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Guidelines for sustainable management of groundwater inflows and geothermal heat in tunnels

Italian Chapter
of the International
Association of
Hydrogeologists (IAH)

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Guidelines for sustainable management of groundwater inflows and geothermal heat in tunnels

The Guidelines for sustainable management of groundwater inflows and geothermal heat in tunnels were developed by members of the Italian Committee of the International Association of Hydrogeologists (IAH) GESTAG working group. The GESTAG working group was set up by the Italian chapter of the IAH (https://www.iahitaly.it). This guideline was approved by the Board of the Italian Chapter of the IAH on 20/09/2022.

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DOI 10.7343/as-2022-592

TABLE OF CONTENTS

DOI 10.7343/as-2022-592

Index of Figures

Index of Tables

DOI 10.7343/as-2022-592

PREFACE

In December 2020, a volume in Italian was published, by Associazione Acque Sotterranee, on the management of groundwater and heat in tunnels; since then it has enjoyed a success that justifies republication. In this new edition, apart from the translation into English, some changes have been introduced, with more attention being paid to heat-related issues and to other energy geostructures, and less to the Italian regulatory framework. This volume is the result of work by a group of experts whose names are specified in the introduction, each of whom has been dealing with a common problem from a different perspective on a daily basis. The group's diversity and its members' resulting multidisciplinary approach add to the value of the work, given the experts' areas of interest and also their different affiliations within academic, professional, business and public bodies.

The overall aim of the volume is to provide a tool permitting an integrated understanding of a set of processes and problems as a basis for enabling others in the field to then undertake studies, conceptual modelling, investigations, projects, monitoring, short and long-term mathematical modelling, forecasts and scenarios of environmental impacts, design of prevention and/or compensation and/or mitigation measures, contingency plans, etc, in the best possible way. The volume is dedicated to the management of groundwater and geothermal heat in tunnels, but can also be seen as an example of an analytical approach applicable to the programming, planning or design of other infrastructural or civil works in general.

In addition to absorbing the general analysis and specific contributions in the volume, it is hoped readers will be stimulated to read between the lines and take a leap forward in the direction of furthering their knowledge on this subject, or transferring their skills, or being inspired to develop a different approach to the next job. In this sense it is superfluous to dwell in this Preface on primary and secondary objectives, or on the target and the contents of these Guidelines, which are contained in the text; rather it is worth imagining its natural future development, beyond these Guidelines or perhaps simply looking forward beyond this edition.

This volume deals with groundwater and heat in the subsoil, addressing both elements with the clear intention of enhancing two resources whose potential is often underestimated. In this sense, it is clear for example that a cost-benefit evaluation aimed at assessing the water resources and geothermal potential of an area affected by a tunnel project which is already in the phase of preliminary design and analysis of alternatives, should be able to identify the capital gains linked to the aforementioned evaluation; this concept could be applied to initial sustainability analyses of many other works.

The valorisation of heat is dealt with mainly by referring to its general principles, but it would be possible in a second phase or in a future edition to develop the same analyses, considerations and principles by analysing and comparing different contexts, as well as to apply the same evaluations to various works such as mines. Other applications could involve transferring the principles of thermal energy valorisation to hydraulic energy, when working on reservoirs, or the field of tunnels, rethinking the valorisation of waste materials produced by excavation works.

In conclusion, thanks are due to the organizations that have made this work possible: the Italian Chapter of IAH (International Association of Hydrogeologists), which proposed and edited it, and the Associazione Acque Sotterranee (ANIPA affiliate and publisher of this Journal), which made publication possible. The volume represents the outset of a journey of shared ideas and resources and of a search for common denominators, which I hope will be profitable, replicable and lasting.

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1 INTRODUCTION

Antonio Dematteis

The *Guidelines for sustainable management of groundwater inflows and geothermal heat in tunnels* have been prepared by the GESTAG (Sustainable Water Management in Tunnels) Working Group, established in 2012 by the Italian Committee of the International Association of Hydrogeologists (IAH). The GESTAG working group is made up of experts from Italy and Europe from different backgrounds, including academics, professionals, contractors, owners, and government agency representatives. Figure below shows the number of members of the Working Group.

The Guidelines aim to respond to a growing need to develop tunnel projects, or more generally underground projects, to higher standards of sustainability and safety. The economic-financial, social, and environmental sustainability of an underground project should be improved by adopting good practices in preserving water resources, groundwater dependent ecosystems and geothermal resources affected by the excavation. Where it is not technically possible to avoid an impact, this must be accurately predicted, quantified, mitigated, compensated for and where possible enhanced, through the adoption of solutions for the use of groundwater and geothermal heat intercepted by the underground works.

The Guidelines provide practical advice and examples on how to manage groundwater and heat impacts in tunnel projects and other underground structures. Emerging trends for the management of water resources are presented, integrating underground construction requirements with the sustainable choices regarding the use of intercepted groundwater and geothermal heat.

The Guidelines are organized in eleven chapters: Chapters 2, 3, and 4 contain a description of methods and technical measures for setting up hydrogeological studies and predictive models of impacts; Chapters 5 and 6 examine the planning of valorisation of intercepted inflows and geothermal heat, Chapter 7 looks at the choice of chemicals to be applied with TBM and drill and blast excavation according to their impact on groundwater quality, and Chapter 8 contains a definition of the monitoring plan criteria. Chapter 9 discusses the so-called non-technical issues relating to communication and social acceptability and Chapter 10 provides the European regulatory framework.

The GESTAG working group published a first version of the Guidelines in December 2020 (Dematteis A, Barla M, Boscaro A, Gargini A, Governa M, Grosso F, Insana A, Marchionatti F, Parisi ME, Perello P, Ranfagni L, Ruffinatto G, Torri R, Vazzoler S, Vincenzi V (2020): Linee guida per la gestione sostenibile delle venute d'acqua e del calore geotermico nelle gallerie, Comitato Italiano IAH, allegato alla rivista Acque Sotterranee - Italian Journal of Groundwater Vol.9 n°162 DOI 10.7343/as-2020-486), which was the result of work carried out in coordination by members of GESTAG, including workshops open to the public organized by GESTAG held in Piacenza (GEOFLUID Conference, 2012), in Rome (IAH meeting, La Sapienza University, 2013) and in Turin (GEAM course, Polytechnic of Turin, 2019). The Italian version of the Guidelines was then presented and discussed in Piacenza (GEOFLUID Conference, 2021) and in Naples (Flowpath IAH Congress, 2021). This new version is the English translation of the Italian version published in 2020, with an expansion of the part relating to the use of geothermal heat, through an updating of Chapter 5.

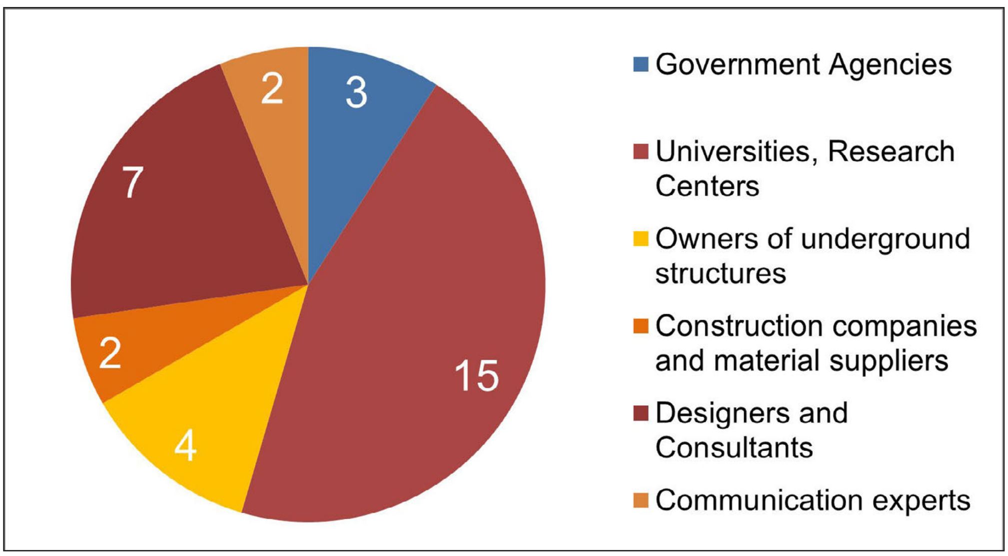

Fig. 1 - Affiliations of the GESTAG Working Group members.

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Tab. 1 - List of GESTAG working group members

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Marco TALLINI	University of L'Aquila
Riccardo TORRI	EGTeam, geologist consultant
Sergio VAZZOLER	Amapola srl, communication expert
Valentina VINCENZI	Geologist, consultant

2 RETURN OF EXPERIENCE

Riccardo Torri

Experience in the field of underground excavations gained since the middle of the last century has made it possible to produce an enormous amount of hydrogeological data. These data were acquired during the various design phases, during the excavations, and in the operation phase of the completed works.

Specifically, the hydrogeological data collected in the design phases were mainly obtained through surveys, both direct (geognostic surveys, hole tests, laboratory analyses, etc.) and indirect (mainly geophysical prospecting); the data collected during and after excavation are instead the result of monitoring in the tunnel (hydraulic load and flow measurements) and environmental monitoring outside the tunnel (measurements at water points such as springs and wells).

These data, collected over time, constitute a set of shared knowledge permitting refinement of the methods of analysis and understanding of geological-hydrogeological issues as well as optimization of engineering solutions for mitigating and/or overcoming them.

During elaboration of the hydrogeological model and definition of the geological and hydrogeological risk connected with the construction of underground infrastructures (road or hydroelectric tunnels, underground power plants, etc.), access to hydrogeological data acquired over time and during practical experience plays a fundamental role both in the initial stages of design and/or feasibility study and when defining more advanced design choices.

This contribution mainly draws on the acquisition and subsequent processing of data either present in the literature or the result of direct experience by designers and construction companies during the excavation of infrastructures which have been completed or are under construction.

Analysis of historical data must first of all meet the criteria of representativeness and comparability with the context that is being faced, at the geological-structural and hydrogeological level. This is essential in order to be able to minimize the uncertainty that the juxtaposition of two contexts, similar but not coincident, implies. It is therefore appropriate that a specific chapter on this issue, in which the benefits and limits of the analysis carried out on historical data are defined, be included in any project.

The main elements that can be deduced from analysis of the return of experience are the following:

1. the tunnel's drainage potential regarding groundwater, in comparable hydrogeological contexts;
2. impacts on groundwater and on withdrawal points (springs and wells), on aquifer-dependent ecosystems (Groundwater Dependent Ecosystems: GDE) and on surface waters (streams and bodies of water, wetlands), as well as on the slope dynamics;
3. the development and planning of project interventions such as excavation and monitoring methods, waterproofing or drainage systems;
4. the drawing up of scenarios exploiting the drained water (eg as a water and/or energy resource).

2.1 Data from previous works

The main feature of bibliographic data is that they are extremely heterogeneous. This clearly critical element is mainly due to the lack of common on-site data collection guidelines. In reality, the issue is not so much the lack of as-built data but rather their dispersion in terms of frequency of acquisition and in their sometimes excessive typological variety: while on the one hand the overall size of the available databases increases, on the other, a lack of coordination increases the difficulty of correlating the data, decreasing their statistical representativeness.

This means the archive of historical data needs to be systemized not only according to future usability, but also, and above all, for implementing efficient databases that are more easily and effectively accessible. This can also facilitate relationships with control bodies, especially during construction, making the provision of any required data quicker, easier and more consistent.

Furthermore, the possibility of analyzing hydrogeological data acquired during the construction phase, by those who build and manage the operational phase of an infrastructure, permits verification of the validity of design choices and tracking of the evolution of the phenomena observed in the tunnel, including over the long term.

The availability of hydrogeological and geological data derived from tunnel excavation has greatly increased over the last 20 years thanks to the introduction of automatic measurement acquisition devices. Devices such as automatic flow meters in tunnels and portals, boreholes equipped with multi-parametric probes and instrumentation for the continuous measurement, storage and transmission of chemical, physical and piezometric parameters are now an integral part of tunnel equipment.

In addition, the structuring of GIS and webGIS databases for data organization and analysis allows for geo-referencing and temporal organization of the acquired data, making them potentially more suitable for cross-analysis with the geological and engineering context in which they were gathered.

The ultimate goal is therefore to render past experience useful for new projects. This would not mean that the availability of data acquired elsewhere can completely replace the need to acquire direct information; however, comparison with similar contexts can for example provide valid support in the early stages of a study, guiding the definition of the conceptual model and general problems and, as a result, defining the survey plan.

2.1.1 Bibliographic sources

Historical data obtainable from bibliographic sources are generally available in qualitative form and are characterized by critical elements such as subjectivity of measurement, variable and sometimes weak reliability of acquisition methods, a

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lack of structured databases and the perishable nature and age of the supports on which they are made available (paper, outdated IT storage methods etc.).

In the best cases, these data have been the subject of specific and in-depth studies enabling the authors to produce articles and scientific publications relating to individual works that contain only their analysis, rarely the actual data.

In other cases, the data are preserved in binders filling warehouses and vaults which are no longer accessible and not overseen, or are at unknown locations.

In the former case, however, the data incorporate an advantage, namely that of being generally published in national and international journals, and so having undergone the necessary scientific validation, especially if subjected to a rigorous process of anonymous peer review. In many cases, these are works that constitute reference points in the field of applied hydrogeology.

In chapter 11 an annotated bibliography organized by topic is provided; here some noteworthy examples containing historical data are given: Bianchetti et al. 1993; Marechal 1998; Pesendorfer & Loew 2004; Masset & Loew 2013; Vincenzi et al. 2014; Ranfagni et al. 2015; Scibek et al. 2016.

2.1.2 On-line Data Bases

By consulting the Internet it is possible to find data relating to the excavation of tunnels and underground works in general. These are mostly lists of tunnels made in various countries and in different contexts and for different purposes. An example is that available on Wikipedia which provides a long list of tunnels complete with end date of works, country and length (https://en.wikipedia.org/wiki/List_of_long_tunnels_by_type).

The database of the International Tunneling and Underground Space Association (ITA-AITES) is more specific, giving access to numerous scientific articles, conference proceedings and technical standards relating to the design and excavation of underground works (https://library.ita-aites.org/).

Another example is that of the USGS (United States Geological Survey) database which permits consultation of the data collected in the hydrogeological field in the United States (National Water Information System NWIS; http://waterdata.usgs.gov/nwis/qw). However, this database is general, not focused on data describing the interaction between underground works and aquifers.

The Australian Tunnelling Society (ATS) database is available on its website (http://www.ats.org.au/resources/tunnel-projects-2/), where it is possible to obtain engineering information (method of excavation) and geological information (soil in which the excavation took place); however, quantitative hydrogeological data are not provided in an organized manner.

It is also possible to carry out bibliographic searches using the search engines of the main scientific journals (www.sciencedirect.com, http://springerlink.metapress.com) or by consulting university library online search engines:

- Federal Polytechnic School of Lausanne: https://www.epfl.ch/campus/library/)
- Massachusetts Institute of Technology: https://lib.mit.edu/search/bento?q=hydrogeology+tunnel

Therefore, although it is possible to obtain data directly from the web, it does not seem that there is a single and specific database collecting hydrogeological and geological data to be used to transfer the accumulated experience to new projects..

2.1.3 Expert consultation

IIn recent decades, with the technological development of mechanized excavation in tunnels and with the increasing awareness of impacts on the water resource and associated ecosystems, clients, designers and construction companies increasingly make use of consultants who are experts in the geological and hydrogeological fields.

Their contributions are often related to their direct and indirect experience in the design and construction phases of underground works, and are fundamental especially in the prediction and quantification of geological and hydrogeological risks and in the context of the study of environmental impacts.

2.2 General remarks on the available data

In general, but with some exceptions, the quality of the available data is higher for works carried out more recently (from the end of the '90s onwards), above all thanks to the possibility of installing automatic monitoring systems both inside the underground works and at sensitive water bodies on the surface. However, for works of strategic importance, significant data are also available for tunnels constructed earlier (e.g. Mont Blanc Tunnel, Simplon Tunnel, "Direttissima" Tunnel of the Apennines). In these cases, the importance of the work made it possible to carry out studies of scientific value such that they still represent an important methodological and applied reference point today (Marechal 1998).

More generally, the analysis of historical data concerns works located in different parts of the world and affected by different geological, tectonic and structural contexts, increasing the statistical representativeness of hydrogeological parameter assessments.

Moreover, in many cases the flow rate data of water inflows are indicated qualitatively, for example with expressions such as "abundant water" or "single point inflow". The quality of the data is therefore related to the observation and acquisition method.

In the most dated documents, information relating to flow rates does not distinguish between transitory and stationary flows. However, this distinction is important for the evaluation of the hydraulic characteristics of rock masses in which the different tunnels have been excavated and allows verification of the impact on the evolution of flow rates over time of parameters such as recharge, storage and variation in the intrinsic permeability of aquifers.

In this regard, the completeness of quantitative hydrogeological data (piezometric load, flow rate of water flows, etc.) is guaranteed only if the data are coupled with geological data. In particular, in a comparison between technical information and the hydrogeological parameters deriving from different works, the availability or lack of data on the stress state of the rock mass is a discriminating factor for a more correct evaluation of the significance of the quantitative hydrogeological data. A lack of geological-structural and geo-mechanical data does not permit in-depth description of the various hydrogeological structures and full comparisons during the design phase.

As a result, hydrogeological parameters such as hydraulic conductivity, transmissivity or storage capacity are difficult to evaluate in the absence of information on transient and stationary flows and on the geological-structural characteristics of the rock mass and/or excavated soils.

The as-built data acquired during and after excavation are of greater value if compared to the observations and analyzes derived from hydrogeological surveys both in the tunnel and on the surface. The availability of surface data has increased in the most recent works, making it possible to acquire information on the influence of the excavation on surface sources and ecosystems connected to water runoff. In this sense, environmental and hydrogeological monitoring of the water and biotic components during and after excavation works is now a fundamental element for the design of an underground work and for its inclusion in the environment.

2.2.1 Flows recorded in the tunnel

In the context of analysis of the variations in flow rate of a tunnel's water flows, numerous physical factors must be taken into account in order to understand the temporal dynamics of the phenomenon:

- the progressive lowering of the hydraulic load (piezometric level) following drainage;
- the extent of the recharge of the aquifers drained in the tunnel;
- the dependence between permeability and the actual stress field.

