Abstract: Many of the large number of underground works constructed or under construction in recent years are in unfavorable terrains facing unusual situations and construction conditions. This is the case of the subject under study in this paper: a tunnel excavated in evaporitic rocks that experienced significant karstification problems very quickly over time. As a result of this situation, the causes that may underlie this rapid karstification are investigated and a novel methodology is presented in civil engineering where the use of saturation indices for the different mineral specimens present has been crucial. The drainage of the rock massif of El Regajal (Madrid-Toledo, Spain, in the Madrid-Valencia high-speed train line) was studied and permitted the in-situ study of the hydrogeochemical evolution of water flow in the Miocene evaporitic materials of the Tajo Basin as a full-scale testing laboratory, that are conforms as a whole, a single aquifer. The work provides a novel methodology based on the calculation of activities through the hydrogeochemical study of water samples in different piezometers, estimating the saturation index of different saline materials and the dissolution capacity of the brine, which is surprisingly very high despite the high electrical conductivity. The circulating brine appears unsaturated with respect to thenardite, mirabilite, epsomite, glauberite, and halite. The alteration of the underground flow and the consequent renewal of the water of the aquifer by the infiltration water of rain and irrigation is the cause of the hydrogeochemical imbalance and the modification of the characteristics of the massif. These modifications include very important loss of material by dissolution, altering the resistance of the terrain and the increase of the porosity. Simultaneously, different expansive and recrystallization processes that decrease the porosity of the massif were identified in the present work. The hydrogeochemical study allows the evolution of these phenomena to be followed over time, and this, in turn, may facilitate the implementation of preventive works in civil engineering.

Keywords: tunneling; geotechnical risk; evaporitic karstification; saturation index

1. Introduction and Objectives

Karst in evaporitic rocks presents a large variety of risks associated with any type of infrastructure. The risk component is inevitable. It cannot be totally eliminated, although it can be reduced to an acceptable level if rigorous studies are performed in the initial phases of geotechnical and geological research. Thus, risk can persist not only during the construction phase, but also throughout the useful life of the infrastructure, since detecting in advance all problems of this nature is practically impossible [1]. Since evaporitic rocks can be karstified in months and/or years, continuous monitoring and surveillance of the hydrogeological behavior of the massif near a tunnel is crucial during its useful life.

Regarding the risk reduction strategy during the previous phases of the investigation, the geological predisposition constitutes the most important factor in determining the karst conditions that could occur on site during construction. Of the set of factors that explains the
development of a karst system, the lithological factor is the most important and necessary, since karst can be considered as intrinsically linked to certain lithologies. In evaporitic rocks, the ease of karstification will depend mainly on the solubility of the mineral specimens present. The prevention and prediction of risks related to karst in evaporites is based on a good knowledge of geological formations with minerals susceptible to dissolution, as well as their location. Secondly, it is important to know the hydrogeological conceptual model prior to the infrastructure construction, as well as the factors that are expected to become involved in the evolution of the massif karstification as a consequence of these anthropic changes.

Regarding the importance of hydrogeology, gypsum and evaporite rocks in general have not aroused the interest of hydrogeologists, since they constitute low-quality aquifers for human water supply and use. The hydrogeological interest lies more in the field of applied geology and geotechnics, as they are related to problematic geological formations in the infrastructures construction and its interaction with water [2].

Among these problems the risk of karstification near tunnels is found. Gypsiferous massifs are not excessively permeable if they are not karstified. However, natural karstification originated in geological times, or was produced in an accelerated way by the alteration of the flow induced by a tunnel construction, for example, which can create a new anisotropic aquifer with a much higher porosity and permeability [3,4].

The knowledge of the mechanisms that operate in karstification and other processes of interaction with water in gypsum and other evaporitic rocks has a clear scientific interest and relevant engineering importance. These mechanisms condition the stability of any civil engineering work located in this type of terrain. Given the large extent that gypsum and evaporite soils reach in general in Spain [5], this becomes one of the problems that most frequently concerns infrastructure construction.

The consequent problems of geological, applied geology, and hydrogeology character are important. Their practical consequences can become even more complex and important if a good geological and hydrogeological knowledge is not available. This also implies knowing the mechanisms that operate between the terrain and the water.

In the case of underground excavations, it is also a problem that is occurring with increasing frequency in the tertiary sedimentary basins of Spain and Europe, as the depth of these new infrastructures reaches more saline units below, where besides gypsum, there may be other more expansive minerals (case of anhydrite) or much more soluble minerals, such as halite, epsomite, glauberite, thanardite, etc. Example cases are tunnels in the French Jura, Wagenburg North in Baden–Württemberg (Germany) [6,7], Lilla tunnel (Lérida, Spain) [8,9], Fabares (Asturias, Spain), Albertia (Alava, Spain) and Regajal (Madrid, Spain) [10–13].

Many infrastructures modify substantially the natural flow of groundwater during their construction, and even during their operation. This is the case in dam foundations on soluble materials, where the speed increase of the seepage can lead to their dissolution. In tunnels dug below the water table, groundwater drainage and karst reactivation of the massif can occur.

The processes and chemical reactions that occur due to interaction of water with the minerals of evaporitic rocks are usually very slow under natural conditions, where hydraulic gradients are usually small, and there is a hydrochemical balance between groundwater and rock. However, the alteration of the underground flow due to the construction of tunnels can accelerate these processes and increase the hydraulic gradient and, consequently, the speed and the water renewal. This can imply loss of tunnel peripheral support mainly by the generation of dissolution voids, which involves important consequences for the stability of the infrastructure and the area around it.

Some of the processes that can occur in the evaporitic massifs that contain the above-mentioned minerals are related to mineral expansiveness and to rock porosity changes. The main processes are dissolution, transformation from glauberite to gypsum, physical erosion, expansiveness of anhydrite, and salt crystallization [10,11]. Among all, it is
worth mentioning dissolution, which greatly affects halite, thenardite, and mirabilite, and
moderately affects gypsum and anhydrite. These modifying processes in evaporitic rock
massifs are accelerated near dams, tunnels, and other structures and could compromise
their stability due to the alteration of the initial hydrogeological conditions.

During tunnel construction, water can significantly accelerate karstification phenomena. Expansion phenomena are also frequent due to the change in anhydrite volume, creeping, corrosion, etc. They are phenomena that, in some way, are interrelated with each other, but are not the subject of this work. This paper deals exclusively with the
first generation of karstification. All these phenomena influence, when planning technical
solutions in the excavation system to limit the active zone [10] as much as possible, the
waterproofing of the tunnel and the support-lining.

The chemistry, flow, and groundwater temperature play fundamental roles in the
processes of dissolution, precipitation, and swelling [14].

In addition to mineralogy, the hydrogeological context knowledge and the conceptual
model of hydrogeological functioning is essential, as has been stated already. The water
mobility is key to estimating the stability of the rock through which it circulates or is
stored. In this sense, to identify supersaturated watertight zones without dissolution,
it may be convenient to use isotopes to determine the water age, such as tritium. It is
convenient, however, to carry out water stability diagrams with respect to calcium and
sodium sulphates that allow one to know if such water can cause dissolution in different
mineral species existing in the massif.

To determine and predict the progress of karstification, it is important to verify if all
the ions are active, since their activity is conditioned by the electrical charges of other ions.
For this reason, it is necessary to obtain the activity coefficients and subsequently determine
the chemical equilibrium of the reactions of the different materials existing and involved
in the dissolution process (saturation index), which will allow the dissolution reaction
direction for each material to be deduced. It is about knowing the residual dissolution
capacity and the tendency to saturation. Additionally, in a particular way, the solid mass
loss and, consequently, the karstification increase due to the drainage to the tunnel or to
the pumping wells, as occurred in the case here studied.

The karst processes and the dissolution of gypsum and evaporitic rocks were discussed
by [15–21], but the saturation index is a novel methodological technique in the tunneling
and civil engineering field and has not been used before, although it has been applied
from a speleogenetic point of view in geomorphology [17]. The need for a saturation index
calculation with respect to several mineral species is justified. It helps to determine the
water capacity to continue dissolving materials and therefore allows the increase in karst
progress to be predicted.

