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Influence of the Construction of the Urdinbide Road Tunnel on the Autzagane Aquifer in Biscay (Spain)

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Abstract: The Urdinbide road tunnel goes through the Autzagane aquifer. This important aquifer is located within the hydrogeological area of the Urdaibai Biosphere Reserve, one of the most important biosphere reserves in the Iberian Peninsula, and it is also used as a source of drinking water for some urban areas in the municipality of Amorebieta-Etxano. The construction of the tunnel could pose a potential risk to the normal functioning of the aquifer, so its design included a special procedure for injecting cement and microcement to waterproof the surrounding area of the drilling, preventing the tunnel from functioning as a drain for the aquifer. The project initially included an intensive hydrogeological characterization of the rock massif, as well as a monitoring phase during the construction works, which allowed a real-time verification of the influence of the tunnel construction on the functioning of the aquifer and the restoration of its normal functioning once the works were completed. The work carried out has shown that the construction of the tunnel has not caused a significant impact on the Autzagane aquifer.

Keywords: tunnel; multilayer aquifer; underground construction; cement; microcement; injections; Flysch; waterproofing

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1. Introduction

The Urdinbide road tunnel is part of a new road communication route between Amorebieta and Muxika (Figure 1). It is in the northern part of the Iberian Peninsula, specifically in the Basque Country, running through the municipalities of Amorebieta-Etxano and Muxika in the province of Bizkaia (Spain).



Figure 1. Location of the study area. Relative situation with respect to the metropolitan area of Bilbao, capital of Biscay, in the north of Spain.

The environmental approval of the project was conditioned on the execution of the tunnel not significantly affecting the Autzagane aquifer, which it was going to pass through, as well as maintaining the existing water catchment and usage systems and the ecological flow of the Ategorri stream, which comes from the springs that supply this aquifer.

During the design phase, the hydrogeological functioning of the aquifer was studied in depth. In addition, during its construction, a thorough hydrogeological monitoring was carried out, including the monitoring of piezometric levels and flow rates. The data obtained were used to calibrate the initial hydrogeological simulation of the aquifer. This hydrogeological monitoring made it possible to quantify the effectiveness of the proposed waterproofing solution both during the construction phase and in the final phase, once the tunnel was completed and waterproofed [1].

There are many references in the scientific literature that analyze the internal dynamics of complex aquifers [2–14] and the influence of the construction of underground infrastructures in these highly permeable environments [15–18] and that study possible strategies to mitigate this phenomenon [19–21].

The Urdinbide tunnel project is characterized by its proximity to the Urdaibai area, of high ecological value, which was declared a biosphere reserve by UNESCO in 1984 [22]. In addition, it has the particularity that the Autzagane aquifer is used to supplement the water supply of an important population center in the municipality of Amorebieta-Etxano. To prevent water from entering the tunnel and draining the aquifer, a strategy of rock mass injection was employed during the construction of the tunnel, which in this particular case consisted of a combination of cement and microcement in stages. In addition, a completely impermeable lining was installed to ensure that the aquifer was not affected in service conditions.

In the particular case of the Urdinbide tunnel, systematic, repetitive, and selective injections (IRS type) were used, with a high-pressure approach [23]. These injections were carried out using a redrilling system in the same boreholes, with incremental lengths in each drilling phase. These were truncated cone-shaped drilling and grouting crowns executed in a minimum set of four stages with cement grouting in the first stages and microcement grouting in the last stages. This set of injections also served to improve the geotechnical quality of the rock mass around the tunnel.

The tunnel waterproofing system should ensure the recovery of the piezometric levels and the functioning of the streams in a normal rainfall regime, as well as maintaining the original compartmentalization of the aquifer and its natural hydrogeological functioning, as imposed by the environmental authorization of the project. The main purpose of this contribution is to describe the influence of the Urdinbide tunnel waterproofing solution on the hydrogeological functioning of the Autzagane aquifer.

2. Materials and Methods

2.1. General Description of Tunnel Works

The Urdinbide tunnel is the main element of the new road between Amorebieta and Muxika. This new road replaces a heavily trafficked route with a high accident rate [1]. It is safer and improves accessibility from the A8 motorway to the Urdaibai Biosphere Reserve area.

The Urdinbide tunnel passes through the Autzagane Pass. It starts at KP 2 + 683, near the entrance to the Biribieta neighborhood and at an altitude of approximately +185 m. It ends at KP 3 + 386, at an altitude of around +180 m, adopting a straight route with a descending slope towards Muxika. The Urdinbide tunnel is twin-tube, with two lanes per carriageway. The average separation between the two tubes is 21.50 m, practically constant throughout all the tunnel.

The length of the tunnel is around 700 m with maximum coverings of around 90 m (Figure 2). This length includes the 116 and 56 m of false tunnel at the south and north portals, respectively.

