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The Role of the Heterogeneity of Volcanic Aquifer Properties in Assessing Sustainable Well Yield: Study Cases from Latium (Central Italy)

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Abstract: Groundwater resources from the volcanic aquifers of northern Latium (central Italy) are widely used to supply local water needs and are mainly captured through wells. Nevertheless, despite the detailed hydrogeological knowledge of these aquifers, not enough information is available on the long-term pumping yield necessary to define the sustainable yield of a well. In this study, data from about 230 pumping tests (mainly step-drawdown and a few constant-flow-rate tests) performed in the volcanic aquifers of the Latium region were analyzed. Specifically, the aquifer formations intercepted by the wells are the fall and flow pyroclastic deposits of the Vico, Vulsini, and Sabatini volcanic districts; lava from the Vico, Cimino, and Vulsini volcanic districts; and Ignimbrite Cimina, one of the main pyroclastic products of the Cimino eruptions. These aquifers were grouped and analyzed by considering the type of permeability, hydrostratigraphic succession, and frequency and thickness of the aquifer horizons intercepted by wells. The results obtained in terms of specific capacity and transmissivity values are comparable among the identified different aquifer formations, showing a good correlation between the two parameters, a strong hydraulic heterogeneity (variability within five orders of magnitude), and variable responses regarding drawdown to pumping. This study highlights that the analysis of drawdown over time at a constant flow is fundamental in heterogeneous hydrogeological environments such as volcanic ones, where the trend in drawdown is often affected by the reduced spatial continuity of the most productive aquifer formations. Knowledge of the trend in drawdown over time, the thickness of the aquifer intercepted by the well, and the operating time of the well is an essential element in defining the sustainable yield of a well.

Keywords: volcanic aquifers; pumping tests; sustainable well yield; Latium (central Italy)

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1. Introduction

During the last decades, the study of volcanic aquifers has received increasing interest from the scientific community, since they represent the unique sources of groundwater for human needs, agriculture, economic activities, and ecosystems in some regions of the world [1–9].

The optimization of groundwater withdrawals from volcanic aquifers is therefore crucial to maximize flow rates for human requirements and, at the same time, to minimize negative environmental impacts. This goal is particularly challenging in these complex geological settings due to the overlapping of several eruption phases and products (i.e., pyroclastic fall and flow deposits, lava flows, and lava domes). These geological features lead to complex and heterogeneous hydrostratigraphy characterized by different types (primary porosity, secondary porosity, and/or dual porosity) and degrees of permeability [8,10–13]. Volcanic aquifers, therefore, constitute a very heterogeneous hydrogeological environment, and it is well known that the spatial heterogeneity of aquifer properties affects groundwater flow and mass transport at different scales (e.g., [14–17]).

An example of such settings is the Pliocene–Quaternary volcanic areas of central Italy, where aquifer systems are widely used to meet local needs for drinking water, irrigation, and industry. These aquifers also supply mineral water for bottling and thermal water for therapeutic purposes [18]. Moreover, in this region, groundwater has arsenic concentrations varying between 1 and 317 μg/L, which poses problems for drinking water use [19–21].

Volcanic aquifers in the Latium region cover about 5400 km^2, representing approximately 31% of the regional area [22]. For these aquifers, groundwater flow patterns are known at the system scale, and estimates of water resources are available [22–24]. These estimates indicate that the volcanic aquifers in Latium provide a total of about 22.4 m^3/s of water resources allocated as follows: 44.7% for drinking water, 28.7% for irrigation, and 26.6% for industrial use. These groundwater resources are primarily extracted by wells [20]. Given this evidence, the sustainability of groundwater withdrawals is a significant concern. In accordance with Alley et al. [25], sustainable groundwater use means balancing withdrawal and use to avoid unacceptable environmental, economic, and social consequences over time. The sustainability of groundwater withdrawals can be applied at different scales, such as in basins, aquifers, or individual wells or well fields (e.g., [26,27]). At the scale of individual wells or groups of wells, understanding the aquifer response to pumping in terms of the propagation of induced drawdown over time and space is pivotal [28,29]. This is because groundwater, which under natural conditions feeds springs, rivers, and wetlands, and sustains dependent ecosystems, and they could be strongly influenced by the effect of pumping. Background knowledge (e.g., [30,31]) made clear that drawdown and consequently aquifer emptying depend on hydraulic diffusivity and on the distance from the boundary to be captured. Depending on these factors, the system may or may not tend toward steady-state conditions. These aquifer features determine the response to pumping and, consequently, the sustainable pumping flow rate. Long-term pumping becomes unsustainable when it leads to a progressive reduction in aquifer storage. Conversely, any pumping rate that ensures significant residual groundwater outflow to natural discharge areas is considered sustainable [27,32]. Therefore, to assess the sustainability of groundwater withdrawals, it is crucial to estimate aquifer hydraulic parameters and, above all, the trend in drawdown over time in the well and aquifer. Currently, limited information is available for volcanic aquifers in central Italy. This study summarizes the results of pumping tests carried out in the volcanic areas of northern Latium to ascertain reliable indications for defining the sustainable flow rate for wells.

2. Geological and Hydrogeological Setting

The study area lies between the Vulsini, Cimino, Vico, and Sabatini volcanic districts located in the northern area of Latium in central Italy (Figure 1). The Latium volcanic activity is part of the Tuscan–Latium volcanic province and began in the late Pliocene, developing along a structurally depressed belt parallel to the Tyrrhenian coast [33].

The Vulsini district (0.6–0.1 Ma), covering approximately 2000 km^2 (Figure 1a), developed during four eruptive phases: Paleobolsena, Bolsena, Latera, and Montefiascone [34]. Volcanic complexes, some overlapping in space and time, have produced a variety of volcanic deposits, including pyroclastic fall and flow deposits, such as the Orvieto Ignimbrite, interspersed with effusive episodes like lava flows and scoria cones [35]. The main volcanic structure is the large Bolsena Lake basin, interpreted as a volcano–tectonic depression. The Vulsini volcanoes show a diverse range of rock types within the potassic series, including

K-basalts; trachybasalts; basanites; and high-potassium rocks like tephrites, phonolites, and trachytes [36–38].