Thus, the main objective of this work is to contribute to a greater knowledge in the
gypsum and evaporitic rocks karstification field in those massifs crossed by tunnels by
applying the saturation index of the mineral specimens present in them. To reach this
main final objective, we address, in an orderly manner, the following specific objectives:
(i) the definition of the geological and hydrogeochemical conceptual model of the site,
characterizing the local petrology and mineralogy; (ii) the chemical characterization of
the groundwater and its evolution over time; (iii) the study of the groundwater chemical
stratification and the potential relationship between the stratification and the geology
and mineralogy of the area; (iv) the determination of equilibrium states of the saturation
reactions of the groundwater regarding the different evaporitic minerals; and (v) the
identification of the modifying processes of mineral transformation as a consequence of
the flow alteration caused by the drainage operations.

2. Description of the Case Study

The case study in this work is the south portal of the El Regajal Tunnel, on the high-
speed railway line from Madrid to Valencia (Figure 1). The area is located between the
provinces of Madrid and Toledo, in its rise from the Tagus river plain to the Ontigola
plateau. The drainage network in this plain is quasi-endorheic, and at its head there are (and were) damp areas prone to flooding. On the eastern edge of these highlands are the so-called Ontígola springs. Their flow drains to the north through the Arroyo de la Vega to the Aranjuez and Tagus River. The tunnel is part of the Aranjuez–Ocaña section of the Levante high speed railway access. Work on the tunnel lasted from 2008 to 2010. It is a double track tunnel with an approximate inner diameter of 8.50 m. The useful section interior is 85.7 m$^2$, but the excavation section reaches 180 m$^2$. The maximum cap is 65 m with an average cap of 40 m. The average slope is 25 thousandths. The total length, including false tunnels, is 2445 m.

Figure 1. High-speed train line and El Regajal tunnel location in the municipality of Aranjuez city, Madrid province.

The tunnel was built with robust sections, preventing decompression of the massif, and avoiding all possible water contributions, both from the very excavation (which was carried out with the least amount of water possible), and from all types of water flow into the tunnel.

For this, the excavation was performed mainly in phases by a roadheader in saline soils and hydraulic hammers in clay soils. The lining was designed as a full section, very close to the excavation front, to achieve a rapid closure of the section [22], avoiding movements and decompressions that would promote incoming water. In the project, a series of standard sections were proposed, which in the construction phase were simplified to four very similar designs (Figure 2), varying only in the inverted vault thickness and its reinforcement. These sections are (1) the excavation in clay and clayey marls (I–M$_1$), (2) the section of glauberite and halite without water (I–R$_N$), (3) the anhydrite and expansive materials section (I–M$_{EXP}$), and (4) the sections with risk of dissolution (I–M$_{PIL}$) [22].
Figure 2. El Regajal tunnel final cross sections.

The tunnel was executed as a false tunnel for the last 334 m of the southern mouth. The southern portal was carried out by a trench excavation 527 m long with a maximum depth of 15 m and an intermediate berm, a width that varies from 80 m on the surface to 40 m at the bottom of the excavation, and slopes of a 1:1 ratio.

In this area, this underground work crosses evaporitic Miocene materials. The final stretch of the tunnel ends in a false tunnel, as mentioned, and a large trench (Figures 3 and 4), both in an ascending slope. This track intersects a subhorizontal geological contact between a lower layer of saline materials (in which halite and glauberite predominate, sometimes in a massive form and others interbedded with clay) and an upper horizon rich in gypsum and clay (Figure 4). During the construction of the southern portal, it was observed that this stratigraphic discontinuity acts as a water exudation zone, and waterproofing and other measures were taken, such as waterproofing of concrete modules joints, injections, etc. [22,23].

In order to avoid problems during construction and exploitation of the tunnel, a drainage well was drilled to the northeast of the trench, near the tunnel portal, to drain the massif. A small wall of cut-off piles was built parallel to the tunnel axis to stop or reduce water infiltration into the tunnel from the ground. The groundwater, pumped since 2011 from the well, was first poured into a decanter before joining the drainage waters from the trench located in the last stretch. Analysis of the drained groundwater indicated an electrical conductivity of about 56,000 µS/cm due to the dissolved salts.

The drainage well was drilled during the construction of the excavation of the false tunnel to work in dry conditions, and it is still (when this work was being delivered) in use to avoid infiltration to the tunnel. Nevertheless, the groundwater extraction, heavily loaded with salts, caused material loss in the tunnel environment due to dissolution in the evaporitic massif (Figure 4D).
Figure 3. Detail of the south portal of the tunnel and trench. The trench is shown on the right side indicating its excavation slopes of the abovementioned portal, which are shown in photos A and B in Figure 4. Piezometers are shown as red circles.

Figure 4. Pictures of El Regajal tunnel and trench. (A). View of the trench from the south portal. Picture taken from the false tunnel looking south. The slopes of the excavation and part of the railway line are visible. (B). Picture of the slope trench showing the evaporitic formation stratification. The arrow points to the contact between the upper gypsum-rich materials and the lower saline materials (halite- and glauberite-rich) that act as a water exudation plane (C). Detail of the water exudation plane. Below it, whitish marks are precipitates of halite, mirabilite, and thenardite. (D). After pumping, water from the trench and drainage well were directed to the El Salobral basin. The picture shows salts that precipitated from the drained groundwater.
To study the system as a whole, a hydrogeological investigation of the tunnel and
the trench environment was carried out. The main objective was to determine the hy-
drogeological development after the construction of the tunnel and inauguration of the
high speed Madrid–Valencia line. In a retrospective way, the hydrogeological process was
inferred before and during the construction of the tunnel [24,25]. This hydrogeological
study addressed two fundamental questions: the analysis of the drained groundwater
origin, and geotechnical risk mitigation. Subsequently, the saturation indices research
presented here was developed.

This work also aims to reflect on the need to carry out prior hydrogeological studies
during the project phase of any tunnel with a regional character without being restricted to
the narrow strip defined around the tunnel axis [26].

3. Methodology

To achieve the objectives proposed above and given the hydrogeochemical nature of
the research, the following methodology was followed:

1. Compilation of background and historical data available (construction project and
data that were collected at the time of construction of the tunnel).
2. Mineralogy identification of the evaporite massif in order to define potentially karsti-
fiable mineralogical species.
3. Analysis of the hydrogeological situation before and especially shortly after the
execution of the tunnel works. The features of the existing aquifers in the area and
the natural hydrological behavior of the streams were defined in order to identify the
piezometric changes and the influence of the water flow in the massif.
4. Modeling of the behavior of the waters of the massif in relation to its dissolution
capacity. This model was made based on the calculation of solute content activities in
those waters. The objective was to fix the saturation index of each salt at the time of
its sample collection. This index established a specific state in the dissolution process
of each salt and, therefore, allowed the karstification degree at that moment to be
estimated and, where appropriate and with more data, the evolution over time to be
determined.

This methodology entailed, therefore, some field work and cabinet and laboratory
work as well.

3.1. Field Work and Laboratory Tests

Firstly, a site geological study (geological cartography) and in depth geological cross
section analysis were performed, which involved a detailed stratigraphy of the different
geological formations. For that, intense field work was carried out, taking advantage
of the outcrops of trench clearings, etc., and the information provided from ten railway
tunnel project boreholes and twenty other boreholes fitted with piezometers (open-pipe
type) specifically carried out later for this specific current work (Figure 3). The borehole
depths ranged between 20 and 45 m. Since it was not possible to visually determine all the
mineralogical species in the sounding recognition obtained from these boreholes, careful
sampling was carried out, identifying and making comparisons with the mineralogical
analysis collected in the preliminary geotechnical tunnel project studies.

The field work included an inventory of forty-five existing water-points in the wider
environment of the study area, which included springs, wells, other boreholes, and streams.
Complementing this information and to determine in detail the hydrogeology of the
site, a piezometric network of 20 boreholes/piezometers was designed. This network
of piezometers helped, among other things, to measure water levels and draw isopieze
maps, thus determining the induced underground flow system. Among the water points,
in addition to the piezometers, the following should be mentioned: the abovementioned
pumping well, the drainage pump of the ditch, and the Ontigola springs, which are located
at 2725 m in the center of the abovementioned village at the public park of Los Manantiales.
The evolution of hydrochemistry was monitored by taking samples at different depths in the most representative piezometers in the network (PZ1, PZ2, PZ3, PZ5, PZ6, PZ7, PZ8, PZ10, and PZ11). In some piezometers, only one sample was performed. These samples were distributed in each piezometer covering the entire studied area in order to collect the ion concentrations in the water. These samples provided results of hydrochemical processes in the field.