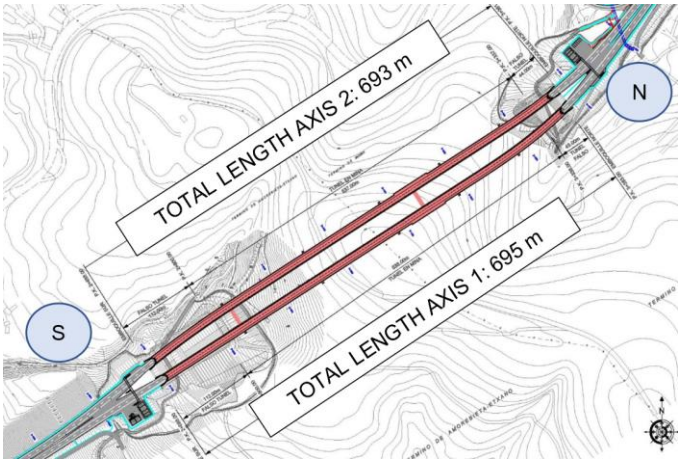


Figure 2. General layout of the Urdinbide tunnel.

The affected area of the aquifer by the tunnel is limited between KPs 2 + 859 and 3 + 019 on Axis 1 (160 m) and between KPs 2 + 840 and 3 + 004 on Axis 2 (164 m). The Urdinbide tunnel has a circular section with an inner radius of 6.53 m in the area outside the aquifer and 6.48 m in the aquifer area (Figure 3), with a height at the center of 1.286 m above the axis with the road surface along the whole length of the tunnel, achieving a minimum clearance of 5 m above the platform edges.

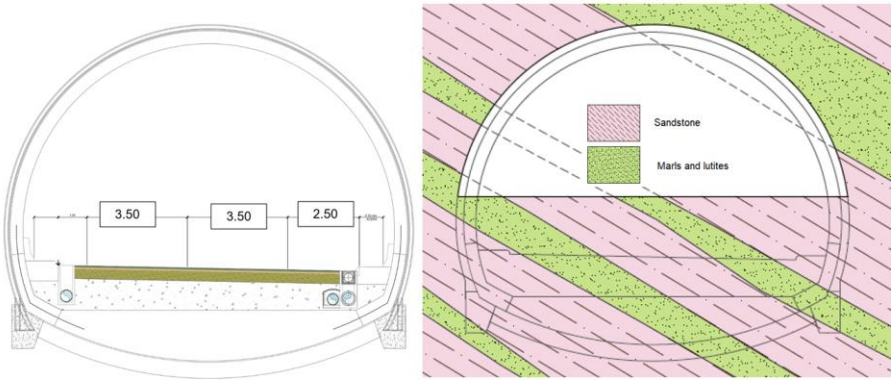


Figure 3. Cross section in aquifer influence zone (**left**). Alternation of sandstone levels with marls and lutites (**right**).

The construction of the project was divided into two stages: an initial project and a completion project, which was executed by the joint venture Viuda de Sainz and Lurpelan Tunnelling. In the completion project, 62 and 63 m were executed in top heading excavation (Axis 1 and Axis 2), as well as 160 and 164 m in bench excavation (Axis 1 and Axis 2). All the pending excavation was in the zone of influence of the aquifer (Figure 4).

2.2. Geological Study

The Urdinbide tunnel is geologically situated in the Basque–Cantabrian Basin, which is about 90 km wide and located between the Bay of Biscay and the Duero Depression. More specifically, the Urdinbide tunnel is located in the Biscay Synclinorium [24]. In the area, the synclinorium mostly forms a large structural valley of the same orientation, traversed by the Ibaizabal River, where the towns of Durango and Amorebieta are located, and which, when obliquely contacting the Cantabrian coast, gives rise to the Bilbao estuary. In Amorebieta, the north slope of the Ibaizabal River valley culminates in the Auztagane Range, crossed by the road to Gernika through the mountain pass of the same name. It is precisely this geographical feature that is intended to be overcome by the excavation and commissioning of the Urdinbide tunnel.

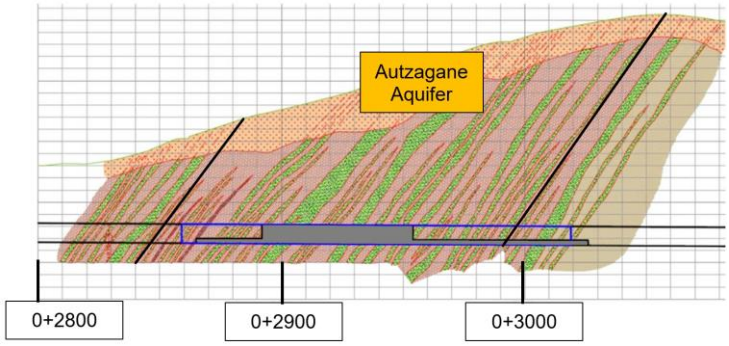


Figure 4. Location of the executed tunnel within the influence zone of the Autzagane aquifer. The figure shows the alternation of more or less permeable layers that explain its nature.

