Drawdown hazard of springs and wells in tunneling: predictive model and verification

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Abstract The present study tests the reliability of the DHI (Drawdown Hazard Index) method for assessing the risk that springs and wells may dry up as a consequence of underground excavation. The case discussed herein concerns the risk prediction for about 100 groundwater points in the context of an 8 km tunnel in the Eastern Pyrenees. Application of the DHI method prior to the beginning of work consented the prediction of a series of water points at risk. Detailed studies and analysis of input parameter sensitivity has further permitted improved definition of the threshold values for defining risk levels. They have also allowed fine-tuning of the method so as to decrease the level of forecast uncertainty. Observation of the effects on the excavation surface, in a geological and hydrogeological context marked by structural anisotropies, has reaffirmed the importance of the reference geological-hydrogeological model for purposes of accurate prediction.

Keywords: groundwater protection, risk analysis, groundwater monitoring, tunneling

1. Introduction

The construction of an underground tunnel in mountain regions may have significant impacts on the regional hydrogeological system. Water drainage through a tunnel is likely to cause a drawdown of the hydrostatic level and a decrease of water-point discharge. This phenomenon can persist after the tunnel construction if the final alignment is not completely water-proof. The drawdown impact can be in terms of both groundwater quantity and quality, and the effects can affect on the surface: vegetation modifications, slope instability, chemistry changes of thermal waters, and hydrogeological basin lowering level.

During the last ten years considerable improvements in the management of hydrogeological impacts relating to underground works on springs and wells have been achieved. Today, this approach is used in very specific contexts, and it is difficult to extrapolate the results achieved so far for other situations. In other words, there are not consolidated methodologies for evaluating tunneling impacts on underground water-resources.

A new approach called Drawdown Hazard Index (DHI, Dematteis et al. 2001) that aims to define a general methodology for evaluating tunneling impacts on groundwater-flow has been previously proposed; since 2001, DHI method was applied to several underground construction design.

This paper presents a recent application of this method to an 8 km tunnel in the Eastern Pyrenees: DHI forecast had been provided during the design phase. Back-analysis has been provided during the excavation and allowed the sensitivity analysis of the fundamental parameters in relation with the hydrogeological context. Great care has been addressed in fault and shear zones and fractured rocks that have an important role in hydrodynamics behaviour of the groundwater systems intercepted by the tunnel. The DHI analysis is carry out on about 100 springs and wells feed by different groundwater systems. The aim of this analysis is to attribute a perturbation probability to each known spring and wells ("water-points" hereafter).

The area of study is situated along the Franco-Spanish border in the eastern sector of the Pyrenees which links the cities of Perpignan (France) to the north and Figueres (Spain) to the south. The underground works consist of two main parallel tunnels each of 8,400 m length, with diameter of about 10 m and interaxis of about 30 m. These are linked every 200 m by connection tunnels perpendicular to their axis. The general project also foresees the realisation of an exploratory gallery of about 450 m, positioned in correspondence to a important ductile-brittle fault line approximately half way up the alignment of the base tunnel, from which two soil treatment tunnels of about 80 and 170 m respectively branch off parallel to the axis of the main work. The secondary tunnels are of about 6 m in diameter.

At the time of writing (May 2007), excavation work has seen the completion of the accessories (intermediate exploratory gallery and treatment tunnels) and of about three quarters of the two barrels of the base tunnel and some relative connection tunnels. The accessory and connection tunnels were accomplished using traditional digging methods, whereas excavation of the two barrels of the base tunnel is being carried out mechanically using two shielded TBM's equipped for direct positioning of the segmental lining. Since the latter does not function as a waterproofing system for the hollow, it can be taken as given that the underground works exert a draining action on the subsurface water that they intercept.

2. Description and analysis of the DHI methodology

The DHI method consists on a probabilistic analysis based on the systems approach applicated on rock engineering (Hudson 1992). Fundamental variables for the aquifer-tunnel system are considered on a binary level through cause-and-effect relationships. The approach of the fully-coupled-model (Jiao 1995) was applied in this study to quantify the impact of a variable change on the drawdown hazard index.

The system aquifer-tunnel is described by means of 8 variables together with their interaction. This method was tested on a real case-study, where data on water-points discharge were recorded before and after the tunnel construction. In order to calculate DHI, a numeric value for all variables describing the hydrogeological condition of each water-point is given.