Likewise, and given that the mineralogical quality of the ground varies depending on the stratification, at different depths in some piezometers (number 6—PZ6, for example) water samples were also carefully taken. Some of the samples were taken during the excavation of the borehole or piezometer.

Water samples were also taken from the water-points around the tunnel, in the drainage well, and at the pump exits. Samples were analyzed, characterizing their composition, activity, saturation, and dissolution capacity in the laboratory (Table 1).

The field works were performed in 2011–12, including sampling. In winter 2012, mineralogical studies were carried out, and, finally, modelling was fulfilled in 2015.

3.2. Modeling

Based on the sample analyses, the evaluation of the chemical activity of the salts was estimated in order to determine the different saturation indices and, therefore, water capacity to continue dissolving saline minerals. In this technique, a calculation model of the ionic activities, the saturation degree, and the dissolution capacity of materials was obtained. For that, a specific and simple model was developed by using an Excel spreadsheet, which allowed us to achieve all calculations. By using this model, the theoretical development of which is described below, mineral transformation of modifying processes in the field were identified. It was then possible to explain them by the flow alteration caused by the tunnel drainage operations.
Table 1. Summary of analysis/tests of water samples.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Analysis/Test Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium</td>
<td>UNE-EN ISO 16995 Determination of the water soluble chloride, sodium, and potassium content.</td>
</tr>
<tr>
<td>Sodium</td>
<td>UNE-EN ISO 16995 Determination of the water soluble chloride, sodium, and potassium content.</td>
</tr>
</tbody>
</table>

3.3. Saturation Index Calculation

In saline waters, not all ions are active, but their activity is conditioned by the electrical charges of other ions. The activity coefficients are calculated applying the Debye–Hückel formula [27], and the activity is determined in mol/L. Subsequently, the chemical equilibrium of the reactions with the different salts are determined, and then the saturation index is obtained in order to determine the direction of each reaction. The process followed to determine the saturation index (SI) is shown below.

The activity of a species or material according to its concentration is defined as

\[ (X_i) = m_i \cdot \gamma_i \]  

(1)

where

\((X_i)\): activity of the species or material under study (mol/L),
\(m_i\): concentration (mol/L), and
\(\gamma_i\): ionic activity coefficient (values are between 0 and 1)

where the activity coefficient depends on

- the radius and the ion charge,
- the dissolution temperature, and
- the water salinity (the higher the salinity, the lower the active proportion of the element).

The activity coefficient is obtained using the Debye–Hückel formula:

\[ \log \gamma_i = \frac{-A \cdot z_i^2 \cdot \sqrt{I}}{1 + B \cdot a_i \cdot \sqrt{I}} \]  

(2)

where

\(\gamma_i\): ionic activity coefficient of the ion \((i)\),
\(a_i\): constant for each ion (it depends on its radius and its charge) (Table 2), and
\(z_i\): valence of the element \(i\).
Table 2. Values of constant $a_i$ in the Debye–Hückel formula.

<table>
<thead>
<tr>
<th>Ion</th>
<th>$Ca^{2+}$</th>
<th>$Mg^{2+}$</th>
<th>$Na^+$</th>
<th>$K^+$</th>
<th>$CO_3^{2-}$</th>
<th>$SO_4^{2-}$</th>
<th>$Cl^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant $a_i$</td>
<td>5.0</td>
<td>5.5</td>
<td>4.0</td>
<td>3.0</td>
<td>5.4</td>
<td>5.0</td>
<td>3.5</td>
</tr>
</tbody>
</table>

$A$ and $B$ are constants that depend on the temperature. They are tabulated, although they can also be obtained in the following way, expressing $T$ in °C:

$$
A = 0.4883 + 8.074 \times 10^{-4} \cdot T \left( \text{mol}^{-0.5} \cdot \text{kg}^{0.5} \right)
$$

(3)

$$
B = 0.3241 + 1.600 \times 10^{-4} \cdot T \left( \text{mol}^{-0.5} \cdot \text{kg}^{0.5} \right)
$$

(4)

The influence of temperature on the activity coefficient is irrelevant for the usual range of temperatures, so that the variation of the saturation index against temperature was not significant in our case of study. This point was checked and validated in piezometer number 6 (Figure 3) for the range of 10 to 19 °C.

Parameter $I$ using the Debye–Hückel formula expresses the ionic force, which also indicates the water salinity:

$$
I = \frac{1}{2} \sum m_i z_i^2
$$

(5)

where

$m_i$: element I concentration (mol/L), and

$z_i$: valence of the element $i$.

The saturation index is related to the chemical equilibrium of the reaction, and it is expressed using the following reaction:

$$
3A + 2B \leftrightarrow 4C + D
$$

(6)

When the reaction is in equilibrium, by the law of mass action, the following is obtained:

$$
K = \frac{\gamma_C^4 \cdot \gamma_D}{\gamma_A^3 \cdot \gamma_B^2}
$$

(7)

where $K$ is a constant (theoretical) that characterizes a reaction at a given temperature (25 °C, if no other is indicated); for example, for gypsum, $K = 10^{-4.58}$ (Table 3). $K$ is also called the dissociation constant (equation in equilibrium).

Table 3. Values of the dissolution constant ($K$) of the evaporitic materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Dissolution Reaction</th>
<th>$K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anhydrite</td>
<td>$\text{CaSO}_4 \leftrightarrow \text{Ca}^{++} + \text{SO}_4^{--}$</td>
<td>$10^{-4.36}$</td>
</tr>
<tr>
<td>Thenardite</td>
<td>$\text{Na}_2\text{SO}_4 \leftrightarrow 2\text{Na} + \text{SO}_4^{--}$</td>
<td>$10^{-0.179}$</td>
</tr>
<tr>
<td>Mirabilite</td>
<td>$\text{Na}_2\text{SO}_4\text{H}_2\text{O} \leftrightarrow 2\text{Na}^{++} + \text{SO}_4^{--} + 10\text{H}_2\text{O}$</td>
<td>$10^{-1.14}$</td>
</tr>
<tr>
<td>Glauberite</td>
<td>$\text{Na}_2\text{Ca(SO}_4)_2 \leftrightarrow 2\text{Na}^{++} + \text{Ca}^{++} + 2\text{SO}_4^{--}$</td>
<td>$10^{-5.245}$</td>
</tr>
<tr>
<td>Epsomite</td>
<td>$\text{MgSO}_4 \text{7H}_2\text{O} \leftrightarrow 2\text{Mg}^{++} + \text{SO}_4^{--} + 7\text{H}_2\text{O}$</td>
<td>$10^{-2.14}$</td>
</tr>
<tr>
<td>Halite</td>
<td>$\text{NaCl} \leftrightarrow \text{Na}^{+} + \text{Cl}^{--}$</td>
<td>$10^{+1.582}$</td>
</tr>
<tr>
<td>Gypsum</td>
<td>$\text{CaSO}_4 \text{2H}_2\text{O} \leftrightarrow \text{Ca}^{++} + \text{SO}_4^{--} + 2\text{H}_2\text{O}$</td>
<td>$10^{-4.58}$</td>
</tr>
</tbody>
</table>

To evaluate the imbalance (no equilibrium) of a dissolution sample and, therefore, the direction of a reaction in such an unsaturated dissolution sample, the ion activity product (IAP) is used. Note that in Equation (7), $K$ expresses equilibrium in the sample:

$$
\text{IAP} = \frac{\gamma_C^4 \cdot \gamma_D}{\gamma_A^3 \cdot \gamma_B^2}
$$

(8)
Saturation index (SI) is a function of the $IAP/K$ ratio, where $K$ is the dissociation constant.

\[
SI = \log\left(\frac{IAP}{K}\right)
\]  

(9)

Regarding the SI, the following cases in relation to a specific material dissolution can occur:

- $SI > 0$, reaction to the left: supersaturated water, therefore precipitation,
- $SI = 0$, equilibrium reaction, and
- $SI < 0$, reaction to the right: subsaturated water, therefore dissolution.