The geology of the Urdinbide massif is characterized by an alternation of sandstone and microconglomerate levels with marls and lutites (Figure 5). This alternating character, typical of flyschoid facies, is identified at all observation scales. The weathering of the massif affects both the sandstone and the lutitic and marl materials. In the first case, the dissolution of the carbonate cement in the sandstones results in sandy materials with the consequent increase in porosity and, therefore, a greater "penetrating" potential of weathering. In the case of lutitic and marl materials, the result of the alteration is clayey materials that do not substantially modify the low permeability of these materials and, therefore, have a lower capacity for alteration in depth.



Figure 5. Calcareous sandstone facies with isolated intercalations of marl material, recognized in the advance of Axis 1.

Vertically, weathering affects the sandstone and sand beds more deeply. Therefore, at the same horizontal level, there are beds or sections of more disintegrated and water-charged materials (the sandstone and sand beds) that vary alternately with other materials that are better geotechnically and more impermeable (the marl material), as shown in Figure 5. These geological characteristics determine the existence of a multilayered, basically confined aquifer. These characteristics are common to the aquifers found in the area.

2.3. Hydrogeological Study

During the project stage, a detailed hydrogeological characterization of the massif was carried out by the company EPTISA, determining the conceptual model of the aquifer's functioning, quantifying its water uses, and establishing the relationship between groundwater and the planned works before their execution. The hydrogeological study and its monitoring during the works were identified as critical elements in ensuring the final success of the project [25].

In order to achieve these objectives and establish the effects that tunnel drilling could have on the natural functioning of groundwater and its uses, various networks of piezometric and forometric control were installed.

Finally, the project included the creation of a series of numerical models of groundwater flow that have allowed validating the conceptual model of natural groundwater functioning and thus predict the effects of the tunnel on the aquifer's functioning and its water uses.

In order to carry out the hydrogeological study, existing information was analyzed first, including the construction projects that the promoter had drawn up in the work area, as well as general geological and hydrogeological studies that encompass the study area [26]. A total of 16 boreholes were drilled in which the piezometric level could be measured, with drilling depths ranging from 17 to 91 m.

In order to obtain the hydraulic parameters of the aquifer, several pumping tests were conducted. In this test, water is extracted in a controlled manner for a significant period of time, which is one of the most widely used methods for obtaining the aforementioned data [27]. In the research campaign carried out for the study, once the piezometric wells and pumping wells were drilled, three pumping tests were carried out in the wells called B-1, B-2, and B-3. Each test consisted of extracting water from the well and observing the variations in the water level depth produced in the pumping well itself and in all the existing perforations in the surrounding area that have been conditioned as piezometers. In each well, a stepped pumping stage, a constant flow stage, and a recovery stage were carried out (Figure 6). Mean permeability values of 3.5×10^{-6} m/s and a storage coefficient of 1.2×10^{-3} were obtained.

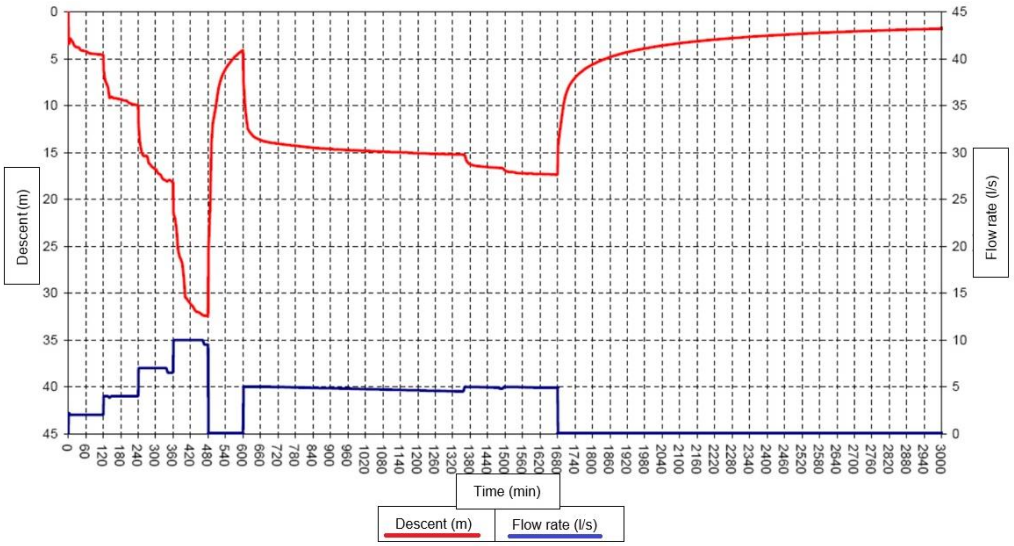


Figure 6. Graphical representation of pumping test data in well B-3.

