activity during upper Pliocene–Pleistocene, which has triggered a general uplift by normal faults and the formation of graben zones. During the following continental environment (Pleistocene–Holocene), karst processes transformed these zones into endorheic ones, allowing the complete absorption of runoff and the formation of seasonal lakes. The largest is the Piano Laceno (20.5 km²), where a small sinking lake exists, which increases during the winter-spring period. As the Caposele spring can be considered the only spring draining the Cervialto Massif (other springs have a considerably lower discharge), this entire endorheic area constitutes part of the recharge area of this spring. Considering the hydrogeological and morphological features, the total estimated recharge area is 110 km² [36], which practically feeds only the Caposele spring.

The Caposele aquifer appears as a slight or moderate karstified system, and the spring discharge is characterized by the smooth shape of the hydrograph, with the absence of a quick flow component [18]. During the hydrological year, two main periods can be distinguished: the

high-flow period during spring-summer time, and the low-flow period during the autumn-winter time; in a typical Mediterranean climate, this characteristic of the flow causes a quasi-opposite response to the rainfall distribution.

Figure 5 shows the Caposele daily spring discharge in the period March 2012–March 2019, with a mean value of 3690 l/s. The minimum occurred in winter 2017, after a long dry period; the maximum occurred in summer 2013, after a very wet hydrological year. Figure 5 also shows the water table level detected in a borehole, P1, located about 400 m from the spring (Figure 4); as the water level into P1 was well-correlated with the spring discharge, it was used for model calibration.

Figure 5. The Caposele spring discharge, Q , and the hydraulic head of the P1 borehole, h , March 2012 – March 2019 period.

The trend inferred by the spring hydrograph analysis highlights the smooth discharge fluctuation, proving the hydraulic behavior of the investigated aquifer; this appears similar to a porous-equivalent medium, thus justifying the use of the EPM approach.

2.2. Conceptual and Numerical Model of Caposele Aquifer

The aim pursued by the modeler in a numerical groundwater simulation is to provide a useful tool supporting the planning and the management of water resources, safeguarding them both quantitatively and qualitatively.

The implementation of a flow mathematical model requires the assessment of a conceptual model for the investigated area. The workflow of Figure 6 summarizes all steps carried out for a groundwater numerical simulation. The conceptual model assessment, in accordance with the geological and hydrogeological features of the Caposele groundwater catchment (Figure 4), plays a fundamental role in the scenarios proposed by the groundwater flow simulation, representing a preparatory phase for the implementation of a numerical model. The shapefile of the Caposele spring catchment was edited using the GIS environment, and was then imported to identify the model domain. The boundaries of the catchment area are coherent with the geological and hydrogeological features of the investigated area, characterized by a karst aquifer with a high transmissivity bounded by a flysch sequence along

the northern side and a less permeable dolomite sequence on the southern side; then, the structured grid was defined.

As the aquifer depth was unknown, the model was run for different thicknesses of the aquifer's saturated zone (TSZ) (100 m, 200 m, 500 m, 1000 m and 2000 m) in order to consider a wide thickness range. The Caposele model domain was defined considering a square with a side of 15 km; then, the grid of the study area was arranged in a plan with a cell sized 100 m $\times$ 100 m, providing a grid with 22500 cells. Along the vertical direction, the model was built considering two layers with equal thicknesses and was run in a steady state condition considering an unconfined aquifer. The boundary conditions were defined according to the physical, hydraulic and hydrogeological features of the modeled area [39].

Among several methodologies to characterize spring cells, the use of a *first type condition of Dirichlet* appears to be the best approach for simulating groundwater flow in a natural system such as the investigated aquifer, which is not influenced by artificial drainage.

The initial and boundary conditions were established considering the discharge value of the spring in order to attribute a recharge amount to the domain (*Neumann type condition*); then, the hydraulic conductivity, K , was assigned and calibrated considering the water table level of the P1 borehole. A constant hydraulic head (417 m a.s.l.) was considered for the cell of the Caposele spring (*Dirichlet type condition*).

The annual mean water amount recharging the aquifer, R , was expressed as the recharge height, estimated by the ratio between the Caposele spring discharged volume and the catchment area, AC , providing $(R)_{AC} = 1.06$ m/y.

Figure 7 highlights the attribution of the recharge to the model domain considering the graphic user interface VISUAL MODFLOW FLEX 2015.1; in the first case (Figure 7a), we fixed a recharge uniformly distributed on the catchment area, while Figure 7b, taking into account topographic features, shows the discretization of the recharge considering both endorheic and open areas.

Figure 6. Workflow showing the steps followed for the groundwater flow simulation.

Figure 7. (a) The recharge amount uniformly assigned to the Caposele catchment area $(R)_{AC}$ and (b) discretized according to the endorheic $(R)_{AE}$ and open areas $(R)_{AO}$ of the model domain. VISUAL MODFLOW FLEX 2015.1 is the graphic user interface used to draw the maps.

We have considered the recharge amount for endorheic areas, $(R)_{AE}$, in which rainfall totally infiltrates (Figure 7b), whereas a minor amount has been considered for open areas of catchment, $(R)_{AO}$, on which the runoff is 34%, as estimated by Fiorillo et al. [36]; of course, the overall mean recharge on the spring catchment remains $(R)_{AC} = 1.06$ m/y, with respect to the same amount discharged by the spring outlet.