This methodology allows the evaluation of the aquifer-tunnel system that defines the drawdown, to get the DHI value for each known water-point. It leads to the achievement of two major goals: (1) detection of critical sectors (vulnerable sectors are normally placed close to low overburden areas and where the particular hydrogeological and structural packing creates critical conditions); (2) identification of areas not at risk, thus water-supply sources, as a compensation measure.

In particular, two groups of parameters have been identified:

- Fundamental variables which characterise the drained aquifer in the section where it is intercepted by the tunnel;
- Key factors which define the specific features of the water point fed by the discharge system.

The parameters of type (a) are: (i) the frequency of fractures (FF); (ii) average permeability of the hydrogeological formation (MK); (iii) overburden thickness (OV); (iv) plastic zone width around the tunnel (PZ), which induces an increase of permeability around the hollow.

The parameters of type (b) are: (i) distance from the tunnel (DT); (ii) an index which depends on whether or not the water point is charged by elements of elevated permeability, such as fault lines or horizons of chemical dissolution (i.e. karst) (FF); (iii) type of source (surface, deep or mixed, defined on the basis of geological, hydrogeological and geochemical data) (TS); (iv) topographic effect (function of the morphological shape of the basin slope) (ET). A rating based on the hydrogeological model is attributed to each of the preceding parameters.

The numerical value of the eight variables is assigned in each case examined according to the criteria shown in Table 1.

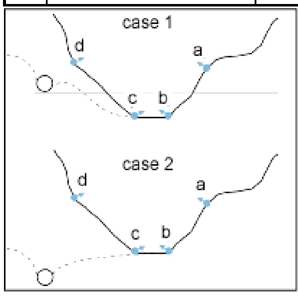
In order to define the processes that occur within the aquifer-tunnel system, the direct interactions between the fundamental variables (type (a)) are analysed and, from there, the perturbations, which are transmitted from one binary interaction to another, are assessed using a global interaction matrix (GIM, Hudson, 1992). This approach allows the definition of the drainage potential (PI) exerted by the tunnel in a given stretch.

Unlike those of type (a), the type (b) key factors do not present reciprocal interactions and take into account all those surrounding conditions that might be determined in the evaluation of the DHI of a water point. This is regardless of the average hydrogeological context of the massif at the level of the tunnel (assessed using the PI index).

The DHI expressed in percentage terms is the product of the drainage potential (PI) for the key factors, normalised with respect to the maximum value, which expresses the theoretical condition of a higher water point DHI.

Tab. 1 - Numerical values of the variables in the DHI method

		PARAMETER	Condition	value	Condition	value	Condition	value	Condition	value	Condition	value	Condition	value	Condition	value
Basic variables	DT	Distance from the tunnel	DT < 200m	1,9	200m < DT < 500m	1,5	500m< DT<1000 m	1,2	1000m< DT<5000 m	1,1	DT > 5000m	0				
	IF	Intersection with major faults	YES	2	NOT	1										
	TS	Spring type (From deep or shallow fluid system)	Deep	2	Deep and shallow	1,5	Shallow	1								
	ET	Topographic effect	see table below													
Key factors	FF	Frequency of fracturation	High	1	Low	0,6	Not	0,1								
	MK	Degree of Permeability	Very high	0,9	High	0,8	From high to medium	0,7	Medium	0,5	From medium to low	0,4	Low	0,2	Very low	0,1
	OV	Overburden	OV < 50m	0,9	50m < OV < 100m	0,5	100m < OV < 500m	0,2	OV > 500m	0,1						
	PZ	Amplitude of the plastic zone	> tunnel diameter	1	< tunnel diameter	0										



case	slope	altitude	ET
1a	0,2	0,2	0,4
1b	0,2	0,2	0,4
1c	1	0,2	1,2
1d	1	1	2
2a	0,2	1	1,2
2b	0,2	1	1,2
2c	1	1	2
2d	1	1	2

Hence, a degree of impact risk, normally divided into four classes (Table 2), is associated with the value of the DHI precisely in each water point analysed.

Tab. 2 - Different degrees of probability associated with the DHI

DHIndex	Class	Probability
0<DHI≤0,1	1	NEGLIGIBLE
0,1<DHI≤0,2	2	LOW
0,2<DHI≤0,3	3	MEDIUM
DHI>0,3	4	HIGH

According to the authors, the class 1 is attributed to those points for which the impact probability is negligible. The class 4, on the other hand, is attributed to those points with significant impact probability. The points, which fall into the intermediate category, are subject to a degree of uncertainty in evaluation that decreases, however, in the passage from the low to the intermediate classes. Indeed, the method does not permit the quantification of impact but only the propensity of a water point to impact, and only then in the context of the relations existing between the various tunnel alignments and the groundwater flow system to which they are linked.
On the basis of these risk levels, therefore, the priority of compensation and/or monitoring interventions can be defined for the various water points, with preference given to those sections where the danger level is greater.
In the same way it is possible to identify those sectors that, in presenting no-risk water points, might be useful for the supply of resource compensations.
The intention of this study is to minimize the uncertainty of evaluation relative to classes 2 and 3 (low and medium level) by defining with greater reliability the limits which describe the various degrees of impact, and, possibly, by reducing the number of risk classes from four to three.