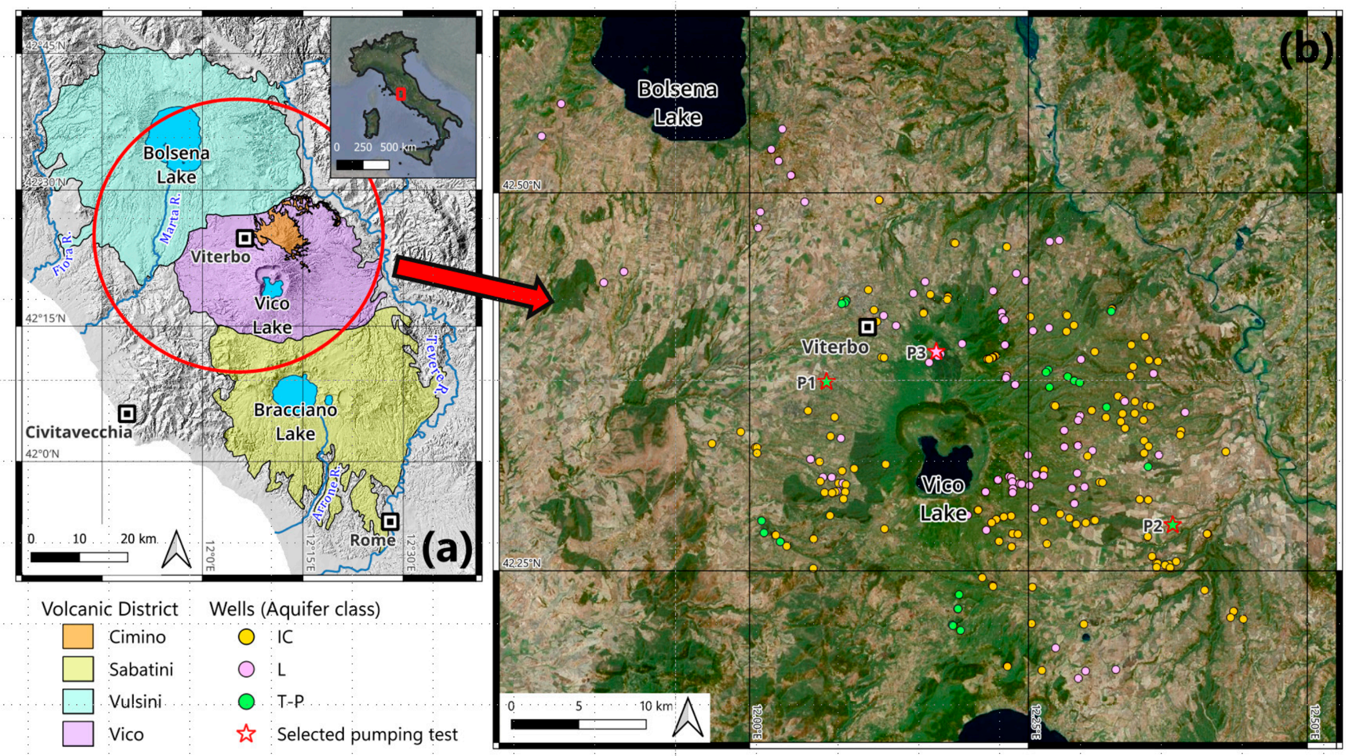

Figure 1. Location maps of the study area (**a**) and tested wells (**b**).

The Cimino district, located further south (Figure 1a), underwent a period of activity between 1.35 and 0.95 Ma. In this period, the formation of over 50 rhyodacitic lava domes, often buried beneath pyroclastic flows and surges, took place. The Ignimbrite Cimina is the main pyroclastic flow product of the Cimino volcano, showing considerable thickness and extent. Volcanic activity ends with the eruption of latitic and olivin-latitic lavas [39,40].

The Vico district was active from 0.49 to 0.095 Ma. It developed as a strato-volcano with a central caldera depression, and it is now occupied by Vico Lake (Figure 1a). Both effusive and explosive eruptions occurred, producing plinian fall deposits, lava flows, and pyroclastic flows leucitic, phonolitic–tephritic, and leucitic–phonolitic in composition [37,41]. The main eruptive product is the ignimbrite "Tufo Rosso a Scorie Nere", a thick pyroclastic flow deposit. Together, the Cimino and Vico districts cover approximately 900 km^2.

The Sabatini district, located in the southern part of the study area (Figure 1a), began its volcanic activity at about 0.55 Ma and covers an area of 1690 km^2. The district experienced eruptions from multiple centres, primarily in the eastern part, producing pyroclastic deposits with trachytic and phonolitic compositions. In the western area, prolonged explosive activity gave rise to thick and extensive pyroclastic flow, fall deposits, and lava flows with high-potassium compositions. Other areas within the district also witnessed volcanic activity, characterized by tephritic and phonolitic lava flows and scoria cones [42]. Around 0.37 Ma, after the paroxysmal phase, the main eruptive centre entered a final phase marked by hydromagmatic eruptions and the collapse of the volcano–tectonic depression now housing Bracciano Lake.

From a hydrogeological perspective, the study area can be divided into defined systems, corresponding to the four outlined volcanic districts [22,24,43]. In these volcanic areas (Figure 1a), the aquifer formations consist of lavas, which generally show high permeability due to fracturing. These formations interchange with pyroclastic fall deposits (such as pumiceous and scoriaceous lapilli horizons and tuffs) that display varying degrees of permeability resulting from primary porosity, and the ignimbrites are characterized by dual porosity [10,44].

At the volcanic district scale, groundwater flow occurs in the basal continuous aquifer with a potentiometric surface that generally follows the topography. The basal aquifer mainly discharges into streams and rivers and feeds alluvial aquifers bordering the volcanic areas. Additionally, springs with relatively low flow rates (<0.05 m^3/s) contribute to the discharge of basal aquifers. Lakes Bolsena, Vico, and Bracciano are interconnected with the basal water table, having feed and drain relationships with groundwater. Due to the complex hydrostratigraphy, which is strongly related to the complex eruptive history of the area, discontinuous perched aquifers of limited extent were identified, feeding streams and springs with low flow rates (<0.01 m^3/s) [10,23,24]. The above-mentioned volcanic aquifer systems are laterally bounded by sedimentary units (Plio-Pleistocene and Meso-Cenozoic) and alluvial deposits (Pleistocene-Holocene). Low-permeability Pliocene and Meso-Cenozoic formations represent the aquifer bottom [24].

3. Materials and Methods

Pumping tests and well data were collected from various sources, including the existing literature [10,20,45], public archives [46], and several unpublished technical reports. The pumping tests concern wells used mainly for irrigation and drinking water and, secondly, for supplying industrial sites. A total of 235 wells were selected for the quality of the acquired information. They are mainly located in the Cimino and Vico volcanic districts and secondarily in the Vulsini and Sabatini districts (Figure 1b). For each well, data on the technical characteristics (depth, diameter, and operating flow rate) and local hydrogeological features (e.g., aquifer formation and its thickness, depth of water level) were acquired. The well's design in terms of the well's screen type, screen slot size, and filter pack is not always known, with this lack of information being particularly relevant to wells serving irrigation. Most of the analyzed data included pumping tests carried out at variable discharge rates, with a maximum duration of a few hours and with drawdown monitoring only in the pumping well (Type A tests). A smaller number of tests were performed over several hours at constant or variable flow rates, involving drawdown measurements on the pumping well and nearby observation wells (if any), as well as the monitoring of the recovery phase (Type B tests).