As the recharge discretization between the closed and open areas of spring catchment does not lead to significant change during flow simulations, we mainly focused on the recharge uniformly distributed on the model domain in order to provide the simplest model.

Following the *Neumann*-type boundary condition with null flow along the borders of the catchment area, the grid inside the shapefile of the aquifer drained by the Caposele spring is active for groundwater modelling (*flow zone*), whereas outside no flow occurs (*no flow zone*).

As concerns the unsaturated zone, even if the vadose zone and its hydraulic features play a crucial role for the Caposele spring catchment, modulating the discharge response [18,40], the numerical code applied in this work (graphic user interface PROCESSING MODFLOW 5.3) mainly focused on the hydraulic behavior of the saturated zone of the aquifer under steady-state conditions. However, the thickness and hydraulic conditions of the unsaturated zone, and the connected percolation processes, become especially relevant for the transient flow condition; these aspects need further in-depth analysis, also using further tools such as MODFLOW SURFACT, R-UNSAT, VS2DI or FEFLOW.

2.3. Model Calibration

First of all, the boundary conditions and the recharge amount for a steady state model were fixed. Successively, the calibration of the model was carried out based on hydraulic head data available for the P1 borehole, varying the input parameter of the hydraulic conductivity until similar values were found for the simulated (output parameter) and observed P1 hydraulic heads.

According to some specific procedures, such as the *trial and error method* and *automatic calibration techniques*, the calibration phase represents the process through which the hydraulic parameters provided in the input for the model are modified, so that they are matched with the observed data. This can be considered a benchmark phase for groundwater modelling because it is preparatory for the implementation of the simulations having a predictive purpose [22], also allowing one to provide for the lack of hydraulic and hydrogeological data. As some physical and hydraulic parameters are not available, the simulated hydraulic conductivity was calibrated on the hydraulic head data of the P1 borehole detected during the time period of March 2012–March 2019; this well is located within the catchment area, about 400 m upstream of the spring outlet.

Figure 8 shows different simulations of the model considering different thicknesses of the aquifer's saturated zone (TSZ), taking into account the narrow values of the hydraulic conductivity, K ; in particular, using the constant recharge amount $R = 1.06$ m/y, and considering the mean value of the hydraulic head detected in the borehole P1, $h = 422.16$ m a.s.l., the K value was found to range from a maximum of 0.01145 m/s, (TSZ = 100 m) to a minimum value of 0.000831 m/s ascribable to a TSZ = 2000 m. The calibration phase highlights the relationship occurring between the TSZ of the aquifer and the hydraulic conductivity of the medium for 3D groundwater, using the EPM approach.

In particular, the *trial and error method*, used to match the simulated hydraulic head with the available observed data, highlights that the hydraulic conductivity of the medium drops with the increase of the aquifer TSZ, in accordance with the hydraulic assumptions followed to build the conceptual and numerical model (*Dirichlet* and *Neumann conditions*). The hydraulic conductivity range found for different scenarios is in agreement with the K values estimated for other karst systems in southern Italy [41,42].

Figure 8. The simulated hydraulic head in the P1 borehole, using different values of the hydraulic conductivity, which was found based on the mean hydraulic head observed in the P1 borehole (422.16 m) and different values of TSZ: (a) 100 m, (b) 200 m, (c) 500 m, (d) 1000 m and (e) 2000 m.

3. Results

The preliminary phase for the groundwater simulation carried out for the investigated aquifer allowed us to get a possible scenario of the mean hydraulic head. It was deduced by model calibration, assuming the abovementioned conceptual model boundary conditions.

Figure 9 highlights the maximum and minimum groundwater levels for TSZ values of 100 m and 2000 m, respectively, considering the mean hydraulic conductivity $K_{\text{mean}} = 0.0048$ m/s obtained for all calibrations, Figure 10 shows the Caposele aquifer fluctuation for different depths, considering a mean recharge amount ($R = 1.06$ m/y); then, the simulation was also carried out considering high recharge ($2 \times R$) and low recharge periods ($0.5 \times R$).

Figure 9. Plan-view of the Caposele unconfined aquifer under steady-state conditions during the mean recharge period ($R = 1.06$ m/y), cell size 100×100 m, $K_{\text{mean}} = 4.8 \times 10^{-3}$ m/s and thickness of the saturated zone of the aquifer (TSZ): (a) 100 m, equipotential lines spaced at 0.5 m; and (b) 2000 m, equipotential lines spaced at 0.1 m. (1) spring; (2) active cell; (3) inactive cell and (4) flow net.

Figure 10. Relationship between the simulated maximum hydraulic head in the aquifer and the thickness of the saturated zone (TSZ), for different recharge amounts uniformly distributed on the catchment area: mean recharge (R), double recharge (2R) and halved recharge conditions (0.5R); dots represent the simulation steps carried out.

