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Determination of the Storage or Porosity Coefficient Using the Natural Logarithm Curve by Means of *in Situ* Measurements

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Abstract

The relevance of studying the storage coefficient variable brings with it the updating of this value in the hydraulic characteristics as part of the hydrogeological parameters applied to each country, where recommended values for the storage coefficient to be used in hydrogeological studies are presented. And the application of a methodology adapted to the conditions of each country, is done under current conditions resulting in reference values. For this research work, an adequate methodology was sought for calculating the storage coefficient with a natural logarithm (LN) arrangement. To achieve this, first, the variables that affect the storage coefficient were identified, then the model was described with the natural logarithm (LN) arrangement, and as a third point the storage coefficient was calculated. In conclusion, in points 1 and 2 it was possible to calculate the storage coefficient from the Natural Logarithm arrangement model, with a correlation equal to $R^2 = 0.99$, and $R^2 = 0.97$ respectively, indicating that this method can be applied as long as there is free aquifer conditions and that manipulation of data alteration is not frequent.

Keywords

Hydrogeology, Storage Coefficient, Transmissibility, Drawdown, Natural Logarithm

1. Introduction

In hydrogeology, the study of the storage, circulation and distribution of groundwater is based, in a saturated and unsaturated manner. The study of geological formations is also based on taking into account the physical and chemical properties, the interactions with the physical and biological environment and their reactions due to anthropogenic activities.

In this sense, the most important hydraulic properties considered in the study of hydrogeology are transmissibility, hydraulic conductivity, hydraulic radius and storage coefficient.

In the study of the storage coefficient, it indicates that there is a concern to have the magnitude of this variable updated in real time, since it presents greater uncertainty for its determination, in this sense, the calculation of this coefficient will depend a lot on the vertical prism of the aquifer of section equal to the unit, and of the height equivalent to the saturated thickness of the same when there is a decrease of the unit of the piezometric level, as dictated [1].

The quantification of the storage coefficient parameter is important in numerous hydrogeological problems, this variable directly affects the flow of the supply wells, the transport of solutes and the fluctuations of the water table, as stated (Saha and Agrawal, 2006; Song and Chen, 2010) cited by [2].

In this sense, the relevance of studying the storage coefficient variable brings with it the updating of this value applied to the hydraulic characteristics as part of the hydrogeological parameters applied to each country, where recommended values for the storage coefficient to be used are presented. In hydrogeological studies. And the application of a methodology adapted to the conditions of each country, is done under current conditions resulting in reference values.

For this research work, the main objective is to develop an adequate methodology for calculating the storage coefficient with a natural logarithm (LN) arrangement. Specifically, firstly, it is intended to identify the variables that affect the storage coefficient, then describe the model with the natural logarithm arrangement (LN), and as a third point is to determine the storage coefficient from the Logarithm arrangement model Natural.

Finally, for the preparation and support of said research, previous studies have been considered and consulted, as a methodology for estimating the storage coefficient.

2. Methodological Design

2.1. Kind of Investigation

This article was designed under the methodological approach of the quantitative approach using the experimental methodology of the case, since this is the one that best adapts to the characteristics and needs of the investigation.

The quantitative approach used data collection and analysis to answer research questions and test previously established hypotheses, and translates into

> "the sequential and probative. Each stage precedes the next and we cannot 'jump' or avoid steps. The order is rigorous, although of course, we can redefine some phase. It starts from an idea that is being delimited and, once defined, objectives and research questions are derived, the literature is reviewed and a theoretical framework or perspective is built. From the questions hypotheses are established and variables are determined; a plan is

drawn up to test them (design); variables are measured in a certain context; the measurements obtained using statistical methods are analyzed, and a series of conclusions are drawn regarding the hypothesis or hypotheses" [3].

From the quantitative approach, the technique of basing the interpretation of data and their analysis using numbers and statistics was taken. It was carried out through the use of standardized procedures accepted by the scientific community in the comparison of the calculation of the storage coefficient using the natural logarithm curve by means of in situ measurement, based on data collection at four different points in the aquifer. Sierras de Managua, Nicaragua.