The acquired data were processed to determine well yields and aquifer parameters and to analyze the different responses to pumping over time in the well and, where possible, in the surrounding aquifer.

For Type A tests (212 tests), the specific capacity of wells ($Qs = Q/sw$) was calculated using the flow rate (Q) and the measured drawdown in the well (sw) at the lowest flow-step, where non-linear head losses are certainly the lowest, thus reducing the influence of well efficiency on the value of Qs. For Type B tests (23 tests), in addition to the specific capacity (Qs) calculated for 21 tests, transmissivity (T) was assessed by using data from the monitoring of the recovery phase in the pumping well and, where available, data from nearby observation wells. In the latter cases, data from observation wells were used also to determine the storage coefficient (S). Aquifer parameters (T and S) were estimated using classical analytical methods widely documented in the literature (Jacob's method, Theis's recovery method, or Neuman's curve-fitting method [47]), and in a few cases, they were also verified through commercial software (Aquifer Test 13.0) [48]. In addition, for constant-flow-rate tests belonging to the Type B class, the drawdown–time trends were analyzed through semi-log plots, and the time series and the first derivative of the drawdown were plotted on bi-log plots. By comparing these with theoretical curves, the flow regime through the flow dimension *n* was identified [49–52].

For the entire dataset, the aquifer formation intercepted by each well was characterized using borehole stratigraphy or, when unavailable, by referring to neighboring boreholes or geological maps of the area. A strong understanding of hydrostratigraphy in these complex and heterogeneous environments is crucial for the accurate interpretation of results, particularly in deriving indications in order to define sustainable yield.

The wells considered and their technical characteristics of major interest for this study, together with the calculated parameters (*Qs*, *T*, and *S*), are shown in Supplementary Materials (Table S1).

4. Results

The investigated wells are located at elevations ranging from 140 and 755 m asl and spread over an area of about 1371 km^2 (Table S1 in Supplementary Materials and Figure 1b). By analyzing the available stratigraphic logs for the boreholes or the study area, wells were classified into three main aquifer categories. These aquifer classes were differentiated on the basis of the permeability type, hydrostratigraphic sequence, frequency and thickness of aquifer horizons, and predominant aquifer formation intercepted by the wells.

The identified aquifer categories can be classified as follows:

T–P class: The fall and flow pyroclastic deposits of the Vico, Vulsini, and Sabatini volcanic districts, often intercepted by the same well. These deposits show primary porosity in unconsolidated fall pyroclastic deposits and dual porosity (matrix and fractures) in tuffs and ignimbrites (Figure 2a,b).

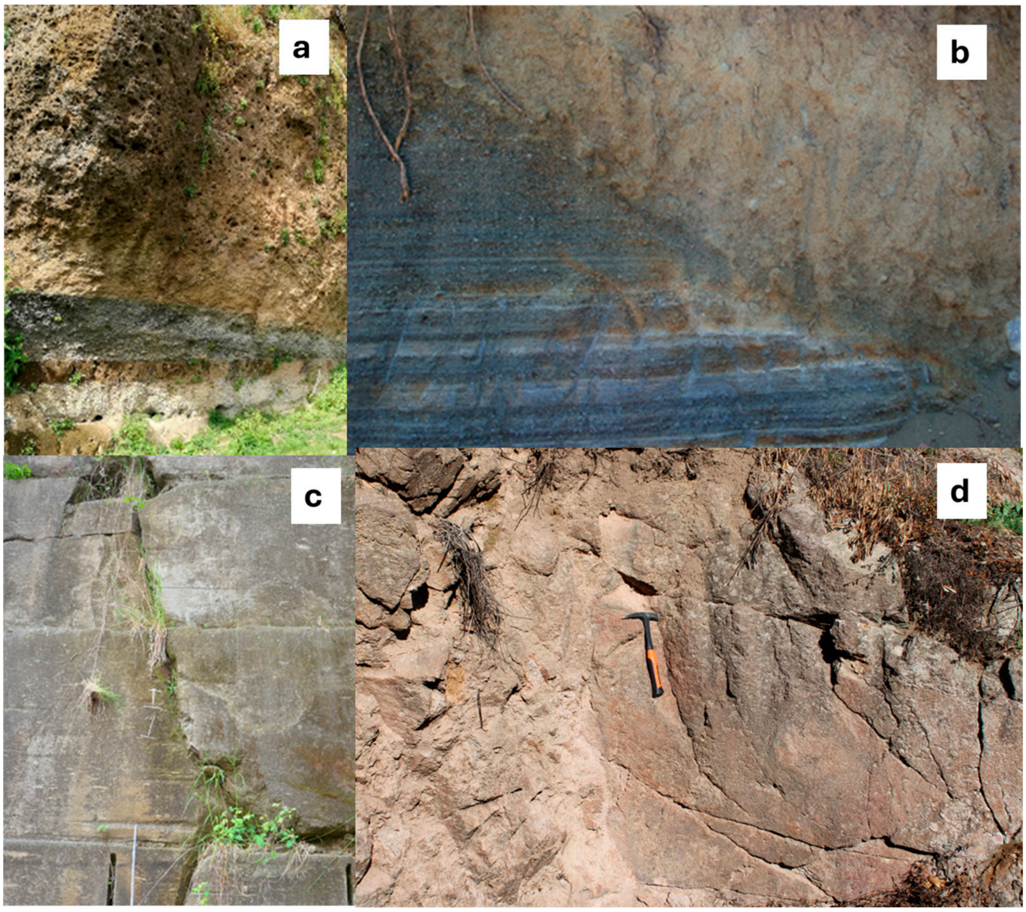

Figure 2. Examples of outcrops of the T-P class, fall and flow deposits f (**a**,**b**); IC class, Ignimbrite Cimina (**c**); and L class, lava dome (**d**).

IC class: Ignimbrite Cimina, the major pyroclastic flow deposit of the Cimino eruptions, is characterized by dual porosity [44]: high secondary porosity due to fracturing and relatively low primary porosity (Figure 2c).