The simulation points out that the hydraulic head of the recharge area drops when TSZ increases, fixing the K_{mean} value as being constant for all the proposed scenarios (Figure 10). This preliminary result allows one to obtain a relationship between the groundwater level fluctuation and aquifer depth, providing details on the water table slope. According to the proposed scenarios, thicker aquifers are characterized by a flat water table, while conversely, a high slope of the water table can be considered an indicator of a saturated zone with less thickness; this also allows one to claim that aquifers characterized by a flat water table are affected by deep groundwater circulation, whereas a higher water table slope is a marker of shallow flow paths.

The flow simulation provided hydraulic head arrays as the output parameters for the model, leading us to hypothesize a possible scenario of the Caposele unconfined aquifer's hydraulic behavior under a steady state condition. Based on the conceptual model assumptions, the hydraulic head, h , estimated by simulation, ranges between the lowest value at the spring ($h_{\text{min}} = 417 \text{ m a.s.l.}$) and the mean of the maximum values reached in all simulations, $h_{\text{max}} \approx 427.5 \text{ m a.s.l.}$ in the recharge area, estimated for the mean recharge condition. Considering the hydraulic head difference between the recharge area and the Caposele spring, $\Delta h \approx 10.5 \text{ m}$, the water table slope has a mean value of about 0.001, which is in agreement with the slope found for other karst aquifers of central-southern Italy [30,43]. However, due to its non-linearity, the slope of the water table progressively increases toward the spring [43,44]; in particular, it has a mean value of 0.008 between the P1 borehole and the spring, and it is almost flat when far from the spring.

The hydraulic head difference that was found, $\Delta h \approx 10.5 \text{ m}$, between the maximum recharge area and the Caposele spring, was proven considering the n.5 groundwater level scenarios proposed for different aquifer TSZs. However, the hydraulic head difference that was estimated is a mean value because it can fluctuate during the hydrological year, reaching values that are higher and lower than the mean value.

3.1. Assessment of Travel Time on Caposele Aquifer

The MODFLOW numerical code used to simulate the groundwater flow for the Caposele aquifer is able to compute the travel time of water along the groundwater flow net.

Particularly, the MODPATH package is able to calculate the groundwater paths together with the velocity vectors estimated cell-by-cell; the effective porosity value, n_{eff} , included in the range 0.01–0.10, was considered for the simulations [30]; then, in order to obtain the travel time for each flow pipe, the MODPATH groundwater flow net was investigated according to the hydraulic approach described by Equations (3)–(7). Table 1 shows the main results obtained by the Caposele aquifer modelling, considering different TSZs, up to a maximum thickness of 2000 m. As the actual effective porosity parameter is not available and no environmental tracers were used to evaluate the actual travel time (Equation (8)), the hydraulic approach adopted using the MODFLOW numerical code was able to find the Darcian (mean) travel time range for different scenarios.

Table 1. The main results obtained from the Caposele aquifer modelling. TSZ, thickness of the aquifer's saturated zone; K , hydraulic conductivity; β , water table slope; v_D , Darcian velocity; t_s , Darcian travel time to reach the spring outlet.

TSZ (m)	K (m/s)	β	v_D (m/s)	t_s (y)
100	1.1×10^{-2}	1.3×10^{-2}	1.5×10^{-4}	45.8
200	5.0×10^{-3}	9.3×10^{-3}	4.7×10^{-5}	71.0
500	4.7×10^{-3}	1.5×10^{-2}	7.2×10^{-5}	121.6
1000	1.8×10^{-3}	1.1×10^{-2}	2.1×10^{-5}	379.1
2000	8.3×10^{-4}	9.4×10^{-3}	7.9×10^{-6}	551.8

The hydraulic conductivity of the medium was estimated by calibrating the model (Figure 8), after which the Darcian velocity (Equation (1)) and Darcian travel time (Equations (5)–(7)) were also computed. Through a flow simulation, the estimated travel time, applying Equations (5)–(7), ranged from a minimum value of 45.8 years (TSZ = 100 m) to a maximum of 551.8 years (TSZ = 2000 m). Considering all scenarios, the hydraulic analysis highlights that the water particle flows faster considering the flow pipes near the spring zone, while, conversely, water needs more time to reach the spring outlet along the flow pipes that are more distant from the discharge area.

The hydraulic approach followed to estimate the travel time along the flow net of the Caposele aquifer using the MODFLOW numerical code also allows one to underline that the knowledge and the setting of the aquifer TSZ in groundwater modelling is crucial for the assessment of the hydraulic parameters of the aquifer.

The Darcian travel time trend, observed for the proposed scenarios, clearly points out fast groundwater paths for aquifers with less thickly saturated zones, and flow paths that are slower belonging to aquifers affected by thicker saturated zones.

In Figure 11, the hydraulic conductivity and Darcian travel time were matched with different TSZs of the model. In particular, the hydraulic conductivity of the medium dropped when the model thickness increased, ranging from a maximum $K = 0.0115$ m/s found for models with less thickly saturated zones to a minimum $K = 0.000831$ m/s attributable to aquifers with a thickness of 2000 m.

Figure 11. Thickness of the aquifer's saturated zone (TSZ) vs. hydraulic conductivity (K); the Darcian travel time (t_s) has been also plotted.