The first of these phenomena is directly related to the other two. In general, it is possible to state that in a context of medium permeable soils and/or rock masses, in the presence of poor recharge (lower than the drainage potential of the tunnel), the lowering of the hydraulic load will be maximum, and vice versa. The reduction of neutral pressures (water pressure in the pores and/or fractures), and the consequent decrease in the intrinsic permeability of the aquifer, in the long term determines a lower drainage and therefore a decreased piezometric lowering. This effect is stronger for deep tunnel sections.

In the light of the above considerations, a distinction is made between peak, transient and stabilized flow in order to clarify the terminologies that will be adopted in this Paragraph. The emptying phase of an aquifer that feeds a natural source can generally be taken as an example to simulate the evolution over time of the flow rate of an inflow into a tunnel. On the basis of this curve we can distinguish three different moments, graphically illustrated in Figure 2.

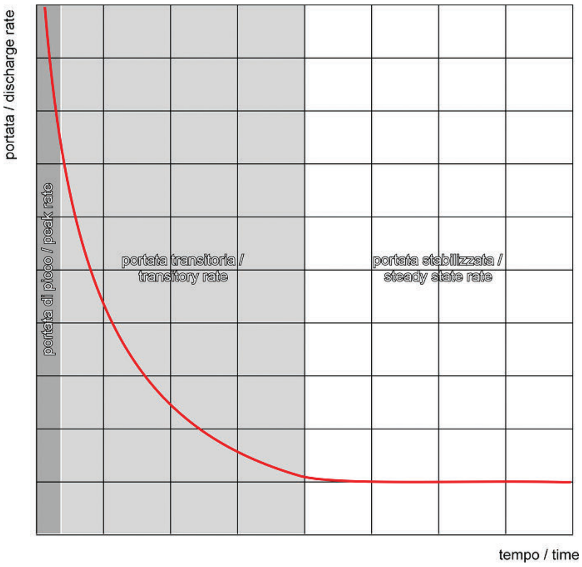

Fig. 2 - Depletion curve of water inflows into the tunnel.

Peak flow

Immediately after the interception of an inflow of water, the decrease in flow takes place very rapidly; the data relating to these first instants of the emptying phase are generally rare and available only for the main inflows in a tunnel. In this phase, the flow rate is influenced mainly by the hydraulic load and permeability and less by the direct recharge of the aquifer intercepted by the excavation.

Transitional rate

The transient flow rate refers to the central and descending part of the curve in Figure 2. It persists until the drainage pressure of the aquifer that feeds the incoming water balances with the flow system that feeds it. This period will be longer or shorter depending on various factors, the main one being the connectivity of the intercepted aquifer with water bodies on the surface or with other deep flow systems. Most of the available bibliographic data refer to this type of flow, because they were analyzed during the works but after some time (days-weeks) from the interception of the inflow. Especially when analyzing sections of long tunnels and with several inflows, the cumulative data are always referable to inflow totals in this development phase. Apparently, data relating to inflows at this stage could be of little significance, since it is often not known at which part of the curve the individual inflows are located

Stabilized flow rate

After some time, flows tend to zero; if the aquifer rock mass empties according to the Maillet model (1905), the depletion phase coincides with the tail of the exponential curve shown in Figure 2 (linear on a semi-log logQ-time diagram). This phase can generally be considered valid only some time, even

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weeks or months, after the end of the excavation of a tunnel or a significant section of it. The stabilized flow rate will be greater or lesser depending on the degree of connection of the intercepted aquifer with the permanent recharge areas generally located on the surface.

2.2.2 Temperature changes

The observations carried out in deep boreholes and in excavated tunnels have revealed how the temperature of the groundwater is in equilibrium with the rock mass. The available data normally derive from measurements made in geognostic boreholes performed both from the surface to tunnel level and from the tunnels themselves (Rybach, 1995; Hokr et al. 2014).

The temperature of the subsoil at depth depends on the geothermal gradient and on local geological and structural geological factors such as the nature of the rock and its thermal conductivity, the presence of fracturing systems (anisotropies) and water circulation in the rock mass, as well as on the outside air temperature at ground level.

In the past, the estimation of the temperature of rocks at great depth was carried out through empirical formulas starting from direct observations in excavated tunnels or through the development of analytical formulas (Andreae, 1948) based on a heavy schematization of the rock mass.

In the 1990s, the development of information technology and investigation techniques allowed the use of numerical models. The forecast of the temperature at tunnel level takes into consideration parameters such as the surface temperature corresponding to the position of the tunnel, the local geothermal gradient and the thickness of the tunnel roof.

For example, in the cases of the Simplon, Mont Blanc and Gotthard tunnels (Alps) a good correspondence was shown to exist between recorded temperature trends and the degree of fracturing of the rock mass, allowing the elaboration of theoretical models for forecasting the flow rates and temperatures expected in the tunnel (Goy et al. 1996; Marechal et al. 1999).

The possibility of intercepting hot water flows has made it possible to design (Pastorelli et al. 2003; Torri et al. 2014) and to build heat enhancement systems in the immediate vicinity of tunnel portals (Rybach & Wilhelm 1995; Hufschmied & Brunner 2010).

2.2.3 Changes in water geochemical characteristics

As in the case of temperatures, water chemistry is assessed on the basis of data obtained from sampling in geognostic boreholes and from water flows into the tunnel or, in the absence of these, on the basis of the proposed hydrogeological model.

By chemical composition we mean the initial composition of water flows. It is assumed that this will remain fairly stable in sectors with low permeability or in the absence of dissolution phenomena. In contrast, ionic concentration may be reduced in sectors with high permeability in which the tunnel will induce intense direct or indirect recharge.

In general terms, the chemistry of waters intercepted by tunnels will be expressed in terms of concentration of the main ions, as they are generally monitored fairly regularly (Pastorelli et al., 2001).

In the most recently built tunnels, analyses are often also available relating to the isotopic composition of the water and its evolution over time, which have contributed to better characterizing hydrogeological circulation and impacts on the surface.

The estimate of water aggressiveness reported in hydrogeological profiles mainly refers to its effect on concrete works induced by the presence of sulfate ion. The aggressiveness classes refer to the UNI technical standard: EN 206: 2016.

2.2.4 Impact on surface waters and GDE

The as-built data acquired during and after excavation take on greater weight if compared to observations and analyses derived from hydrogeological surveys both in the tunnel and on the surface. In the most recent works, the availability of surface data has increased; this makes it possible to acquire information on the influence of the excavation on surface sources and ecosystems connected to groundwater runoff. In this sense, the environmental and hydrogeological monitoring of the water and biotic components during and after excavation works is now a fundamental element for the design of an underground work and for its inclusion in the environment.

2.3 Data analysis criteria (Database creation)

The main purpose of this chapter is to provide indications or guidelines for the creation of a historical data base and its sharing through the creation of a free access computer catalog for designers, clients, companies, etc.

The types of data useful for a correct and exhaustive bibliographic analysis are therefore listed below. The list has been drawn up in such a way as to be useful not only for the user consulting the database but also for those who find themselves needing to collect as-built data because they are involved in various capacities in the construction of an underground work.

Based on the data found in the bibliography, and depending on design needs, 5 sections have been identified which contribute to obtaining a complete picture of the context of the work: i) general information on the work; ii) geology; iii) geo-mechanics/excavation method; iv) hydrogeology; v) ecosystems (GDE - Groundwater Dependent Ecosystems).

The following list constitutes an outline which, although already detailed, could and should be expanded according to the local conditions of each project

For each section it would therefore be desirable to be able to collect the following information.

a. General information on the work:

- Name
- Geographical Sector
- Type (tunnel, base mountain or side tunnel)
- Dimensions (length/height/width/diameter etc.)

- Thickness of the cover
- Any exploitation of the water drained from underground works

b. Geology

- Geological unit
- Main and secondary lithotype
- Structural context (main position)
- Temperature of the water drained during and after excavations
- Geothermal gradient

c. Geo-mechanics/Excavation methods

- Medium RMR (Rock Mass Rating) class
- Type of fracture
- Presence of soft soils
- Method of excavation (traditional and/or mechanized) and speed of advancement
- Temporary and final type of lining
- Waterproofing
- Presence of water inflow management systems (drains, niches, water collection, water removal system, etc.)

d. Hydrogeology

- Discharge rate and type (peak, transient or steady)
- Rock temperature during and after excavations
- Aquifer type
- Average permeability
- Thickness of the aquifer crossed
- Hydraulic load
- Type of water inflow
- Extension of the charging area
- Water temperature (min/max/med)
- Other water chemical-physical parameters (pH, redox potential, electrical conductivity)
- Hydrochemical facies and isotopic characteristics

e. Ecosystems (GDE - Groundwater Dependent Ecosystems)

- Type of environment (source, wetland, lake, stream, karst system, etc.)
- Distance and elevation relationships with the tunnel
- Ecometric indicators
    - water chemical-physical parameters (flow rate, temperature, hydrochemical facies, etc.)
    - biotic parameters (algae, vegetation, macro/micro-invertebrates, vertebrates, etc.)
- Type of water circulation (deep, superficial, mixed)
- Expected and/or recorded impact (time delay of impact manifestation - the latter aspects can be represented as percentiles, for example by altitude ranges or distance ranges).

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3 HYDROGEOLOGICAL STUDY

Fabrizio Grosso and Paolo Perello

In the past the design of major works involved a predominantly "static" approach to the study of groundwater, i.e. aimed at evaluating the reference piezometric structure for the geotechnical and structural design (estimation of interstitial stresses, hydraulic loads on structures, etc.).In contrast, over the last 15-20 years, planners and control bodies have developed an increased awareness of environmental aspects and the protection of water resources. In particular, the need to integrate a "dynamic" approach into the study of groundwater in design studies has emerged, aimed at evaluating changes over time in aquifers' equilibrium caused by the inclusion of the work. These aspects concern piezometric changes, temporary or permanent, and consequences for the conservation and availability of the resource, as well as for the ecosystems dependent on the aquifer.

A design study of interference with aquifers involves the application of consolidated but constantly evolving techniques in the fields of hydrogeology, underground hydraulics and monitoring. The interference assessment tool consists of scenario simulations, through the development of conceptual and mathematical models (see also Paragraph 4.7.3) which are constantly checked and calibrated starting from the results of geological and hydrogeological surveys and from the data flow deriving from monitoring in the before construction, construction and after construction phases. The aim of the scenario models is always direct mitigation of interferences, through feedback to the design activity.

For non mitigable interferences, i.e. where effects on aquifers cannot be eliminated in absolute terms or at financially sustainable costs, minimization or compensation interventions will mainly address reduction of the socio-economic effects of impacts, for example with the development of alternative emergency, medium-term and final water supply plans (see also Paragraph 4.8.2).

The methodological and operational guidelines for scenario modelling and monitoring activities are therefore summarized below, with reference to various applications, related to large infrastructures in both plain alluvial aquifer settings and in fractured hydrogeological complexes.

3.1 Operational scheme of the activities

The evaluation of a large underground work from the point of view of interference with the aquifers must follow a well-defined logical scheme with the aim of implementing knowledge, and as a result defining the conceptual or numerical model of reference starting from the preliminary study up to the after-construction operational phase.

In Figure 3 the development over time of the aforementioned activities is shown in diagram form. The main aim of hydrogeological assessments is the definition of the reference hydrogeological model. This should be achieved starting from the preliminary design, which in the diagram coincides with time t = 0; it should then proceed with the carrying out of the separate hydrogeological study activities aimed at the progressive implementation and definition of the model, developing simultaneously with the work project stages and therefore to an ever greater degree of in-depth analysis, and focused on the main critical issues. With reference specifically to the design and construction phases of the work, the diagram highlights the general time schedule of the different hydrogeological study activities. The vertical red arrows highlight the continuous contribution made by the results from the individual activities to the evolution of the study and to the definition of the model during the development of the different design and construction phases of the work. Parallel to the progressive definition of the hydrogeological model, the blue arrows highlight the continuous feedback into the design of the infrastructure and the interventions for reuse and mitigation of any interference.

The need to follow a complete evaluation process through all the phases of design, construction and post-construction

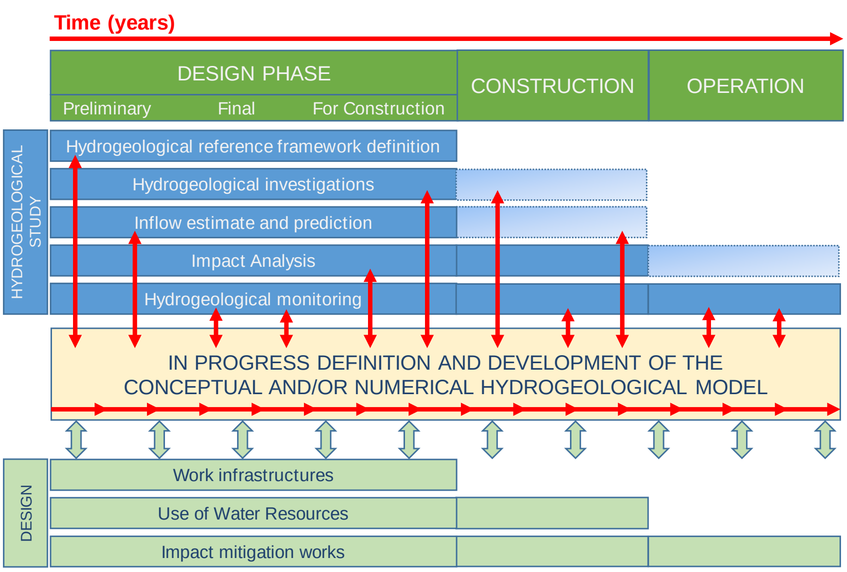

Fig. 3 - Flow chart for the definition and development of the conceptual and/or numerical hydrogeological model of an underground work. The time schedule of the phases, from study and design to construction, is shown at the top. The design activities for the minimization of hydrogeological impacts are shown at the bottom.

of the work should be emphasized. This is because all the activities are linked and in sequence, rendering ineffective both tardy assessments and mitigation interventions carried out once the work is completed, and those defined in the preliminary phase and not supported by adequate feedback from monitoring of the work in progress.

3.2 The geological model: fundamental element of the hydrogeological model

A reliable hydrogeological model cannot exist in the absence of in-depth investigations and analyses that have made possible a prior or parallel reconstruction of a geological model which is as accurate and reliable as possible.

The reconstruction of the geological model should always be based on the sum of three types of surveys: i) surface data, i.e. geological survey, ii) data from direct surveys, such as boreholes; iii) data from indirect surveys, i.e. mainly geophysics. In all cases, in the description of the investigations within the project, a clear distinction should be made between gathered and interpreted data as well as the type of investigation adopted, in order to be able to retrace the path of reasoning and verify the information provided, for both design and control purposes.

On the reliability of the hydrogeological model and the key elements and development criteria, see also specific references (Perello et al. 2003, Perello et al. 2006, Bianchi et al. 2009, Perello 2011, Dematteis & Soldo 2015).

3.2.1 Geological survey

The geological survey is fundamental. Without going into detail, the important aspects in performing the surface survey are:

- its extension over a suitably large area around the tunnel, proportionally greater as the depth of the work increases;
- a detailed examination of as many outcrops as possible at the mesoscale is necessary, with observational criteria which are not only purely geometric, but also genetic (stratigraphic analysis, intersection relationships between surfaces etc.);
- in addition, for hydrogeological issues stratigraphic reconstructions of Quaternary deposits and their relationships with the lithotypes of the bedrock are extremely important. In fact, in a mountainous-hilly environment Quaternary deposits are often the main elements for spring recharge;
- in the case of sources in a mountainous-hilly environment it is important since these are often linked to delicate balances between several local factors.

3.2.2 Direct investigations

Direct surveys are a fundamental element in all contexts, from mountainous to lowland areas. Some important aspects to be taken into account for carrying out these types of surveys are briefly outlined:

- the number of investigation points is obviously very important in determining an effective result; however, it should also be considered that a correct positioning of the investigation points can lead to a better and more effective resolution of interpretative problems than uncritical positioning of a greater number of points;
- the probes for the development of an infrastructural project must be carried out entirely with continuous coring, since this permits a general contextualization and, by projecting them in depth, makes possible lateral correlation with data collected at higher substrate levels than those in which the probing intercepts the route of the tunnel;
- especially for hydrogeological aspects, it is important to have direct investigations for the quaternary coulters, even if they are placed far above the level of the work, for the reasons already mentioned above and linked to the importance of the relationships between deposits and bedrock; it should also be considered that for hydrogeological aspects, it may be essential to carry out probes even at some distance from the axis to investigate specific issues;
- although cored, for all boreholes where the hole is self-supporting it is advisable that surveys be carried out with a borehole tele-viewer (BHTV) since these allow a better contextualization of the hydraulic tests and their extrapolation.

3.2.3 Indirect investigations

Indirect investigations can be of different types and are appropriate for investigating possibly deep but not excessively complex contexts, where there are elements capable of determining significant conflicting effects, resistivity, etc. In general, investigations of this type may for example be fundamental for defining the spatial pattern of contacts between quaternary deposits and substrate, or the presence of levels with a strong difference in grain size within quaternary deposits (aquifer-aquiclude limits); on the other hand, they are not very effective for highlighting geological elements within crystalline substrates, unless one proceeds with extremely detailed investigations. For this type of investigation, there are basically two main recommendations:

- always proceed with a calibration of the results by means of surveys;
- the interpretation of the data should be undertaken in close collaboration between the team of geologists responsible for creating the geological model and the team of geophysicists carrying out the survey.

3.2.4 Use of the best scientific methods

Generally speaking, the criteria used to determine a geological model for a tunnel, especially when this involves very long stretches, must be demonstrably scientifically state of the art. This means that while not analysing issues at a level comparable to that of scientific research, it is necessary that the reference models used are benchmarked to the most modern advances in knowledge in terms of geological-

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structural, stratigraphic and petrographic analysis.