2.2. Execution Time

For the development of the research, there were three weeks for data collection in situ, and the search for information sources for data collection, two weeks for data analysis, and two weeks to interpret the results and final writing of the report. This was done during the period from December 2022 to January 2023.

2.3. Technique and Methods of Data Collection

The method to determine the storage coefficient is based on pumping tests, drainage experiments, water balance and gravity measurement as established by (Johnson, 1967; Walton, 1970; Neuman, 1987; Pool and Eychaner, 1995) quoted by [2].

Primary Sources

- On-site pumping tests.
- Main bibliography related to the calculation of the storage coefficient.
- Scientific articles that provide information related to the calculation of the storage coefficient.

Secondary Sources

Library of the Nicaraguan Institute of Territorial Studies (INETER). General Directorate of Water Resources.

Library of the National Water Authority (ANA). General Directorate of Water Resources.

SINIMBU, interactive water and sanitation maps, Government of Reconciliation and National Unity, Nicaragua.

2.4. Universe

The southern sub-basin of the Sierras de Managua aquifer.

2.5. Population

The sub-basin II and III of the Sierras de Mangua aquifer.

2.6. Sample

Four points of interest to implement the gauging with pumping, in sub-basin II and III of the Sierras de Managua aquifers.

2.7. Inclusion Criterial

It has been established as inclusion criteria, all those points of interest in which pumping tests have been carried out, and these are chosen for their hydraulic characteristics.

2.8. Exclusion Criterial

All those points that are not of interest, and that pumping tests have not been carried out, have been taken as exclusion criteria.

3. Theoretical Aspects

According to (Villarroya, 2009) dictates that, from the hydrogeological point of view, the following types of aquifers are distinguished; aquifer: as the geological formation capable of containing and transmitting water in significant quantities, for example, the fluvial terraces, the limestone of the páramo de la Alcarria, etc.; the aquitards: they are considered a geological formation capable of containing water and transmitting it slowly, for example, sandy silts, and in part, the tertiary detrital aquifer of Madrid; aquicludes: they are geological formations capable of containing water but not transmitting it, for example, clayey formations, in fact they are considered "impermeable"; the aquifugal: they are considered geological formations that do not contain or transmit water, for example, igneous rocks that are not fractured or weathered.

From this, for [4], describes the aquifers according to their type, these are: porous aquifers, karstic aquifers and fissured aquifers. Also [4] refers to free or phreatic aquifers, as the volume of water that saturates the pores and fractures of the formation and is released by drainage spontaneously or forced by man, and, therefore, produces a simple desaturation. In addition, he shares [4] that free aquifers are in direct contact with the ground surface and the water table is subjected to atmospheric pressure, examples of which are terraces and alluvial plains.

Following [4], he calls confined or captive aquifers, as the volume of water that is surrounded in the subsoil above and below by impermeable materials. The weight of the upper materials supposes a load or pressure on the water called interstitial tension, and on the physical skeleton of the aquifer called intergranular tension. In this sense, when it is pumped, the water released by these aquifers comes both from the decompression of the ground, and from the water itself.

Finally, for [4], the last classification of aquifers are semi-confined aquifers, considered as the amount of water in a physical system made up of a well-fed upper aquifer, a semi-permeable package or aquitard, and a lower aquifer in good conditions. Of semi-confinement. The difference in piezometric level between the aquifers causes a vertical transfer of water up or down, depending on the position of the piezometric levels of both aquifers.

Within the hydraulic parameters of an aquifer, the following are of interest: porosity and types of porosity, permeability or hydraulic conductivity, transmissibility and specific flow, storage coefficient, and radius of influence.

As already described, what is of interest in this article is the analysis for calculating the storage coefficient, for which there are several methods for determining it depending on the aquifer, whether confined, semi-confined or free, the following stand out: Thiem, Jacob, Theis, De Glee, Hantush, theoretical ascents, Dupuit, Boulton and Neuman.