The inverse relationship found between the K values and model thickness is coherent with 3D groundwater modelling. Considering the Caposele discharge as a fixed, unique and constant spring outlet, a thicker aquifer needs a low hydraulic conductivity and a long travel time to satisfy the same discharge of less thick model.

3.2. Flow Vectors

The flow pipes assessment for the investigated area allowed one to understand the hydraulic behavior of groundwater from the recharge zone toward the spring area. The numerical simulation of the Caposele aquifer also allowed one to estimate the flow vectors; in particular, the groundwater flow net highlighted the different flow directions along the aquifer (Figure 12, Table 2). The analysis focused on the area within 1 km upstream the Caposele spring, where the flow lines converge, following which the flow vectors were geometrically estimated.

Table 2. The main results obtained by flow vectors analysis; α , slope angle of the flow vector; v_x , horizontal velocity; v_y , vertical velocity; Q_{FP} , discharge of the flow pipe; Q_x discharge of the horizontal component of the flow; Q_y discharge of the vertical component of the flow.

Flow pipe	α (°)	v_x (%)	v_y (%)	Q_{FP} (l/s)	Q_x (l/s)	Q_y (l/s)
1	5	3.9	0.3	147	135	12
2	8	5.0	0.7	185	163	22
3	17	5.1	1.5	259	199	60
4	26	5.8	2.8	368	246	122
5	42	5.1	4.6	554	288	266
6	53	6.0	8.0	1142	491	651
7	81	2.1	3.3	1032	144	888

Figure 12 shows the geometric approach followed to estimate the x and y vectors, whose values are duly tabulated. A hydraulic approach was proposed to assess the vertical and horizontal contributions of groundwater flow to spring discharge. Assuming that the medium can be considered homogeneous and hydraulically isotropic, and that the fluid is incompressible, the flow equation can be simplified under the Laplace law [45,46]:

$$\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial z^2}\right) = 0 \quad (9)$$

Figure 12. The flow net sketch of the spring zone with the relative vectors of the groundwater flow; the hydraulic parameters obtained from the analysis are duly shown in Table 2.

Here, h is a scalar function, twice differentiable in space; based on Equation (9) for the graphical solution of the 2D flow net, some hydraulic parameters of the Caposele groundwater flow were estimated. The simulation focused on the flow mesh of groundwater, on which the vectors analysis was performed. Then, the Darcian velocity was computed, considering the hydraulic conductivity obtained by model calibration and the relative hydraulic head (Figure 8). To assess the vertical and horizontal contribution of groundwater flow to spring discharge, a geometrical approach was followed; its graphical results are described in Figure 12.

For each flow mesh at a distance of up to about 1 km from the spring zone, the velocity vectors v_x and v_y and their relative discharges Q_x and Q_y were estimated. The main results obtained from the vector analysis are duly shown in Table 2, pointing out the geometrical and analytical parameters obtained by the flow net analysis carried out along the 2D vertical plane of the Caposele spring zone. In particular, deeper flow meshes of groundwater highlight a predominance of the vertical velocity vectors v_y on v_x , and consequently the vertical component of the discharge Q_y is predominant along deeper flow meshes. The ascendant flow detected near the spring zone is a hydraulic phenomenon common also to other springs of southern Italy [41,47].

3.3. Flow Pipes

The hydraulic approach and methodology argued for a generic model drained by a unique spring (Figures 1–3) was applied to the study area; accordingly, we carried out zoning on different flow pipes for the Caposele spring catchment.

In particular, Figure 13a shows one of the cross-sections (B'S') considered for the flow pipes assessment; the boundary conditions of the 2D vertical model were inferred by a 3D groundwater analysis on plan-view. Figure 13b shows the map of the obtained flow pipes' starting areas when running the model up to a maximum depth of 2000 m.

Considering the different scenarios proposed, the flow pipe areas farthest from the spring zone mainly contribute to spring discharge. Although their geometry varies with the aquifer TSZ, the preliminary results obtained in this paper support, for each scenario considered in the modelling, the major influence of flow pipe areas that are more distant from the spring zone in the discharge processes.

Figure 13. (a) 2D vertical groundwater model along the cross-section trace B'S'; (b) Caposele spring catchment zoning in flow pipe areas (FPA) for a model thickness of 2000 m; each flow area is marked by different colors and the related item.

Given that for the flow pipe areas belonging to the maximum recharge area, water needs more time to reach the spring outlet, its relative travel time is higher than for flow pipe areas near the discharge zone; this means that, independently from the thickness chosen for the model, the groundwater age of the recharge area is higher than for the water flowing near the spring zone. The main hydraulic parameters of groundwater zoning in flow pipe areas for a model with a thickness of up to 2000 m are duly listed in Table 3. In particular, the contribution to the discharge of different hydraulic sectors decreases towards the spring.