Activities that are often not performed in applied geology because they are too close to the field of scientific research of basic geological disciplines may instead be essential for establishing the existence of important geological elements that are sometimes not easily grasped by other means because they are buried underground or not easily investigated with traditional types of surveys. By way of example, paleontological-stratigraphic analyses can significantly contribute to the reconstruction of successive lithological units, especially in sectors with little continuity between one outcrop and another (e.g. numerous sectors of the central-southern Apennines). A meso-scale structural analysis according to genetic criteria with interpretation of the deformation sequences can be very important for interpreting the necessarily discontinuous data deriving from probes in a complex orogenic sector (e.g. the Alpine chain). Likewise, in Quaternary and Pliocene contexts contributions from sedimentology become important to ensure a more reliable reconstruction of the geometries of bodies with different permeabilities.

3.2.5 Geological representations and 3D models

The method of presentation of the conceptual geological model should be mentioned. The model is basically aimed at providing a three-dimensional view of the geological elements. This visualization should be provided through vertical sections and profiles, positioned on the plan so as to intercept the areas which are considered most critical, and exemplifying the general problems.

Visualizations through numerical modelling are also desirable, especially for their subsequent use in hydrogeological modelling. However, the purpose of these 3D models should be defined clearly and in advance. Indeed, a robust 3D model can only be obtained after much investment in terms of time and cost, without which it risks being completely useless and sometimes even misleading. In general, it is advisable to create detailed 3D geological models only for limited areas of the project area where there are significant problems, specifically of a hydrogeological nature.

3.3 Pre-construction phase

The hydrogeological study and monitoring activities in the pre-construction phase should lead to the definition of the unaltered natural framework of the reference underground water circulation, and predict any subsequent modification of the hydrological regime connected with the construction of the planned infrastructure.

Analysis is based on the development of **the conceptual hydrogeological model of reference** through: the structural reconstruction of the relationships between the aquifer complexes, the definition of the hydrological regimes, the recharge areas and the methods and depths of underground water circulation, assessment of the terms of the hydrogeological balance of the aquifers concerned and of their hydrodynamic parameters as well as hydrogeochemical characterization.

To support conceptual schematization, an analytical, classification or numerical model can be developed, either general or with reference to detailed sub-models, through the application of specific calculation codes, the reliability of which will however be proportional to the degree of detail and depth of the conceptual model of reference and factual data available for calibration.

3.3.1 Conceptual hydrogeological model

The reference scheme or “conceptual hydrogeological model” in practice comprises a three-dimensional representation, through appropriate stratigraphic and hydrogeological sections, of the geometry of the aquifers, of the trend of permeability limits and thresholds, of the underground flow methods (recharge areas, underground watersheds, drainage lines, interchanges with the surface water network, etc.) and the range of variability of the hydrodynamic parameters considered most representative for each aquifer formation.

The definition of the reference model takes place through the different activities, listed in Figure 3, that make up the hydrogeological study, in particular:

- the definition of the reference framework of available hydrogeological data;
- experimental investigations;
- hydrogeological monitoring.

The definition of the reference framework is a systematic bibliographic activity, aimed at acquiring data and documentation related to the water resource of the territory affected by the project. Specifically, the following must be acquired:

- official documentation relating to water concessions, including small and large diversions from watercourses;
- any available gathered data relating to water points (meaning springs, wells, piezometers, waterways, wetlands);
- historical hydrometric data (piezometric levels, average flow rate of springs, extraction flow rate, etc.), hydrogeochemical and quality data;
- the meteo-climatic data relating to rainfall and total monthly and annual average temperatures from longstanding weather stations operating in the study area for at least twenty years.

The reference framework must be completed by the identification and acquisition of experiences and studies in contexts similar to that of the survey, for which reference should be made to the contents of Chapter 2.

Considering the geological context already adequately known, the definition of the conceptual hydrogeological model takes place on the basis of specific experimental investigations which can be summarized as follows:

- inventory of water points (captured and non-captured sources, wells) and inventory of surface water bodies (watercourses and wetlands);
- qualitative and quantitative characterization of the water points, also as a prerequisite for the definition of the monitoring plan;

- specific tests for the evaluation of hydrodynamic parameters (pumping tests, downhole permeability tests, source ceased flow rate analysis), and for evaluation of water circulation mode (tests with tracers, pumping tests);
- geological and geo-structural survey.

The on-site inventory of water points should expand and develop the information obtained from the preliminary definition of the reference framework from bibliographic bases and data collection from institutions.

The size of the area to be investigated depends on the context of the study and should include the hydrogeological basin affected by the work. Since the definition of the extent of hydrogeological basins is not always easy, especially in the initial planning phase of the surveys, as an indication, at least for mountain areas, the census should necessarily extend to the limit of the main hydrographic basins affected by the work, possibly also already including in this phase adjacent basins if bibliographic research reveals indications of extension of hydrogeological basins in this sense. The size of the survey area may also vary in relation to particular local contexts.

In areas on plains the extent of survey areas can be identified according to the depth of the works and the permeability characteristics of the land, as well as the dynamics of the underground water circulation, possibly identified in previous studies.

The inventory of water points constitutes a source of fundamental data for defining the model, so it must be carried out or at least closely supervised by personnel with suitable hydrogeological experience, able to acquire and filter with adequate critical awareness the information obtained through direct contact with the owners and managers of the water resources identified. From this point of view, it should be noted that often the characteristics of a certain water point are not computerized or systematically archived, but are simply known to the technicians who directly manage these works, or to the private citizens who have them in concession. This aspect assumes particular importance for the purposes of the reliability of the data gathered: especially in the case of older artefacts, it is not rare for example that the flow rate of a captured source must be measured by summing the outflow of several pipes in different places. The information derived from the inventory should be organized in monographic files to constitute an easily consultable computerized database.

The inventory of surface water bodies is also of considerable importance, and should include the sections of watercourse relating to the hydrographic basins underlying the works, unless indicated otherwise by the structural geological context, or where the hydrogeological and hydrographic basins do not coincide. The activity should be aimed at verifying the presence of deep outflow in watercourses and must therefore be carried out during dry periods; measurement of the rate of decrease of the dry period flow in the low recharge period is of hydrogeological value for an estimate of the underlying underground water resources. Flow measurements at different altitudes along the watercourse are useful, at least upstream and downstream of the intersection with the underground structure. Surface intake or draining works must be surveyed and checked in the sections of interest.

Simultaneously with the inventory activities regarding both the water points relating to outflows from underground flow systems and surface water courses, quantitative (flow rate, piezometric level) and qualitative characterization measures must be carried out. The latter essentially includes determination of the basic chemical-physical indicators (conductivity, pH, temperature) and of the main ions (for example Ca, Mg, Na, K, HCO_3, Cl, SO_4, NO_3). In certain contexts, it may also be useful to determine some isotopes (for example ^{18}O, ^{2}H, useful for evaluating the water infiltration rate, or ^{3}H, which can provide information on water residence times), or of some recharging indicator parameters from particularly deep circuits of hydrothermal origin (for example Li and Br) or parameters useful for determining the state of thermal rebalancing at system depth (SiO_2). Chemical and isotopic determinations will involve a sample number of water points, from those most representative of the water circulation modes. These assessments are also prerequisites for the definition of the hydrogeological monitoring plan (for which see the relevant chapters).

Investigations for the evaluation of hydrodynamic parameters must be planned in advance as part of the project investigations aimed at defining the geological-geotechnical reference framework. For the location and characteristics of the boreholes, the designers will therefore need to consult the hydrogeologist in order to optimize the survey plan, also considering the needs of hydrodynamic characterization of the aquifers and with the aim of creating a piezometric control network potentially functioning from the time of execution of project investigations. For this reason, boreholes equipped with piezometers should never intersect the underground excavation, so they can continue to be used afterwards.

Furthermore, when planning the surveys, the possibility of setting up wells/piezometers suitable for carrying out pumping tests and adjacent control piezometers must also be planned with the aim of determining the hydrodynamic parameters in particularly significant contexts from the hydrogeological point of view.

Hydrodynamic characterization is frequently based on short-term borehole tests, such as Lugeon- or Lefranc-type tests, whose usefulness for characterizing the permeability of aquifers is however limited to the specific points. With reference in particular to Lugeon tests, widely used in Italy for the hydrogeological characterization of fractured media, it is important to note that these are not specifically designed to evaluate hydrogeological characteristics, but to estimate the injectability of fractured media with cement mixtures. Their use for hydrogeological purposes must be based on a choice of appropriate pressure steps: particularly high injection pressures are often used, which are appropriate for evaluating injectability but not for estimating hydrogeological aspects, as high pressures often cause changes in the rocky medium

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around the hole, altering the result.

Tests between packers, with constant flow or load, and which can also be performed in small diameter holes, may be more appropriate than Lugeon tests for fractured media. These tests, even if carried out over shorter periods and at reduced quantities (in terms of extracted/injected fluids), are comparable to long-term pumping tests. In recent years, some specialized companies have equipped themselves with devices suitable for carrying out such tests, whose execution is becoming more and more frequent. A final note regarding these tests and Lugeon tests should be made regarding the length of the test chamber used for fractured media. This length must be chosen according to the scale at which the permeability of the medium is considered significant. Test chambers that are too short (a meter or a few meters long) risk returning permeability values relating to single or a limited number of fractures and not considering connectivity between these fractures on a hectometric -decametric scale, which instead is the truly significant parameter when considering tunnel excavation.

Medium-/long-term pumping tests permit characterization of larger portions of the aquifer in the porous medium and can also be used for the characterization of fractured aquifers. For the latter, results are more representative of single aquifer tracts and less of the aquifer as a whole. Modelling of a transient drawdown test also permits characterization of dynamic storage parameters.

In order to evaluate the relationships between surface and underground outflows, in addition to the aforementioned flow measurements, measurements can be taken in the hydrographic network by means of tracers, which constitute an important reference technique for specific situations not exclusively linked to particular karst contexts.

In contexts in which surface geo-structural surveys can be carried out, discontinuities in rock masses affected by excavations are characterized in terms of opening, spacing, persistence, roughness, hydraulic conditions, filling of the discontinuities and their spatial arrangement. In this way the hydraulic conductivity of investigated masses is estimated, even if issues in transferring geo-mechanical data of the outcrop to the context of the aquifer unit at depth must be taken into account. From this point of view, surveys with a video camera down the hole (e.g. BHTV, ATV) also take on a significant role, since they provide indications on the orientation of the discontinuities at depth, which can be correlated with those identified by the surface survey.

On the basis of the results of the hydrogeological surveys and an initial definition of the conceptual model, an adequate hydrogeological monitoring plan should also be prepared, for the purpose of experimental control with automatic instrumentation or through measurement of the dynamics of the aquifers in the whole period of time including the realization of the project (before construction phase, works phase and post construction).This activity certifies the qualitative and quantitative availability of water resources before execution of any work (before construction), contributes to its definition, or, by means of a continuous supply of data, "in progress" recalibration of the hydrogeological model, and the successive feedback for planning (see the chapter dedicated to monitoring plans).

- analysis of rainfall and aquifer recharge patterns:
    - climate conditions;
    - hydrogeological balance of the aquifer or aquifers of interest;
    - estimation of effective infiltration (analysis and calculation of the areal indices relating to the parameters that determine the infiltration capacity and evaluation of the average annual volumes of infiltration regarding the structure of interest);
    - comparative check of the above estimated recharge and discharge of the system based on measurements of the flow rate of the sources or of the base runoff of watercourses;
- interpretation of hydrochemical and isotopic data when available;
- interpretation of structural reliefs;
- identification and interpretation of relevant tectonic structures;
- verification and analysis of any karst phenomena;
- correlation with fragile structures (e.g. faults, joints);
- definition of the overall characteristics of the water supply circuits;
- plans of hydrogeological complexes, iso-piezometric map, hydrogeological sections.

3.3.2 Numerical models

Numerical models for flow simulation, together with more traditional monitoring techniques, constitute very useful tools and working standards for the design of underground works. A deterministic approach allows the definition of optimized solutions in terms of both reliability and minimization of costs and impacts.

Numerical modelling should schematize the simulation context of even markedly heterogeneous environments, such as fractured aquifers. As part of the design of a tunnel infrastructure, numerical modelling should initially be prepared in the design stage and then progressively developed during the progressive stages of the work's design, to an increasingly greater degree of in-depth analysis, and focused on specific objectives, which may be local or on a larger scale.

During design, local modelling can be effectively applied in critical sectors, in sectors with specific conditions or in sectors clearly delimited by geological structures of primary importance, aimed for example at:

- simulation of specific hydrogeological conditions emerging from structural studies, heterogeneity of hydraulic conductivity characteristics in sectors involved in the works;
- choice of the most effective drainage solutions to be adopted during the construction phase to reduce pressures on the excavation face, in different typological conditions of permeability and hydraulic load, or to mitigate the

dam effect, in particular in the case of lowland aquifers in urban areas;

- verification and control of evaluations carried out with analytical (see also Paragraph 4.7) or empirical methods (for example Heuer 1995, 2005).

Unlike local scenarios, large-scale models necessarily introduce simplifications to describe complex hydrogeological systems and require detailed knowledge that is not always obtainable outside the axis and range affected by the works in the project. These numerical models, which in any case presuppose the availability of a complete and reliable conceptual reference model and sufficient data for calibration, allow attainment of a level of knowledge higher than that deriving from conceptual schemes and "models". Among other things, they permit control of the entity of inflows into the tunnel at equilibrium with the recharge, that is the estimate of drained flows and after construction effects on the hydrogeological system as a function of the specific recharge capacity of the aquifers.

Therefore, unlike local scenarios, large-scale models have the purpose of characterizing at the scale of hydrogeological basins, in terms of:

- before construction hydrogeological balance;
- after construction hydrogeological balance;
- overall effects, by area, on surface water resources.

In both cases, particular care must be taken in the correct interpretation and use of the basic data (see Paragraph 3.2 above) for modelling purposes, a crucial aspect for the reliability of the modelling result.

Finally, it is important to recall that more complex numerical models can be applied only if supported by an adequate experimental characterization developed in the context of hydrogeological surveys and monitoring, allowing the development of a detailed conceptual model of the site and an adequate calibration of the numerical simulations performed. This concept is also taken up in Paragraph 4.7.

The implementation of a numerical simulation model, starting from the conceptual model, is meaningful above all for environments with a reduced degree of geological-structural "complication", i.e. where each element of the conceptual model can be adequately parameterized. In particularly complex hydrogeological environments, the application of a numerical model is necessarily based on extreme schematizations and on the attribution of partly random variables, thus constituting a parametric evaluation tool rather than a specifically deterministic one.

In this sense, numerical modelling is a tool that should be used at different levels, adapting the calculation tools to the degree of complication of the conceptual model. In this regard, there are important differences in modelling applications between porous aquifers, such as lowland alluvial complexes, and fractured aquifers.

Numerical simulations, necessarily simplified, are usually performed in steady state. This condition constitutes a necessary standard for most of the scenario models referring to fractured aquifer complexes, due both to the lack of time-dependent calibration data to support transient simulations, and in particular to the poor reliability of methodologies for the evaluation of dynamic storage parameters in such contexts

Taking into account the aforementioned limits as of the characterization phase at the conceptual scheme level, in the conditions of flow in the fractured medium under examination, the model must be calibrated on the basis of:

- the piezometric data locally available at the level of the underground works in the project;
- the mass balance at the hydrogeological basin scale: the various components of the hydrogeological balance (direct and lateral recharge, anthropogenic withdrawals, surface runoff) must "close at zero", or present discrepancies compatible with the level of uncertainty on the hydrogeological parameters, and in particular there must be correspondence with the estimate of the discharge of the underground water circulation systems;
- a larger scale verification of correspondence, based on the assumptions made, with the general scheme of underground water circulation (slope circulation, adaptation of the piezometry to the main watersheds, etc.).

With reference to this last point, in the conditions under examination the calibration of the model in the permanent regime schematization constitutes a relatively "reliable" process, even in the absence of multiple-point piezometric data.

With reference to the activity flow chart in Figure 3, the subsequent evolution of the model consists in its application as a decision support tool (Decision Support System, DSS), through the overlaying of project elements as different alternatives that are normally subject to evaluation in the preliminary study and design phase of a complex work. This process therefore consists in the verification of different design solutions, such as in specific alternatives of tunnel layout, location of windows and steep service tunnels, particular mitigation interventions, etc., characterized by specific conditions of impact on the underground water system.

In steady state, the result of interest from the scenario model for the purposes of the decision-making process is the alteration of piezometric conditions induced by the work. This indication is obtained by comparing the fields of static loads with those referred to the work calculated by the simulation model through the usual calculation techniques in a GIS environment.

3.4 Works/Construction phase

With reference to the scheme of activities in Figure 3 and the more general indications given in Paragraph8.4, during the construction phase monitoring should be planned, aimed at quantitative verification of the conditions defined on the basis of the scenario models in the pre-construction phase.

On the basis of the flow of monitoring data as well as of the stratigraphic data during construction of the underground work (e.g. in-progress revision of the project's geological profile along the tunnel axis), it is possible to verify and possibly make changes to the conceptual hydrogeological

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model and its possible analytical or numerical mathematical developments, only where there are significant deviations from the forecasts referred to in the previous phase.

3.4.1 Criteria for hydrogeological monitoring during construction

Monitoring of the work progress (see also specific Paragraphs 8.3 and 8.4) usually has the following objectives, which are directly linked by cause-effect:

- verification of the drainage volumes induced by the work, or of the embankments for keeping the site area clear of water;
- verification of the effects of the construction site on the surrounding piezometric regime and on the system of wells, springs and base flow of watercourses.

As in the before-construction phase, there is a difference in the methodological approach to monitoring with reference to works in alluvial lowland aquifers and in fractured systems. Specifically, in the case of drainage works in lowland aquifers, the control of drainage volumes is usually referred to the construction site embankments built to ensure safe conditions in the work area or to the construction of floodgates or walls as barriers. In this case monitoring consists of volumetric meter checks of the draining flow rate and of piezometric changes in the surroundings, hence the verification of the forecasts made with the flow model.

In fractured systems, monitoring for drainage tunnels is more complex, as the drainage trend refers to a transient phase piezometric reduction, followed by stabilization in an equilibrium regime with recharging. Furthermore, tunnel drainage is not usually referred to a single continuous aquifer but more frequently to distinct hydrogeological-structural complexes and units and is much more concentrated close to the main lines of discontinuity. In relation to the state of progress of the tunnel, the flow rate has a complex trend, referring to exhaustion and subsequent stabilization in an equilibrium regime of the flows along the fractured layers gradually intercepted as the excavation proceeds.