L class: Lava from the Vico, Cimino, and Vulsini volcanic districts. Primarily permeable because of fracturing (Figure 2d), the degree of fissuring is variable in relation to the effusive eruption styles and volcano–tectonic processes of different volcanic districts [10].

Well depths range from 17 to 278 m, with the shallower one intercepting the T–P aquifer class, while the deepest intercepts the IC class. The saturated thickness varies between a few meters and several tens of meters (Table S1 of Supplementary Materials).

For 233 tests, *Qs* was calculated by referring to the lowest pumping rate for Type A tests and the early time drawdown for Type B tests. Table 1 and Figure 3 show the statistical parameters of *Qs* for the entire dataset and differentiated by the aquifer class.

Table 1. Statistical parameters calculated on *Qs* (in m^2/s).

Aquifer Class	All	T–P	L	IC
Number	233	26	80	127
Min	6.06×10^{-6}	3.00×10^{-5}	6.00×10^{-6}	8.00×10^{-6}
Max	5.00×10^{-2}	1.80×10^{-2}	5.00×10^{-2}	2.06×10^{-2}
Mean	2.30×10^{-3}	2.27×10^{-3}	2.46×10^{-3}	2.20×10^{-3}
Geometric mean	6.57×10^{-4}	6.28×10^{-4}	6.64×10^{-4}	6.60×10^{-4}
Median	6.00×10^{-4}	7.15×10^{-4}	7.75×10^{-4}	5.20×10^{-4}
25th perc.	2.13×10^{-4}	1.78×10^{-4}	2.23×10^{-4}	2.11×10^{-4}
75th perc.	2.00×10^{-3}	1.90×10^{-3}	2.00×10^{-3}	2.00×10^{-3}
Standard error	3.31×10^{-4}	7.92×10^{-4}	7.40×10^{-4}	3.57×10^{-4}
Standard deviation	5.05×10^{-3}	4.04×10^{-3}	6.62×10^{-3}	4.02×10^{-3}
Variance	2.55×10^{-5}	1.63×10^{-5}	4.38×10^{-5}	1.62×10^{-5}
Coefficient of variation	219.70	178.12	268.74	182.89
Skewness	5.37	2.82	5.80	2.95
Kurtosis	39.32	8.92	37.43	8.91

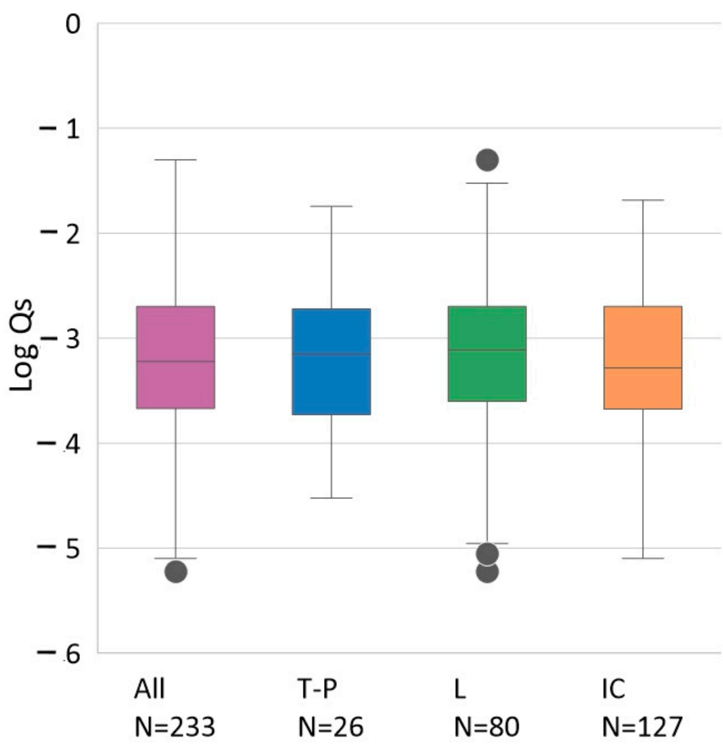

Figure 3. Range of *Qs* variation determined for all tests and for the different aquifer classes.

The results highlight that most of the *Qs* values (25th and 75th percentiles) fall within two orders of magnitude (10^{-3}–10^{-4} m^2/s), regardless of whether all tests or individual aquifer classes are considered. The geometric mean and median values also show little variation across all tests and different aquifer classes. However, the minimum *Qs* value for the T-P class is almost an order of magnitude higher than that of all tests and other classes. Furthermore, no correlation was found between *Qs* and the well depth or aquifer formation thickness when considering the entire dataset.

For the 23 Type B tests, which lasted several hours, transmissivity (*T*) was calculated using data from the recovery phase or, in a few cases, data acquired in observation wells. Type B tests mainly involved the IC and L aquifer classes, with only seven wells intercepting the T-P class. Statistical parameters calculated on *T* values are presented in Table 2 and Figure 4. As with *Qs*, most *T* values range within two orders of magnitude (10^{-3}–10^{-4} m^2/s). However, considering the maximum and minimum values, a wider range of variation is observed (10^{-6}–10^{-2} m^2/s), similarly to the *Qs* distribution.

Table 2. Statistical parameters calculated on *T* (in m^2/s).

Number	23
Min	5.80×10^{-6}
Max	4.00×10^{-2}
Mean	4.44×10^{-3}
Geometric mean	7.61×10^{-4}
Median	8.12×10^{-4}
25th perc.	2.10×10^{-4}
75th perc	5.80×10^{-3}
Standard error	1.88×10^{-3}
Standard deviation	9.04×10^{-3}
Variance	8.16×10^{-5}
Coefficient of variation	203.51
Skewness	3.28
Kurtosis	11.43

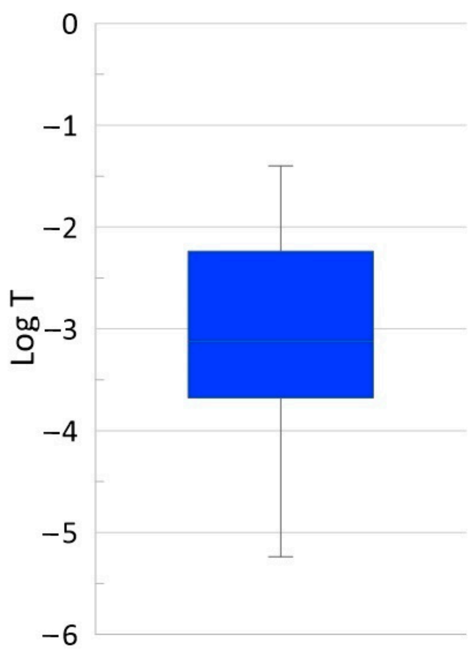

Figure 4. Range of variation of *T* obtained from 23 tests.