3. Geological and hydrogeological setting

Assessment of impact has been made on the basis of detail studies that have consented the correct parameterisation of the variables of the DHI method. In particular, the fine-tuning of a sufficiently reliable geological model of reference has permitted the reconstruction of kinematic relations between the different geological elements observed on the terrain, as well as the formulation of a hydrogeological reference model coherent with the hydrochemical and permeability data obtained from slug tests. Sectors of characteristic hydrodynamic pertinence (hydrogeological complexes) have been identified, as have the areas of major hydrogeological criticity intercepted by the underground works.

3.1. Reference Geological Model (RGM)

The area under examination is situated within the massif of the Albères, one of those that constitute the Hercynian basement of the eastern sector of the Pyrenees chain (Figure 1). The Pyrenees are made up of rocks belonging to the Pre-Mesozoic series metamorphosised during the Hercynian orogeny, in the Upper Paleozoic, hence involved in the Alpine deformative phases.

The stratigraphic sequence of the Paleozoic basement of the Albères consists of sandstones and pelites with subtle intercalates of limestones and volcanic rocks.

In particular, along the alignment of the excavation works, which are the object of the present study, the following lithostratigraphic units can be distinguished from south towards north:

- granodiorites (beginning at the southern portal for about 30% of the alignment);
- schists and granodiorites (about 30% of the alignment);
- schists and diorites (about 20% of the alignment);
- gneiss (about 10% of the alignment);
- black schists (about 10% of the alignment as far as the northern portal).

Finally, in the sector of the northern portal, the base tunnel alignment crosses the Roussillon Mio-Pliocenic basin made up in part of rather coarse (pebbles and boulders) fluvial deposits.

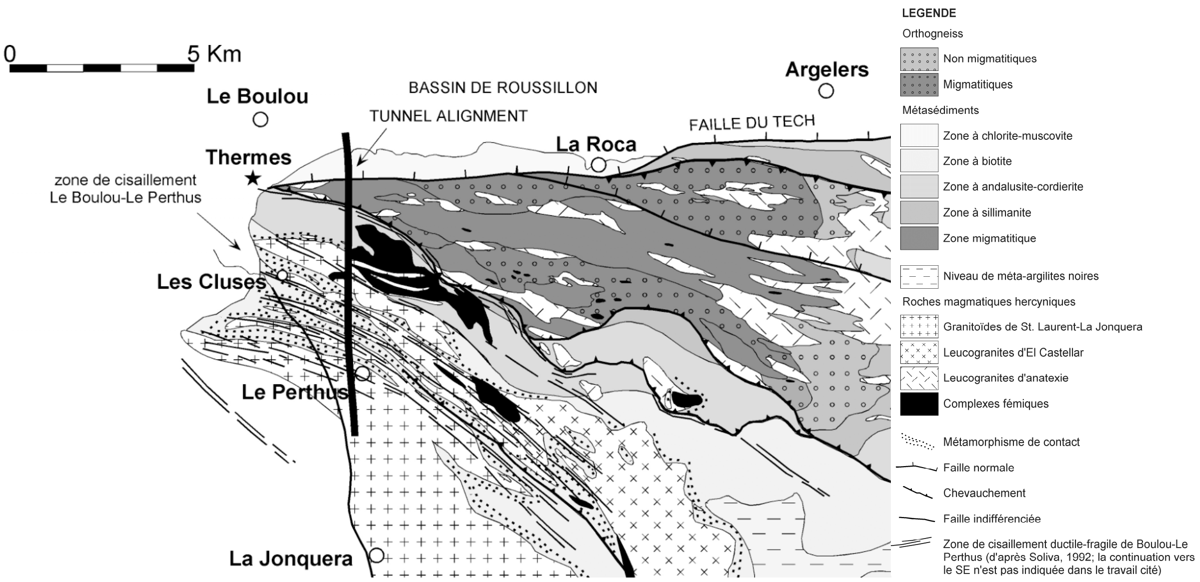


Fig. 1 - Geological framework of the area under examination

In various ways, and at a regional level, the alignments of the underground excavations intersect several important tectonic structures whose role in the organisation of groundwater flows is vital.