In consideration of the great variability in flow rates in a tunnel under construction and the need to reconstruct an emptying regime which also covers the later post-construction phase, the best methodological approach for fractured systems is that of continuous acquisition of monitoring data (see also Paragraph 8.4.4).

As a good operational practice, the setting up of a monitoring network should be carried out mainly by means of continuous acquisition of flow rate data. Especially during the construction phase, to define any interference on the source supply regime and/or the base runoff of watercourses, correlations with tunnel drainage referring to short time intervals generally corresponding to interception along the advance front of permeability thresholds or draining fractured bands are indicative.

The acquisition of data through monthly or even seasonal monitoring (Paragraph8.4.4)in many cases does not provide unambiguous interpretable indications, in particular for a limited period of time such as the construction phase: variations in the hydrological regime induced by interference with the tunnels may not be distinguishable from the natural fluctuations associated with the seasonal charging regime.

Continuous data acquisition, integrated with a remote transmission system designed for real-time alerting of potentially critical conditions (Paragraph 8.4.4), allows for the timely activation of procedures, as per the "Emergency plans for mitigation and compensation" specifically prepared in the before-construction phase. These plans refer to emergency interventions (including within 24-48 hours of the occurrence of a water event) or permanent compensating intervention, previously planned at the final design level, based on the water risk framework deriving from the scenario models.

3.4.2 Criteria for the prediction of sections with high flows in the excavation phase

During the excavation phase, intersection with significant underground flow systems can cause serious surface interference with water resources that are susceptible because of their environmental value or because they are used for drinking or irrigation purposes. In specific cases where the problem is particularly critical, it may be appropriate to locate exactly and in advance the sections of the tunnel in which it will be necessary to limit inflows to avoid excessive impacts on the surface. Since there are always uncertainties in the definition of a hydrogeological model, it is often difficult to establish the precise position of the sections in which a given flow system will be intercepted by the tunnel on the basis of the design hydrogeological model alone.

Therefore, since uncertainties and unforeseen events are inevitable in the case of complex contexts, to avoid unsustainable impacts it is often necessary to implement investigation and monitoring procedures aimed at identifying and characterizing susceptible aquifers during construction, in order to design adequate waterproofing interventions. It should be specified that identification of the critical areas before their intersection by excavations is desirable because generally, at the design level, it is preferable to implement preventive interventions to reduce permeability if significant inflow containment results are to be obtained. A later reduction in significant inflows, after their occurrence, often has little chance of being effective, or in any case much less so than preventive waterproofing, due to the fact that when the flows towards the tunnel are particularly intense (i.e. once activated), injections of sealing products by probing are less effective, both because of the washout caused by the strong flow, and because of plasticization around the cable, which determines the creation of new fractures and the widening of pre-existing ones.

These considerations apply above all to tunnels dug in contexts where the hydraulic load is high (indicatively higher than 5-10 bar), because for tunnels dug under lower loads, in extreme cases it is possible to proceed ex-post, by putting in place a non-draining coating able to counteract the hydraulic loads that would gradually return.

There are not many options available for advance identification of incidents during excavation: they comprise basically three, of which only one in practice guarantees the desired result:

- geoelectric prospecting;
- thermographic surveys;
- surveys in progress.

As far as geo-electric prospecting is concerned, this is mainly by the BEAM (Bore-tunneling Electrical Ahead Monitoring) method, widely used in recent years for monitoring progress from the head of TBMs. Theoretically, these methodologies can trace the presence of more or less water-saturated areas beyond the excavation face of a tunnel. The data obtained with these methodologies can be effectively interpreted in simple contexts, when there are abrupt variations linked to well-defined geological elements. However, the interpretation for hydrogeological purposes is more complex and less effective in complex contexts, such as those of excavation in fractured crystalline rocks, where a continuous comparison with other data is necessary.

Feedback can be obtained from the second method mentioned, i.e. from thermographic measurements obtained in shallow (10-15 m) radial boreholes, in which temperature measuring cells are installed. In this case, the monitoring starts from the assumption that as excavations approach an important flow system, temperature gradients are observed. The main problem associated with thermometric surveys is the complexity and slowness of their implementation, requiring times that are not compatible with excavation progress, especially if mechanised.

However, when advancing in a context where limited water flows are always present, a simpler solution is that of regularly measuring the temperature of these small flows with a common portable thermometer. Conductivity can also be a significant indicator and can easily be measured using a simple portable conductivity meter.

Geoelectric surveys and temperature monitoring are thus quick and practical but not very precise monitoring systems, which can therefore be applied in contexts where the risks are not particularly high or in which it is still possible to remedy at project level a failure to identify a flow system.

The third option listed, namely that of probing as drilling advances, is essentially the most effective method for preventing intersections with important flow systems. This option is costly from the construction point of view, since it obviously implies an interruption in construction, but if well organized and integrated in site operations, it can have little impact on excavation times. The option is more easily applicable in tunnels dug by means of traditional or mechanized excavation with a road header, while it may impact more heavily on time in sites where a TBM is used.

The option involves the systematic drilling of boreholes ahead of the excavation face when the areas approached are considered delicate due to possible intersection with important aquifers. The probes may be carried out without continuous cores, although the optimal solution is always to have continuous coring probes. If continuous cores are not obtained, it is advisable to record all drilling parameters, keep track of intersections with aquifers and examine the cuttings. Boreholes should always be carried out using a blowout preventer, or at least with a threaded flange in the face that allows for screwing a shut-off valve onto the hole mouth. These precautions are necessary because in the event of intersection with an important aquifer system, it is advisable to block water drainage while waiting to decide which design solutions to adopt.

As regards the length of the drilling, approx. 100-150 m are suggested, which can usually be reached within a few hours or a day with common drilling rigs, including those mounted on TBMs. Subsequent surveys must have a partial coverage of at least 20-30 m.

Once the survey has been carried out, obviously if no water veins have been intercepted the result of the survey is certain and simple. On the other hand, when a significant vein is intercepted, the problem arises of understanding whether it is linked to a stable and well-recharged flow system, or to a minor system with little recharge. Under possible high hydraulic loads and small storage coefficients (as is often the case, especially in rock masses) even a lower flow system is able to provide very high flow rates initially, such as to give the impression of being faced with a significant system.

To discriminate rapidly between these two cases, the most meaningful parameter to monitor is the flow rate. Very rapid reductions, with a lowering of the flow rate of 50% or more in a few hours compared to the flow rate recorded approximately one hour after the end of the perforation, are mostly symptomatic of local systems with little recharge. On the other hand, when the decrease in flow rates is slower, it is necessary to proceed with greater caution and, in general, before resuming excavation, to monitor other parameters such as temperature, conductivity and pH for a few days to observe the variations.

It is also fundamental to take water samples at regular intervals (days) and send them for laboratory analysis.

3.5 After-construction phase

In the schematization of the hydrogeological study activities reported in Figure 3, the after construction phase includes **monitoring activities specifically aimed at verifying the permanent effects induced by the work** on underground circulation, on piezometric levels and on source flow rates.

It is in this phase that detailed planning of mitigation and/or alternative supply interventions is refined on the basis of the deficits actually found following the construction of the work. These interventions replace or supplement any emergency solutions already implemented during construction. However, it should be reiterated that in a post-construction phase it is generally very difficult to implement significant interventions to reduce flow rates in a tunnel with the aim of restoring hydraulic loads and initial circulation, for the reasons already explained in the previous Paragraph. This is especially true in the case of tunnels with high hydraulic heads. On the other

DOI 10.7343/as-2022-592

hand, it is possible to carry out mitigation or compensation interventions of a different type (see Paragraph4.8).

In this sense, monitoring and implementation of mitigation interventions (see Paragraph4.8) represent the end point of a flow of activities, as per the diagram in Figure 3, which, starting from the progressive refinement of the conceptual and numerical models developed, entails having on the one hand an adequate certification of the "environmental" effects on the groundwater sector, and on the other the detailed definition of design solutions for water supply or environmental compensation already tentatively prepared at a preliminary level in support of the design of the work.

In the case of large tunnel works, post-construction monitoring is usually extended to cover several years, for the reasons indicated below, confirmed by analysis of the measured data:

- effects of resource depletion may occur in a very short time, particularly in cases where overflow conditions of the water network are altered, with consequent drying up of springs;
- more frequently, the effects of interference are revealed by the drainage of the base flow, i.e. the deepest component of the underground flow, on which short-period flow peaks from shorter and shallower supply circuits are usually superimposed.

In this second case, even after interference, the peak values of the flow sometimes remain almost unchanged, while great reductions in or the elimination of dry period flow rates are observed. In the event of partial interference, these conditions have the sole effect of an increase in the flow rate variability index, following the reduction of dynamic storage and consequent alteration of the exhaustion rate. Certification of interference, or its exclusion, is therefore possible through the elaboration of exhaustion curves in relation to seasonal recharge and comparison with the same conditions detected in the pre-construction phase.

The duration of post-construction monitoring therefore depends mainly on the hydrological significance of the monitoring period. "Ordinary" hydrological conditions, comparable with similar pre-construction conditions, permit an interference evaluation even for relatively short historical series, although always in the order of an entire hydrological year. Normally, post-construction monitoring involves reduction over time of the measuring points with respect to the initial set, following progressive definition of the conditions of interference (or absence of)of the completed work, starting from the most evident situations up to those for which a judgment can only derive from statistical processing based on multi-year historical series of measurement data, which should also be conducted in relation to the real socio-economic importance of the water resource. For a detailed discussion of the aspects linked to monitoring however, see the relevant chapter.

It should be clear is that starting from the pre-construction phase, continuous data acquisition is the method that guarantees the most effective and usually unambiguous interpretation of these data through the construction and post-construction phases, allowing certification of interference, or absence of, in all conditions of the water supply circuit, with the work in the tunnel. This is because availability of continuous data permits separation of the hydrogram related to the base flow from short-duration peaks, allowing suitable correlations between flow rate and recharge rate in each phase.

In the context of alluvial lowland aquifers, in the post-operam phase monitoring is usually referred to groundwater levels in wells or piezometers and possibly to flow rates of springs. In these contexts, the completed structure is in most cases totally waterproofed, so monitoring aims to verify the existence and extent of a barrier effect resulting from the insertion of an underground work in comparison to the forecasts made by modelling. The post construction monitoring data can be interpreted correctly through re-elaboration of the numerical scenario models used starting from the before-construction and construction site phases, in consideration of the variability of background data.

4 HYDROGEOLOGICAL INTERFERENCE AND RISK OF IMPACT

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Under favorable hydrogeological conditions, tunnel excavation can determine significant interference with underground water circulation and as a result with surface water circulation fed by underground flow systems. **Hydrogeological interference** can be defined as a measurable, transient or permanent change in the distribution of the hydraulic head, water storage and groundwater (in flow path, direction and intensity); it can determine "impacts" both on excavation during the execution of the work, and on the external water environment.

While by "**interference**" we mean any measurable change in the groundwater flow system, by "**impact**" we mean an effect that is not only measurable but, as defined by Legislative Decree 152/06, "significant" (which can be interpreted as unwanted or harmful) for the work itself, for the environment and for man.

We can define three basic areas or contexts of hydrogeological impact:

1. area of the underground excavation;
2. area of the aquifer;
3. area of the ecosystem.

4.1 Area of the underground excavation

The impacts may affect excavation operations, the stability of the work and the duration of execution, with possible implications for workers' safety conditions. The primary cause is huge inflows of water in the tunnel (called inrush) which can cause: accidents at work, flooding of the excavation with damage to machinery and the construction site, interruption of work, reduction in production rates. The phenomenon can be accompanied by the transportation of suspended material with effects associated with the surface, especially in the case of limited coverage (ground collapses, formation of holes, subsidence). These events are generally related to crossing areas with high transmissivity/permeability or going over permeability limits.

In the past, hydrogeological prospecting carried out in the preliminary design or executive design phase were mainly aimed at forecasting the potential occurrence of such impacts and therefore at verifying the safety and productivity conditions of the excavation, with little consideration for undesirable effects on the natural hydrogeological regime. Much importance was given to the "project" and little to the "setting" in which the project took place. This approach has changed in recent decades, although there is still a long way to go in terms of evolution in standards of regulation and above all awareness.

4.2 Area of the aquifer

Hydrogeological interference temporarily or permanently modifies groundwater flow systems (GFS), understood as the natural paths of groundwater from the recharge area to the discharge area. The interference can be caused by the interception of groundwater by the excavation and/or by the detensioned/altered area surrounding the excavation (draining underground work), or by the barrier effect that an impermeable underground work exerts on the groundwater flow (dam effect).

The impacts are observable and quantifiable at the surface (water courses, springs) or by monitoring boreholes (wells, piezometers), in terms of:

1. decrease in the flow rate of springs until they are completely dry;
2. decrease in the base flow of water courses (fed by the aquifer) until completely dry in periods of absence of rainwater runoff;
3. decrease in the level of lakes (fed by the aquifer) until complete drying up;
4. lowering of the hydraulic head in wells and piezometers until completely dry;
5. decrease in the specific flow rate of wells (flow rate/unit of lowering) and consequent decrease in the sustainable operating flow rate (safe yield);
6. variations in the hydraulic head upstream and downstream of the "dam" with undesirable geotechnical effects, damage to structures, flooding of underground utilities, migration of pollutants dissolved in the aquifer;
7. deterioration of the natural chemistry and of the thermal regime of groundwater due to drainage or transfer from other aquifers.

4.3 Area of the ecosystem

Associated with the impacts on the aquifer are those on the biocenoses (plants and animals) that depend, in whole or in part, on groundwater. In this case we are referring to ecosystems dependent on groundwater (GDE, Groundwater Dependent Ecosystems). Ecosystems are important both for their intrinsic value and because they guarantee ecosystem services to the environment and the socio-economic system, as well as to human well-being: their loss represents damage and a cost to the whole of society.

4.3.1 Definition of GDEs

A GDE is an ecosystem (the set of a community of living beings, called a biocenosis, and a physical environment in which it lives, called a biotope) which depends entirely or almost entirely on groundwater discharge, proximity to the saturation zone (aquifer), and groundwater chemistry (Bertrand et al. 2012; Cantonati et al. 2020; Kløve et al. 2011).

Therefore, a GDE is located near the water table or near a delivery area of groundwater circulation, and benefits from the particular hydrological and hydrochemical conditions typical of groundwater, including the steadiness of parameters. A quantitative or qualitative impact on groundwater circulation obviously determines an impact on the biocenosis, causing it to suffer even as far as complete extinction.

GDEs can be divided into superficial or underground and

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are all located in areas where groundwater flow emerges or in areas with reduced depth to the water table, characterized by the decrease of the hydraulic head upwards inside a porous medium aquifer:

1. **Superficial GDEs** located near discharge:
    - **springs;**
    - **lotic environments** (with running water) corresponding to **stretches of water courses fed by the aquifer** (including the hyporeic area below the riverbed) and in which the base flow is essential for maintaining the biocenosis;
    - **lentic environments** (calm water or very slow outflow) with the presence of a sheet of water above the surface, such as **lakes, ponds, swamps** where the supply contribution from the discharge, possibly balanced by evaporation or discharge to other superficial bodies, is essential for the biocenosis
    - **wetlands and peatlands**, generically defined as wetlands, located at discharge points, with the aquifer always saturated or reduced depth of the water table; they can be defined as GDEs when fed only or mainly by the aquifer (fen wetland or minerotrophic peat bogs) and not exclusively from direct rainfall (bog wetland or ombrotrophic peat bogs);
2. **Freatophytic arboreal biocoenosis**: wooded areas with reduced depth of the water table and biocoenosis closely controlled by aquifer presence and its chemical composition;
3. **Hypogeal GDEs**: biocoenosis that develop inside the aquifer or the vadose area, in particular caves and karst systems, but also stygofauna (fauna adapted to living inside the porous aquifer, including with interstitial porosity; Cantonati et al. 2020).

From types 1) to 3) the degree of ecosystem saturation, the so-called sphere of discharge (Springer et al. 2008) increases: from a water body flowing to the surface in the case of springs, to complete saturation of the soil in the case of wetlands, up to the aquifer with variable depth in the case of phreateophytic and cave communities.

The presence and distribution of GDEs in a given territory must be verified by means of census and classification: for a site to be a GDE, its ecological, and not only its hydrogeological, value must be recognized. A GDE not only contributes to the water balance of a hydrogeological basin, but guarantees the functionality of a given ecosystem and provides ecosystem services to the environment and society.

4.4 Definition of targets and impact indicators

For the purposes of forecasting, assessment, prevention and mitigation of impacts (specific actions which we will discuss later), the associated impact **targets** and **indicators** must be defined, within the scope of the **impact areas** described above.

By applying the consolidated **"source-pathway-target"** paradigm of all environmental risks, we can define the following elements:

- interference, understood as the source of impact danger and represented by the disturbing effect of the underground work (drainage, barrier, pollution, etc.); corresponds to the source of danger;
- the hydrogeological connection (or simply "connection"), represented by the groundwater circulation system and the degree of connection that this system determines between the interference and the impact target;
- the impact target (or simply "target"), represented by the water point or GDE where the impact occurs or where there is a potential risk that it may occur;
- the impact indicator (or simply "indicator"), represented by a measurable physical property or quantity, which quantifies the impact and allows comparisons with situations not disturbed by the work (pre-construction situations).

The measurement or monitoring of the impact indicators, associated with the targets, must be hydrogeologically significant (in relation to seasons and the variability between differing hydrological years) in before-construction conditions, for the purpose of direct verification of any impact conditions during the excavation phase (in progress) and after excavation (after construction).

The indicators illustrated below are quantitative. The impact on surface water and groundwater bodies can also be qualitative, revealed through alterations in the chemical composition of the water and/or contamination as a result of the effects of disturbance/pollution of water circulation or pollution from discharges into riverbeds from construction sites. To verify the qualitative impacts, specific chemical indicators can be defined.

1 - *Target: Spring*

This involves a single spring or groups/fronts of springs genetically linked to the same hydro-structure. The impact manifests itself in a decrease in the natural flow up to complete seasonal or perennial drying (quantitative impact).

The basic indicators are: spring flow rate (in the case of uptaken springs this must include any uncaptured or overflow water); specific temperature and electrical conductivity of spring water. Electrical conductivity and temperature are the simplest physical-chemical parameters to be determined in situ and can indicate any alterations in groundwater circulation. Specific physical indicators (e.g. turbidity) or chemical indicators (e.g. pH, dissolved oxygen, redox potential) can be determined in situ to verify specific hydrodynamic alterations or discharges.