The expressions according to the pumping test are described below:

For a confined aquifer with a pumping test in a permanent regime, in which the levels in the well stabilize after a while and this does not vary with the pumping and at the same time the aquifer acts as a means of transmitting the recharge and that the pumping does not take water from storage, we have Thiem's method:

$$h_o - h = \frac{Q}{2 * \pi * T} * \ln \frac{R}{r} \tag{1}$$

where:

h_o = initial piezometric level;

h = piezometric level at point r;

Q = pumping flow;

T = transmissibility;

$h_o - h$ = descent;

R = radius of influence;

r = distance from the point to the well axis.

For a free aquifer with pumping test in a permanent regime, according to [5], in which the levels in the well stabilize after a while and this does not vary with pumping and at the same time the aquifer acts as a transmission medium of the recharge and that the pumping does not take water from the storage, we have the Dupuit method:

$$h_o^2 - h^2 = \frac{Q}{\pi * T} * \ln \frac{R}{r} \tag{2}$$

where:

h_o = initial piezometric level at the point of observation;

h = level at the observation point at the end of pumping;

Q = pumping flow;

T = transmissibility of the aquifer;

$h_o - h$= descent at the point of observation;

R = radius of influence (distance, from the pumping well, at which the descent is zero);

r = distance from the observation point to the axis of the pumping well.

For a confined aquifer with a variable regime pumping test, according to [5] in which the levels in the well vary throughout the test, which means that the extracted water comes totally or partially from the aquifer storage. These tests are usually at a constant flow where the control variable is the level, but they can also be carried out at a constant level by varying the flow to keep the level constant, using Jacob's method:

$$h_o - h = s = 0.079\frac{Q}{T} * \ln\frac{2.25 * T * t}{r^2 * S} \tag{3}$$

where:

s = is the drop measured at time t, from the start of pumping, at the measurement point located at distance r from the axis of the pumping well;

Q = pumping flow;

T = transmissibility of the medium;

S = storage coefficient of the medium.

In the following order, the types of pumping tests at constant flow are detailed, the most common and interpretation methods to be used in the study of confined, semi-confined or free aquifers, see Table 1.

Table 1. Types of pumping tests at constant flow and interpretation methods to be used in the study of confined, semi-confined or free aquifers.

Aquifer Type	Test Type		Analysis Method
Confined	Permanent regime		Thiem equation
	Variable regime	Descent Interpretation	Theis equation Jacob's logarithmic approximations
		Recovery interpretation	Theis recovery equation
semi-confined	Permanent regime		Ecuación de De Glee o de Jacob-Hantush
	Rariable regime	Descent Interpretation	Hantush equation
		Recovery interpretation	Theoretical promotion analysis
Free	Permanent regime		Thiem's equation and Jacob's correction Dupuit equation
	Variable regime	Descent Interpretation	Theis equation Jacob's logarithmic approximation Dupuit correction Boulton's equation Neumann's equation
		Recovery interpretation	Theis recovery equation

Note: table organized from the fundamentals of method by [5].

Finally, (Villarroya, 2009) [4], proposes as a definition the storage coefficient (S) as the volume of water that is capable of releasing an aquifer prism of unitary base and height of the saturated thickness (b), when the hydraulic potential. The unit varies, it is a dimensionless parameter.

4. Results

After having analyzed each of the methods for the analysis of the pumping test according to the type of aquifer, the variables that affect the calculation of the storage coefficient have been identified, these are: the flow, the drop-in level or drawdown, transmissibility, and distances between the observed point and the point from where it is observed.

From the analysis of each of the methods, an arrangement is made that consists of structuring data from the tests carried out, which is capable of processing a collection of data of the same or different type, associating it with a sequential order number, resulting in an easy-to-understand methodology for calculating the storage coefficient.

The data obtained from the test point 1, coordinates WGS-84 UTM 1,343,608 North, 575,425 East at a height of 69 msnm, constant flow rate of 35 gpm with a time of 480 minutes, in a confined environment. See **Table 2**.