The Le Boulou-Le Perthus fault zone is intercepted by the alignment of the base tunnel in the southern sector, this fault zone is about 5 km thick and is characterised by the development of an intense foliation of N100°E to N120°E direction with vergence to the north. The granitoids, which are subject to ductile deformation, acquire a gneissic texture which increases in intensity the more it draws nearer to the main mylonitic horizons.

The Montesquieu fault zone is made up of two distinct zones each of about 15 metres in thickness with a direction ranging from E-W and ENE-WSW. Both have a complex geometry and are composed of different anastomotised cataclastic planes characterised by the presence of cataclastic breccias and a clayey gouge. The shear planes incorporate lithons of schist from metric to decametric in size, often altered due to circulation of hydrothermal fluids along the damage zones

The Le Boulou fault zone represents an important regional structure from both a hydrogeological and a geomechanical point of view: the former because of the presence of hydrothermal springs aligned along the deformation zones; the latter due to the poor quality of the soils. It has an average E-W direction and the main structure inclines 50-70° towards the north. It is a deformation zone of complex geometry characterised by diverse anastomotised tectonic planes ranging from metric to decametric in size for an overall thickness of about 50 m.

The central zone is made up of clayey material (fault gouge), while the damage zones are characterised by schists and cataclastic gneiss. The processes of argillification are connected to a reduction of feldspar due to mechanical friction along the fault planes and, most probably, to the hydrothermal circulation along the damage zones associated with the main fault line; the presence of hydrothermal flows is likewise evidenced by the observation of recent deposits made up of gravels and sands cemented by a carbonatic matrix with associated carbonatic cement breccias which present phenomena of alteration and hydrothermal cementation (patinae of microcrystalline silica).

3.2. Reference Hydrogeological Model (RHM)

From the hydrogeological point of view, these formations have been divided into hydrogeological complexes characterised by different classes of permeability. The hydrogeological characterisation and the distinction into complexes according to hydrodynamic behaviour have been made on the basis of data obtained from 100 slug tests realized along the alignment of the tunnel. In the ambit of the present study, the classes of permeability have been attributed according to the AFTES (Association Française des Travaux En Souterrain, 1993) norms. The soils tested show in most cases a permeability due to scarce, if not inexistent, primary porosity. On the other hand, they sometimes present good permeability determined by secondary porosity, and the groundwater flows develop in accordance with the extent of fracturing and interconnection of the shear systems.

Six different hydrogeological complexes have been identified. These have allowed characterisation of the MK (average permeability of the hydrogeological formation) and FF parameters relative to the state of massif fracturing.

Complex 1 – Quaternary deposits: consists of alluvial and alluvial-colluvial deposits. They form aquifers of limited lateral extension, which occupy the bottom of the valley of the main watercourses with which they are in hydraulic equilibrium. They are not intersected by the alignment of the excavation works and they have been assigned a rate of medium to high permeability.

Complex 2 – Detritic deposits: direct measurements were not carried out on these soils. Their hydrodynamic characterisation has therefore been estimated and they have been attributed a medium rate of permeability.

Complex 3 – Metapelites, gneiss and schists: the permeability levels measured in the slug tests are generally in the order of 1E-07 m/s which is of low/medium rate. Along the zones of intense fracturing, the tests evidenced a characteristic anisotropy of the field of permeability, with the horizontal component being greater than the vertical one and groundwater flows being markedly compartmentalised. This result is in line with the detailed geological study, which describes the presence of sub-vertical to sub-horizontal fault planes characterised by formation of fault gouge along the deformation planes. The latter constitute hydraulic barriers to the groundwater flows which, rather, proceed along the damage zones.

Complex 4 – Diorites, basic rocks and massive granodiorites characterized by a low rate of permeability, which, on the basis of their brittle behaviour (as a response to the deformations), becomes medium-high in correspondence to the zones of intense fracturing. The values of permeability measured in the slug tests vary from 8E-08 m/s for normal fracturing conditions and 6E-06 m/s for the zones of intense fracturing due to the well-developed degree of interconnection between the fractures.