The frequency of pre-construction and in-progress measurements must be defined according to the importance of the spring and the risk of impact.

2 - *Target: Surface water bodies*

These can be water bodies with a lotic environment (flowing water, therefore water courses) or a lentic environment (such as lakes, ponds, lagoons).

In the case of a lotic environment, the target is the base flow component (guaranteed by the aquifer) of the total outflow of the watercourse: therefore, the event runoff components (surface runoff + hypodermic runoff) are excluded. A quantitative impact manifests itself in a decrease in the base flow (decrease in flow rate in the riverbed), up to complete cancellation (drying up in seasonal periods in which runoff is absent or minimal).

In the case of a lentic environment (with natural feed from groundwater runoff), a quantitative impact manifests itself in a decrease both in the level, and therefore in the stored volume, and in the flow rate of any water leaving the environment.

For watercourses, the indicators are: **flow rate of the base flow**; in situ physical-chemical parameters of the base flow water: **temperature**; **specific electrical conductivity**; **pH**; **turbidity**. The pH and turbidity can highlight discharges from construction site activities.

The before construction and in-progress measurement of the "flow rate of the base flow" indicator must be carried out on appropriate sections of the riverbed and in hydrological conditions that exclude or minimize the runoff component (therefore avoiding periods of rainfall; it is advisable to carry out the measurements at least 3 days after the last rainfall in the watershed or at least 7 days after particularly prolonged rainy periods). In addition, any deviations or drains in the riverbed must be measured. For low flows and in specific thermal conditions, the effect of evapotranspiration should not be overlooked.

For the lotic environments the indicators are: **water level**; **base flow rate of the outflows**; in situ physical-chemical parameters of the water, possibly measured on the base outflow of the emissary, similar to those measured on water courses.

3-Target: Well/ Piezometer

These are boreholes, fitted or not fitted with a pump, which draw on a permeable hydrogeological unit (aquifer). The impact manifests itself both as a variation in the hydraulic head (lowering until complete drying up, or raising in the case of a barrier effect), and as a decrease in the yield of the well.

The static type indicator is the **static hydraulic head** measured in the well/piezometer (by static we mean measured as the average of at least 3 successive measurements at intervals of 10 minutes with no appreciable variation; in the case of a well we mean measured in a similar way, after a shutdown period of at least 24 hours and in any case to be evaluated based on use). The dynamic type indicator is the **specific discharge** of the well, also known as the well yield, which is calculated as the ratio between pumping flow and stabilized drawdown (L/s per meter of drawdown) for flow rates lower than the relative critical flow to that well in conditions not disturbed by other pumping within the area of influence; it is representative of the dynamic conditions of the system, and defines the aquifer ability to support extraction; stabilized drawdown can be assumed as the drawdown measured in the well after 1 hour of pumping. The specific discharge can also be estimated for a piezometer, by means of a portable electric pump (volumetric or peristaltic).

For wells it is important to determine the critical flow rate by carrying out a step drawdown test (SDT). The critical flow rate is that in which the ratio between linear head losses and total well losses is equal to 0.8. The performance of the test must take into account seasonal variations. Performing a step test in the before construction stage is important for distinguishing any poor capture efficiency linked to the specific well which could then generate an erroneous definition of the impacts.

The before construction and in-progress measurement of the static groundwater level indicator is all the more frequent, going from occasional or seasonal monitoring to more frequent discontinuous monitoring, to continuous monitoring with a pressure transducer, in relation to the importance of the aquifer and the risk of impact. The specific discharge dynamic indicator must be detected at least on a seasonal basis. In the before construction survey of both indicators, attention must be paid to any interference from neighboring drawdowns

4-Target: GDE (Groundwater Dependent Ecosystem)

Where a site is defined as a "GDE", hydrogeological monitoring should be based on indicators verifying the quality of the physical-chemical state adequate for guaranteeing the existence of the biocenosis. Therefore, for GDEs associated with springs, rivers and lakes, reference should be made to the respective targets in the two previous subsections. In the case of GDEs associated with wetlands (peat bogs, wetlands) and phreatophytic plants, a suitable indicator is hydraulic head, monitored in piezometers or mini-piezometers; for GDEs associated with caves and karst systems, reference should be made to the spring or stream targets, in relation to any emerging or groundwater circulation.

In all types of GDEs it is advisable to integrate hydrogeological monitoring with specific biological and ecological indicators, identified on a case-by-case basis and capable of verifying any suffering in the biocoenosis.

4.5 Hydrogeological impact risk analysis

The analysis of the risk of impact due to interference by the underground work on groundwater circulation represents a prognosis of the expected effects.

There is a hydrogeological impact where the hydrogeological interference as defined at the beginning of the chapter (and associated with the concept of hazard), determines significant direct or indirect effects on a series of objectives such as: population and human health; biodiversity; local area, soil, water, air and climate; material assets, cultural heritage, landscape; interaction between the factors listed above (all these words are taken from the general definition of impact of Legislative Decree 152/2006).

The following are analyzed below: the definition of impact risk ('risk' for short); methods or tools for risk assessment;

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representation of risk; risk mitigation interventions; the role of monitoring when forecasting risk and verifying impact.

4.6 Definition of risk and its components

The risk of hydrogeological impact is a probabilistic term and is related to the probability that a certain phenomenon of disturbance of the natural hydrogeological system (interference) determines significant effects for the environment and the community (impact) on certain targets (as listed in the Paragraph previous). Hydrogeological interference, with its associated impact, manifests itself at the target, after its effects have manifested themselves along the pathway, when the indicators record the exceeding of certain predetermined thresholds, which are evaluated taking into account suitable and hydrogeologically significant pre-construction monitoring.

The general analytical formulation of risk is adapted to the specific context as follows:

$$R = I \times C \times V$$

where:

R = **Risk** of occurrence of a hydrogeological impact on a certain target;

I = **Interference** (probability that a certain stretch of underground work induces measurable effects of hydrological and hydrochemical, hence hydrogeological, perturbation on the rock mass); it can be associated with the concept of Hazard;

C = **Connection** (hydrogeological connection path, represented by the related interpretative conceptual model, between the disturbance point where the interference originated and the impact target); it can be associated with the concept of Pathway and therefore also of Susceptibility, therefore the probability that the natural system is able to "defend" the targets from impact;

V = **Value** of impact target (ecological-environmental or socio-economic in relation to the target's final use in the local context and the presence/absence of alternative sources and/or the feasibility of mitigation or compensation works).

Interference is a probabilistic factor and therefore subject to forecasting with some risk of uncertainty. It quantifies, for example: the probability that during excavation, in a certain stretch of tunnel there will be water inflows of a certain capacity, or that a certain underground work, if it has a dam effect, could induce a change in the piezometric level beyond a certain threshold, etc.

Connection indicates, here too probabilistically, the effect on the impact target in relation to its degree of hydrogeological connection with the perturbation point, origin of the interference. For example: tectonic structures or permeability thresholds; degree of karstification; depth and extent of the underground water circulation system; permeability barriers or buffering hydrogeological units, etc.

The value of the target is considered both from the point of view of providing ecosystem services and from the socio-economic point of view.

Risk assessment derives from the intersection of the project framework with the hydrogeological conceptual model and with the distribution and characterization of the targets. It represents a forecasting and probabilistic scenario simulation, carried out with parametric, analytical or numerical methods, referring to both the construction phase and the post-construction phase.

The existence of unacceptable risk conditions must be linked to the exceeding of Indicator thresholds by values predetermined on the basis of the results of before-construction monitoring (which will have defined the extent of seasonal hydrological cyclical phenomena); the thresholds can be "scaled" with an increasing degree of severity, passing from a state of "anomaly" or "attention" to that of "alarm" or "emergency", in relation to the intensity and temporal continuity of the indicators exceeded.

4.7 Risk assessment tools

Risk assessment is carried out in the following steps:

1. Definition of the reference hydrogeologically significant area and targets;
2. Definition of indicators and thresholds;
3. Choice and application of the evaluation method.

The procedure of risk assessment is summarized in Figure 4; it ends with the graphical representation of results.

4.7.1 Definition of the reference hydrogeologically significant area and of the targets

The extent of the area affected by the assessment varies on a case-by-case and, within the same project, section by section basis, depending on the hydrogeological characteristics and the persistence of the tectonic structures and permeability thresholds. The hydrogeologically significant area corresponds to the area subject to environmental monitoring.

For its definition, it is also important to consider previous case histories in similar geological conditions; at this stage it is essential to consult the data available in the literature (see Chapter 2 "Return of experience"). For example, in the case of the Florence-Bologna TAV tunnels, dug mainly in turbidite rock masses with medium-low permeability at the bulk permeability scale, the real propagation band of the impacts with respect to the axis of the tunnel was found to vary between less than 0.2 km and 5 km, in relation to the persistence and hydraulic diffusivity of the structures crossed. In karst systems, the expected extent of the effects could be much greater.

The targets, subject to before-construction, during construction and post-construction environmental monitoring, must be included in a list that includes: springs, stretches of waterways, lakes, wells, piezometers, GDEs. This list, included in the preliminary conceptual model, is refined and integrated during before-construction monitoring and definitively codified at the beginning of in-progress monitoring.

The final product of this phase is the mapping of the potential impact area together with the location and characterization of the targets. Each target must be equipped for indicator monitoring operations.

Defining the potential impact area and targets

- The potentially pronte to impact area has to be defined by means of hydrogeological conceptual model and case histories
- Categories of targets to impact: spring, surface waters, wells, GDE

Defining the impact indicators and the impact thresholds

- Primary indicators (flow rate and hydraulic head) and secondary indicators (surface water stage, wells specific discharge, wells yield, land subsidence, …)
- Impact threshold: to be defined with respect to a hystorical monitoring data series of the reference indicator; different levels can be defined (i.e. attention threshold, alarm threshold, emergence threshold)

Choosing and applying the forecasting method

- Parametric methods
- Mathematical methods
  - Analytic models
  - Numerical models

Representing interference level and risk level

- Interference: to be represented along the tunnel longitudinal axis with color/symbol graduation
- Risk: to be represented on the targets to impact with color/symbol graduation adapted to the defined impact thresholds

Fig. 4 - Risk Assessment procedure.

4.7.2 Definition of indicators and thresholds

The indicators are hydrological and hydrochemical (section 4.4).

The definition of the thresholds must be based on an adequate historical series of pre-construction monitoring data that as far as possible reflects both seasonal and multi-year hydrological variability. Pre-construction monitoring must also define the quantification of the effects of any withdrawals pre-dating the works. Definition of the thresholds must in any case take into account the uncertainty inherent in the predictability of hydrological events. It may be helpful to define thresholds of different intensity, for example: attention threshold, alarm threshold, emergency threshold. Passing the first may be due to simple natural hydrological variability; the second (less likely) and the third (moderately certain) instead indicate the occurrence of an ongoing impact situation. It is evident that a seasonal drying up of a spring or a sudden drawdown of hydraulic head in a well should not necessarily always be associated with an impact.

See Chapter 8, monitoring, for more information on this.

4.7.3 Choice and application of the risk assessment method

Assessment is of two components of risk: Interference and Connection. The two classic questions associated with the forecast are: "What is the probability of having water inflow of a certain flow rate in a certain section of the tunnel?" (Interference); "What is the probability that water inflow determines effects on the indicators at the impact target beyond a certain threshold?" (Connection).

Parametric methods: also known as matrix methods or scoring and weighting methods. These identify physical quantities or properties considered significant for the determination of the Interference (for example: hydraulic conductivity of the rock mass, RQD index, thickness of the overburden, intersection of the excavation with fractures, etc.) and of the Connection (e.g. distance between the excavation face and target, proximity of the target to tectonic structures or permeability thresholds also intersected by excavation, hydrogeological classification of the target, etc.), parameterize and combine them with each other by crossing on a matrix or by assigning multiplier weights to obtain a probabilistic index of relative impact risk assigned to the target. A so-called contingency matrix is used, which crosses different quantities or properties (similar to the Leopold matrix for environmental impact assessment). As examples we cite the method for determining the DHI (Drawdown Hazard Index) associated with the risk of drying up of springs (Dematteis et al. 2001), and the Cesano et al. 2003 method. Parametric methods are not physically based and therefore they are to some extent subjective. Moreover, they have several advantages: they require a small amount of input data, they consider numerous parameters and are sufficiently quick and quantitative, allowing relative comparisons between different contexts or targets.

Mathematical methods: these simulate the real process of hydrogeological interference between the underground work and groundwater flow systems in the porous medium in a physics-based manner (one-, two- or three-dimensional), requiring appropriate simplifications. The deterministic codes adopted can be analytical or numerical. The analytical methods are based on relatively simple algorithms, simple and stationary boundary conditions and a simplified isotropic hydraulic conductivity distribution (Zhang & Franklin 1993; Goodman et al. 1965; Barton 1974; Federico 1984; Lei 1999, 2000; El Tani 1999). Numerical methods are based on

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complex codes, and imply greater flexibility and adaptability to the real physical world but are more demanding in terms of the user's scientific competence and sensitivity, financial resources and availability of input data. The application of numerical modeling and its potential in the context of hydrogeological studies for underground works is dealt with in these guidelines in Chapter 3. See also: Font-Capò et al. 2011, Vincenzi et al. 2010. The use of these tools for the assessment of risk of impact of the work on targets is still not frequent, although the possibility of assigning a quantified probability distribution to the forecasts (for example with simulation of the expected variability of the input parameters through methods such as the Montecarlo method) can greatly contribute to an accurate assessment of prediction reliability. The worth of creating a numerical model must be assessed on the basis of: completeness of the basic data available, geographical distribution of the surveys and tests, reliability of the reference geological and hydrogeological model (at the scale required by the model), availability of data for calibration (hydraulic heads, flow rates).

4.7.4 Representation of the degree of interference and risk

The Risk of exceeding certain thresholds of the impact indicators can be associated with appropriate symbols or colors, to:

- targets (i.e. springs, stretches of water courses, wells, GDEs etc.);
- impact areas (planimetric projection of the areas where the aquifer suffers an impact).
- in the choice of colors, red will indicate the situation of greatest risk (for example risk of total or partial drying up for a spring) and other less bright colors will signal risks of lesser intensity. In the same way, the sections of the tunnel with the greatest probability of inducing water inflows will be highlighted with an appropriate chromatic scale.

In order to overcome the inherent uncertainty associated with probabilistic risk assessment, it is recommended two methods are used in parallel which are completely independent of each other in terms of philosophy of approach: for example, a parametric method and a numerical model. For each single target, the risk color, coded in the same way, will not necessarily always be the same, therefore the actual conditions of existence of a certain degree of risk could be ascertained with a "traffic light" type evaluation: in the case of reciprocal confirmation by one method with respect to the other, the predictive power of the evaluation is strengthened, while it is weakened if one of the two evaluations contradicts the other. Obviously, different combinations will be found as outcomes of the two assessments, and it should be borne in mind that the final risk assessment should stay on the side of caution in accordance with the precautionary principle.

4.8 Interventions for the mitigation/compensation of impacts

We refer here to design actions or works aimed at preventing or mitigating the impacts on the targets caused by the work, or to compensate them if they cannot be eliminated.

4.8.1 Area of excavation site

Tunnel waterproofing intervention

This is carried out when it is necessary to limit drainage by the tunnel to preserve the lowering of the hydraulic head in the volume of porous medium subject to interference. It can be envisaged from the design stage or designed and built during construction if unexpected critical situations arise. In the intervention envisaged by the project, mostly this is a matter of sealing measures capable to sustain greater neutral pressures; in that activated in emergency conditions, extreme waterproofing is generally applied using special products injected during the advancement phase (see Chapter 8).

Drainage through the tunnel

This is intervention carried out when the work creates a dam effect, typical for example of works relating to urban nodes or large underground stations, placed transversely to the groundwater flow direction. Generally, it involves by-pass systems, working either passively (drains connected by pipes that convey water through the two sides of the barrier, rebalancing the hydraulic heads) or actively (through pumping and appropriate re-injections). The design of these interventions is essential to prevent unwanted phenomena such as: flooding of underground utilities (upstream); subsidence and damage to buildings (downstream). The project must accurately verify not only feasibility and hydrogeological quantification, but also issues of maintenance and duration of the work, minimizing risks of clogging and loss of efficiency, very likely when re-injecting water into the porous medium. It is important to check the state of groundwater contamination, frequent in urban areas, to avoid the risk of direct transfer of contamination from one portion of the aquifer to another or to other aquifers.

4.8.2 Area and environmental context

Emergency compensation intervention

This is intervention provided by the monitoring plan that can be activated during construction if exceeding thresholds of impact on targets (e.g. emergency threshold). It involves extraordinary water supply projects that should already be identified in the design phase, following impact risk assessments, and simultaneously with the implementation of the in progress monitoring program. It is useful to prepare the necessary authorizations well in advance of the presumed time of impact.

Definitive mitigation or compensation intervention

This intervention should be considered "structural" and therefore permanent. It can be divided into the following types:

Definitive procurement systems to replace the impacted captations

These interventions must be planned and (possibly) carried out before the start of the works in cases where the risk of impact is judged to be such as to require preventive intervention. For new groundwater withdrawals, water points not subject to risk of impact must be selected. In the case of impacts on springs, the new withdrawals can not uptaken springs up to that moment, but also wells or withdrawals in the riverbed, or enhancements of existing withdrawals on already exploited aquifer sectors. In the case of impacts on wells, the effectiveness of an in-depth study of existing wells can be assessed. In all cases, the hydrogeological and environmental sustainability of the new withdrawals must be evaluated in advance, avoiding the transfer of unsustainable exploitation situations to other aquifers, which could create undesirable "cascade" effects.

Intervention to mitigate or compensate for the drying up of the base flow of water courses

Impact mitigation or compensation interventions can be aimed at restoring or reducing environmental damage resulting from the decrease or complete drying up of the base flow in the surface network, obviously also resulting from the drying up of springs. Such a resource deplenischment can have consequences from points of view which are both ecological (e.g. impact on GDEs, riparian vegetation, watering of wild species) and anthropogenic/recreational (activities such as canyoning, fishing, summer hiking). The different measures, mitigating or compensatory, are in this case to be carried out in the riverbed:

- by-passing in the riverbed to cross sections where there is a loss of runoff under the riverbed due to drainage by the tunnel below;
- design and construction of small reservoirs to ensure a minimum vital flow to the affected sections;
- water raising from the tunnel, through pumping systems, bringing the water now discharged to the lower base level (represented by the tunnel) back to a higher base level;
- waterproofing in the riverbed to prevent leaks below.