The data obtained from the test point 2, coordinates WGS-84 UTM 1,343,626 North, 583,455 East at a height of 71.48 msnm, constant flow of 361 gpm with a time of 900 minutes, in a confined environment. See **Table 3**.

The data obtained from the test point 3, coordinates WGS-84 UTM 1,343,627 North, 583,442 East at a height of 73.32 msnm, variable flow rate of 506.33 gpm with a time of 630 minutes, in a confined environment. See **Table 4**.

The data obtained from the test point 4, coordinates WGS-84 UTM 1,343,626 North, 583,453 East at a height of 69.21 msnm, variable flow of 515.14 gpm with a time of 680 minutes, in a confined environment. See **Table 5**.

The methodology for Jacob's arrangement begins with the value of Theis, where $\mu = r^2 * \frac{s}{4 * T * S} \leq 0.05$ this is the argument of the well function and expresses an error of 5%. For this, the initial conditions must be seasonal, so the first step is to graph the drawdown versus the time of each observed point, the work scale of the abscissa axis must be logarithmic. See **Graphs 1-4**.

With the graphs present the trend line, the logarithmic equation and its correlation see **Table 6**.

The next step from expression 3, calculate the transmissibility, that is: $s = 0.183\frac{Q}{T}$, T is solved, and "s" is obtained from the results of the logarithmic equation obtained, and Q the flow in m^3/day, this is done for the four points, see **Table 7**.

Continuing with the methodology, calculate the time when the decrease is equal to zero from the expressions obtained in **Table 6**, the following **Table 8** is obtained:

Table 2. Data from the pumping test point 1 at constant flow in a confined medium.

Time in minutes	Abat (feet)	Abat (m)	Time in minutes	Abat (feet)	Abat (m)
0	0	-	45	0.5	0.15
1	0.025	0.01	50	0.525	0.16
2	0.05	0.02	55	0.55	0.17
3	0.075	0.02	60	0.575	0.18
4	0.1	0.03	70	0.6	0.18
5	0.125	0.04	80	0.625	0.19
6	0.15	0.05	90	0.65	0.20
7	0.175	0.05	100	0.675	0.21
8	0.2	0.06	110	0.7	0.21
9	0.225	0.07	120	0.725	0.22
10	0.25	0.08	150	0.75	0.23
12	0.275	0.08	180	0.775	0.24
14	0.3	0.09	210	0.8	0.24
16	0.325	0.10	240	0.825	0.25
18	0.35	0.11	270	0.85	0.26
20	0.375	0.11	300	0.875	0.27
25	0.4	0.12	330	0.9	0.27
30	0.425	0.13	360	0.925	0.28
35	0.45	0.14	420	0.95	0.29
40	0.475	0.14	480	1	0.30

Source: Own elaboration, test carried out on December 2, 2022.

Table 3. Data from the pumping test point 2 at constant flow in a confined medium.

Time in minutes	Abat (feet)	Abat (m)	Time in minutes	Abat (feet)	Abat (m)
0	96.5	29.42	270	122.764	37.43
10	97.438	29.71	300	126.516	38.57
20	98.376	29.99	330	132.144	40.29
30	99.314	30.28	360	138.71	42.29
40	100.252	30.56	420	148.09	45.15
50	101.19	30.85	480	157.47	48.01
60	102.128	31.14	540	166.85	50.87
80	104.004	31.71	600	178.106	54.30
100	105.88	32.28	660	189.362	57.73
120	107.756	32.85	720	200.618	61.16
150	109.632	33.42	780	211.874	64.60

Continued

180	111.508	34.00	840	223.13	68.03
210	115.26	35.14	900	234.4	71.46
240	119.012	36.28			

Source: Own elaboration, test carried out on December 10, 2022.

Table 4. Data from the pumping test point 3 at variable flow in a confined medium.