During the hydrological study, 41 water points were identified. The main use of groundwater resources in the area closest to the south portal of the Urdinbide tunnel occurred in the headwaters of the Ategorri stream. In this sector, there were a total of 4 groundwater intakes, 3 surface water intakes, 1 distribution chamber, and a reservoir, connected by a complex network of pipes (Figure 7), all belonging to the water supply system of the Amorebieta-Etxano municipality.

A forometric network was also installed in order to allow continuous monitoring of the flow rates of the springs and intakes in the study area. To implement this control, the following infrastructure was established to determine the circulating flow rates: 3 electromagnetic flow meters with a diameter of 50 millimeters (two of them in the pipes entering the distribution chamber and the third in the pipe that goes from the Ategorri-A weir to the reservoir) and a 3-inch Parshall flume in the Ategorri stream upstream of the weir.

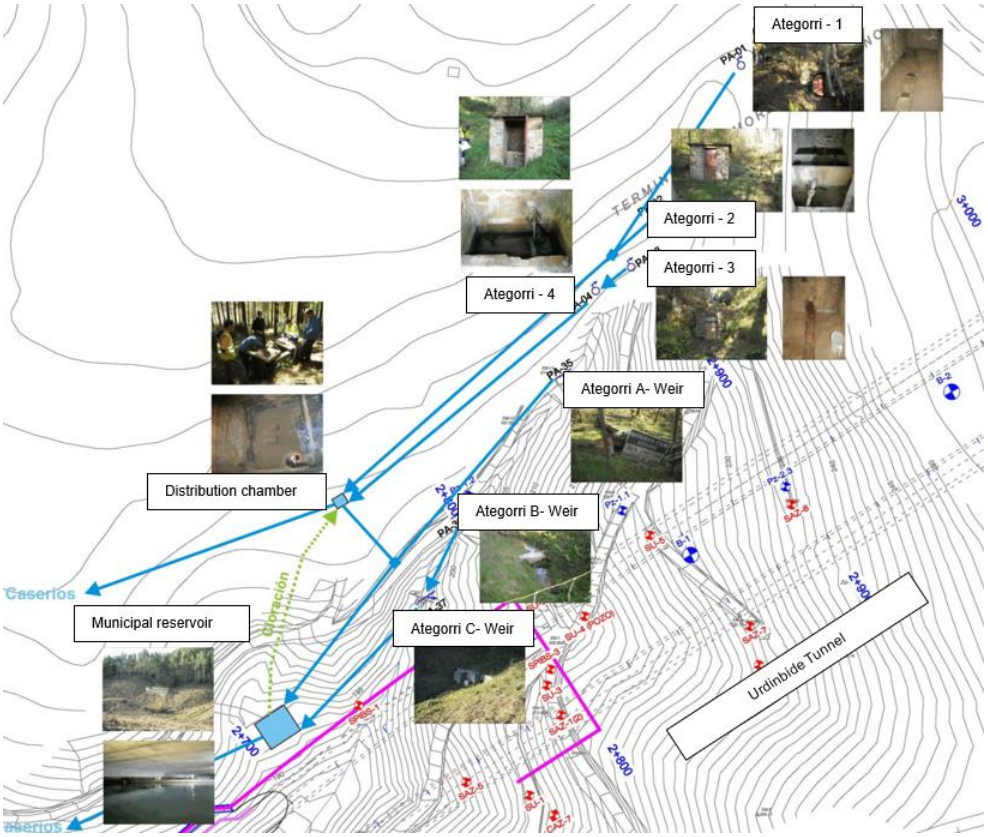


Figure 7. Inventory of main water points close to the south portal of the Urdinbide tunnel (4 groundwater intakes, 3 surface water intakes, 1 distribution chamber, and 1 reservoir).

2.3.1. Conceptual Hydrogeological Functioning Model

The hydrogeological conceptual model of the Autzagane aquifer was intended to convey the essence of the fundamental principles and basic functionality of the system, which it represents, and was defined by its nature, recharge and discharge mechanisms, and the groundwater flow scheme within it. The aquifer was divided into several hydrogeological sectors based mainly on the identified zones of groundwater discharge during the inventory of water points, although hydraulic continuity could exist between adjacent sectors. The hydrogeological sector of the Autzagane aquifer that is most directly related to the Urdinbide tunnel is the Ategorri sector.