In addition, for the Type B test, the relationship between *Qs* and *T* was examined. As shown in Figure 5, a power–law relationship (Equation (1)) exists between the two variables (expressed in m^2/s), with a coefficient of determination R^2 of about 0.80:

$$T = 1.00Qs^{1.03} \quad (1)$$

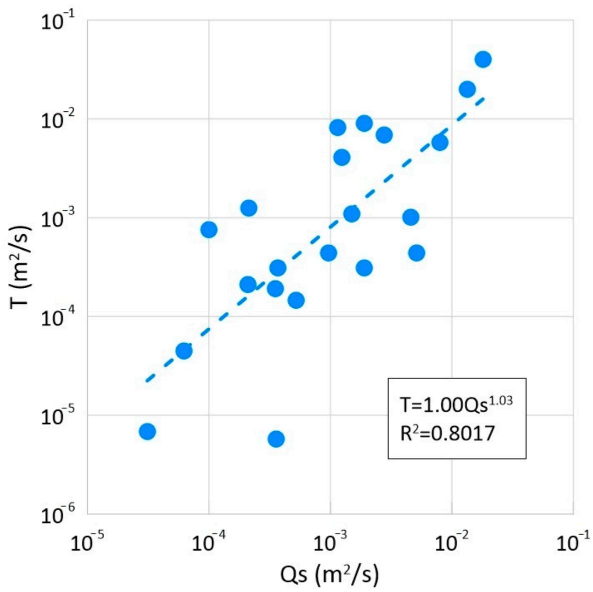

Figure 5. Relationship between specific capacity (*Qs*) and transmissivity (*T*) values.

The determination of storativity (*S*) was possible only for four tests. For two tests carried out in the IC class aquifer, the *S* values are 1.40×10^{-3} and 4.96×10^{-3}. For two tests in the T–P class, the *S* values are 1.31×10^{-3} and 3.86×10^{-2}. A previous study [18] carried out in a broader region, including the current study area, determined *S* values from 10 pumping tests, ranging from 10^{-3} and 10^{-2}.

Besides specific capacity and aquifer parameters, the drawdown trend over time for long duration, constant-flow-rate tests were thoroughly analyzed. Different pumping responses were observed, reflecting the inherent heterogeneity characterizing the intercepted aquifer. In some cases, the drawdown response tends toward a quasi-steady-state condition, while in others, a transient regime was evident, even with varying trends during the pumping period. Three significant examples are illustrated below: two tests for wells (P1 and P2) intercepting the T–P aquifer class and one test for a well (P3) crossing the L and IC aquifer classes (Figures 1b and 6).

Pumping well P1, which is 50 m deep, intercepts the aquifer formation for 30 m, consisting of fall and flow pyroclastic deposits from the Vico volcano (Figure 6). A constant-flow-rate pumping test of 7.7 L/s was carried out for approximately 405 h. The test included drawdown monitoring in the well and in two observation wells (P1–OW1 and P1–OW2) located 32 and 57 m apart from the pumping well, respectively. The semi-log plot of the drawdown–time (Figure 7a) shows a similar trend toward the quasi-steady-state regime for the well and the two observation wells up to the first 1000 min of the test, followed by an increase in curve slopes. Except for the first few minutes of the test, where drawdown in the well is affected by the wellbore storage effect, both the wells and observation wells respond simultaneously and homogeneously to pumping. The derivative drawdown time bi-log plot (Figure 7b) shows a similar trend for the well and the two observation wells again, with a sequential variation in flow dimensions from n = 2 ascribable to radial flow (in the early time), followed by a flow dimension of n = 1 due to linear flow.

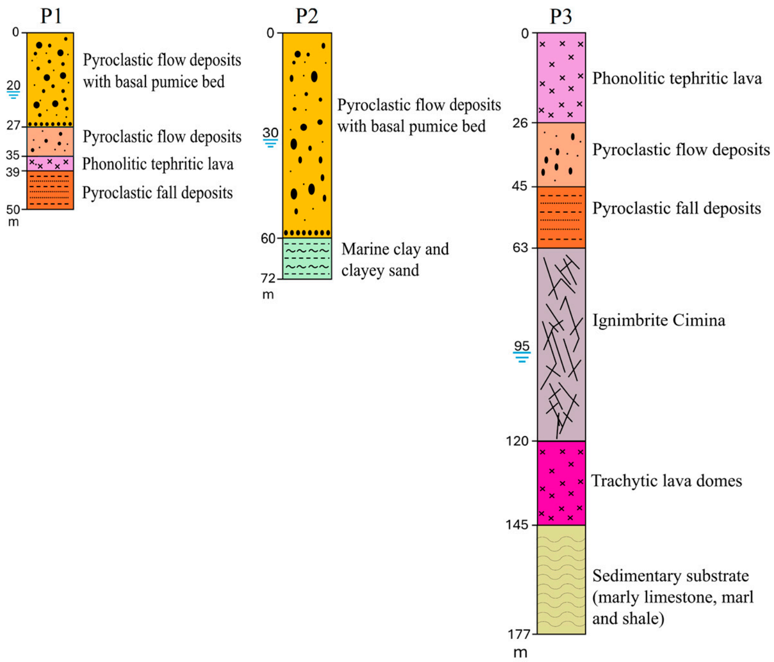

Figure 6. Stratigraphy of wells P1, P2, and P3, blue lines represent water table depth.