Time in minutes	Abat (feet)	Abat (m)	Time in minutes	Abat (feet)	Abat (m)
0	87	26.52	160	240.5	73.32
20	107	32.62	180	240.5	73.32
30	107	32.62	190	240.5	73.32
40	109	33.23	210	240.5	73.32
50	239	72.87	270	240.5	73.32
55	240	73.17	330	240.5	73.32
60	240	73.17	390	240.5	73.32
80	240	73.17	450	240.5	73.32
100	240	73.17	510	240.5	73.32
110	240	73.17	570	240.5	73.32
120	240.5	73.32	630	240.5	73.32

Source: Own elaboration, test carried out on December 12, 2022.

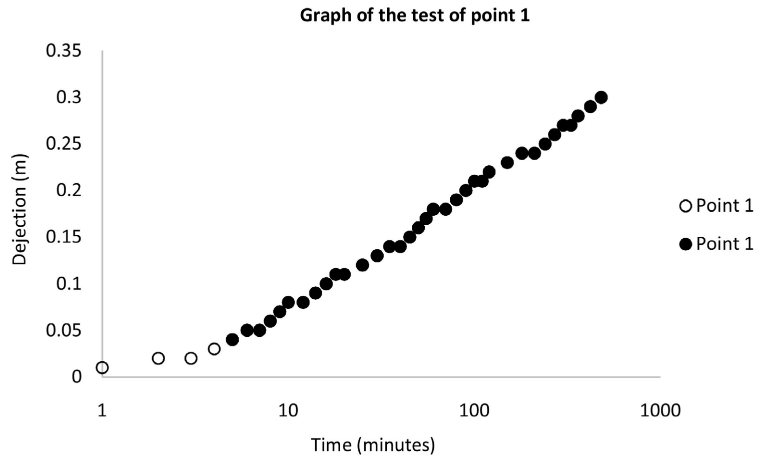
Table 5. Data from the pumping test point 4 at variable flow in a confined medium.

Time in minutes	Abat (feet)	Abat (m)	Time in minutes	Abat (feet)	Abat (m)
0	80	24.39	175	148	45.12
5	111	33.84	180	154	46.95
10	113	34.45	185	219	66.77
15	114	34.76	190	223	67.99
20	114	34.76	205	224	68.29
30	115	35.06	215	224.5	68.45
35	116	35.37	225	225	68.60
45	116	35.37	245	225	68.60
47	116	35.37	260	226	68.90
49	116	35.37	270	226	68.90
55	117	35.67	275	226.5	69.05
60	117	35.67	280	227	69.21
65	117	35.67	290	227	69.21
70	117	35.67	295	227	69.21

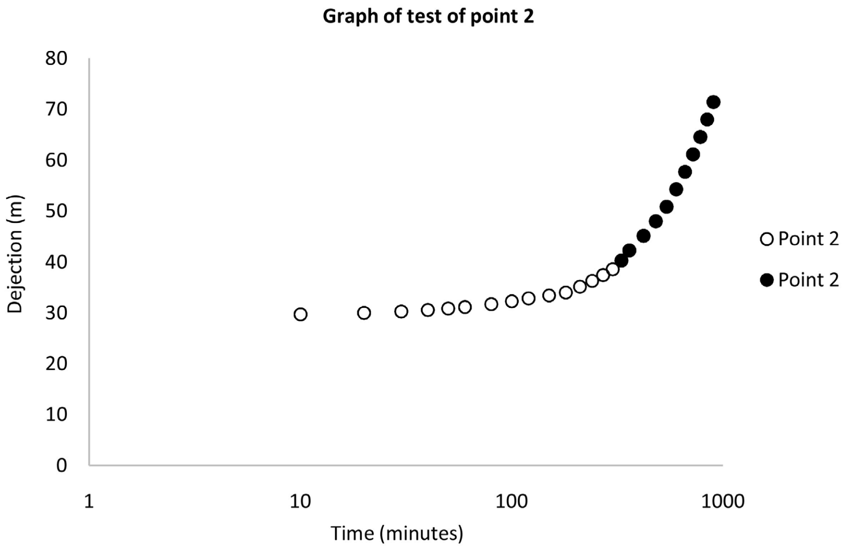
Continued

75	118	35.98	305	227	69.21
80	119	36.28	310	227	69.21
85	119	36.28	320	227	69.21
95	119	36.28	380	227	69.21
105	120	36.59	440	227	69.21
120	125	38.11	500	227	69.21
150	126	38.41	560	227	69.21
160	128	39.02	620	227	69.21
165	146	44.51	680	227	69.21

Source: Own elaboration, test carried out on December 12, 2022.