4.9 Return of experience and bibliographic references

The considerations and recommendations contained in this chapter mainly derive from experience gained by the writers on the consequences of the excavation of the Florence-Bologna High Speed-High Capacity railway tunnels. For more details on the hydrogeological aspects related to the project and on the conceptual hydrogeological model, see: Canuti et al. 2009; Gargini et al. 2006, 2008; Vincenzi et al. 2009, 2014. The authors also took into account published experiences on the effects of tunnels on groundwater circulation in crystalline (Masset & Loew 2010) and metamorphic (Bearmar 2012) rock masses.

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5 USE OF WATER INFLOWS

Antonio Dematteis

There are numerous examples of road and railway tunnels where the water drained from the tunnel is collected and used for different purposes, e.g. as a supply of drinking water or for agricultural or tourism and bathing purposes. In some cases, typically in long and deep tunnels, the heat associated with the water is also recovered.

This chapter provides guidance to the various considerations and steps involved in studying and evaluating the possible uses of the water drained from tunnels. It is good practice to consider these possibilities from the earliest stages of a tunnel project.

5.1 Background

The Italian and the European regulatory frameworks and principles of sustainable design state that water and geothermal resources are common goods, and therefore should be preserved rather than wasted. From this point of view, right from the design stage of an underground infrastructure it must be assessed whether the possibility of groundwater drainage is predictable, so that a study on the quantity and quality of the inflows can be prepared to support evaluation for making use of the drained water possible.

To understand in which cases it is possible to use drained water, a first basic distinction to be made is between fully waterproofed and draining tunnels.

Waterproofed tunnels are widely adopted in urban areas to avoid environmental impacts and subsidence that inflow may generate, which could cause damage to the buildings above the tunnel. Tunnel Boring Machines can maintain controlled pressure at the excavation face, typically by methods called Earth Pressure Balance or Bentonite Slurry, and avoid inflow during excavation. The technology available on the market today enables balancing water pressure of up to around 8-10 bar at the face. During operation, the waterproof installed at the extrados of the tunnel will avoid inflow and the final lining of the tunnel will support the hydraulic loads.In these cases, heat recovery can be considered, as indicated in Chapter 6.

In deep tunnels in mountain regions, where the water pressure can easily exceed 10 bar, groundwater is normally drained into the tunnel during excavation. In the long term, the lining is equipped with radial drains designed to avoid a high hydraulic load on the extrados of the tunnel structure, which would require an uneconomical lining thickness.

In deep tunnels that cross protected areas, natural parks or simply areas where the effect of groundwater drawdown could cause unacceptable impacts on GDE, injections into the ground in front of and surrounding the tunnel can be made from the tunnel as excavation proceeds. In these cases, inflows could be reduced by pre- and post-grouting within predefined limits. The limits are calculated in advance based on a vulnerability study, and generally range from several liters per minute to several liters per second per kilometer, depending on the hydrogeological context and on the protection required.

Many examples exist where draining tunnels combine the tunnel's main purpose (e.g. rail, road, or otherwise) with the collection of inflow that is used outside for agriculture, industry, drinking water supplies, hydroelectricity, geothermal, fire protection, and other uses. The use of drained water from tunnels has moreover increased the positive effect that a tunnel has on the social and productive context, contributing to its sustainability from an economic, social, and environmental point of view.

Figure 5 shows an example from the Lötschberg railway tunnel (CH), where the naturally hot water collected in the tunnel, with a flow rate of about 100 l/s at a temperature of 17-20 °C, is exploited on the north side portal. The water is used to grow tropical fruits and to produce sturgeon caviar on a fish farm.

Fig. 5 - Tropenhaus Project at Lötschberg railway tunnel (CH):example of use of thermal water drained by a deep tunnel.

However, based on the authors' experiences, it appears that often there are major administrative obstacles to the valorization of water inflow in tunnels.

The absence of rules and regulations tailored to tunneling hinders public administrators and supervisory entities which must issue and monitor water use concessions; on the other hand, it also legitimizes the managers of underground infrastructures who exclude multiple use tunnels. As an example, without specific regulations a railway operator is not encouraged to build and manage its infrastructure jointly with an aqueduct operator in the same area.

It is in fact desirable that the guidelines provided in this section can also be used as an outline for a new, specific legislation, which favors the development of projects for the use of drained water in tunnels.

5.2 Design of possible uses of water

The use of drained water necessitates assessment of its quality and quantity, the compatibility of the materials used for temporary and final support of the tunnel structure that could come into contact with groundwater, and the water demand, i.e. the water needs of the area close to the tunnel.

Any use of water also involves consideration of the local regulatory framework, such as concession law, rights for water exploitation, water quality standards and catchment area protection standards, closely related to aquifer vulnerability.

The feasibility study for using the inflow should include the following four main sections:

1. Description of the geological and hydrogeological background (*see also Chapter 3 of this guideline for a more extensive description of how to set up a hydrogeological study in a tunnel*):
   a. Localize the inflow along the tunnel alignment. To be exploited, groundwater must be collected and transported outside the tunnel with pipelines. The length of the pipelines is one of the fundamental input data required to evaluate the feasibility of recovery of water and possibly thermal energy;
   b. Hydrogeological conditions of the inflow area. It should be defined whether the inflow is expected to emerge at separate points or continuously along a whole section of tunnel. This will permit choice of the most suitable type of water catchment. The inflow could originate from localized defects or from larger areas, such as fractured zones, fault zones, or porous aquifers that are intersected by the underground excavation;
   c. Water head. Expected hydraulic pressure along the tunnel, in transient conditions during excavation and in a steady state during operation of the infrastructure, are important input data for predicting the quantity of groundwater available over time;
   d. Amount of inflow. A forecast of transient and steady state discharge is needed for planning the use of the drained water. For the long term, it is also important to report whether seasonal fluctuations exist. Ultimately, the actual exploitation potential must be assessed based on long-term steady conditions and considering seasonal fluctuations;
   e. Groundwater temperature. The water temperature in transient and steady-state conditions should be predicted, as should any expected long-term seasonal variations in temperature;
   f. Groundwater Quality. The analysis of the quality of the inflow, if it already exists, or the prediction of the water quality by means of a hydrogeochemical study on piezometers and other water points in the area can be used to select the possible use of water, as described in point 2 below. The analysis protocol must be defined on the basis of the specific use that will be identified using the survey indicated in point 2, and in accordance with the limits and guidelines dictated by local regulations;
   g. Hydrogeological study of the catchment area. The catchment area that feeds the tunnel inflow should be known. A geological and hydrogeological description of the area between the infiltration area and the inflow will provide information on the origin of groundwaters, on their physical-chemical quality, on seasonal variations in flow, and on any hydraulic connections with other surface water bodies, such as rivers, lakes or the sea. Finally, it should permit assessment of the vulnerability of the groundwater to be collected in the tunnel (see next point);
   h. Vulnerability. The vulnerability of the aquifers feeding the inflow should be assessed, especially if the identified use is for drinking water.
2. Survey on the possible use of water. Depending on the quality and quantity of water available, as per point 1, the type or types of possible uses can be identified. In this phase, verification is formal, taking as a reference the quality requirements provided by the local public authority responsible for control. The uses might be for example:
   - drinking water,
   - irrigation,
   - fish farming,
   - industrial, and
   - recreational / health
   - thermal/energy recovery.

The result of this verification will indicate possible potential uses.

3. Assessment of the demand. The demand for water and thermal energy in the area close to the tunnel portal will guide decisions on the possible use of the water. The need for water or thermal energy associated to the water in the area close to the tunnel are better identified once the following are known:
   a. population, including fluctuations driven by tourism
   b. existing and future business activities, such as agricultural, manufacturing, industrial, etc.,

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   c. water flow rates coming out of the tunnel (expected or measured),
   d. future projected demand.

This assessment should consider the current situation and future projections. For the feasibility phase, reference can be made to planning/land use regulations provided by the local authorities in charge of urban, agricultural, industrial and environmental development. More in-depth studies are required for the subsequent phases.

4. Design requirements for the water collection system:
   a. Analysis of local administrative and environmental constraints. According to the uses identified at points 2 and 3, the local legislation for water collection should be considered.
   b. Verification of the access rights to the tunnel during operation. Since some water uses, such as drinking water, require frequent access to the collection system to check the quality of the water, it is necessary to verify the compatibility of water collection with tunnel use, which could be rail, road, or other. It should be noted that unfortunately the constraints of access to the tunnel established by the owner or the operator of the tunnel have often been a real obstacle to projects for using water inflows. Certain implementation methods can eliminate or limit the interference of these activities with tunnel operation, and therefore should be evaluated and possibly identified at the design stage.
   c. Analysis of the urban and environmental constraints defined by the local authorities in the area outside the tunnel.
   d. Preliminary design of the water collection system and of the water supply pipes. The water collection system should be accessible where possible, for inspection, maintenance and cleaning with variable frequency and methods according to use.
   e. Description of the type of tunnel support structures installed close to the water collection system, for example, bolts, wire mesh, ribs, shotcrete, poured or precast concrete, grouting and/or chemical injections, etc. This will allow for evaluation of possible interaction between groundwater and installed support materials, for structure durability and groundwater quality purposes.
   f. Technical specifications of the materials used for the water collection system, including temporary and permanent lining, drainage system, grout curtains, etc. Durability of materials, potential toxicity, and risk of release of pollutants in contact with groundwater should be known. If no information is available, ad hoc testing on potential polluting release are advised. Chapter 7 gives more information on support materials that can be used to reduce the risk of groundwater contamination.
   g. Risk analysis of groundwater contamination. Groundwater interaction with tunnel support materials should be assessed, in the collection system and in nearby areas. In addition, the risk of contamination from accidental spills that may occur in the tunnel during operation should also be evaluated (particularly in road and rail tunnels).
   h. Economic feasibility analysis.

5.3 Monitoring

Finally, a groundwater monitoring plan should be established based on the expected water use and consistent with local legislation. Monitoring must begin at least one seasonal cycle before the operation of the groundwater collecting system. This period can start when the tunnel excavation phase is still in progress. Monitoring must then continue throughout the operational phase of the tunnel.

To enhance the water inflow, one good practice is to set up a temporary water collection system (typically during the completion of the tunnel excavation phase). This will permit checking of the quantity and quality of groundwater over time and verification of the design assumptions.

Flow rate and quality parameters, e.g. electrical conductivity, temperature and pH, should be monitored on site several times a day before the operation of the groundwater collecting system. More detailed analyses (e.g. chemical, bacteriological and isotopic analysis) during this initial period and subsequently may in some cases be required, to improve hydrogeological understanding, or to verify that the water is suitable for the identified use, in accordance with relevant local regulations.

6 HEAT EXPLOITMENT FROM THE GROUND

Marco Barla, Alessandra Insana, Francesco Cecinato, Daniela Blessent, Daniele Pedretti, Paolo Cerutti

6.1 General Considerations

The need to reduce carbon dioxide emissions and to significantly increase energy production from renewable sources in response to climate change has led to an emerging interest in geothermal resources, especially shallow ones. Their use is independent of geographical location, since they are accessible all over the world, making them a local, reliable, and economically competitive energy source. Recent research developments show how, in addition to conventional open-loop and closed-loop geothermal systems, it is also possible to use geotechnical structures in contact with the ground as heat exchangers, so-called energy geostructures (EGS). They consist of equipping underground structures with closed-loop ground source heat pump systems, hence serving the dual purpose of (1) supporting soil and/or the overlying building and (2) exchanging heat with the surrounding ground (Brandl, 2006). EGS have been shown to represent a viable alternative to more traditional borehole heat exchanger (BHE) systems, since they remove the need (and cost) for special purpose excavations, whilst benefitting from a larger efficiency (e.g., as represented by the COP) compared to other (non-geothermal) space heating/cooling systems.

The fluid flowing in the tube heat exchangers embedded in the geostructure allows heat transfer from the ground to the buildings or vice versa, through ground source heat pumps. These pumps absorb heat from a low temperature fluid and transfer it, at a higher temperature, to another fluid. In heating mode, the heat pump transfers heat from the subsoil to the building. In cooling mode, the process is reversed, and heat is removed from the building and transferred to the subsoil, through a reversible valve that changes the fluid direction in the pump. From the same equipment it is therefore possible to obtain a heating system for the winter and a cooling system for the summer. The main elements of a heat pump are the evaporator, the compressor, the condenser, and the expansion valve (Fig. 6). In the evaporator the heat is transferred from the subsurface to the refrigerant fluid characterized by a low boiling point (working fluid) flowing within the heat pump. As its temperature rises, the fluid evaporates and flows into the compressor, which, by compressing it, increases its temperature. Subsequently, the hot vapor transfers its heat to the fluid in the distribution system. Then in the condenser the vapor falls in temperature and returns to its liquid state. It then passes through an expansion valve and is cooled further to start the process again.

This chapter will address the possible use of EGS to exploit heat from the ground surrounding an underground excavation such as a tunnel. While Section 6.2 below will provide a glimpse of the different types of EGS, Section 6.3 will describe the main phases of thermal design, which is the primary interest of these Guidelines, with particular reference to energy tunnels

6.2 Energy geostructure types

Several EGS types exist that are currently being developed and experimented by both academics and professionals worldwide. While the basic construction principle is similar for all EGS (namely, embedding pipe heat exchanger loops within the geostructure, typically attaching them to the reinforcement cage prior to concreting), every EGS must be considered on its own with respect to both thermal and (thermo-)mechanical analysis and design criteria, since they are characterized by different loading, geometry and boundary conditions. In this section, an overview is provided of the main EGS types, including energy tunnels (Section 6.2.1), energy piles and micropiles (Section 6.2.2), energy walls (Section 6.2.3).

6.2.1 Energy tunnels

Tunnel linings can be adapted to become an energy geo-structure, by fixing the geothermal coil circuit between the primary and secondary lining in tunnels excavated

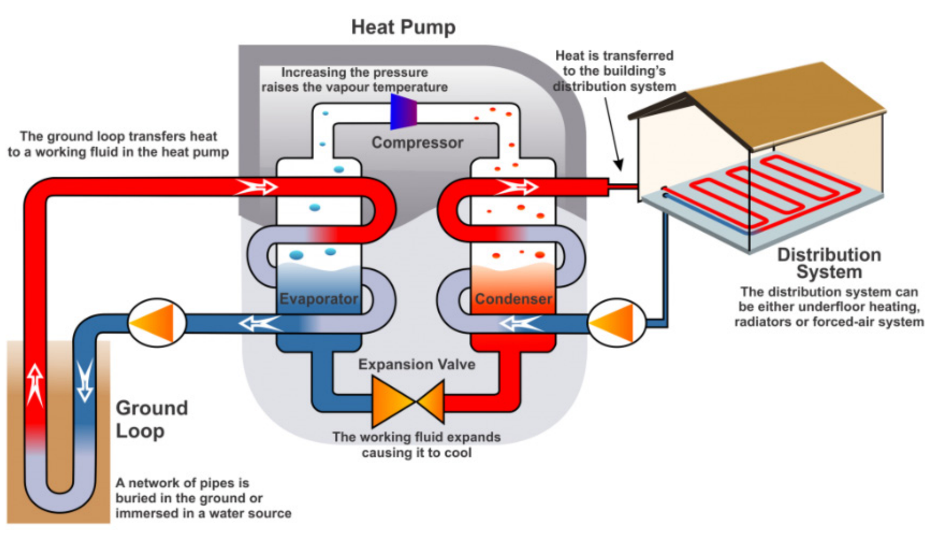

Fig. 6 - Schematic representation of a ground source heat pump installation (from EECA y GNS 2013).

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by conventional methods, or by incorporating it in the prefabricated segments, for tunnels excavated using a mechanized technique (Adam & Markiewicz 2009, Barla et al. 2016, Barla et al. 2019). The thermal energy extracted can have various uses, including air conditioning for underground/ subway stations and buildings, the heating of the lining itself, and de-icing tunnel portals, bridge decks and road surfaces in general.

The design process that leads to the construction of an energy tunnel goes beyond specific regulatory references and cannot be reduced to a series of verifications, whether structural and/ or geotechnical. It necessarily involves a wide range of issues, including planning the energy supply and distribution in the area. Therefore, as in the case of the recovery of water drained by the tunnel described in Chapter 4, the possibility to build an energy tunnel should necessarily be planned from the feasibility study phase of an infrastructure. Only in this way is it possible to ensure that the infrastructure can contribute to sustainable development, by being integrated into the energy planning of the territory.

More specifically, the thermal activation of tunnel linings involves at least two technical aspects, to be considered during the design phases: 1) structural design, which includes the mechanical effects induced by temperature variations on structural elements to ensure their long-term integrity, and 2) analysis of energy optimization to maximize efficiency at the same cost, i.e. thermal design. If the structural project can reasonably be further developed in the more advanced design phases, the thermal project must be implemented since the conception of the infrastructure.

6.2.2 Energy piles and micropiles

Energy piles (EPs) were among the first type of EGS to be historically developed. Pile types that are most commonly equipped with heat exchangers are rotary bored and continuous flight auger (CFA) ones. The former are the easiest to construct, in that (1) one or more sets of plastic heat exchanger U-loops can be attached to the reinforcement cage before lowering it, then (2) the cage is lowered and finally (3) concrete is poured, while the geothermal circuit is kept full of fluid and pressurized to contrast fluid concrete pressure. CFA piles, on the other hand, usually require a slightly more complex procedure to introduce the geothermal circuit. In fact, in this case the reinforcement cage is introduced after concreting while the concrete is still fluid. An account of the most relevant construction challenges for cast-in-situ EPs can be found in Loveridge et al. (2013).

In addition to the above, other types of EPs have gained some popularity in recent years, including precast thermoactive driven piles (Alberdi-Pagola & Poulsen 2015, Alberdi-Pagola et al. 2019) and micropiles (Salciarini & Cecinato, 2021).

Despite EPs can be considered the most similar shallow geothermal installation to BHEs, due to their similar (axisymmetric) geometry and boundary conditions, important differences exist and bespoke analyses are required (Loveridge & Powrie 2013).