The recharge of the Autzagane aquifer occurs through the infiltration of precipitation. The development of a significant layer of surface alteration and the moderately sloping terrain in the area promote a high infiltration coefficient in relation to the total usable rainfall (precipitation minus evapotranspiration). The average precipitation in the area is 1550 mm/year.

Regarding the discharge, the Autzagane aquifer is crossed by the heads of several streams that run in a NNE–SSW direction. These small valleys locally represent the axes of the lower relative elevation of the portion of the aquifer situated on both sides of them, and, therefore, constitute the discharge zones, through springs or diffuse discharges to the streams, of these sectors. The presence of lutitic and marly layers that separate the permeable sandstone layers of the aquifer causes the discharge of each sector to occur not at a single point corresponding to the intersection of the aquifer roof with the stream (as would be the case in a homogeneous aquifer) but at a series of springs along the stream related to each permeable level separated by less permeable intercalations.

This phenomenon was evident in the Ategorri sector, where there were four stepped springs in its headwaters (Ategorri-1 to 4). According to the data provided by the study's forometric monitoring network, the subterranean discharge in the Ategorri stream system

would be around 4 L/s, of which 1.4 L/s were used for the partial supply of the municipality of Amorebieta-Etxano through the capture of the headwater springs of the Ategorri stream.

The circulation of groundwater from the recharge zones of the aquifer (the interfluves) to the discharge lines (the streams) occurred mainly through the permeable sandstone levels in the direction of the layers. Most of the groundwater flow occurred under confined conditions. The groundwater in the massif had a medium mineralization, and its hydrochemical facies was calcium bicarbonate [1].

2.3.2. Numerical model

The hydrogeological study included a numerical modeling of the behavior of groundwater in the massif crossed by the Urdinbide tunnel, which aimed to predict its response to the construction of the work. The Visual MODFLOW 6 software [28] was used to carry out the numerical model of the flow in the study area. This software was used because it is based on finite differences and can represent well the physical processes related to groundwater flow. The geometric scope of the modeled area can be seen in Figure 8. The aquifer was divided into discrete elements of a maximum width of 25 meters, achieving a mesh in which each cell represents a prism whose hydrogeological characteristics are constant throughout its volume.

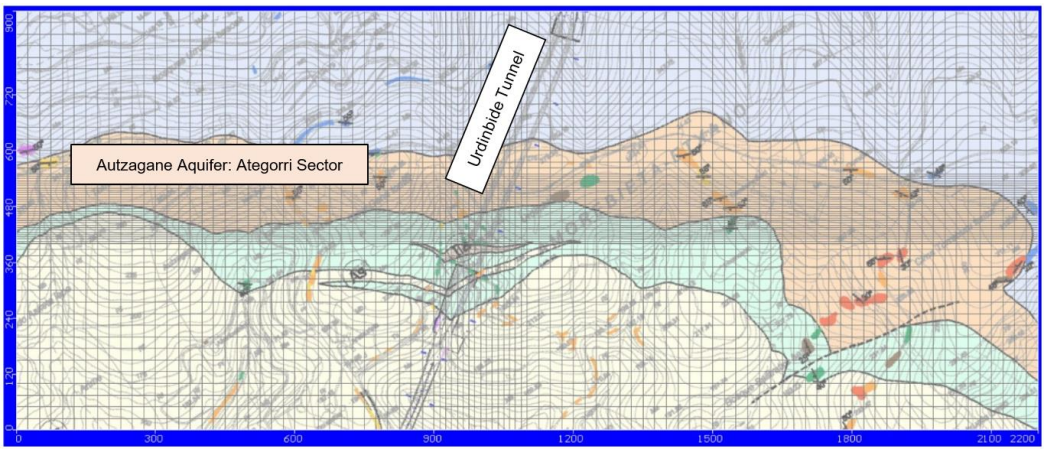


Figure 8. Model scope and surface discretization of the model in cells. Mesh with a maximum width of 25 m.

The spatial discretization of the model is shown in Figure 9.

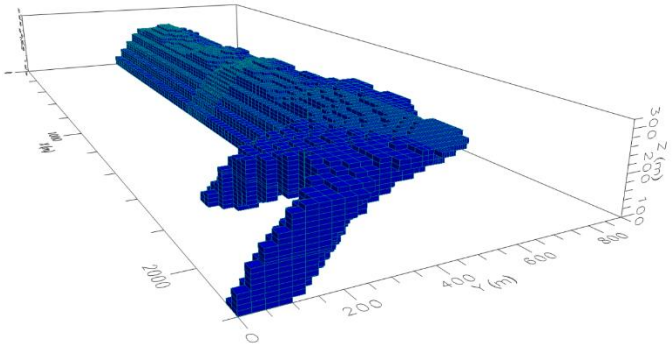


Figure 9. Three-dimensional view of the model showing the discretization in layers, using the Visual MODFLOW software.