4. Geology and Hydrogeology

4.1. Stratigraphic Synthesis and Mineralogy of the Site

The area of study is located in the Tajo basin that occupies the central part of the Iberian Peninsula. This basin was formed and filled in the Cenozoic by several basement uplifts [28]. Saline rocks in this basin are abundant [29] and have been dated to the Neogene (Figure 5). Miocene deposits of the Tajo basin were divided by [30] into three main units: the lower or saline unit, the intermediate or middle unit, and the Upper Miocene units. The lower unit, where the tunnel is located, is Lower Miocene in age (23.2–16.2 Ma), and it was formed in a wide saline lake system that occupied the basin center [31]. The saline deposits, a succession up to 500 m thick, are composed of alternating anhydrite, halite, and glauberite beds with some thin layers of interbedded fine detritic sediments [29]. At the top of the lower unit, there is a 10–20 m thick alternation of thin layers (tens of cm thick each) composed of secondary gypsum, both alabastrine and macro-crystalline, interbedded with shales and marls (Figure 4B). This unit was interpreted as a weathering cover, a product of the replacement of glauberite and anhydrite by gypsum [30]. The top of the lower unit is established at a paleokarstic surface [32]. Higher up in the sequence, the Miocene middle unit is mostly composed of primary gypsum forming tabular beds up to 1 m thick (Figure 4B). This unit passes upwards into abundant carbonate bodies and is characterized by the absence of evaporitic minerals such as halite or glauberite. During this period, there was a significant progradation of siliciclastic sediments that reached the central part of the basin. Sedimentation during the Miocene upper unit was dominated by carbonates and marls [31].

In the area of the south exit of the tunnel, the materials found in the boreholes are at the base a minimum of 10 m of massive layers of halite and glauberite covered by a 2 m thick brecciated layer of glauberite, anhydrite, and gypsum in a clayey matrix that gradually passes to about 15 m of massive beds of glauberite and thenardite with minor contents of mirabilite, polyhalite, and epsomite. This sodium sulphate-rich layer passes upwards to a 10 m thick layer of interbedded clay and secondary gypsum after glauberite and anhydrite. The contact between the lower Na-rich and the upper gypsum-rich layers is made by a 1 to 4 m thick transition layer where glauberite and anhydrite is being transformed into secondary gypsum. According to the classification defined by [30], the Na-rich facies at the base belong to the lower unit, while the upper part, rich in secondary gypsum, corresponds to the weathering cover. A representative geological cross section is included in Figure 6 across the section between the origin of the false tunnel and the trench, covering the most affected draining area of the study.
thick brecciated layer of glauberite, anhydrite, and gypsum in a clayey matrix that gradually passes to about 15 m of massive beds of glauberite and thenardite with minor contents of mirabilite, polyhalite, and epsomite. This sodium sulphate-rich layer passes upwards to a 10 m thick layer of interbedded clay and secondary gypsum after glauberite and anhydrite. The contact between the lower Na-rich and the upper gypsum-rich layers is made by a 1 to 4 m thick transition layer where glauberite and anhydrite is being transformed into secondary gypsum. According to the classification defined by [30], the Na-rich facies at the base belong to the lower unit, while the upper part, rich in secondary gypsum, corresponds to the weathering cover. A representative geological cross section is included in Figure 6 across the section between the origin of the false tunnel and the trench, covering the most affected draining area of the study.

Figure 6. Geological cross section between the origin of the false tunnel and the last trench placed in the south portal. My\textsuperscript{a}: gypsum with gray clay; My\textsuperscript{b}: gypsum with brown marl clay; R: anthropic filler; QV: alluvial (lime, clay, pebbles); MG: massive glauberite, occasionally with gray clay; MH: massive and crystalline halite; CL: contact layer between tertiary units. Weathered and fractured; PZ-3: piezometer (in black, piezometer projection; in blue, piezometer in the cross section); SH2: borehole; (600.9): ground level; 20.30: boring depth.

4.2. Hydrogeological Synthesis
4.2.1. Evaporite Aquifers before the Tunnel Construction

Under natural conditions, without any human action or alteration, in this area the following sectors (Figures 1 and 5) within the evaporite massif were defined [25].

1. Ontígola springs sector. About 3 km to the east of the southern mouth of the El Regajal tunnel, there are the so-called Ontígola springs, as mentioned, with an appreciable flow (4 L/s in the middle of 2012, low water), and originating the stream that runs northward to Aranjuez city and the Tagus rivers (Figure 5). These springs drain an aquifer comprised of karstified gypsum of the evaporitic massif upper part, as well as of the alluvial subalve drainage. This aquifer is a good example of the aquifer types that exist in the area, associated with the massif upper gypsum, calcium sulfate facies groundwater, etc.

2. Intermediate sector. Includes the highlands or intermediate plain between the above-mentioned springs and the southern El Regajal tunnel portal of the tunnel and the trench. The consequent drainage difficulty of this plain explains the existence of a water table close to the surface. Regajal is a Spanish place name that means mud, pond, swamp, or quagmire.

3. The aquifer in the area of the El Regajal tunnel portal. The existence of old lagoons that were drained and desiccated to about 4 m deep during the construction of the N-IV highway (Figure 1) is known. These lagoons drained a shallow gypsiferous aquifer that included the upper part of the evaporitic massif and perhaps spots of terraced deposits located in the surroundings.
4.2.2. Conceptual Model of Induced Flow after the Construction of the Tunnel in 2012

According to [25], when southern El Regajal tunnel mouth excavation began, the approximate water table level was about 4 m deep, which coincides with the drainage of the old lagoon. In this first stage, water was pumped directly from the excavation. Subsequently, the abovementioned drainage well was drilled. It is clear that the trench excavation and the drainage well pumping caused water table lowering in this entire aquifer sector. This was the situation in 2012 [25], as seen in the isopieze map in Figure 7. The piezometric contour map was obtained with the information of the piezometric network and shows the flow situation, already altered by the drainage operations.

Therefore, Figure 7 shows the potentiometric surface in which the drawdown cone produced by the pumping and the trench catchment creating an influence radius of about 1000 m can be easily seen. The continuity of the piezometric contours and the existence of the macrocone evidence the behavior of the massif as a single aquifer, with neither having separated compartments nor hung levels.

5. Results

5.1. Hydrogeochemistry: General Characteristics and Ion Distribution

The characteristics and chemical facies of the groundwater reflect the stratigraphy and mineralogy of the site rocks, with an increase of the salinity in depth, and a groundwater stratification according to their salt concentration. According to the results of the chemical analyses, the groundwater can be assigned to sulphated calcic facies down to approximately 5 m depth. At greater depths and in the catchment areas, the dominant water facies is sulphated sodic.

The results of the chemical analyses of the water are shown in Table 4. The last lines of the table show the results of the water taken from the two existing catchments in the
area of study, the drainage well and the pump room, as well as the union of both of them at the exit.

Table 4. Chemical parameters (mg/L) of water from different sampling points (except for PZ 6, which is shown in Table 5).