Graph 1. Logarithmic trend for trial 1. Note: The graph shows that from value 5 a linear trend will be displayed.



Graph 2. Logarithmic trend for trial 2. Note: The graph shows that from value 16 a linear trend will be displayed.

Table 6. Comparison of the trend line, logarithmic equation and correlation.

Point 1	Point 2	Point 3	Point 4
$y = 0.0571\ln(x) - 0.0588$	$y = 30.479\ln(x) - 138.65$	$y = 0.071\ln(x) + 72.9$	$y = 1.0426\ln(x) + 62.873$
$R^2 = 0.99$	$R^2 = 0.97$	$R^2 = 0.62$	$R^2 = 0.43$

Note: Own elaboration based on the data obtained from the tests.

Table 7. Calculation of transmissibility for each point tested.

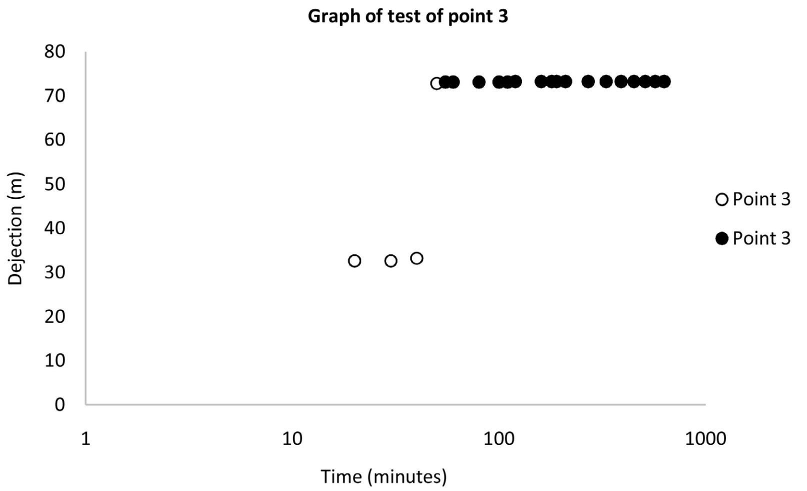
Point 1	Point 2	Point 3	Point 4
$T = 0.079\frac{Q}{s}$	$T = 0.0.79\frac{Q}{s}$	$T = 0.079\frac{Q}{s}$	$T = 0.079\frac{Q}{s}$
$Q = 228.96\ \text{m}^3/\text{day}$ $s = 0.0571$	$Q = 3672.50\ \text{m}^3/\text{day}$ $s = 30.479$	$Q = 3314.64\ \text{m}^3/\text{day}$ $s = 0.071$	$Q = 3371.24\ \text{m}^3/\text{day}$ $s = 1.0426$
$T = 316.77\ \text{m}^2/\text{day}$	$T = 9.518\ \text{m}^2/\text{day}$	$T = 3688.12\ \text{m}^2/\text{day}$	$T = 255.45\ \text{m}^2/\text{day}$

Note: Own elaboration based on the data obtained from the tests.