6.2.3 Energy walls

So-called energy walls (EWs) include cast in situ thermo-active diaphragm walls, made of reinforced concrete vertical slabs, sheet pile walls and different types of earth retaining structures made of adjacent piles. In spite of the relatively straightforward construction procedures, involving the attachment of the U-loops to the reinforcement cages prior to concreting, EWs pose significant challenges regarding their thermal performance and operation. In fact, their geometry and boundary conditions are very different to those of EPs. The large surfaces available suggest a high energy exchange potential, but the presence of air on the excavation side exerts a major influence on their thermal performance. Depending on the use of the excavation space, the air temperature boundary condition can exhibit diverse variation patterns with time. For example, for EWs installed as the perimeter walls of an underground car park, the boundary air temperature is likely to follow (with some attenuation) the seasonally changing outdoor one. For EWs used in a metro tunnel, on the other hand, the air temperature is likely to be quite 'hot' regardless of the season, due to the heat rejected by trains' passage (especially due to breaking) and underground station heated spaces in winter.

From the EW thermal performance point of view, Sterpi et al. (2020) identified as key factors the layout of heat exchanger pipes and the embedment depth, concluding that the energy performance can be improved by limiting the thermal interference between different pipe branches. Di Donna et al. (2017) identified the most influential factors to maximise thermal output of EWs, suggesting that increasing the number of pipes is the primary route to increasing energy efficiency in the short term. However, the thermal properties of the wall concrete and the temperature excess within the excavation space are also important, with the latter becoming the most significant in the long term. This confirms the benefits of exploiting, for winter use, EWs in railway tunnels and metro stations where additional sources of heat are available.

In addition to the energy performance, the mechanical one is of paramount importance for EWs due to their primary geotechnical/structural function. In particular, it is essential to account for any additional thermally induced internal actions in the structural design, and make sure that thermo-mechanical displacements lie within acceptable limits.

6.3 The thermal project for energy tunnels

The objective of the thermal project is the quantification of the heat exchange with the ground according to the specific conditions of the site, to assess the real energy efficiency of the installation, indicating its economic viability and environmental sustainability. Determining the efficiency of the system essentially involves the quantification of the heat extracted or transferred to the geothermal reservoir by means of the tunnel lining. Environmental sustainability, on the other hand, refers to the evaluation of the effects of the thermal project on the surrounding environment, in order to

limit their impact.
Since thermal projects in tunnels are a recently introduced technology, there are no clear methodological or normative indications to follow. A procedure for thermal energy tunnel design is proposed and schematized in the flow chart shown in Figure 7.

First, it is necessary to conduct an additional investigation whose accuracy will depend on the design phase considered. The objective is to determine the hydrogeological characteristics of the geological formations hosting the tunnel, since they influence the heat exchange processes. The useful parameters to determine are shown in Table 1. In situ testing techniques include Thermal Response Tests (TRT), widely used for BHEs and EPs, that are useful to assess the thermal conductivity of the soil, the thermal resistance of the heat exchanger, and the undisturbed temperature of the soil. Laboratory testing is divided into stationary methods (e.g. hot plate) and transient methods (e.g. needle probe, transient plane source) to evaluate thermal conductivity, thermal diffusivity, and volumetric heat capacity.

6.3.1 Measurement of thermal and hydraulic properties

When dealing with energy tunnels, additional investigations need to be carried out. Indeed, routine investigations do not provide any information about soil/rock thermal properties, groundwater temperature and, sometimes, about permeability. Both laboratory and in situ tests can be carried out to this aim (Table 2). The most common available techniques will be briefly described in the following.

Laboratory measurements do not account for site-specific conditions such as the presence of groundwater flow, spatial heterogeneity, and scale effects that directly impact actual thermal properties (Vieira et al. 2017). However, these analyses are relatively cheap and can be a suitable method to provide a first estimation of soils and rock thermal properties. Several tools can be employed to measure thermal properties (Raymond et al. 2017). Both steady state and transient methods exist.

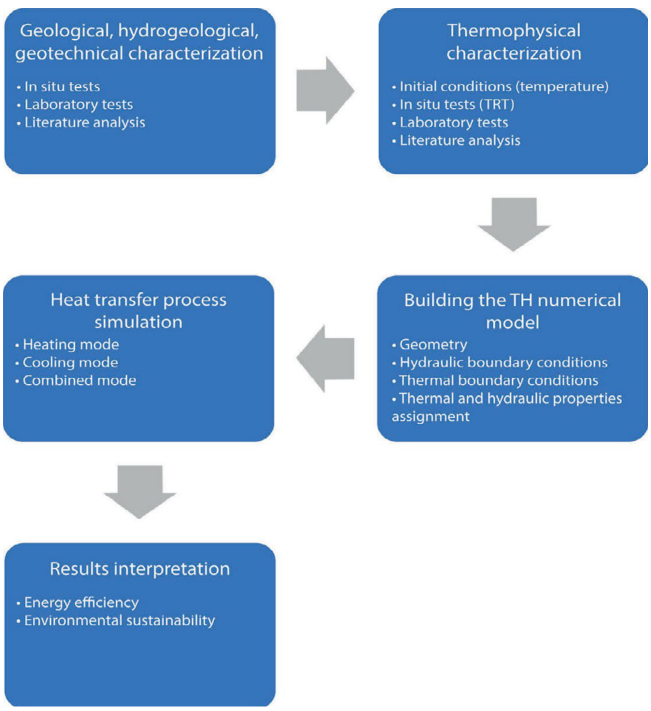

Fig. 7 - Thermal design procedure for an energy tunnel (Barla 2020; Insana 2020).

In steady state methods (e.g. guarded hot plate, divided cut-bar, thermal cell) a constant thermal flow is applied through the specimen to obtain a thermal gradient, the measurement is taken when temperature does not vary with time and interpretation is done through the Fourier's law. The duration of such tests is long, hence moisture migration and heat losses may affect the result. A heat flow meter can be used to quantify the thermal conductivity of plugs, which can be obtained from rock samples collected at outcrops or from drilled cores. The measurement can be done at a controlled temperature, from both dry and water saturated samples, to represent the temperature-dependency of thermal conductivity.

Transient methods are shorter, therefore with no moisture migration issues, and are performed at a smaller scale compared to steady state methods. A thermal conductivity scanner with an infrared heat source can be applied for transient thermal conductivity and diffusivity analysis of hand specimens and core samples at room temperature. The transient heat transfer analysis achieved with this tool has a small depth of penetration and allows a local evaluation along the scan line, being useful to identify potential heterogeneity in the rock sample. A needle probe can be used as well for transient thermal conductivity and diffusivity analysis at room temperature. A narrow hole must be drilled in the sample where a temperature sensor is inserted and then the thermal conductivity is calculated from the transient temperature perturbation. The heat pulse transmitted to the sample has a limited depth of penetration, such that this analysis reveals point values that are representative of the homogenous samples.

It is highlighted that in the case of coarse soils the appropriate density and moisture content need to be reconstituted before performing the test.

The Thermal Response Test (TRT) is an in-situ technique that allows to evaluate ground thermal properties, i.e. undisturbed temperature, effective soil/rock thermal conductivity and thermal resistance, accounting for groundwater and other disturbances. It can be conducted using the conventional method or recently developed methods.

In the conventional method a constant heat power is injected into a borehole heat exchanger, 150-200 mm in diameter, via circulating fluid and the temperature response in measured. In a first stage undisturbed ground temperature is measured, then a constant thermal power is injected for 2-3 days, inlet and outlet temperature, flow rate, ambient temperature and electrical power are measured every 1-10 minutes and a recovery phase is then performed. As ground heat flow is radial, it can be represented as a line source. Hence, thermal conductivity and thermal resistance can be interpreted by

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means of the Infinite Line Source (ILS) mathematical model of heat transfer.

More recent methods are focused on reducing cost using heating cables that do not require water circulating in the BHE: this new approach permits the use of a smaller power source and simpler test execution (Raymond et al. 2020). Two main cable installations can be used: continuous and interchanging sections of heating and non-heating cable. Heating cables are located in the water column of the BHE, together with submersible temperature sensors or with fiber optic distributed temperature sensing technology. The analysis of the temperature data collected during the test to estimate the thermal conductivity of the lithological formation is similar to that of a conventional TRT, based on the infinite line source solution (Stauffer et al. 2014). A finite heat source solution must be used when a TRT with heating cable sections is conducted, to reproduce the measured temperatures along the heating sections, which are usually 1–2 m long. Both solutions assume only conductive heat transfer. However, water movements due to free convection that can occur at the interface between heating and non-heating sections make the test analysis more complex. Perforated rubber discs have been installed at the boundary between heating and non-heating sections to reduce free convection effect. Field tests have shown that the continuous heating cable is more accurate than the heating sections TRT (Vélez et al. 2018). Additionally, a method to infer groundwater flow direction and magnitude with temperature sensors surrounding the heating cable has been proposed (Raymond et al. 2020).

Undisturbed ground temperature can also be evaluated at different depths in a piezometer by means of a phreatimeter with thermocouple or can be monitored continuously and remotely.

As regards the hydraulic properties, pumping tests or slug tests can be used for the measurement of hydraulic conductivity. In the former, a well is pumped at a controlled flow rate and water-level response is measured in one or more surrounding observation wells and optionally in the pumped well itself. In the latter, water is quickly added or removed from a groundwater well and the change in hydraulic head is monitored with time. Additionally, a laboratory or portable permeameter can be used to quantify the permeability of the formation in core samples or in the field, respectively.

Laboratory measurements can then be compared with those conducted in the field to analyze the scale effect and obtain a more detailed quantification of the thermal and hydraulic values to be used in the numerical models, as described in the next section.

6.3.2 Thermo-hydraulic numerical modeling

The amount of exchangeable heat depends on several factors. To obtain a first approximate assessment, it is possible to use the nomograms suggested by Insana and Barla (2020) where the amount of exchangeable heat is evaluated as a function of several parameters, such as subsurface temperature, groundwater flow, soil thermal conductivity, orientation of the groundwater direction, and the inlet temperature of the heat transfer fluid.

For a more complete quantification, a 3D thermo-hydraulic numerical model reproducing a portion of a thermally activated lining must be created. For example, in the case of energy segments, it is possible to reproduce a limited number of tunnel rings equipped for heat exchange (see Alvi et al., 2022). In general, finite element or finite difference methods specifically coded to solve THM (Thermo-Hydro-Mechanical) or TH (Thermo-Hydraulic) mathematical formulations, are used, depending on the physical phenomena to be simulated. Typically, the analyses are performed by reproducing the operation of the lining for a certain number of years to analyze not only the short-term effects, but also and above all the long-term ones. To build a numerical model, it is necessary to reproduce the correct geometry of the tunnel faithfully, including the layout and geometry of the geothermal installation; moreover, the hydrogeological and thermal conditions of the subsurface must be incorporated in the model as boundary and initial conditions. For example, groundwater flow can be reproduced by applying a hydraulic head difference on the boundaries of the model as a boundary condition to reproduce the flow direction observed in situ, with a magnitude depending on the hydraulic conductivity of the existing geological formations. In a transient simulation, the initial conditions must describe the initial value of the hydraulic head and temperature in the whole model. Next, the analysis is conducted by imposing the temperature at the inlet and the flow velocity at the inlet and outlet of the tube heat exchanger and calculating the temperature at the outlet, which will depend on the heat transfer mechanism that is numerically reproduced during the simulation. By varying the inlet temperature, the analysis can permit simulation of the average behavior in the different periods of activation of the geothermal installation. For example, by applying an inlet temperature of between 24° and 28°C, it is possible to simulate summer operation, when excess heat is injected and allowed to disperse back into the ground. On the contrary, by imposing an inlet temperature of between 3° and 6°C, it is possible to simulate winter operation, when heat is extracted from the ground.

Finally, by varying the inlet temperature cyclically, in accordance with the annual operating mode, it is possible to simulate the seasonal behavior of the installation and evaluate the long-term effects.

The thermal power exchanged in winter and summer can be calculated from the temperature difference between the inlet and outlet of the tube heat exchangers and used to determine the geothermal potential of the tunnel section of interest. This assessment is necessary in order to select the ground source heat pump size most appropriate to each project.

As regards the environmental sustainability analysis, the objective is to verify the impact of the energy tunnel lining on the surrounding environment and possible positive and negative interferences with other existing plants (open-loop, closed-loop, ecc.). A thermo-hydraulic numerical model can also be used for this purpose, to reproduce the groundwater flow and assess the magnitude of the thermal variations induced in the aquifer and in the subsoil for the real operating conditions of the energy geostructure (Barla et al., 2018).

Finally, one of the peculiarities of energy tunnels that can significantly affect their performance is the air temperature inside the tunnel, as shown in several studies (Bourne-Webb et al. 2016; Insana and Barla 2020; Ma et al., 2021).

Tab. 2 - Key properties and parameters required for the thermal design of an energy tunnel.

Propriety or parameter	Symbol	Unit	Material	Testing method
Thermal conductivity	λ	W/mK	Soil/Rock, concrete	TRT, needle probe, transient plane source
Specific heat capacity	S_c	J/kgK	Soil/Rock, concrete	Transient plane source
Undisturbed temperature	T_0	°C	Soil/Rock	TRT, measurement at different depths with phreatimeter with thermocouple in piezometer
Effective porosity	n_e	-	Soil/Rock	Tests with artificial tracers
Horizontal and vertical hydraulic conductivity	K_h, K_v	m/s	Soil/Rock	Pumping tests, slug tests, laboratory and portable permeameters
Groundwater velocity	v	m/s		Piezometric surveys (phreatimeter measurements), test with artificial tracers
Depth of piezometric level	f	m		Piezometric surveys (phreatimeter measurements)
Groundwater flow direction	df	°		Piezometric surveys (phreatimeter measurements)

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7 CHEMICAL PRODUCTS USED IN EXCAVATION

Alessandro Boscaro

A wide range of chemicals are used for tunnel excavation, both in the case of mechanized excavation with full section cutters (TBM) and in the case of excavation with traditional methods. Many of these chemicals can come into contact with groundwater and tunnel drainage water and must therefore be evaluated not only from a technical and operational point of view, but also from the point of view of their environmental impact.

Even more so in the case of the use of the tunnel as a water capture infrastructure, it is necessary to have full knowledge of the materials used during excavation, in order to be able to assess the vulnerability of the captured resource upon entering the drainage work.

In recent years, research and development activities by companies producing materials for the tunneling industry have brought to the market various solutions capable of reducing/minimizing this impact, for example by varying the formulations of some products (e.g. foaming agents used for soil conditioning during TBM excavation, Earth Pressure Balance type, EPB) or through technological solutions that completely avoid contact between chemicals and groundwater (e.g. in the case of water infiltration through joints between segments of concrete in tunnels excavated with shielded TBMs, it is possible to seal the joint using suitable plastic strips, thus avoiding the injection of resins onto the inner side of the tunnel lining).

Below some of these solutions are considered.

7.1 Mechanized tunnel excavation with TBM - Soil conditioning products

Mechanized excavation with EPB type TBMs involves the use of chemical products that are mixed with the soil during the advancement of the machine, in order to facilitate and accelerate excavation operations. The most common product, used on practically all EPB TBMs, is a foaming agent, the main raw material of which is a surfactant mixed in aqueous solution with various other ingredients (polymers, solvents, etc.). From a technical and operational point of view, the choice of foaming agent is mainly based on its compatibility with the soil to be excavated (for example, there are formulations particularly suitable for excavating clayey soils, generally characterized by "adhesion" characteristics that can hinder the advancement of the TBM EPB). At the same time, the environmental characteristics of the foaming agent are equally important, as this chemical product comes into contact not only with the soil, but also with groundwater and with the water contained within the excavated material (extracted in most cases by means of a horizontal conveyor belt along the tunnel and then temporarily stored in construction site areas, where the water drained from it is collected and treated as necessary).

Each single ingredient of the foaming agents therefore contributes to the degree of environmental impact of the finished product.New formulations of foaming agents have become available on the market in recent years, featuring greater and more rapid biodegradability, less organic material entering the soil (with the same technical conditioning result) and lower eco-toxicity indices compared to "traditional" formulations.

In particular, as regards potential impact on groundwater and drained waters, eco-toxicity indices are measured in terms of "standard" aquatic organisms, such as algae, crustaceans and fish. The higher this index (expressed in mg of product per liters of water), the lower the toxicity of the product.

The following two graphs (Fig. 8) show a comparison between the eco-toxicity data of an innovative foaming agent formulation and two "traditional" products.

Both indices:

- EC50 = toxicity for the crustacean Daphnia Magna according to OECD 202
- LC50 = toxicity for Danio Rerio fish according to OECD 203

of the innovative foaming agent are tens of times higher than the other two. This means that, in order to have the same toxic effect on the organism under examination, it is necessary to increase the concentration of this product by dozens of times compared to more "traditional" products.

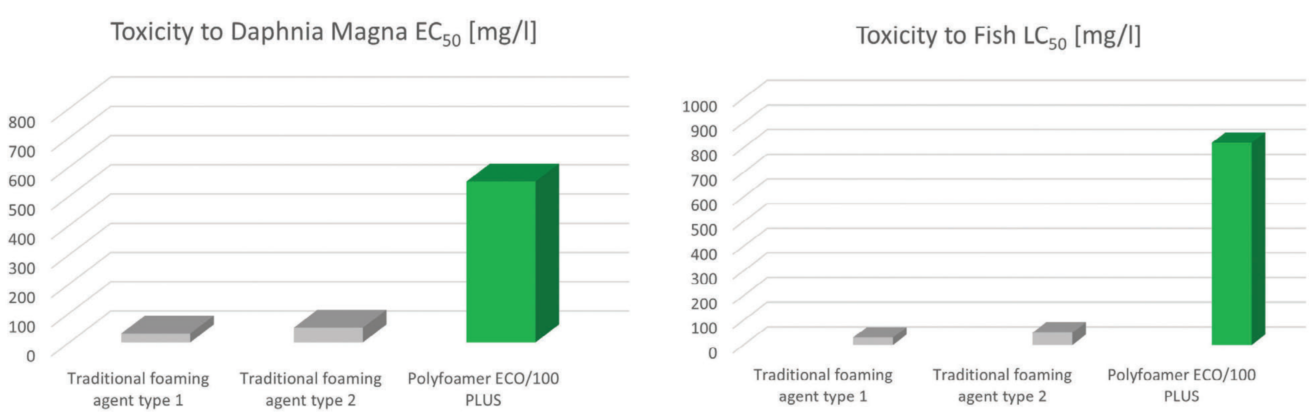

Fig. 8 - Comparison between the ecotoxicity data of "traditional" foaming agents and of a more innovative one.