The simplification of using a single value for each of the hydrogeological parameters corresponding to the set of geological materials that make up the modeled aquifer has been considered. By carrying out pumping tests in wells B2 and B3, representative values for the entire Autzagane aquifer were established, but during the model calibration phase, these

values were slightly adjusted as it was considered that these corrections had a favorable impact on the model's fit to the known real functioning. Thus, the final adjusted hydraulic parameters are shown in Table 1.

Table 1. Adjusted hydraulic parameters.

Hydrostratigraphic Unit	Horizontal Permeability (m/s)	Vertical Permeability (m/s)	Storage Coefficient	Efficient Porosity (%)
Autzagane Aquifer	2.5×10^{-6}	2.5×10^{-6}	1×10^{-5}	5

Once the scope of the modeling had been established, the following actions on the system were considered: precipitation infiltration, discharges at the head of the Ategorri stream, discharges from other springs, and drainage from the existing tunnel of the Amorebieta-Etxano railway line. The model was adjusted in steady state, with the following water balance, which was consistent with the measured discharge in the entire Ategorri stream (Table 2).

Table 2. Annual water balance of the Autzagane aquifer in the natural regime after recalibration.

	Balance Items	Flow (L/s)
INPUT	Precipitation infiltration	9.1
OUTPUT	Ategorri stream (springs and diffuse discharges)	4.1
	Etxanosolo stream (springs and diffuse discharges)	1.5
	Torreburu spring	1.9
	Asketa spring	0.8
	Sastratxu spring	0.1
	Existing railway line tunnel	0.7
	Total	9.1

The calibrated model was used to establish the long-term response between two opposite scenarios: the scenario before the tunneling works and the limit scenario in a completely drained hypothesis. Figure 10 shows the isopiezometric lines of the model for the situation prior to the impact of the works in a section perpendicular to the Ategorri stream.

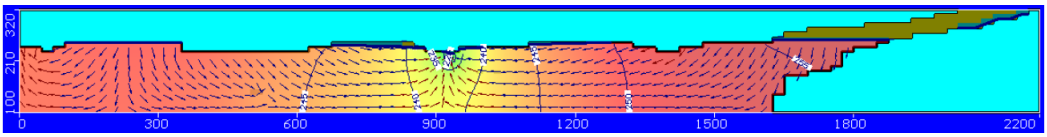


Figure 10. Isopiezometric lines for the situation before tunnel construction, using the Visual MODFLOW software.

Table 3 illustrates a comparison of flows between the natural situation (shown in Table 2) and the hypothesis of total draining tunnel. It should be noted that under this working hypothesis, the tunnel would be working as a scour outlet, with a flow rate of 6.6 L/s, leaving the Ategorri stream and its associated springs without flow.

Figure 11 shows the isopiezometric lines of the model for the situation considering a draining tunnel.

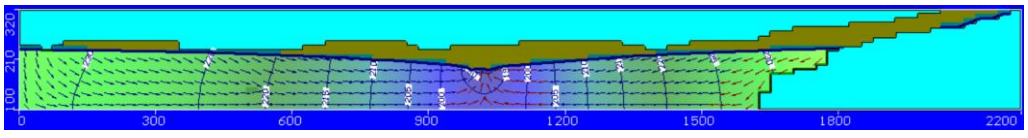


Figure 11. Isopiezometric lines for the hypothesis of draining tunnel, using the Visual MODFLOW software.

Table 3. Comparison between the natural regime and a draining tunnel regime.

	Balance Items	Flow in Natural Regime (L/s)	Flow with Draining Tunnel (L/s)	Variation
INPUT	Precipitation infiltration	9.1	9.1	-
OUTPUT	Ategorri stream (springs and diffuse discharges)	4.1	0	−100%
	Urdinbide tunnel	-	6.6	-
	Etxanosolo stream (springs and diffuse discharges)	1.5	0.8	−46%
	Torreburu spring	1.9	1	−47%
	Asketa spring	0.8	0.2	−75%
	Sastratxu spring	0.1	0	−100%
	Existing railway line tunnel	0.7	0.5	−28%
	Total	9.1	9.1	-

Finally, the hydrogeological model was used to obtain the limit flows that could be evacuated through the Urdinbide tunnels, guaranteeing the necessary flow in the Ategorri stream to supply the neighborhoods of Amorebieta-Etxano under normal conditions (1.4 L/s). The waterproofing solution for the tunnels, both during their construction and in service, had to be sufficient to guarantee a water discharge in the tunnel of less than these values (4.7 L/s).