<table>
<thead>
<tr>
<th>Sample Depth</th>
<th>Na⁺</th>
<th>Ca²⁺</th>
<th>SO₄²⁻</th>
<th>Cl⁻</th>
<th>Mg²⁺</th>
<th>K⁺</th>
<th>CO₃⁻</th>
<th>CO₃²⁻</th>
<th>NO₃⁻</th>
<th>Conductivity (µS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZ-1 13 m</td>
<td>53.086</td>
<td>686</td>
<td>101.682</td>
<td>5.141</td>
<td>1.072</td>
<td>145</td>
<td>270</td>
<td>0</td>
<td>13</td>
<td>94.900</td>
</tr>
<tr>
<td>PZ-2 14 m</td>
<td>53.462</td>
<td>698</td>
<td>103.967</td>
<td>584</td>
<td>339</td>
<td>67</td>
<td>199</td>
<td>35</td>
<td>5</td>
<td>91.100</td>
</tr>
<tr>
<td>PZ-3 15 m</td>
<td>9.650</td>
<td>554</td>
<td>21.234</td>
<td>346</td>
<td>215</td>
<td>14</td>
<td>215</td>
<td>0</td>
<td>15</td>
<td>29.300</td>
</tr>
<tr>
<td>PZ-5 17.6 m</td>
<td>46.476</td>
<td>658</td>
<td>87.620</td>
<td>2.850</td>
<td>631</td>
<td>102</td>
<td>176</td>
<td>24</td>
<td>5</td>
<td>84.500</td>
</tr>
<tr>
<td>PZ-7 8.5 m</td>
<td>1.812</td>
<td>511</td>
<td>5.144</td>
<td>29</td>
<td>837</td>
<td>3</td>
<td>162</td>
<td>0</td>
<td>0</td>
<td>8.270</td>
</tr>
<tr>
<td>PZ-7 25 m</td>
<td>53.720</td>
<td>590</td>
<td>103.650</td>
<td>9.178</td>
<td>1.792</td>
<td>119</td>
<td>597</td>
<td>0</td>
<td>5</td>
<td>98.000</td>
</tr>
<tr>
<td>PZ-7 30 m</td>
<td>76.308</td>
<td>590</td>
<td>136.729</td>
<td>20.138</td>
<td>2.005</td>
<td>648</td>
<td>306</td>
<td>113</td>
<td>5</td>
<td>120.600</td>
</tr>
<tr>
<td>PZ-8 15 m</td>
<td>59.717</td>
<td>570</td>
<td>100.489</td>
<td>15.278</td>
<td>1.074</td>
<td>101</td>
<td>665</td>
<td>0</td>
<td>7</td>
<td>105.100</td>
</tr>
<tr>
<td>PZ-10 5 m</td>
<td>298</td>
<td>499</td>
<td>1.952</td>
<td>34</td>
<td>103</td>
<td>3</td>
<td>195</td>
<td>0</td>
<td>72</td>
<td>3.060</td>
</tr>
<tr>
<td>PZ-11 12 m</td>
<td>1.473</td>
<td>416</td>
<td>5.190</td>
<td>36</td>
<td>361</td>
<td>2</td>
<td>128</td>
<td>0</td>
<td>0</td>
<td>7.720</td>
</tr>
<tr>
<td>Final discharge basin</td>
<td>n.a.</td>
<td>43.741</td>
<td>654</td>
<td>106.187</td>
<td>414</td>
<td>599</td>
<td>27</td>
<td>264</td>
<td>38</td>
<td>5</td>
</tr>
<tr>
<td>Trench pumping</td>
<td>n.a.</td>
<td>4.520</td>
<td>622</td>
<td>84.349</td>
<td>484</td>
<td>213</td>
<td>145</td>
<td>18</td>
<td>7</td>
<td>81.200</td>
</tr>
</tbody>
</table>

Table 5. Distribution of the water chemical concentration in PZ-6.

<table>
<thead>
<tr>
<th>Sampling Depth</th>
<th>Concentration (mg/L)</th>
<th>5.00 m</th>
<th>10.50 m</th>
<th>18.00 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>428</td>
<td>5.971</td>
<td>49.610</td>
<td></td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>570</td>
<td>519</td>
<td>682</td>
<td></td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>2.374</td>
<td>13.073</td>
<td>100.593</td>
<td></td>
</tr>
<tr>
<td>Cl⁻</td>
<td>122</td>
<td>154</td>
<td>1.820</td>
<td></td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>133</td>
<td>249</td>
<td>837</td>
<td></td>
</tr>
<tr>
<td>K⁺</td>
<td>1.9</td>
<td>5.6</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>CO₃⁻</td>
<td>202</td>
<td>213</td>
<td>304</td>
<td></td>
</tr>
<tr>
<td>CO₃²⁻</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>77</td>
<td>48</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Conductivity (µS/cm)</td>
<td>30.830</td>
<td>18.680</td>
<td>89.900</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 shows the data recorded at different depths (5.00 m, 10.50 m, and 18.00 m) in PZ-6 (Figure 3). This piezometer is located in one of the less disturbed sectors of the aquifer by the pumping operations. A prevalent increase of concentration of ions against depth can be clearly observed. This trend depends on each ion, which represents a specific predominant mineral.

The electrical conductivity of the groundwater was found to be consistently high, which gives an idea of the high concentration of salts. The measured values ranged between 3.000 µS/cm in shallow groundwater (up to 5 m) and 120.000 µS/cm in the deepest parts. Figure 8 shows a plan view of the distribution of the conductivities in the depth range 5 to 15 m. Figure 9 shows the conductivity distribution with depth in a vertical section parallel to the false tunnel.

The sulphates in water have their origin in the dissolution of gypsum, anhydrite, thenardite, glauberite, mirabilite, polyhalite, and epsomite. The depth distribution (Figure 10) shows that sulphates increased up to 30 m, where the gypsum, glauberite, and thenardite layers are located. At greater depths, halite predominates.

Figure 11 also shows the depth distribution of the chloride concentration (mg/L). It can be seen that the concentration and dispersion of the values increased with depth, as it approached the lower halite layer. The highest ionic concentrations were found in the deepest part of the drawdown cone.

The origin of the sodium concentration in water is related to the presence of thenardite, glauberite, halite, and mirabilite. High sodium concentrations were found mostly in the lower part (Table 4), probably due to the proximity to the halite layer. It is relevant that the highest values of sodium concentration were associated with the depression cone near the drainage well, similar to what happens with chlorides.
The electrical conductivity of the ground water was found to be consistently high, which gives an idea of the high concentration of salts. The measured values ranged between 3,000 $\mu$S/cm in shallow groundwater (up to 5 m) and 120,000 $\mu$S/cm in the deepest parts. Figure 8 shows a plan view of the distribution of the conductivities in the depth range 5 to 15 m. Figure 9 shows the conductivity distribution with depth in a vertical section parallel to the false tunnel.

**Figure 8.** Conductivity at depth between 5 m and 15 m.

**Figure 9.** Conductivity ($\mu$S/m) profile along the railway track.

The sulphates in water have their origin in the dissolution of gypsum, anhydrite, thenardite, glauberite, mirabilite, polyhalite, and epsomite. The depth distribution (Figure 10) shows that sulphates increased up to 30 m, where the gypsum, glauberite, and thenardite layers are located. At greater depths, halite predominates.

**Figure 10.** Vertical profile of sulphate content (mg/L) in the evaporitic aquifer along the false tunnel showing drainage well pump (left side of the draw) and trench (right side of the draw).

Figure 11 also shows the depth distribution of the chloride concentration (mg/L). It can be seen that the concentration and dispersion of the values increased with depth, as it approached the lower halite layer. The highest ionic concentrations were found in the deepest part of the drawdown cone.

**Figure 11.** Relation between depth and chloride and sulphate content in the evaporitic aquifer.

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The presence of magnesium in water is probably due to the dissolution of epsomite. The values of magnesium concentration vary from 100 mg/L to more than 2000 mg/L. Magnesium concentration increased with depth, which seems logical due to the higher abundance of this mineral at depth. Finally, the potassium content could be explained by...
Figure 10. Vertical profile of sulphate content (mg/L) in the evaporitic aquifer along the false tunnel showing drainage well pump (left side of the draw) and trench (right side of the draw).

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The presence of magnesium in water is probably due to the dissolution of epsomite. The values of magnesium concentration varies from 100 mg/L to more than 2000 mg/L. Magnesium concentration increased with depth, which seems logical due to the higher abundance of this mineral at depth. Finally, the potassium content could be explained by the dissolution of polyhalite. Values of potassium in water ranged from a few mg/L to several hundred mg/L, increasing with depth.

5.2. Geochemistry Behavior. Saturation Index

Tables 6 and 7 show the calculated activity of the different sample ions at the drainage pump exit.