Table 3. The main results obtained from aquifer zoning in flow pipe areas for a thickness of the aquifer's saturated zone TSZ = 2000 m. FPA, flow pipe area; R, recharge; Q, discharge outlet.

item	FPA km ²	R (Mm ³ /y)	R (%)	Q l/s
1	4.1	4.3	4	147
2	5.2	5.5	5	185
3	7.9	8.4	7	259
4	11.3	11.8	10	368
5	17.1	18.0	15	554
6	33.9	35.9	31	1142
7	30.5	32.4	28	1032
TOT	110	116.5	100	3687

4. Discussion

Groundwater modelling was carried out for the Caposele karst aquifer, which has a hydraulic behavior similar to a porous-equivalent medium and an EPM approach was used. Nevertheless,

a groundwater numerical simulation was also successfully applied to karstified aquifers [10,48–50], with satisfying results.

The input parameters in the flow simulation, together with an accurate modelling strategy [51], play a crucial role for groundwater analysis, affecting the efficiency and then the interpretation of the model.

Emblanch et al. [52] exploited chemical and isotopic tracers to evaluate the contribution of different water components discharging at the Fontaine de Vaucluse karst spring near Avignon (Southeastern France), considering two different hydrodynamic phenomena of the aquifers: (i) a perfect piston flow (PF), where each recharge event pushes the previous one towards the hydrological outlet; (ii) a well-mixed model (WMM), where the discharged water is a mixture between all aquifer components [52,53]; the aforementioned systems point out two extreme flow modalities; in nature in particular, the majority of aquifers highlight an intermediate behavior between the PF and WMM modalities.

The numerical simulation performed for the Caposele aquifer relies on the boundary conditions of the conceptual model subsequently implemented with the MODFLOW numerical code. The accuracy of the model depends on the number and kind of the assumptions, together with the type of mathematical and physical conditions on which it is based. A numerical flow simulation using the EPM approach is able to simplify the modelling of the heterogeneous structure as an aquifer system [53–56]. The methodology described in this paper, considering all workflow steps shown in Figure 6, led to an understanding of the results obtained by both a travel time analysis and aquifer zoning in flow pipes, also allowing for the detection of a hydraulic phenomenon of ascendant flow near the discharge zone.

The groundwater flow simulation was carried out considering a combined 2D-3D approach because the model was run both along a cross-section (2D view) and a horizontal view (3D), considering a TSZ that was variable from 100 m up to 2000 m. The preliminary results obtained from the travel time assessment gave an overview of the behavior of the fluid flow in the karst aquifer, in this case comparable to a porous medium.

The flow net drawn for the generic model, then extendable to the Caposele aquifer, points out three different groundwater paths: a descendant groundwater behavior in the farthest zone from the spring (main recharge area), a sub-horizontal path in the central zone, and a prevalent ascendant flow near the spring zone, in accordance with the previous results deduced from the analysis of other karst aquifers in southern Italy [47].

As the actual TSZ is unknown and specific hydrogeological data are not available, the approach followed in the modelling regarded the design of several scenarios that varied the aquifer depth, in order to find a reliable range representative of the TSZ of the Caposele spring catchment. The trend of hydraulic heads observed for different simulations (Figure 10) allowed us to make preliminary remarks between the TSZ and water table slope. For a very thick aquifer affected by deep groundwater circulation, the water table is almost flat and the water table slope between the recharge area and spring zone is low; conversely, a high water table slope may be an indicator of a TSZ that is not very thick.

Due to the lack of actual effective porosity, only the Darcian travel time was computed. The assessment of travel time in groundwater represents an arduous challenge for modelers and for hydrogeologists; its estimation depends on the conceptual model developed and on the boundary condition set.

In particular, Jing et al. [57] underline the influence of input parameters in groundwater models on the travel time distribution assessment for a catchment area; indeed, several methods, pinpointed and proposed by the literature to assess travel time, are affected by uncertainty, depending also on the internal hydraulic properties of the catchment areas that are modeled.

The flow vectors analysis highlighted that the vertical discharge component, Q_y , increased towards deeper flow meshes (Figure 12) and supported the presence of an ascendant flow near the spring zone, as observed for other springs in the southern Apennines [41,47]. It can be inferred that carbonate aquifers of southern Italy affected by a huge water storage capacity and a very low water table slope

are characterized by a deep groundwater circulation, triggering an ascendant flow located near the basal spring zone. In particular, karst aquifers affected by karst phenomena develop a conduit/shaft net leading to a flow hierarchization [58] that rules the groundwater path; the ascendant flux can lead to the formation of subvertical conduits and many karst springs are fed by a typical subvertical conduit, such as the Vauclusian types [47].

5. Conclusions

The zoning of the Caposele spring catchment in different flow pipe areas, together with the assessment of the Darcian travel time of groundwater, allow one to better understand the hydraulic behavior of the aquifer and to underline the different responses of the groundwater in terms of the flow net shape, in horizontal and vertical plains.

By using the EPM approach, the groundwater flow simulation was carried out considering a combined 2D-3D approach because the model was run both along a cross-section (2D view) and a horizontal view (3D), considering two equally sized layers and setting the TSZ of the aquifer as being variable, from 100 m up to 2000 m.