2.3.3. Design of Waterproofing System

Due to the foreseeable impact of the tunnel construction on the Autzagane aquifer, the design project had planned the implementation of pre-excavation waterproofing injections from the advance fronts and the construction of a definitive watertight lining in the section that crosses the aquifer in order to guarantee its preservation. The main objectives of these injections were reducing the permeability of the rock mass to a level that the water infiltration into the tunnel would not exceed the maximum flow that could be extracted without significantly affecting the aquifer and the water catchment system and also achieving a crown of improved soil with a minimum thickness of 3 meters around the perimeter of the excavation (an increase in the GSI value by 20 points was required [29]).

The injections were executed from inside the tunnel. They consisted of truncated cone-shaped enclosures outside the excavation perimeter (Figure 12). The geometry of the injections was adapted to the orientation of the stratification surfaces of the rock mass so that the base of the truncated cone surface (plane defined by the end points of all the boreholes) was always a virtual plane parallel to this stratification. The injections were planned in two phases, top heading excavation and bench excavation, due to geometrical requirements. The treatment crowns were carried out in 4 stages, consisting of 30 drill holes in the top heading excavation phase and 19 drill holes in the bench excavation phase [30].

Stages 1 and 2, the outermost ones, were the first to obtain the outer wrapping. The other successive stages were implemented to intensify the degree of treatment. This system of execution allowed selective injection by sections and was used with satisfactory results in the tunnel sections already executed. The type of mixtures using cement and microcement was adjusted according to the gauged flow rates in each borehole, as well as the presence or absence of solid drags [31–33].

2.4. Hydrogeological Monitoring of the Tunnel during the Construction Phase

During the construction of the tunnel, an intensive hydrogeological monitoring was carried out to verify the working hypotheses. This monitoring consisted of continuous reading of the piezometric and forometric network installed in the study area. The construction of the tunnel caused a drop in water levels in the northern and central areas of

the aquifer, and had a one-off impact on the municipal water intakes from the springs at the headwaters of the Ategorri stream.

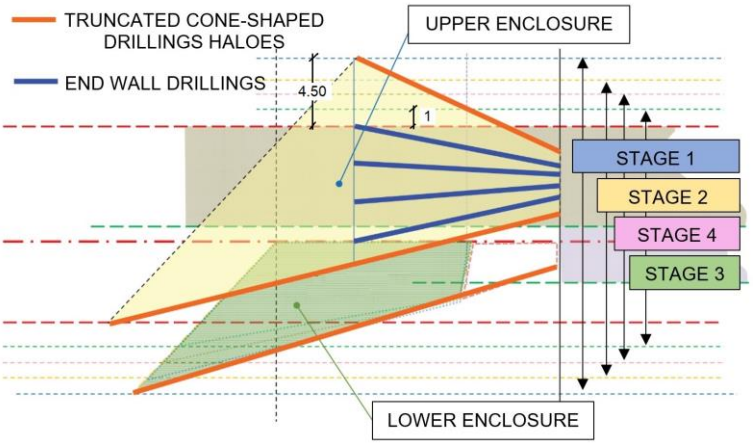


Figure 12. Schematic longitudinal profile of injection treatment. Stage situation.

The magnitude of these impacts was related to the phase of greatest activity during excavation, where potential temporary impacts during construction would be maximum.

The execution of preinjections and the advance excavation of tunnel tubes caused a depression of between 15 and 25 m compared with the over 50 m of maximum water column that existed above the tunnel level before the works (Figure 13).