Complex 5 –The Le Boulou fault line: to this complex belong the soils, which constitute the damage zone of the Le Boulou fault line with a medium-high degree of permeability (K=3E-06 ÷ 2E-05 m/s). This fault differs from the core zone made up of substantially impermeable (K=4E-08 ÷ 2E-07 m/s)

clayey material (fault gouge). Along this structure are localised a number of thermo-mineral water points which are an economical resource for the area. For this reason, particular attention was dedicated to them with the aim of assessing the risk of interference of this fault line with the tunnel.
Complex 6 – Granodiorites of oriented texture and mylonites: the re-crystallisation and the formation of sericitic-argillaceous minerals along the schistous planes and the deformation determine a lowering of permeability. The latter values measured in the slug test range from 5E-09 to 4E-07 m/s and the degree of permeability is therefore low. On the other hand, it is possible to recognise horizons of fracturing characterised by a medium level of permeability (K=1E-07 ÷ 1E-05 m/s) but with a low degree of interconnection.
Three hydrogeochemical types were identified which allowed identification of water points the recharging of which is guaranteed from deep groundwater flow systems and from canal network tributaries:

a) Na-HCO3 waters with high ionic salinity (80 - 180 meq/l) and high PCO2 (close to 1 bar);
b) Ca-HCO3 waters with medium-low ionic salinity (20 - 50 meq/l) and high PCO2 (0.3 – 1 bar) which reveals their particular aggressiveness;
c) Ca-HCO3 waters with low total ionic salinity (<20 meq/l) and low PCO2 (in general 0.001 – 0.05 bar) which constitute most of the waters sampled in the sector of study.

In Figure 2 are shown the triangular diagrams of the main ionic species, which highlight how sodium is the dominant cation in the thermo-mineral waters, while calcium is more present in the other waters.

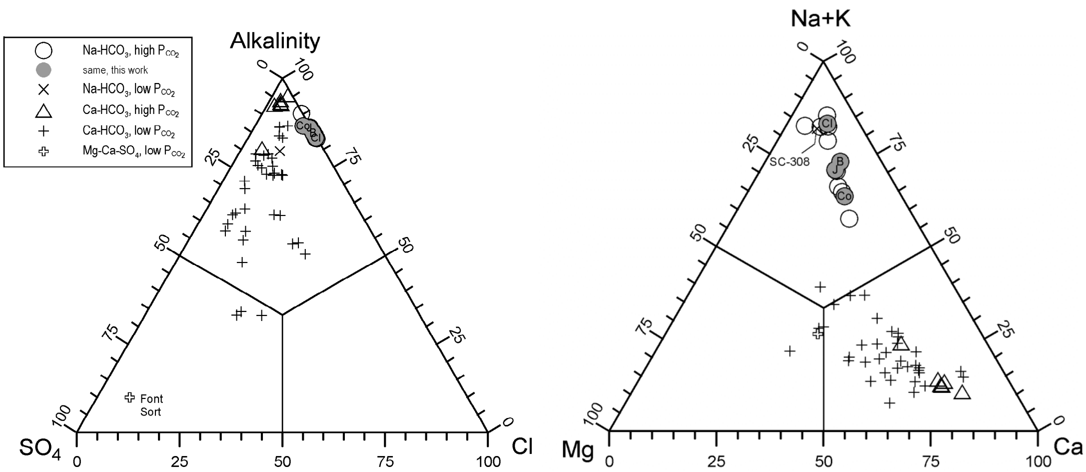


Fig. 2 - Triangular diagrams of the main ionic species. The circular symbols indicate the water points recharged by deep groundwater flows

The waters of group (a) are connected to deep groundwater circuits; the waters of group (b) and group (c) are tributaries of surface canal networks. The waters of group (b) differ from those of group (c) on the basis of the greater CO2 component originating in deep groundwater circuits and released most probably by waters of type (a) during their climb to the surface.
Springs with waters of group (b) have been characterised as mixed, that is, charged by deep and surface groundwater. The water points of type (a) have been generally characterised as charged exclusively by surface groundwater; in cases where these are connected to circuits which, even though surface, develop along preferential flow routes (such as fault and intense fracture zones which might be intercepted further down by the underground excavations), they have been characterised as being of the mixed type.

4. Data analysis

Analysis for verification of the DHI method is based, therefore, on a comparison between the forecast, on the one hand, and direct observation of the impacts, on the other. Since 2004, hence before digging began, the water points analysed have been subject to monitoring of their main chemical and physical features (electric conductibility, temperature, pH, Eh, flow rate of the springs, piezometric level of the wells, piezometers). This permits verification of the impact and a better characterization of the hydrodynamic behaviour of the groundwater flow systems identified. An example of water point monitoring is shown on Figure 3.