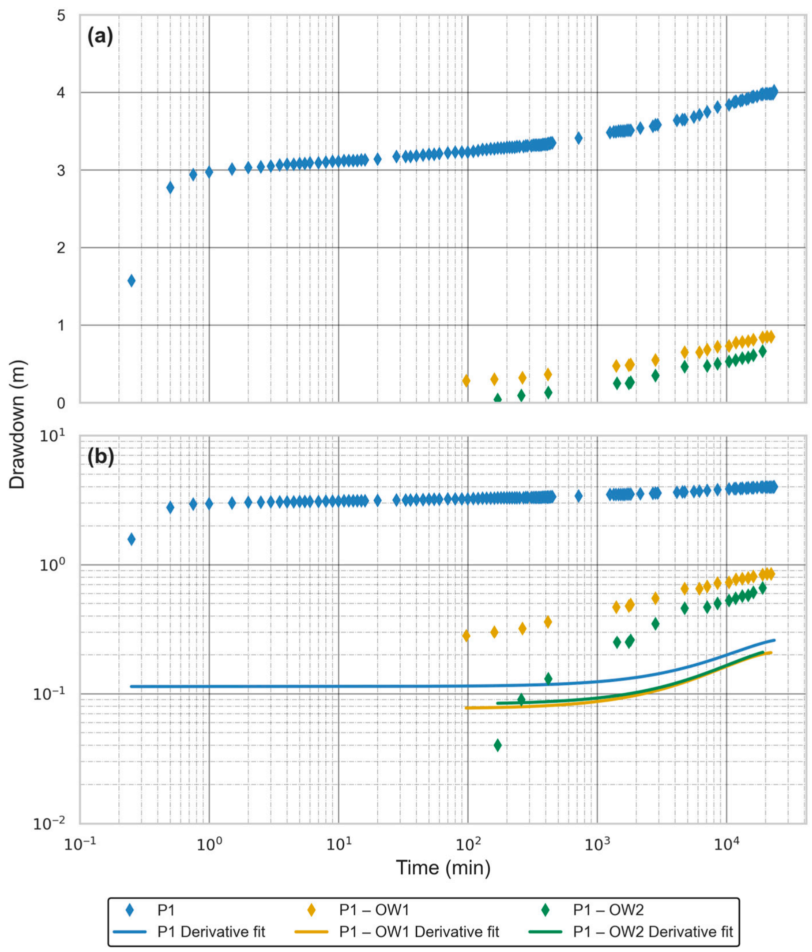

Figure 7. (**a**) Semi-log plot of drawdown–time in the pumping well and in two observation wells; (**b**) bi-log plots of the drawdown and derivative in the well and in two observation wells in the T–P Class.

The pumping test performed in well P2, which is 72 m deep, shows the response to the pumping of the aquifer hosted within the pyroclastic flow deposits of the Vico volcano (Figure 6). The saturated thickness intercepted by the well is 30 m. Drawdown was monitored in the well and in an observation well (P2–OW1) at a 31 m distance and during a constant-flow-rate test performed at 10 L/s for about 480 min. The semi-log plot in Figure 8a exhibits an initial transient trend that turns, in the later period of the test, toward a quasi-steady-state response. Conversely, monitoring well drawdown–time trend tends toward the steady-state condition after the first 100 min of pumping.

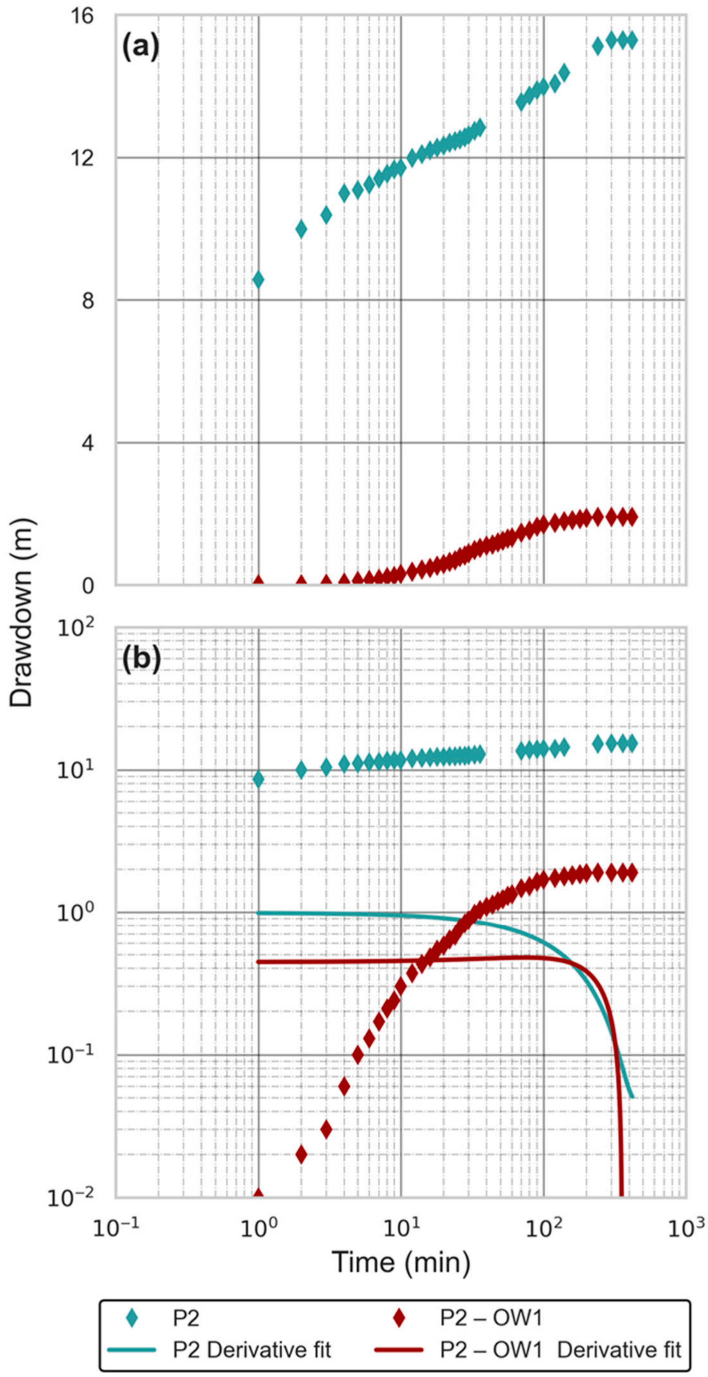

Figure 8. (**a**) Semi-log plot of drawdown–time in the pumping well and in one observation well; (**b**) bi-log plots of the drawdown and derivative in the well and in one observation well in T–P Class.

From the comparison of the semi-log plot of the drawdown and the bi-log plot of the derivative, a tendency toward a steady-state regime is clear, especially for the observation well (Figure 8b). Indeed, in P2–OW1, the sequence of flow dimensions changes from $n = 2$, typical of radial flow, to $n = 4$, indicative of the presence of a constant head boundary. For the pumping test, a similar sequence is obtained, but with a radial flow followed by a flow dimension of $n > 2$. This different response to pumping is likely ascribable to the diverse degree and type of permeability typical of pyroclastic deposits.

Well P3, with a depth of 177 m, mainly intercepts Cimino dome lava and partially the Ignimbrite Cimina at a thickness of 50 m (Figure 6). The test was performed at a constant flow rate of 20 L/s for 183 h, monitoring the drawdown only in the pumping well. The drawdown–time trend shows a transient response to pumping throughout the test duration, with an increase in drawdown in the late period (Figure 9a). From the derivative signal of the drawdown (Figure 9b), it is possible to identify a flow dimension of $n = 2$ up to 200 min due to a radial flow, followed by a steepening of the derivative curve, which tends to a flow dimension of $n = 0$ probably due to the effect of a no-flow boundary. The behavior highlighted by the semi-log and bi-log trends of the drawdown is characteristic of a heterogeneous fractured aquifer.