The implementation of the conceptual model features through the numerical analysis represents a simplification of the more complex phenomenon that groundwater flow constitutes. Nevertheless, it is useful to understand the hydraulic response of the aquifer; this could be useful in practice, since it may allow one to optimize groundwater management in areas of interest. Besides, it can be a tool that is extendable to other sample aquifers, particularly to unconfined groundwater that is totally drained by a unique spring outlet, with the aim to support other problems related to groundwater risk assessment. Groundwater modelling, with its forecasting scenarios, can be a precious tool, supporting water management such as aqueduct companies, helping relative stakeholders in decision-making and problem-solving relative to water resources optimization. However, due to the lack of measurements of some hydraulic parameters such as the actual effective porosity, it is not easy to estimate the actual travel time of groundwater flow; this aspect needs further in-depth analysis; in particular, a combined geochemical-hydrogeological approach, based on the use of isotope and environmental tracers could be useful to validate the hydraulic model designed in this research, allowing for the improvement and further detailing of the range proposed for the travel time. The elaborations performed are the result of some assumptions and simplifications necessary in designing the model.

In the future, the measurement of parameters by means of in situ surveys would be desirable, in particular the assessment of the actual travel time of groundwater flow in saturated zones through a hydro-geochemical approach which could further support and enhance the model.

In particular, the use of some specific natural tracers (^3H , ^{13}C , ^{14}C , ^{222}Rn), could be suitable for groundwater age estimation and would be desirable in the case of such a significant aquifer, which is exploited for drinking purposes.

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References

1. Gallegos, J.J. Modeling Groundwater Flow in Karst Aquifers: An Evaluation of MODFLOW CFP at the Laboratory and Sub-Regional Scales. Master's Thesis, Florida State University, Tallahassee, FL, USA, 2011.

2. White, W.B. *Geomorphology and Hydrology of Karst Terrains*; Oxford University Press: Oxford, NY, USA, 1988; p. 464.
3. Tóth, J. A Hydrogeological Study of the Three Hills Area, Alberta. In *Also: Alberta Geological Survey Bulletin Series*; Research Council of Alberta: Edmonton, AB, Canada, 1968; p. 24.
4. McDonald, M.G.; Harbaugh, A.W. A modular three-dimensional finite difference groundwater flow model. In *U.S.G.S Techniques of Water Resources Investigations*; series number 06-A1; U.S.G.P.O: Denver, CO, USA, 1988; p. 586.
5. Chiang, W.H.; Kinzelbach, W. Processing Modflow. In *A Simulation System for Modelling Groundwater Flow and Pollution*; Springer: Hamburg, Germany, 1998; p. 342.
6. Chiang, W.H. *3D-Groundwater Modeling with PMWIN: A Simulation System for Modeling Groundwater Flow and Transport Processes*, 2nd ed.; Springer: Berlin, Germany, 2005; p. 397.
7. D'Agnese, F.A.; Faunt, C.C.; Turner, A.K.; Hill, M.C. Hydrogeologic evaluation and numerical simulation of the Death Valley regional ground-water system, Nevada and California, using geoscientific information systems. In *U.S.G.S. Water-Resources Investigations Report*; Branch of Information Services [distributor]; U.S. Geological Survey: Denver, CO, USA, 1997; Volume 96, p. 124.
8. Hill, M.C. The Practical Use of Simplicity in Developing Ground Water Models. *Groundwater* **2006**, *44*, 775–781. [[CrossRef](#)] [[PubMed](#)]
9. D'Agnese, F.A.; Faunt, C.C.; Hill, M.C.; Turner, A.K. Death Valley regional ground-water flow model calibration using optimal parameter estimation methods and geoscientific information systems. *Adv. Water Resour.* **1999**, *22*, 777–790. [[CrossRef](#)]
10. Teutsch, G. An extended double-porosity concept as a practical modeling approach for a karstified terrain. Hydrogeological Processes in Karst Terranes. In *Antalya Symposium and Field Seminar*; IAHS: Wallingford, UK, 1990; pp. 281–292.
11. Scanlon, B.; Mace, R.; Barrett, M.; Smith, B. Can we simulate regional groundwater flow in a karst system using equivalent porous media models? Case study, Barton Springs Edwards aquifer, USA. *J. Hydrol.* **2003**, *276*, 137–158. [[CrossRef](#)]
12. Huntoon, P.W. Is it appropriate to apply porous media groundwater circulation models to karstic aquifers. In *Groundwater Models for Resources Analysis and Management*; El-Kadi, A.I., Ed.; Lewis Publishers: Boca Raton, FL, USA, 1995; pp. 339–357.
13. Halihan, T.; Wicks, C.M. Modeling of storm responses in conduit flow aquifers with reservoirs *J. Hydrol.* **1998**, *208*, 82–91. [[CrossRef](#)]
14. Panagopoulos, G. Application of MODFLOW for simulating groundwater flow in the Trifilia karst aquifer, Greece. *Environ. Earth Sci.* **2012**, *67*, 1877–1889. [[CrossRef](#)]
15. Tóth, J. A theoretical analysis of groundwater flow in small drainage basins. *J. Geophys. Res.* **1963**, *68*, 4795–4812. [[CrossRef](#)]
16. Shoemaker, W.B.; Kuniansky, E.L.; Birk, S.; Bauer, S.; Swain, E.D. *Documentation of a Conduit Flow Process (CFP) for MODFLOW-2005*; U.S. Geological Survey Techniques and Methods: Reston, VA, USA, 2008; Chapter A24; p. 50.
17. Bonacci, O. Karst spring hydrographs as indicators of karst aquifers. *Hydrolog. Sci. J.* **1993**, *38*, 51–62. [[CrossRef](#)]
18. Fiorillo, F. Spring hydrographs as indicators of droughts in a karst environment. *J. Hydrol.* **2009**, *373*, 290–301. [[CrossRef](#)]
19. Darcy, H. *Les Fontaines Publiques de la Ville de Dijon, Exposition et Application des Principes a suivre et des formules a employer dans les questions de distribution d'eau*; Victor Dalmont Editeur: Paris, France, 1856; p. 643.
20. Whitaker, S. Flow in Porous Media I: A Theoretical Derivation of Darcy's Law. *Transp. Porous Media* **1986**, *1*, 3–25. [[CrossRef](#)]
21. Nield, D.A.; Bejan, A. *Mechanics of Fluid Flow through a Porous Medium*. In *Convection in Porous Media*; Springer: New York, NY, USA, 2013; pp. 1–29.
22. Anderson, M.P.; Woessner, W.W. *Applied Groundwater Modeling*; Academic Press: San Diego, CA, USA, 1992; p. 381.
23. Pollock, D.W. *User Guide for MODPATH Version 7. A Particle-Tracking Model for MODFLOW*; Open File Report 1086; U.S. Geological Survey: Reston, VA, USA, 2016; p. 35.