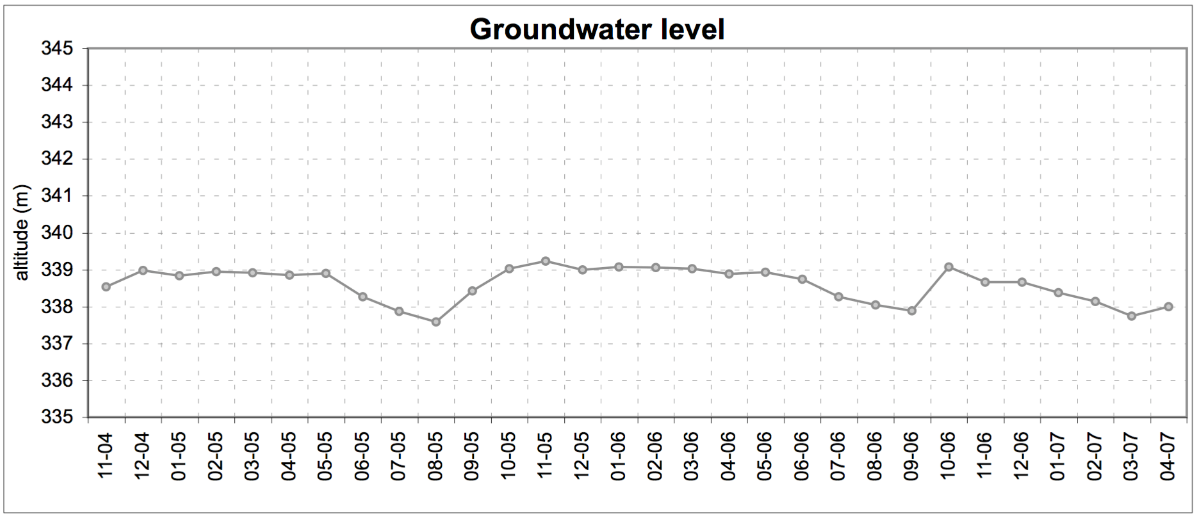


Fig. 3 – Groundwater level variation measured on a monitoring piezometer

The choice of the water points considered for risk analysis was made on the basis of the preliminary hydrogeological study in the context of which an area of possible impact was identified of about 2 km in on each side with respect to the axis of the base tunnel and a census was carried out of the water points present. In some sectors the area was extended in such a way as to take into consideration the impact study water points of particular interest for domestic use on the part of local communities: such is the case with the springs supplying the thermal baths located in the area of study (about 2.5 km from the axis of the tunnel alignment) and those supplying drinking water (about 5 km from the alignment).
The DHI method was applied to 94 water points and more precisely to 57 springs, 21 private wells and 16 piezometers, the latter positioned mostly in line with the excavation project. The water points were chosen from among those used for drinking water, for domestic use, for irrigation purposes and from among the piezometers located in the ambit of the project phases of the excavation work.
The first assessment of impact using the DHI method was carried out before digging began, but already in the light of detail studies that permitted the characterisation of groundwater flow systems intercepted by the excavation works. With digging underway, with new and more detailed studies to hand and, finally, with the availability of data deriving from the first impacts observed on the monitored water points, it was decided to repeat the assessment of the hydrogeological risk by checking the preceding risk level attributed and, where possible, validating the DHI method using back analysis.

5. Discussion of the results

In line with the degrees of risk attributed by the DHI method (1 zero, 2 low, 3 medium and 4 high), in Table 3 are given the indices of probability of drying up assigned to each water point included in the present study.

Tab. 3 - Classes of probability attributed to water points prior to the DHI verification and validation phase

CLASS	*PROBABILITY*	*N° of point*	
1	NEGLIGIBLE	67	71%
2	LOW	14	15%
3	MEDIUM	5	5%
4	HIGH	8	9%
		94	100%

72% of water points analysed do not present any risk, their DHI being below 0.1. The remaining 28% show a low to high risk level. In line with the reference hydrogeological model which describes a marked compartmentalisation of the groundwater flows, the totality of water points with medium to high degrees of risk are located near the alignment of the tunnel, at a maximum distance of 500 m and in correspondence with sectors in which the alignment intercepts the major shear zones and for which the data at our disposal has evidenced the presence of active groundwater flow systems (K>1E-06 m/s). The concomitance of these conditions determines, therefore, a strong if not absolute probability that those flow systems will be affected by the excavation project.
Moving now to an analysis of the results of the matrix calculus, the impacts effectively observed have not affected those water points to which a zero or low degree of risk (classes 1 and 2) has been attributed. In the first analysis it is possible to conclude, therefore, that there is no risk involved for those points whose DHI is below 0.2.
The points, which are, however, impacted upon have been classified at medium to high risk (classes 3 and 4), that is, with DHI above 0.2.