<table>
<thead>
<tr>
<th>Ion</th>
<th>C (mg/L)</th>
<th>M</th>
<th>C_m (mol/L)</th>
<th>z</th>
<th>I</th>
<th>a</th>
<th>log Υ</th>
<th>Υ</th>
<th>Υ’ (mol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>10.447</td>
<td>23</td>
<td>0.45422</td>
<td>1</td>
<td>0.75030</td>
<td>4.0</td>
<td>−0.20426</td>
<td>0.6248</td>
<td>0.283792</td>
</tr>
<tr>
<td>Ca⁺⁺</td>
<td>503</td>
<td>40</td>
<td>0.01258</td>
<td>4</td>
<td>0.75030</td>
<td>5.0</td>
<td>−0.72121</td>
<td>0.1900</td>
<td>0.002389</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>21.897</td>
<td>96</td>
<td>0.22809</td>
<td>4</td>
<td>0.75030</td>
<td>5.0</td>
<td>−0.72121</td>
<td>0.1900</td>
<td>0.043341</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>558</td>
<td>35.5</td>
<td>0.01572</td>
<td>1</td>
<td>0.75030</td>
<td>3.5</td>
<td>−0.61880</td>
<td>0.6042</td>
<td>0.009497</td>
</tr>
<tr>
<td>Mg⁺⁺</td>
<td>382</td>
<td>24.3</td>
<td>0.01572</td>
<td>1</td>
<td>0.75030</td>
<td>5.5</td>
<td>−0.68126</td>
<td>0.2083</td>
<td>0.003275</td>
</tr>
<tr>
<td>K⁺</td>
<td>18</td>
<td>39.1</td>
<td>0.00046</td>
<td>1</td>
<td>0.75030</td>
<td>3.0</td>
<td>−0.23557</td>
<td>0.5813</td>
<td>0.000268</td>
</tr>
<tr>
<td>CO₃H⁻</td>
<td>278</td>
<td>61.1</td>
<td>0.00455</td>
<td>1</td>
<td>0.75030</td>
<td>5.4</td>
<td>−0.17222</td>
<td>0.6726</td>
<td>0.003060</td>
</tr>
<tr>
<td>CO₃²⁻</td>
<td>0.001</td>
<td>60</td>
<td>0.00000</td>
<td>4</td>
<td>0.75030</td>
<td>4.5</td>
<td>−0.76615</td>
<td>0.1713</td>
<td>0.000000</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>6</td>
<td>62</td>
<td>0.00010</td>
<td>1</td>
<td>0.75030</td>
<td>3.0</td>
<td>−0.23557</td>
<td>0.5813</td>
<td>0.000056</td>
</tr>
</tbody>
</table>

Table 6. Ion activity in water at the drainage pump exit, where C is concentration (mg/L); M is molecular mass; C_m is molar concentration (mol/L); z is valence; I is ionic strength; a is constant for each ion, which depends on its radius and its charge (Table 2); Υ is activity coefficient, and Υ’ is activity in mol/L.
Table 7. Chemical equilibrium and water saturation at the drainage well according to different evaporitic minerals, where K is dissociation constant, IAP is ionic activity product, and SI is saturation index.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>K</th>
<th>IAP</th>
<th>SI</th>
<th>Reaction Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td>0.00003</td>
<td>0.00010</td>
<td>0.5952</td>
<td>saturated</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>0.00004</td>
<td>0.00010</td>
<td>0.3752</td>
<td>saturated</td>
</tr>
<tr>
<td>Thenardite</td>
<td>0.66222</td>
<td>0.00349</td>
<td>-2.2781</td>
<td>dissolves</td>
</tr>
<tr>
<td>Mirabilite</td>
<td>0.07244</td>
<td>0.00349</td>
<td>-1.3171</td>
<td>dissolves</td>
</tr>
<tr>
<td>Glauberite</td>
<td>0.00001</td>
<td>0.00000</td>
<td>-1.1969</td>
<td>dissolves</td>
</tr>
<tr>
<td>Epsomite</td>
<td>0.00724</td>
<td>0.00014</td>
<td>-1.7079</td>
<td>dissolves</td>
</tr>
<tr>
<td>Halite</td>
<td>38.19443</td>
<td>0.00270</td>
<td>-4.1514</td>
<td>dissolves</td>
</tr>
</tbody>
</table>

Table 7 shows the chemical equilibrium and the water saturation index (SI) for the different evaporitic minerals. Table 8 shows the conductivity, the total salt concentration, and the volume of salt dissolved per month in the massif. Water was slightly saturated in gypsum and anhydrite, with a very high electrical conductivity of 31.200 µS/cm. However, the saturation point of gypsum was far from what it would have been in the case of containing only calcium sulphate (whose average saturation concentration is 2.6 g/L). This is due to the presence of the other ions, and in particular the Cl\(^-\), which together determine the chemical activity of sulphate ions. The coexistence of dissolved gypsum and Cl\(^-\), modifies the chemical activity of sulphate ions. In fact, the incipient gypsum saturation in water samples of PZ-11 (SI = 0.3) and anhydrite (SI = 0.08) with a calcium sulphate concentration of 5.600 g/L and an electrical conductivity of 7.770 µS/cm was observed. In these conditions, the water was still dissolving the gypsum despite the apparent saturation evidenced by such a high conductivity.

Table 8. Electrical conductivity and concentration of total salts. Material dissolved in the drainage well.

<table>
<thead>
<tr>
<th>Electrical Conductivity (µS/cm)</th>
<th>Dissolved Salts Concentration (g/L)</th>
<th>Salts Dissolved Volume (m³/Month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.200</td>
<td>33.8</td>
<td>88.6</td>
</tr>
</tbody>
</table>

Likewise, the subsaturation of water should be highlighted with regard to the rest of the evaporite minerals (thenardite, mirabilite, glauberite, epsomite, and halite), which accentuates the water dissolution capacity and, therefore, the potential loss of material in the massif by dissolution (karstification). The monthly volume of dissolved material is 88.600 m³, increasing progressively the volume of pores and caves in the massif and therefore modifying its mechanical characteristics. Table 9 shows the saturation index (SI) of water from different sampling points.

The progress of the saturation index with depth for the different minerals is shown in Figure 12. Water is slightly saturated (>0) for gypsum and anhydrite at all depths, for epsomite and mirabilite only below 16 m, and for the rest of the minerals, saturation is never reached. The lines corresponding to thenardite and mirabilite, and also to gypsum and anhydrite, are parallel, since they have the same chemical composition except for their respective water contents.
Table 9. Saturation indexes (SIs) of the existing materials at scheduled representative sampling points. SI < 0, subsaturated water in each mineral; SI > 0, supersaturated water.

<table>
<thead>
<tr>
<th>Sample Location</th>
<th>Gypsum</th>
<th>Anhydrite</th>
<th>Thenardite</th>
<th>Mirabilite</th>
<th>Glauberite</th>
<th>Epsomite</th>
<th>Halite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ontigola 1 Spring</td>
<td>0.24</td>
<td>0.02</td>
<td>-6.78</td>
<td>-5.82</td>
<td>-6.06</td>
<td>-2.45</td>
<td>-6.53</td>
</tr>
<tr>
<td>Ontigola 2 Spring</td>
<td>0.23</td>
<td>0.01</td>
<td>-6.33</td>
<td>-5.37</td>
<td>-5.62</td>
<td>-2.41</td>
<td>-6.23</td>
</tr>
<tr>
<td>Ontigola 3 Spring</td>
<td>0.22</td>
<td>0.2</td>
<td>-5.8</td>
<td>-4.83</td>
<td>-5.09</td>
<td>-2.64</td>
<td>-5.58</td>
</tr>
<tr>
<td>PZ-5 8.5 m</td>
<td>0.32</td>
<td>0.1</td>
<td>-4.15</td>
<td>-3.19</td>
<td>-3.35</td>
<td>-1.67</td>
<td>-6.08</td>
</tr>
<tr>
<td>PZ-6 5.0 m</td>
<td>0.28</td>
<td>0.06</td>
<td>-5.54</td>
<td>-4.58</td>
<td>-4.77</td>
<td>-2.56</td>
<td>-6.01</td>
</tr>
<tr>
<td>PZ-6 10.5 m</td>
<td>0.54</td>
<td>0.32</td>
<td>-2.86</td>
<td>-1.9</td>
<td>-1.84</td>
<td>-1.97</td>
<td>-4.9</td>
</tr>
<tr>
<td>PZ-10 5.0 m</td>
<td>0.2</td>
<td>-0.02</td>
<td>-5.89</td>
<td>-4.93</td>
<td>-5.21</td>
<td>-2.7</td>
<td>-6.71</td>
</tr>
<tr>
<td>PZ-11 12.0 m</td>
<td>0.3</td>
<td>0.08</td>
<td>-4.27</td>
<td>-3.31</td>
<td>-3.48</td>
<td>-1.96</td>
<td>-6.06</td>
</tr>
<tr>
<td>Final Discharge Basin</td>
<td>0.28</td>
<td>0.06</td>
<td>-4.46</td>
<td>-3.5</td>
<td>-3.69</td>
<td>-2.31</td>
<td>-4.78</td>
</tr>
<tr>
<td>Tunnel Discharge Basin</td>
<td>1</td>
<td>0.78</td>
<td>-0.68</td>
<td>0.28</td>
<td>0.81</td>
<td>-1.23</td>
<td>-3.8</td>
</tr>
<tr>
<td>Trench Drainage</td>
<td>1.01</td>
<td>0.79</td>
<td>-2.64</td>
<td>-1.68</td>
<td>-1.14</td>
<td>-1.62</td>
<td>-4.67</td>
</tr>
<tr>
<td>Drainage Well</td>
<td>0.6</td>
<td>0.38</td>
<td>-2.28</td>
<td>-1.32</td>
<td>-1.2</td>
<td>-1.71</td>
<td>-4.15</td>
</tr>
</tbody>
</table>