24. Bear, J. *Hydraulics of Groundwater*, McGraw-Hill Series in Water Resources and Environmental Engineering; McGraw-Hill: New York, NY, USA, 1979; p. 569.
25. Dupuit, J. *Etudes Théoriques et Pratiques sur le Mouvement des Eaux dans les Canaux Découverts et à Travers les Terrains Permèables*, 2nd ed.; Dunod Éditeur: Paris, France, 1863; Volume 49, p. 336.
26. Forchheimer, P. *Über die Ergiebigkeit von Brunnen-Anlagen und Sickerschiltzen*; Ing.-Ver.: Hannover, Germany, 1886; Volume 32, pp. 539–563.
27. Strack, O.D.L.; Barnes, R.J.; Verruijt, A. Vertically Integrated Flows, Discharge Potential and Dupuit-Forchheimer Approximation. *Groundwater* **2006**, *44*, 72–75. [[CrossRef](#)]
28. Leray, S.; Gauvain, A.; de Dreuz, J.R. Residence Time Distributions in non-uniform aquifer recharge and thickness conditions. An analytical approach based on the assumption of Dupuit-Forchheimer. *J. Hydrol.* **2019**, *574*, 110–128. [[CrossRef](#)]
29. Zerihun, Y.T. Extension of the Dupuit-Forchheimer model for non-hydrostatic flows in unconfined aquifers. *Fluids* **2018**, *3*, 42. [[CrossRef](#)]
30. Celico, P. *Prospezioni Idrogeologiche*; Liguori Editore: Napoli, Italia, 1988; Volume 2, p. 436.
31. Wachniew, P.; Zurek, A.J.; Stumpp, C.; Gemitzi, A.; Gargini, A.; Filippini, M.; Rozanski, K.; Meeks, J.; Kværner, J.; Witczak, S. Towards operational methods for the assessment of intrinsic groundwater vulnerability: A review. *Crit. Rev. Environ. Sci. Technol.* **2016**, *46*, 827–884. [[CrossRef](#)]
32. Hrachowitz, M.; Benettin, P.; Van Breukelen, B.M.; Fovet, O.; Howden, N.J.K.; Ruiz, L. Transit times: The link between hydrology and water quality at the catchment scale. *Wiley Interdiscip. Rev. Water* **2016**, *3*, 629–657. [[CrossRef](#)]
33. Jasechko, S.; Perrone, D.; Befus, K.M.; Bayani Cardenas, M.; Ferguson, G.; Gleeson, T. Global aquifers dominated by fossil groundwaters but wells vulnerable to modern contamination. *Nat. Geosci.* **2017**, *10*, 425–429. [[CrossRef](#)]
34. Vitale, S.; Ciarcia, S. Tectono-stratigraphic setting of the Campania region (southern Italy). *Journal of Maps* **2018**, *14*, 9–21. [[CrossRef](#)]
35. ISPRA. Geological Map of Italy, 1:50.000 Scale. In *Istituto Superiore per la Protezione e la Ricerca Ambientale*; Ministry of Environment: Rome, Italy, 2009. Available online: http://www.isprambiente.gov.it/Media/carg/450_SANTANGELOLOMBARDI/Foglio.html, http://www.isprambiente.gov.it/Media/carg/468_Eboli/Foglio.html (accessed on 14 April 2020).
36. Fiorillo, F.; Pagnozzi, M.; Ventafridda, G. A model to simulate re charge processes of karst massifs. *Hydrol. Process.* **2015**, *29*, 2301–2314. [[CrossRef](#)]
37. Fiorillo, F.; Pagnozzi, M. Recharge process of Matese karst massif (southern Italy). *Environ. Earth Sci.* **2015**, *74*, 7557–7570. [[CrossRef](#)]
38. Pagnozzi, M.; Fiorillo, F.; Esposito, L.; Leone, G. Hydrogeological features of endorheic areas in southern Italy. *Ital. J. Eng. Geol. Environ.* **2019**, *1*, 85–91.
39. Coelho, C.D.; Faria, A.C.S.; Marques, E.A.G. Comparative analysis of different boundary conditions and their influence on numerical hydrogeological modeling of Palmital watershed, southeast Brazil. *J. Hydrol. Reg. Stud.* **2017**, *12*, 210–219. [[CrossRef](#)]
40. Fiorillo, F.; Doglioni, A. The relation between karst spring discharge and rainfall by the cross-correlation analysis. *Hydrogeol. J.* **2010**, *18*, 1881–1895. [[CrossRef](#)]
41. Fiorillo, F.; Leone, G.; Pagnozzi, M.; Catani, V.; Testa, G.; Esposito, L. The Upwelling Groundwater Flow in Karst area of Grassano-Telesse Springs (Southern Italy). *Water* **2019**, *11*, 872. [[CrossRef](#)]
42. Lancia, M.; Saroli, M.; Petitta, M. A double scale methodology to investigate flow in karst fractured media via numerical analysis: The Cassino plain case study (Central Apennine, Italy). *Hindawi Geofluids* **2018**, *12*, Article ID 2937105. [[CrossRef](#)]
43. Fiorillo, F.; Petitta, M.; Preziosi, E.; Rusi, S.; Esposito, L.; Tallini, M. Long-term trend and fluctuations of karst spring discharge in a Mediterranean area (central-southern Italy). *Environ. Earth Sci.* **2015**, *74*, 153–172. [[CrossRef](#)]
44. D’Agostino, N.; Silverii, F.; Amoroso, O.; Convertito, V.; Fiorillo, F.; Ventafridda, G.; Zollo, A. Crustal deformation and seismicity modulated by groundwater recharge of karst aquifers. *Geophys. Res. Lett.* **2018**, *45*, 12–253. [[CrossRef](#)]
45. Laplace, P.S. Mémoire sur la Théorie de L’anneau de Saturne. In *Mémoires de Academie Royale des Sciences de Paris, France*; 1787; p. 1789.