5.1. Process of verification and validation of the DHI method

During verification and validation of the DHI method the possibility of diminishing the degree of uncertainty of predictions was assessed in two ways:

1. Reducing the risk class by reformulating the classes of risk probability according to the following scheme:

class 1	Negligible probability
class 2	Low probability
class 3	High probability

2. Setting the intervals of pertinence of the three new classes in such a way that the one describing uncertainty of the prediction (new class 2) is as narrow as possible.

In particular, the water points upon which no impact was observed present DHI values below 0.16. The limit identifying any given risk (certain or uncertain) was therefore raised to 0.16, thus annexing to class 1 (negligible probability) several of the points to which previously a low risk of impact had been attributed.
In line which what has been described, a lowering of the limit which discriminated between medium and high risk levels was effected, that is, between the points of increased impact probability (high level) and those of less likely probability. Indeed, following a precautionary approach, in the evaluations carried out so far this distinction was hardly considered at all, since the totality of water points with at least a medium risk level had been inserted into the priority compensation plan.
It was therefore decided for the present study to leave aside the distinction between medium and high risk levels and to consider only the high risk level (new class 3), the lower limit of which was set at 0.24 and no longer 0.3.
The results of this new assessment are presented in Table 4.

Tab. 4 - Classes of probability attributed to water points following DHI verification and validation phase

CLASS	*PROBABILITY*	*N° of point*	
1	NEGLIGIBLE	72	77%
2	LOW	9	10%
3	HIGH	13	14%
		94	**100%**

On Figure 4, the validation process is shown. It is possible to observe a clear correlation between the DHI evaluation and the impacts observed on the field. The classification of the drawdown probability index is done in order to preserve an intermediate class (class 2 – low probability) where are placed the water points affected and not affected by the tunneling.