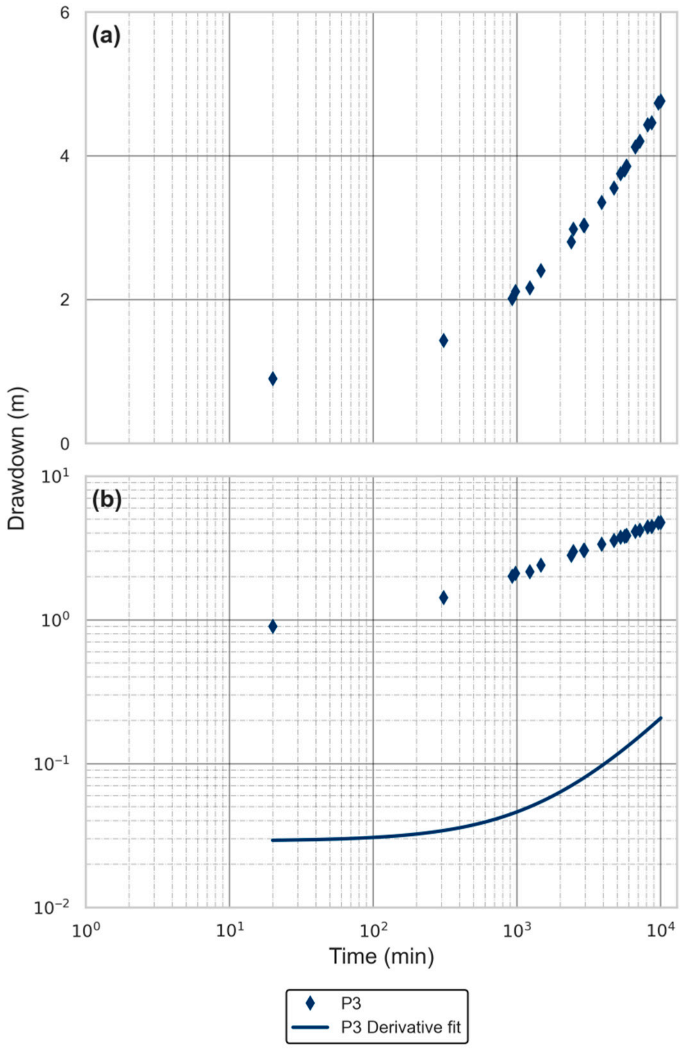

Figure 9. (**a**) Semi-log plot of drawdown–time in the pumping well; (**b**) bi-log plots of the drawdown and derivative in the well in L and IC Classes.

5. Discussion

The different response to pumping observed for the investigated volcanic aquifer reflects the hydrogeological features of pyroclastic and volcanic rocks. Although the specific capacity (Qs) depends on the well's efficiency, using the values at the lowest flow-step, appears to be a reliable indicator of the considerable hydraulic heterogeneity of the aquifer formations intercepted by the wells. Indeed, Qs values vary among five orders of magnitude, with most values falling within the range of 10^{-4} to 10^{-3} m^2/s (see Table 1). This high degree of heterogeneity is further emphasized by the significant variation in parameter values among closely spaced wells and, in some cases, by the different drawdown trends between pumping and observation wells. The transmissivity (T), although derived from a limited number of tests, also shows significant variations, with the most frequent values spanning two orders of magnitude. This variability aligns with the observed range of the specific capacity (Qs).

In addition, the good correlation between specific capacity and transmissivity (Figure 5) suggests that Qs can be used as a reliable parameter for the preliminary assessment of site-specific hydrogeological features, particularly T. Equation (1), describing the relationship between the two parameters, produced results comparable to those obtained from a larger number of tests even in different hydrogeological settings [11,53–56].

The significant variation in Qs and T likely reflects the extreme variability in the nature, thickness, continuity, and age of the stratigraphic unit characteristics of volcanic areas, as also observed in other contexts [2,9,12,13,57,58]. The limited available storativity values (ranging from 10^{-3} and 10^{-2}) coupled with local hydrostratigraphy and drawdown–time trends observed during pumping tests suggest that aquifer responses for the examined cases are consistent with unconfined or semi-confined aquifer conditions.

Nevertheless, aquifer response to pumping is a function of both hydraulic diffusivity ($D = T/S$) and distance (x) from the boundary to be captured. Theis [30] highlighted that the response of a confined aquifer to withdrawal depends on time constant t_c, included in the u terms of the Theis equation [59]:

$$u = \frac{\left(\frac{x^2 S}{4T}\right)}{t} = \frac{t_c}{t} \tag{2}$$

where t is the duration of pumping. The drawdown will show a little increase over time when t is significantly higher than t_c (i.e., $t > 10^3 t_c$): that is, a trend toward steady-state conditions. Therefore, the duration of the transient phase decreases for smaller values of x and S or for higher values of T. These two conditions are more typical of confined aquifers than unconfined ones [31]. In any case, pumping leads to aquifer emptying, and the tendency toward steady-state conditions depends on D and x, whatever the aquifer type.

Using Equation (2) and the calculated T and S values, it is possible to examine the possible local response to pumping within the study area. For this purpose, it was necessary to determine the distance (x) of pumping wells from boundaries to be captured, such as streams, rivers, lakes, and other recharge boundaries, as well as the pumping duration, which is strictly related to groundwater usage (drinking water supply, irrigation, and industrial purposes). Figure 10 illustrates the relationship between the time constant (t_c), the distance to the boundary (x), and different pumping durations (t) for various groundwater usage scenarios. The distance (x) ranges from 10 to 5000 m. The time constant t_c was calculated for both the maximum and minimum values of hydraulic diffusivity. The graph also includes lines representing $t = 10^3 t_c$ for the maximum and minimum t_c values.