46. Narasimhan, T.N. Laplace equation and Faraday's lines of force. *Water Resour. Res.* **2008**, *44*, 11. [[CrossRef](#)]
47. Fiorillo, F.; Esposito, L.; Testa, G.; Ciarcia, S.; Pagnozzi, M. The Upwelling Water Flux Feeding Springs: Hydrogeological and Hydraulic Features. *Water* **2018**, *10*, 501. [[CrossRef](#)]
48. Angelini, P.; Dragoni, W. The problem of modelling limestone springs: The case of Bagnara (North Apennines, Italy). *Groundwater* **1997**, *35*, 612–618. [[CrossRef](#)]
49. Keeler, R.R.; Zhang, Y.K. Modeling of groundwater flow in a fractured-karst aquifer in the Big Springs Basin, Iowa. *Geological Society of America Abstracts with Programs* **1997**, *29*, 25.
50. Quinn, J.J.; Tomasko, D.; Kuiper, J.A. Modeling complex flow in a karst aquifer. *Sediment. Geol.* **2006**, *184*, 343–351. [[CrossRef](#)]
51. Fabbri, P.; Gaetan, C.; Zangheri, P. Transfer function-noise modelling of an aquifer system in NE Italy. *Hydrol. Process.* **2011**, *25*, 194–206. [[CrossRef](#)]
52. Emblanch, C.; Zuppi, G.M.; Mudry, J.; Blavoux, B.; Batiot, C. Carbon 13 of TDCI to quantify the role of the unsaturated zone: The example of the Vaucluse karst systems (Southeastern France). *J. Hydrol.* **2003**, *279*, 262–274. [[CrossRef](#)]
53. Jankovic, I.; Fiori, A.; Dagan, G. Effective conductivity of isotropic highly heterogeneous formations: Numerical and theoretical issues. *Water Resour. Res.* **2013**, *49*, 1178–1183. [[CrossRef](#)]
54. Dagan, G. Analysis of flow through heterogeneous random aquifers by the method of embedding matrix: 1. Steady flow. *Water Resour. Res.* **1981**, *17*, 107–122. [[CrossRef](#)]
55. Ababou, R.; McLaughlin, D.B.; Gelhar, L.W. Three-Dimensional Flow in Random Porous Media. Ph.D. Thesis, Parsons Laboratory, Massachusetts Institute of Technology, Cambridge, MA, USA, 1988; p. 836.
56. Dagan, G. *Flow and Transport in Porous Formations*; Springer: Berlin, Germany, 1989; p. 465.
57. Jing, M.; Heße, F.; Kumar, R.; Kolditz, O.; Kalbacher, T.; Attinger, S. Influence of input and parameter uncertainty on the prediction of catchment-scale groundwater travel time distributions. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 171–190. [[CrossRef](#)]
58. Király, L. Karstification and groundwater flow. In *Evolution of Karst: From Prekarst to Cessation*; Gabrovšek, F., Ed.; ZRC Publishing: Ljubljana, Slovenia, 2002; pp. 155–190.

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