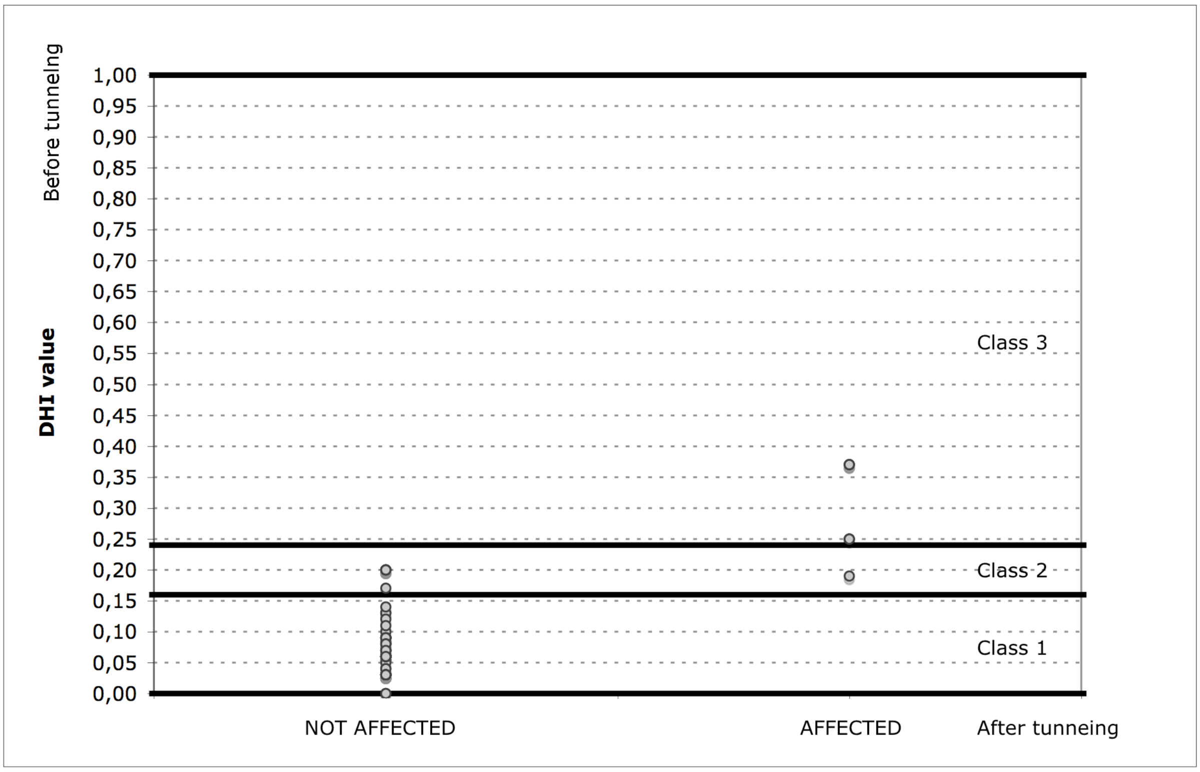


Fig. 4 – Validation data process

77% of water points analysed showed a negligible impact probability against the 72% of the prediction made with the old classification, whereas the water points with a high impact probability went from 8 to 13%, that is equal to the sum of the water points which, in the preceding evaluation, had a medium and high degree of risk.

The detailed analysis of the result highlights how of those points with negligible impact probability (class 1), the 80% are represented by water points charged by surface canal networks, while the remaining 20% is represented by points which pertain to mixed and deep groundwater circuits but which are found at distances of over 500 m from the excavation works.

As regards the waters points nearest (DT<200 m) to the axis of the tunnel alignments, these are charged exclusively by surface networks positioned in aquifers of low to medium permeability (parameter MK between 0.4 and 0.5) and do not present relations with the fault lines identified on the terrain (parameter IF=1) or belts of fracturing intersected by the tunnel (parameter FF=0.1).

The water points charged by deep groundwater circuits, connected to a zone of intense fracturing in conditions of medium permeability levels, such as the hydrothermal springs, also present a negligible impact probability, but only because they are located at over 1 km from the base tunnel. It should also be noted that these springs are to be found at a level comparable if not lower to that of the excavation works in the section in which the latter intersect the groundwater circuit which charges them. Hence the effect of the topography index assumes minimum values (ET=0.2) for which even a reduced distance would not determine a higher impact probability. From the analysis of the sensitivity of parameter DT, in the flow conditions described, only if these water points were found at a distance below 200 m would a low impact probability be assigned to them. This guarantees the feasibility of precautionary approach, which informs the probabilistic models.

The water points which reveal high impact probability (class 3), which are actually impacted, are all found at a distance below 500 m and are charged by mixed groundwater circuits which develop along the damage zones of the main tectonic structures (medium-high permeability levels). In effect, this condition represents one of the worst among those that the DHI method takes into consideration. The remaining points with increased impact probability are to be found in the sector in which the tunnel must still be bored.

The water points with low probability (class 2) are located at a distance below 500 m and are more or less all charged by surface canal networks but which, most probably, are in equilibrium with deeper circuits in connection with sectors of intense fracturing. For these points the prediction of impact is uncertain but not negligible.

6. Conclusion

The possibility of verifying and validating, via back analysis, the prediction of impact made with reference to water points following underground excavation has allowed a better definition of the classes of impact probability identified with the DHI method and of setting the threshold values which distinguish them. In particular, eliminating the medium probability class, which was of little and sometimes no practical use, has reduced the classes of impact probability.

Although each context, such as the one described in this article, is specific from a geological point of view, the system approach of the DHI method is put in place with the purpose of rendering the evaluation of the risk probability as representative as possible apart from the geological makeup. Furthermore, it is proposed to simplify the readings of the results for the planning and environmental impact phases of underground excavation work.

The formulation of the impact levels proposed in this study is as follows (Table 5):

Tab. 5 - Different degrees of probability associated with the DHI after the process pf verification and validation

DHIndex	Class	Probability
0<DHI≤0,16	1	NEGLIGIBLE
0,16<DHI≤0,24	2	LOW
DHI>0,24	3	HIGH

In the light of above, measures for confronting each single case, according to a principle of priority with respect to the impact risk highlighted, have been proposed for each of the three risk classes. The actions foreseen do not disregard the carrying out of a sufficiently detailed geological, hydrogeological and hydrochemical analysis for the purpose of characterising single water points for the application of the DHI method. Taking the main chemical-physical features as the base action (CE, T, pH, Eh, flow rate and/or piezometric level), the following scheme is proposed:

Class	*Probability*	*Priority*	*Action*
1	Negligible	None	No action
2	Low	High	Design of alternative mitigation measures
3	High	Absolute	Design and realization of alternative mitigation measures before tunneling

The localization of the alternative mitigation resources could be focused on the areas where the DHI analysis highlights the presence of water points classified on class 1; the design of the mitigation measures must be realized with respect to the final destination and systems of use of all the water points present in the sectors under examination. In this way it is possible to design compensation measures capable of meeting the needs of the local communities affected by the underground excavation project.

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