![Progress of saturation (saturation index) against depth in piezometers of water intake.](image-url)
It can be deducted that gypsum, when accompanied by other evaporitic minerals (anhydrite, mirabilite, halite, etc.), shows the combined action of the rest of the ions, which manifests itself in the different ionic forces and ionic activities produced. Therefore, the saturation index (SI) is critical to determine the direction of the reaction and to determine whether the groundwater is saturated in different saline minerals or if it will continue dissolving minerals and creating or enlarging pores.

The combined influence of ions directly affects the water saturation in relation to each of the minerals. Taking as an example the gypsum’s solubility, it is remarkably modified; therefore, waters with a high electrical conductivity and a high saline concentration remain unsaturated in gypsum, having the capacity of dissolving this mineral. The described phenomenon can be observed in Table 8; an electrical conductivity of 31.200 µS/cm was measured in the water, which is slightly high and, nevertheless, the water remains unsaturated in relation to the thenardite, mirabilite, glauberite, epsomite, and halite, while in the absence of these other minerals, the gypsum saturation is reached at only 2.600 µS/cm [21].

6. Discussion

From the results obtained and considering the evolution observed in groundwater (piezometers PZ-1 to PZ-17) and in the surface waters analyzed, some aspects can be highlighted. The water flowing through the evaporitic deposits to the drainage well has two origins: (i) rain infiltration water (vertical flow), and (ii) lateral incoming flow, mostly from the aquifer of the Ontígola springs, located outside the piezometric contour map (Figure 7).

In its circulation, the infiltrated water quickly reaches equilibrium or becomes slightly saturated in sulphated calcium salts in the upper part of the aquifer. For the rest of the evaporitic minerals, the waters remain unsaturated, and rapid dissolution takes place at depth. Even so, water is only saturated in glauberite, anhydrite, and thenardite at levels below 16–20 m, and it remains unsaturated in epsomite and halite. This process is showed in Figure 12, where the prevalence of linear trends shows this phenomenon.

The incoming water to the system affected by the pumping should originally have the average chemical characteristics of the Ontígola springs. The characteristics of the outgoing water are different than those of the Ontígola spring due to the pumping operations. The chemistry variation from the original water (Ontígola springs) to the outgoing water (average of the two main catchment points, the drainage well, and drainage of the trench) is shown in Table 10. The resulting increase in salt concentration is 58.8 g/L.

Table 10. Concentration variations between surface waters of the Ontígola springs and drainage points.

<table>
<thead>
<tr>
<th>Ions</th>
<th>Concentration of Ontígola Springs (Initial Water Chemistry) (mg/L)</th>
<th>Concentration at Trench and Well Drainage Water (mg/L)</th>
<th>Difference (mg/L)</th>
<th>Difference (%) over Ontígola Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>213.74</td>
<td>7.48350</td>
<td>7.26976</td>
<td>3.40122%</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>581.67</td>
<td>562.50</td>
<td>−19.17</td>
<td>−3.30%</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>1.99994</td>
<td>53.12300</td>
<td>51.12306</td>
<td>2.55623%</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>235.59</td>
<td>521.00</td>
<td>285.41</td>
<td>121.15%</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>178.99</td>
<td>297.50</td>
<td>118.51</td>
<td>66.21%</td>
</tr>
<tr>
<td>K⁺</td>
<td>22.03</td>
<td>81.50</td>
<td>59.47</td>
<td>269.95%</td>
</tr>
<tr>
<td>CO₃H⁻</td>
<td>276.10</td>
<td>233.00</td>
<td>−43.10</td>
<td>−15.61%</td>
</tr>
<tr>
<td>CO₃²⁻</td>
<td>0.00</td>
<td>9.00</td>
<td>9.00</td>
<td></td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>115.93</td>
<td>56.20000</td>
<td>−59.73</td>
<td>−49.59%</td>
</tr>
<tr>
<td>Conductivity (µS/cm)</td>
<td>3.58667</td>
<td>56.20000</td>
<td>52.61333</td>
<td>1.46691%</td>
</tr>
<tr>
<td>Salts content</td>
<td>3.210</td>
<td>58.780</td>
<td>55.570</td>
<td>1.83115%</td>
</tr>
</tbody>
</table>

Table 11 shows the variation of the saturation index of the different salts before and after the water infiltration process of the Ontígola springs and its subsequent pumping and draining through the massif. Figure 13 shows the clear trend of the subsaturated waters.
towards saturation in several salts. However, water can only be considered saturated in gypsum and anhydrite with saturation indexes close to zero, being at equilibrium reactions. The presence of ions of different saline compounds in dissolution leads to a general subsaturation state for the rest of the salts at the drainage points, although less obvious than in the original water.

Table 11. Saturation index between surface waters of Ontígola springs and catchment points.

<table>
<thead>
<tr>
<th>Material</th>
<th>Saturation Index (SI) in Ontígola Springs</th>
<th>Saturation Index (SI) in Outcoming Drainages</th>
<th>Variation of Saturation Index (%) Over Ontígola One</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td>0.23</td>
<td>0.80</td>
<td>247.83%</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>0.01</td>
<td>0.58</td>
<td>5.70000%</td>
</tr>
<tr>
<td>Thenardite</td>
<td>−6.30</td>
<td>−2.46</td>
<td>−60.95%</td>
</tr>
<tr>
<td>Mirabilite</td>
<td>−5.34</td>
<td>−1.50</td>
<td>−71.91%</td>
</tr>
<tr>
<td>Glauberite</td>
<td>−5.59</td>
<td>−1.17</td>
<td>−79.07%</td>
</tr>
<tr>
<td>Epsomite</td>
<td>−2.50</td>
<td>−1.67</td>
<td>−33.20%</td>
</tr>
<tr>
<td>Halite</td>
<td>−6.12</td>
<td>−4.41</td>
<td>−27.94%</td>
</tr>
</tbody>
</table>

Figure 13. Saturation index evolution across locations: Ontígola springs and water drained and pumped from the ground.
6.1. Porosity Increase in the Evaporitic Massif Due to the Drainage from the Well and the Trench

The variation of saline concentration between the incoming water to the system and the water collected from the catchment points allows the total amount of dissolved evaporitic minerals and the volume that it occupied in the terrain to be estimated. The input flow data between the two catchment points averages 4 L/s (drainage well: 2.5 L/s, trench: 1.5 L/s). The average dissolution is 58.800 g/L with 90.188 g/L in the trench and 33.787 g/L in the drainage well.

Considering an average density of the evaporitic minerals of 2.47 t/m³, the yearly volume of salts dissolved is about 2.772 m³. This figure is obtained from the monthly dissolution estimated in the trench area of 142 m³/month (350.7 t/month) and from the drainage well (88.6 m³/month, 218.94 t/month).