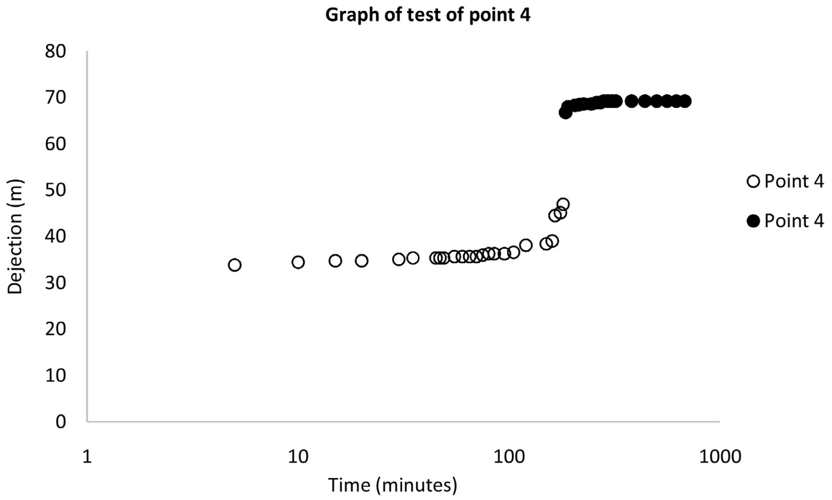
Table 8. Time when the descent is equal to zero.

Point 1	Point 2	Point 3	Point 4
If $y = 0$ then $x = e^{\frac{0.0588}{0.0571}}$ $x = 2.80$ min $x = 0.0019$ day	If $y = 0$ then $x = e^{\frac{138.65}{30.479}}$ $x = 94.54$ min $x = 0.065$ day	If $y = 0$ then $x = e^{\frac{-72.9}{0.071}}$ $x =$ error	If $y = 0$ then $x = e^{\frac{-62.873}{1.0426}}$ $x = 0$ min
		The way to obtain the data was not indicated, possible error of the person	The way to obtain the data was not indicated, possible error of the person

Note: for points 1 and 2, a time is observed when the decrease is equal to zero, in points 3 and 4 the time is not displayed, so human error is attributed when carrying out the test.



Graph 3. Logarithmic trend for trial 3. Note: The graph shows that from value 16 a linear trend will be displayed.



Graph 4. Logarithmic trend for trial 4. Note: The graph shows that from value 28 a linear trend will be displayed.

The next step is to calculate the storage coefficient from expression 3, when the time is given, the slope or "*s*" is equal to zero, so an arrangement is made to the expresión $h_o - h = s = 0.079\frac{Q}{T} * \ln\frac{2.25 * T * t}{r^2 * S}$ remaining as follows:

$$\underbrace{s = 0.079\frac{Q}{T}}_{\text{equal to zero}} * \underbrace{\ln\frac{2.25 * T * t}{r^2 * S}}_{\text{equal to one}}$$

$$\ln(1) = \frac{2.25 * T * t}{r^2 * S} = 1$$

$$S = \frac{2.25 * T * t}{r^2} \tag{4}$$

Equation (4) would be the equation with the arrangement to determine the storage coefficient in tests 1 and 2.

Where:

T = transmissibility in m^2/day;

t = time when descent equals zero, in minutes;

r = is the distance from the tested well to the observation well in (m).

Therefore, the storage coefficient for wells 1 and 2 are determined from expression 4, knowing the distance from the tested well to the observation well, in the case of point one it will be 3 m and in the case of point two will be 30 m.

Applying expression 4, there is a storage coefficient of 0.15 for point one, and for point two the storage coefficient is 0.001.

5. Conclusions

According to the analysis to determine the storage coefficient of an aquifer, variables such as transmissibility, flow, drawdown, and time were determined.

From the tests carried out, point 3 and point 4, it is concluded that the way to obtain the data was not adequate, since the possible error caused is assumed to be human manipulation, however, in points 1 and 2 it was achieved. Develop the arrangement for the model of the Natural Logarithm curve from Jacob's approach.

In this case, to determine the storage coefficient with the arrangement of the Natural Logarithm curve, it was possible to quantify thanks to the initial characteristics such as the constant flow in a confined environment.

Finally, in points 1 and 2 it was possible to calculate the storage coefficient from the Natural Logarithm arrangement model, with a correlation equal to $R^2 = 0.99$, and $R^2 = 0.97$ respectively, indicating that this method can be applied as long as there are conditions of free aquifer and that manipulation of data alteration is not frequent.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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