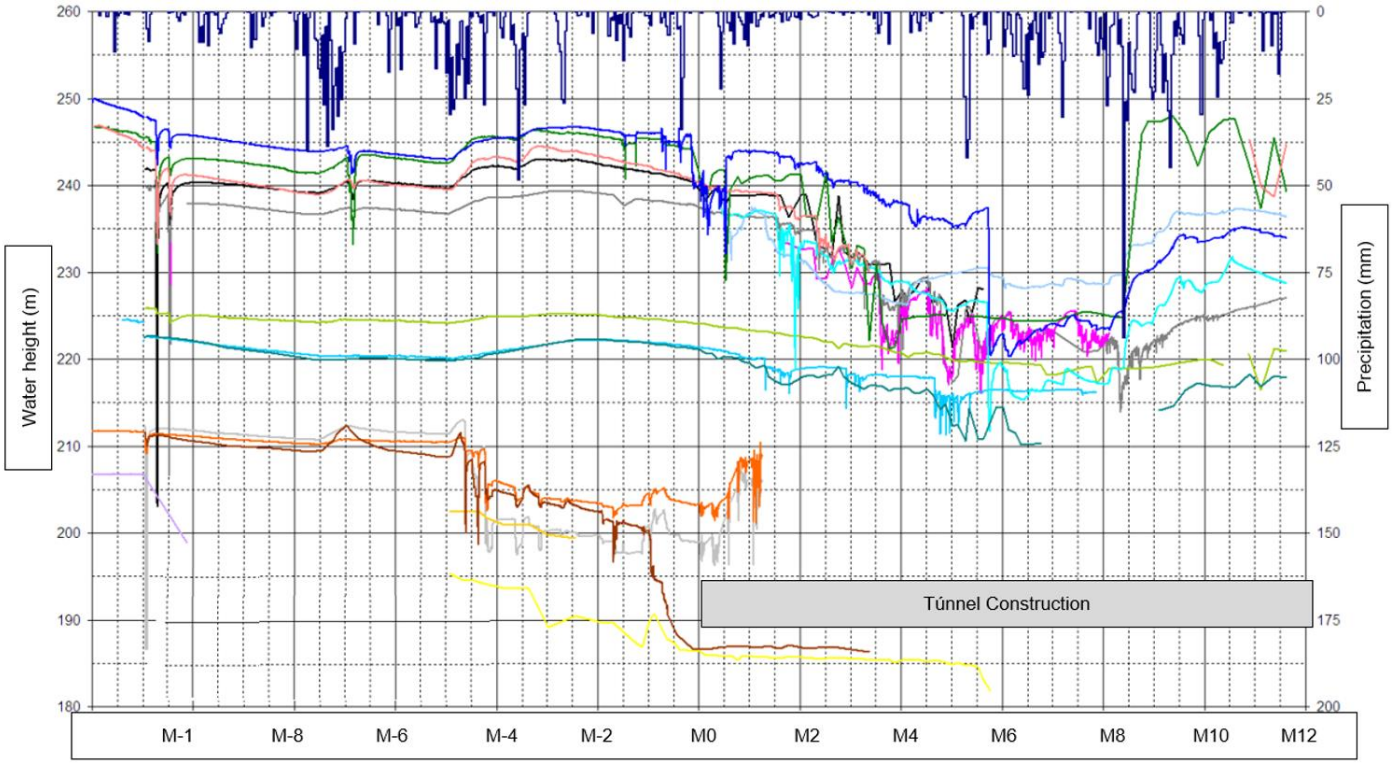


Figure 13. Evolution of the water level in the piezometers of the Autzagane aquifer. Evolution of the total precipitation in the area. The different colors correspond to different piezometers installed in the study area.

An extraordinarily dry and prolonged drought period that occurred in this area sensibly coinciding with the beginning of tunnel construction in the aquifer also contributed to the magnitude of these impacts.

The effectiveness of the waterproofing injections carried out, together with the recovery of the usual precipitation regime, partially reversed the impacts that the tunnel construction had caused on the natural functioning and use of the Autzagane aquifer. Since the commissioning of the tunnel in 2018, hydrogeological monitoring has been carried out during the operation phase. Since then, the maximum flows measured through the tunnel have been less than 2 L/s, far from the limit imposed to guarantee the functioning of the aquifer and the municipal water catchment (Table 4).

Table 4. Determination of the limit flow values ensuring the water supply in the Ategorri stream.

	Balance Items	Flow in Natural Regime (L/s)	Flow Limit Values (L/s)	Variation
INPUT	Precipitation infiltration	9.1	9.1	-
OUTPUT	Ategorri stream (springs and diffuse discharges)	4.1	1.4	−65%
	Urdinbide tunnel	-	4.7	-
	Etxanosolo stream (springs and diffuse discharges)	1.5	0.8	−46%
	Torreburu spring	1.9	1.3	−31%
	Asketa spring	0.8	0.3	−63%
	Sastratxu spring	0.1	0	−100%
	Existing railway line tunnel	0.7	0.6	−14%
	Total	9.1	9.1	-

3. Results

From the monitoring of the hydrogeological performance of the aquifer during the construction of the tunnel, it can be established that if precautions had not been taken to carry out prior waterproofing injections before tunnel excavation in the Autzagane aquifer, the water level in it would have dropped to the elevation of the tunnel, all the springs and other underground discharges towards the Ategorri stream would have dried up, and the excavation itself would have drained practically all the resources of this sector of the aquifer.

The effectiveness of sequential waterproofing prior to excavation was high, as it has allowed the recovery of piezometric levels and the resurfacing of affected springs as soon as precipitation regimes returned to normal once the tunnel construction was finished. The injection system maintained the original compartmentalization of the aquifer, as demonstrated by the registered piezometry, without the tunnel unifying the piezometric levels of the different subsectors.

In general terms, the natural hydrogeological functioning of the aquifer has been preserved. The waterproofing system used preserved not only the aquifer but also the original drainage points that constitute the springs of the Ategorri stream.

The waterproofing solution, consisting of a combination of cement and microcement injections specifically designed for the characteristics of the study area, has therefore made it possible to comply with the main requirement imposed by the project's environmental authorization, no significant impact on the Autzagane aquifer.

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

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