6.2. Porosity Increase in the Evaporitic Massif Due to the Transformation of Glauberite to Gypsum

The water presence or simply the moisture can produce the replacement of glauberite into gypsum (solid) and mirabilite (dissolved) by incongruent dissolution. The transformation of glauberite into gypsum is a prototype of an incongruous dissolution reaction, the result of which is the neoformation of amorphous gypsum and the enrichment of groundwater in sulfate anion and sodium cation. This transformation entails a 27% decrease in volume and favors the generation of moderate voids in the ground, generally from pre-existing joints and cracks [33]. The diameter of the created voids can range from a few millimeters to several decimeters. These processes can be increased by the massif permeability achievement, which will tend to promote the renewed groundwater circulation and, therefore, karstification. This transformation process has slow kinetics in natural conditions, but it can be fast (days or months) in the presence of renewed “fresh” waters with high capacity to dissolve and transform the glauberite. The following possible patterns have been inferred from the behavior of each mineral observed in this study. Figure 14 represents a vertical section through the complex CaSO₄NaSO₄–NaCl–H₂O units. The water turns glauberite into gypsum by these ways: (1) through the upper gypsum aquifer with the formation of an horizon of secondary gypsum after glauberite, (2) through karstic formations caused by the volume reduction in the transformation process of the glauberite into gypsum, (3) by karst caused by the gypsum dissolution, (4) through faults, (5) by the “water call” process caused by the excavation of the tunnel, and (6) through non-closed drill holes, which reduce the phreatic level.

![Figure 14. Vertical section through the complex CaSO₄NaSO₄–NaCl–H₂O units and ways that water transforms glauberite into gypsum.](image)

Both the well and the trench lowered the phreatic level below the contact level between gypsum and glauberite at 590 m a.s.l. in a considerable area. Therefore, during the pumping process, the transformation of glauberite into gypsum was produced, which
implied a reduction of 28% of the initial volume. The effects of this process are difficult to quantify, but certainly it contributed hastily to the formation of a new aquifer, in the form of a semi-circular sinkhole around the well, where the porosity and permeability were significantly increased.

The new drainage level of the trench increased the underground flow in the saline layers down to 20 to 25 m deep, a zone where water previously barely circulated. This is the reason why waters collected at the drainage points are so saline. The large volume of additional terrain involved is large enough to maintain the current salinity levels for years.

Water comes out with a higher saline concentration in the trench than in the drainage well because the matrix flow is more important in the trench (the catchment is linear and not punctual, as in the well). Additionally, the saturated zone of the source basin of the trench is entirely located in the glauberite layer.

6.3. Distribution and Development of Porosity and Karstification in Space and Time

The most likely consequence of drainage by pumping is the development of a conduit network near the well caused by direct dissolution and erosion. It remains unknown how this porosity increase is distributed, although it is plausible that the voids are concentrated around the pumping. In the initial stages, a conduit network would be established in the preferred direction oriented (i) to the maximum hydraulic slope, and (ii) along the horizontal stratification planes, where the flow resistance is lower, taking advantage of the levels of halite and sodium sulphate with higher solubility. Figures 7–11 support these observations.

In the first phase, the stimulated water circulation caused the decrease of the phreatic level, the evacuation of the underground water stored in the upper part of the evaporitic aquifer, and in the overlying terrace, radially propagating the development of the porosity.

The analyzed karst system has a single outgoing point and multiple incoming points along the aquifer’s feeding area (Figure 15). Hydrochemistry also plays an important role, because from the subsaturated water from the rain or irrigation recharge, with the capacity to dissolve the saline minerals, it becomes saturated in sulphates when interacting with gypsum. However, water remains subsaturated and with the capacity to dissolve halite, thenardite, mirabilite, and epsomite, up to the pumping point, inclusive. It was verified that the main factor in karstification is the presence of hyper-soluble materials, in which the water is predominantly subsaturated and the dissolution process continues due to the change of saturation point, in some cases extraordinarily (Figures 11 and 12).

Figure 15. Possible development of karstic networks from the drainage well and the trench.
7. Conclusions

The study and monitoring of the evaporitic massif drainage of El Regajal (Madrid–Toledo), in the works of the trench and the false tunnel of the Madrid–Valencia high-speed railway line, has allowed the hydrochemical evolution of the water in evaporitic materials to be determined.

The piezometric contours map, obtained from the piezometric control network, shows a macrocone of depression around the pumping and at the catchment of the trench, with an influence radius of at least 1000 m. The topographic height of these two drainage points determines the new hydrogeological base level, which is lower than Ontígola springs, located 2.5 km eastwards, and with whose aquifer they are hydraulically and laterally connected.

The continuity of the potentiometric surface and the existence of the macrocone of depression show that the evaporitic massif behaves hydrogeologically as a single aquifer, without separate compartments or hanging levels in vertical. This does not imply that, on a small scale, the groundwater circulates preferably through the horizontal stratification planes, karstic conduits and fractures [33].

The minerals composing this evaporitic massif are arranged in horizontal layers with gypsum dominating in the upper and thenardite, glauberite, halite, mirabilite, and polyhalite in the lower. The characteristics and chemical facies of the groundwater reflect the stratigraphy and mineralogy of the area, with an increase of salinity at depth, and groundwater stratification. The sulphated sodic water facies are dominant in the catchment areas.

The hydrochemical study of the water samples in the different piezometers at different depths, including the calculation of their activities, has allowed the saturation index for different saline materials to be identified, and the water residual dissolution capacity was largely surprising despite electrical hyperconductivity, as is shown in Figures 7–11.

Except for gypsum and anhydrite, which appear saturated in most of the piezometers, especially at the points located at low depth, all the present minerals of evaporitic origin in this massif are susceptible to be dissolved according to the groundwater chemistry, at least to 16 m depth. Below this depth, the water remains subsaturated in relation to thenardite, mirabilite, epsomite, glauberite, and halite.

The alteration of the underground flow and the consequent water renewal of the aquifer by the infiltration of rainwater and irrigation are the cause of the hydrogeochemical imbalance and of the modification of the massif characteristics. These changes, in general, cause an important loss of material, changing the strength of the terrain and the increase of voids index. These processes have been quantified, highlighting the dissolution of halite, thenardite, and mirabilite to an extreme degree, and to the gypsum and anhydrite to a moderate degree. They also include different expansive and recrystallization processes that decrease the massif porosity. Likewise, the transformation of glauberite into gypsum by incongruent dissolution, the physical erosion by water circulation, the anhydrite swelling by hydration, and the crystallization of new salts were identified. It was estimated that the evaporitic material lost in the area from the ground by dissolution is about 2.700 m³/year, extrapolating the results of study as constant over time.

All these processes are originating a new aquifer by karstification and a new evaporitic massif by mineralogical transformation. It is estimated that the porosity near the tunnel increased by 1% during the construction period.

The processes occurring in an evaporitic massif, such as the one under study, are identifiable and in any way quantifiable, in relation to the contents of the different evaporitic minerals (gypsum, halite, thenardite, mirabilite, glauberite, epsomite, and anhydrite). These processes are the increase of voids by erosion, dissolution, and by mineralogical transformations and, on the other hand, recrystallization processes, some of them expansive, which would decrease the rock porosity, neutralizing the increase of the porosity, but with consequences in the geomechanical properties [34].
Quantifying the magnitude of these processes separately is complex, but generally, the processes increasing the porosity will be dominant over time, since as the circulation of the renewed water increases, the processes of dissolution and mineral transformation are being accelerated.

A measurement campaign of the ions existing in the water at different depths would offer more clarity about the evolution of these phenomena over time, which would facilitate the implementation of preventive and corrective measures in Civil Engineering.

Author Contributions: Conceptualization, J.A.M.P.; I.M.P., and E.S.P.; methodology, J.A.M.P.; software, J.A.M.P. and I.M.P.; validation, J.A.M.P. and I.M.P.; formal analysis, C.S.S. and E.S.P.; investigation, E.S.P.; resources, C.S.S.; data curation, C.S.S.; writing—original draft preparation, I.M.P.; writing—review and editing, I.M.P. and E.S.P.; visualization, I.M.P.; supervision, I.M.P. and E.S.P.; project administration, I.M.P.; funding acquisition, C.S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Fundación Agustín de Betancourt (FAB 2011).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors sincerely thank J.I. Escavy Fernández for advice and support in stratigraphic synthesis and mineralogy of the site, Eng. Mariano López Serrano for his contribution to the manuscript editing, and three anonymous reviewers who improved the original manuscript with their advice and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

References
2. Milanović, P.; Maksimovich, N.; Meshcheriakova, O. Overview of Dams and Reservoirs in Evaporites. In Dams and Reservoirs in Evaporites. Advances in Karst Science; Springer: Cham, Switzerland, 2019; pp. 21–33. [CrossRef]