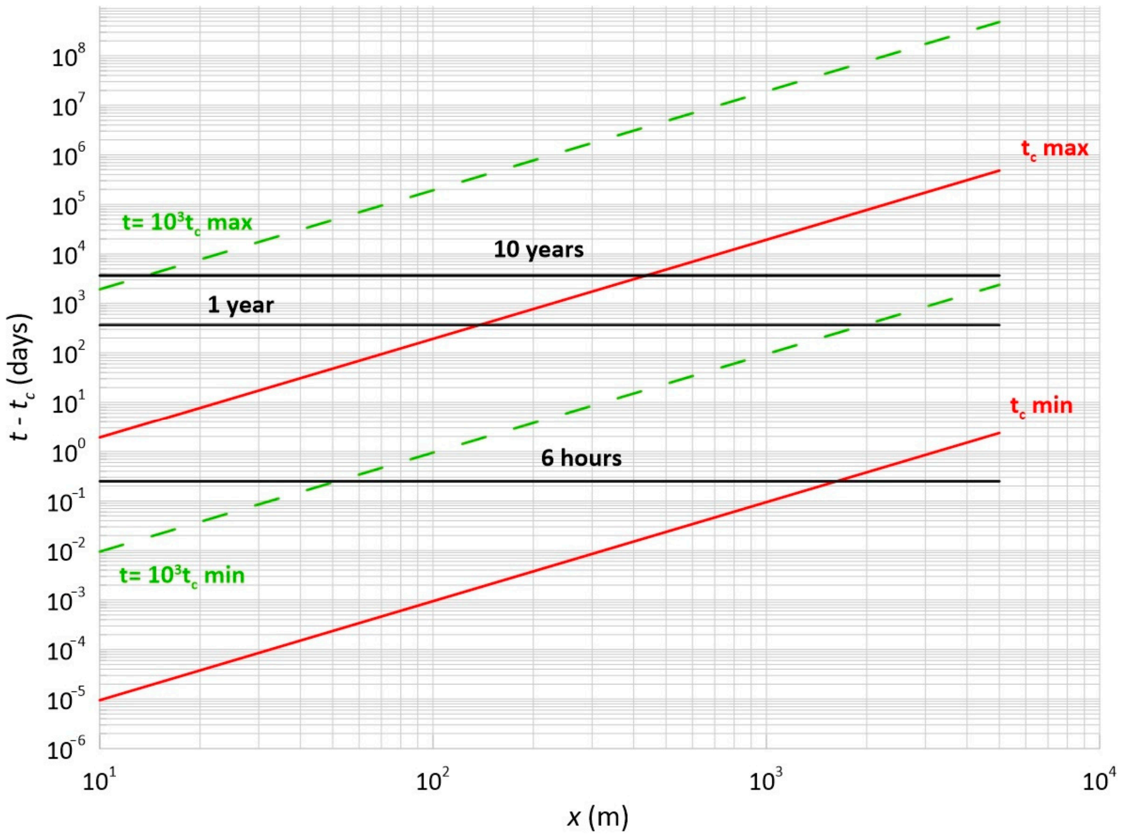

Figure 10. Time constant (t_c) and pumping time (t) variations as a function of boundary distance (x). The values of t_c were derived from the most frequent range of hydraulic diffusivity (D) obtained from pumping tests.

Assuming a 6 h withdrawal period for irrigation, the graph highlights that the steady-state condition is only reached for the maximum D value ($t = 10^3 t_c min$) for a boundary distance of less than 50 m (Figure 10). If a longer pumping duration of one year is considered (e.g., for drinking water supply), steady-state conditions may not be reached for low D values ($t = 10^3 t_c max$), while they can be attained for the maximum D values and boundary distances of less than about 1 km. It is important to remark that Figure 10 depicts the Theis-confined aquifer model. In semi-confined and unconfined aquifers, such as those examined in this study, steady-state conditions may be achieved, respectively, more quickly or slowly than in confined aquifers. In addition, the scenarios shown in Figure 10 assume a constant hydraulic diffusivity between the pumping well and the boundary to be captured. Instead, the hydraulic diffusivity of volcanic and pyroclastic formations can vary even on a hundred-metre scale, as the results of pumping tests show.

Understanding the long-term drawdown trend of these complex and heterogeneous volcanic aquifers is crucial for sustainable groundwater management. The constant flow rate pumping tests examined (e.g., Figures 7–9) often show a transient response regarding drawdown. Consequently, assessing sustainable pumping rates is challenging without knowledge of the long-term pumping behavior. According to Van Tonder [60], the sustainable yield of a well is defined as the discharge rate that will not cause the water level in the well to drop below a prescribed limit. This assessment depends on the aquifer's type and on the saturated thickness intercepted by the well. Therefore, information on drawdown trends, extrapolated from sufficiently long pumping tests, is necessary for making reasonable predictions.

In fact, by applying Van Tonder's method [60] to well P3, different sustainable pumping rate values may be obtained depending on whether the early-time drawdown curve

(<1000 min) or the late-time steeper portion of the curve is considered. This means that the test duration is critical in defining a well's sustainable yield, as also highlighted in low-permeability aquifers [61] and in high-permeability and heterogeneous fractured aquifers [62]. Conversely, long-duration constant flow rate tests, aimed at defining sustainable operational flow rates, can be costly for continuous (drinking water) use. This issue can be overcome by monitoring the first operation phase of the well, as suggested by Misstear and Beeson [63]. However, the primary factor in defining a well's operating flow rate should be the long-term drawdown trend. This is certainly more significant than relying solely on aquifer hydraulic parameters (T and S), especially in heterogeneous hydrogeologic environments such as volcanic ones where the trend in drawdowns can be affected by the limited spatial continuity of productive aquifer layers.

6. Conclusions

A large number of pumping tests (235) were carried out in the volcanic aquifers of northern Latium, characterized by complex hydrostratigraphy due to the intricate eruptive history, including effusive and explosive episodes. This results in significant hydraulic heterogeneity, both horizontally and vertically, caused by spatial variations in aquifer formations differing in the type and degree of permeability. The heterogeneity inherent in these aquifers is reflected in the wide variability of both specific capacity and transmissivity values (five orders of magnitude) obtained by the analyses of the pumping test. The values also show a good correlation between the two parameters, suggesting that the specific capacity could represent a reliable indicator of aquifer transmissivity. Furthermore, the different aquifer responses to pumping are evidenced by diverse drawdown trends over time, underlining this complexity. Indeed, the key finding of this study is that understanding the drawdown trend over time, relative to the expected pumping duration for various water uses, becomes crucial for defining a sustainable pumping flow rate.

Specifically, for irrigation wells that require intermittent and short-duration pumping, it is necessary to consider the transient response of drawdowns that may affect the operating flow rate and the interference with neighboring wells. For wells that require continuous pumping, such as those used for drinking water, understanding the long-term drawdown trend and the distance from the boundary to be captured is essential. In both cases, constant flow rate pumping tests (or step-drawdown tests interpreted to provide the specific drawdown over time) are preferred in order to extrapolate the most reliable drawdown trend for the expected pumping durations during the operation phase.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w17030409/s1, Table S1: Dataset of tested pumping wells.

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