In addition to lower toxicity, the quantities of surfactant and other organic substances introduced to the soil and consequently to the drainage water are also reduced, thus making their treatment and disposal easier.

7.2 Mechanized excavation of tunnels with TBM - Injection mixture for behind the segments and alkalinity

During the excavation of tunnels with any shielded TBM (be it pressure, such as EPB machines or slurry TBMs, or open, i.e. single or double shielded rock), it is necessary to fill the annular space that is inevitably created between the lining in concrete segments and the soil or surrounding rock mass. In the case of excavation in soil, this filling must be carried out simultaneously with the excavation, in order to avoid subsidence of the soil towards the lining segments, potentially dangerous,including superficial subsidence phenomena. In rock, on the other hand, annular filling can be performed both simultaneously with the advancement of the machine, and therefore directly from the shield, and a few meters further back, and therefore from holes prepared in the concrete segments. In any situation, however, the filling must be carried out in the best possible way, as it significantly affects the quality of the tunnel lining: for example, any gaps left behind the segments will very likely cause ovalization of the segments or cracking of the concrete, and favor the entry of water into the tunnel (from the joints between the segments and through cracks).

The method commonly used for back filling is defined as "two-component", as it involves the use of an extremely fluid cement grout, stable and with long-lasting workability (therefore easy to pump), to which a second component, i.e. an accelerator, is added immediately before injection into the space.

The two-component mixture, as well as all the other existing filling methods (non-accelerated mortar, pea-gravel followed by blocking of the interstices with grout), is cement-like and so the groundwater that then comes into contact with the filling tends to alkalize. Because of this, most of the water that infiltrates the tunnel (for example, through the brushes of the shield or through cracks) and which is subsequently pumped out,hasan alkaline pH.

In some situations, it is possible to replace the cement with other mineral binders, maintaining the technical characteristics of the filling mixture, but significantly decreasing the alkalinization of the water in contact with it and so facilitating treatment before disposal.

Another example of a technological solution forthe behind-segment filling mixture, with advantages in terms of its impact on water, is the use of a stabilizing polymer, which can permit the water collected in the tunnel (and subsequently mechanically treated, normally with a filter-press) to be used for the production of the filling mixture itself. This water, as mentioned above, is alkaline and contaminated with various chemical elements: as is, its use for the production of two-component filling mixture is not possible, as it significantly worsens the technical characteristics (for example, volumetric stability is reduced, as bentonite does not activate if mixed in alkaline waters, and the development of mechanical strength is usually slower and lower). The addition of a specific stabilizing polymer to the water collected from the tunnel eliminates these technical drawbacks and thereforepermits the recovery/recycling of such water for the production of the behind-segment filling mixture.

7.3 Mechanized excavation and traditional tunnel excavation - Consolidation injections at the face

Many materials are available on the market for reinforcement injections at the face of a tunnel, whether it is excavated using the mechanized method or the traditional method.The choice of product, and more generally of the method of intervention, depends on numerous factors, such as grain-size and porosity in the case of injections into soil, opening of fractures in the case of injections into rock masses, presence of water, etc.

There are products specially formulated for face consolidation injections for which water release tests are available to demonstrate the non-release of chemical elements (including nitrates, sulfates, copper, lead, hydrocarbons, etc.) in groundwater. For the maximum accepted concentrations of these elements, see D.M. 05/04/06 n. 186 Annex 3.

7.4 Mechanized excavation and traditional tunnel excavation - Secondary waterproofing injections

Water infiltration through the concrete lining of a tunnel is a fairly common phenomenon. The problem is generally solved by injecting special resins: many different types are available, to be chosen based on the characteristics of the individual intervention. For example, some single-component or two-component polyurethane resins are able to generate an expansion reaction as soon as they come into contact with water, forming an impermeable closed cell foam: these resins are therefore very suitable for injections behind the lining, intended to stop major water infiltration. Acrylic resins, on the other hand, are characterized in the liquid state by a very low viscosity, while once the reaction has taken place they generate an elastic material with a gel-like consistency: they are therefore particularly suitablefor injection into cracks in concrete or inside joints potentially subjected to movement,for example.

Some of these injection resins, thanks to their formulation and the very low degree of release of chemical elements into the water with which they can come into contact, have certifications that permit their use even in contact with cold drinking water, in accordance with BS 6920-1: 2014.

A further technological innovation results infull avoidance of injection of resins behind the lining and so contact between groundwater and resins: in some cases, water infiltration through the joints, for example between the concrete segments in tunnels dug with shielded TBMs, can be stopped using a special non-flammable plastic strip, which seals the joint on the intrados. A resin is then injected into the space between the plastic stripand the gaskets preassembled on the

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segments. The resin therefore remains confined to this space and is not injected onto the back of the lining. The plastic striphas special ribs that avoid the risk of leakage from the joint during injection of the resin.

7.5 Waterproofing of tunnels and structures with synthetic membranes

For the waterproofing of tunnels and other artifacts such as stations, wells, by-passes, etc., loose laid synthetic membranes are widely used, available in different materials, each with its own technical characteristics, and thicknesses. The use of a dry laying system is particularly suitable for this type of structure (tunnels, underground works in general), as the laying supports (e.g. shotcrete) are usually irregular. For this reason, of the synthetic membranes the most widely used material is PVC-P (polyvinyl chloride plasticized) which, due to its excellent workability, permits easier installation, limiting application costs and improving the final quality of the waterproofing system.

Regarding synthetic membranes, there are numerous systems that can be used to waterproof an underground work. Basically it is possible to divide these systems into two large families: drained systems, and undrained systems with waterproofing generally known as 'full round' (Figure 9). While the former reduce the level of the aquifer to a greater or lesser extent (at least locally), the latter guarantee its maintenance, avoiding possible alterations in the hydrogeological conditions of the soil. The use of full-round systems (i.e. those systems in which the structure is waterproofed on its entire surface) where possible is therefore preferable, as the environmental impact (footprint) at the hydrogeological level is limited or in any case lower, compared to drained-type systems. The application of full-round waterproofing systems is used in tunnels which are not very deep, with water pressures on the extrados generally below 8-10 bar.

The full-round waterproofing systems have a PVC-P-based membrane or mantle (of different thicknesses according to the pressures involved) as a key element, but are in fact made up of a series of "accessory" elements that guarantee the correct functioning of the system. The following system components play a key role:

– Leveling layer in PP (polypropylene): protects the membrane from perforation by the substrate.
– Waterbar (joints) for subdivision/second layer in PVC: necessary to 'section' the tunnel, meaning the waterproofing system works in independent sections (any damage and related consequences will remain limited to the section concerned, making repair easier and cheaper).
– Backup systems (injection pipes and/or valves): injection systems set up during the construction of the waterproofing system that allow intervention to repair any damage (operations that can be carried out after the construction of the work, avoiding invasive techniques such as perforations that would further damage the mantle).
– Sealed anchoring elements (e.g. for supporting frames or equipment): systems used to create fixing points (in the support, through the membrane) without compromising the waterproofing of the system.

The materials used for the construction of the waterproofing system (and in particular its two key elements,i.e. the membrane and the waterbars) must obviously possess the minimum mechanical and life expectancy requirements necessary to perform the function for which they are used (waterproofing).

Furthermore, in view of a possible interaction with groundwater, it is important that the membranes be of high chemical stability, which results on the one hand in maintenance of their mechanical properties, and on the other in limited migration of chemical substances from the mantle to groundwater in the long term. Table 4 shows the minimum requirements for PVC-P membranes.

It is also essential that if the structure (and therefore the membrane) comes into contact with aquifers intended for drinking water, the mantle is appropriately certified according to the current legislation governing the use of plastic products

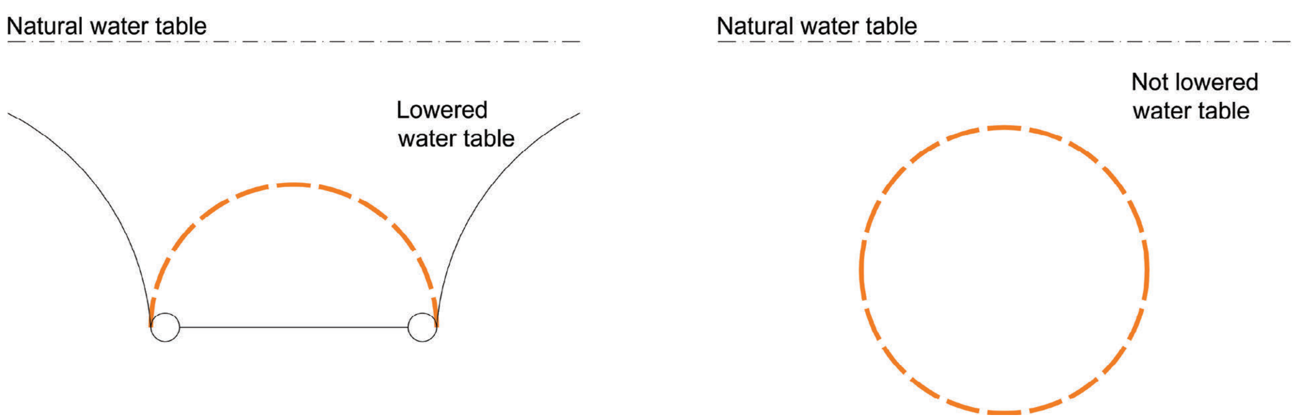

Fig. 9 - Conceptual diagram of a drainage tunnel (left) and a tunnel with full-round waterproofing (right).

Tab. 3 - Mass variation and mechanical performance tests on PVC-P membranes (minimum requirements).

Behavior after storage in aqueous solution (EN 14415) Liquid type 2, 360 d at 50 °C	
Variation in tensile strength and elongation at break (%)	≤ 25
Variation in dynamic puncture test (perforation) (%)	≤ 40
Mass variation (%)	< 7
Behavior after storage in aqueous solution (EN 1847) Liquid type 3, 120 d at 23 °C	
Variation in tensile strength and elongation at break (%)	≤ 25
Variation in dynamic puncture test (perforation) (%)	≤ 40
Mass variation (%)	< 7
Behavior after storage in hot water (SIA V 280 Nr. 13) 240 d at 50 °C	
Variation in tensile strength and elongation at break (%)	≤ 25
Variation in dynamic puncture test (perforation) (%)	≤ 30
Mass variation (%)	≤ 3
Dimension variation (%)	≤ 3

in contact with food (as regards the Italian legislation, DM n.174 of 06/04/04 and EU Regulation n.10/2011).

Last but not least, it should be remembered that generally the real effectiveness of these interventions depends on how they are implemented on site and the expertise of the personnel involved. Therefore, particular care must be taken in the selection and training of specific personnel and in the supervision of the work.

DOI 10.7343/as-2022-592

8. MONITORING

Maria Elena Parisi

8.1 Purpose and phases

As is well known, the monitoring of surface and underground water resources is a necessary and indispensable activity that characterizes all the phases concerning an underground work. Chapter 9 presents national (Italian) reference regulations on monitoring, to which reference must be made for the design of a monitoring plan. In this chapter we report some indications deriving from experience gained on previous projects, including large ones (for example the Turin-Lyon railway connection, but not only), with the aim of integrating the regulatory indications.

Monitoring involves following phases:

- preliminary, background information: data gathering and reconstruction of knowledge about the water environment affected by the new work, in order to identify the environmental quality status of surface and groundwater and to characterize the aquifers; this knowledge makes it possible to protect the water component and mitigate possible impact by means of proposals for suitable excavation methods and/or the implementation of protection and mitigation measures;
- before construction: monitoring carried out at least 1 year before the commencement of works, which serves to provide a comparison with what will occur during the work, reflecting t0;
- in progress: delicate phase in which the water resource (external to the work and in the tunnel) must be checked during the execution of the works to verify that works do not interfere with the water resource; should this occur, continuous monitoring should enable immediate activation of suitable intervention to reduce the impact; on the contrary, see Chapter 4 above: in the design phase, risk analysis should foresee the most probable impacts in order to permit implementation of preventive systems before excavation in order to either prevent the impact from occurring or to intervene to compensate rapidly;
- after construction: once the work is completed and operating, monitoring is a means of checking the new context over time (manifestation of late impacts), as well as of validating long-term forecasts and a return of experience.

8.2 Regulatory compliance

The monitoring must be such as to comply with legislation and what may be required by control bodies during the Environmental Impact Assessment procedure (“Environmental Conditions”, see Chapter 10). Relevant legislation must be considered at different levels: international (for example tunnels crossing national borders), national, regional and local.

For a full discussion of regulatory issues, see Chapter 9.

8.3 Monitoring dynamics

Obviously the monitoring network needs updating during the various phases of the process: the preliminary network, defined as ‘before construction’, should be integrated and updated according to the data collected and the new analyses performed during the final design stage. The effectiveness of monitoring becomes clear during the course of the works: at this stage it is possible to verify the predicted hydrogeological model and fine tune it with real data, and to check the effects of the tunnel on the aquifers from an environmental point of view.

It is essential that measurements from inside the tunnel are interpreted together with those from outside; otherwise they will not be useful and will not give the expected results. The real context and what is happening will thus be clarified.

The occurrence of even temporary unforeseen impacts during construction should lead to integration of the monitoring network, as well as of the frequency and possibly the parameters, depending on the problems arising.

During excavation, monitoring the flow of water into the tunnel is fundamental. This should take place immediately at the first hint of water coming into the tunnel, since a rapid flow decrease could result in a missed measurement and interpretation and consequent realization of specific laboratory analysis for a better understanding of water circulation, satisfying the twin objectives of verifying the conceptual hydrogeological model, and environmental protection of the hydrogeological system.

8.4 Outline of a Water Resources Monitoring Plan

A Water Resources Monitoring Plan forms part of the Environmental Monitoring Plan, a much wider program that includes dust, atmospheric emissions, vegetation, noise, asbestos, fauna, etc. In these guidelines only the water component is covered.

Monitoring for tunnel construction includes:

- hydrological (surface water) and hydrogeological (groundwater) monitoring, combined or not and to the same level of detail or not, depending on the planned work;
- environmental monitoring, to verify and check the impacts of the tunnel on aquifers, on the GDE and on the surrounding underground and superficial ecosystems.

Figure 10 presents a summary scheme of the main aspects to be considered in defining an environmental monitoring plan for water resources, in the order in which the various aspects are briefly discussed in the following Paragraphs.

8.4.1 Definition of monitoring objectives

Before starting a monitoring activity, it is necessary to define what is to be monitored, and this starts with a CENSUS process covering the hydrological and hydrogeological targets.

The census initially involves gathering detailed bibliographic sources on the area affected by the project, retrieving data on works already carried out, contacting the public bodies present in the area (Arpa, Region, universities,

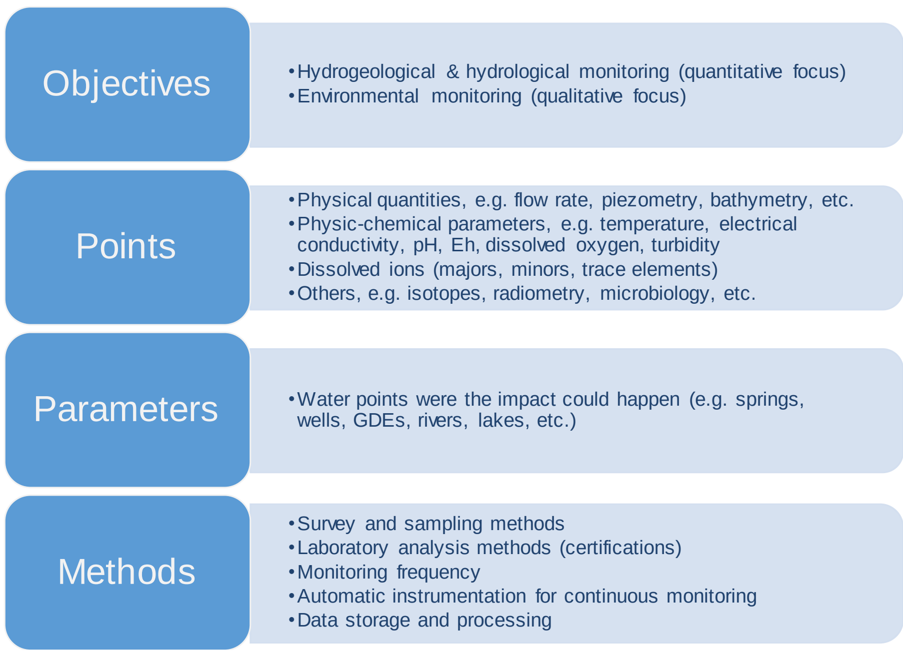

Fig. 10 - Main aspects to be defined in the preparation of a Monitoring Plan.

municipalities, etc.), service managing bodies, possibly also local associations, etc. This reference survey provides information on the project environment and the quantity and quality of available data, which will later have to be implemented with new measurements.

This information makes it possible to plan the subsequent census, which will require local surveys to verify the available data and expand the hydrological, hydrogeological and environmental database.

8.4.2 Hydrological and hydrogeological monitoring points

- surface water points:
  - rivers and streams;
  - lakes/other bodies of water;
- underground water points:
  - springs;
  - wells;
  - piezometers;
- GDE (Groundwater Dependent Ecosystems);
- water points in the tunnel:
  - water flows: single inflows at the excavation face and in the tunnel section not yet lined;
  - hydraulic load measurement points on the extrados of the tunnel. These measurements are carried out with pressure sensors to be installed in boreholes made in advance during excavation, or between the lining of the tunnel and the rock mass. The monitoring of hydraulic loads is essential in the case of lined and waterproofed tunnels;
  - measuring points of the total flow rates drained in the excavation: in the case of draining (or not yet lined) tunnels, high frequency monitoring (preferably automated) of the total flow rates drained by the tunnel is essential. Generally, this monitoring is performed at the entrance, where the total cumulative flow entering the tunnel is measured. It is also possible to install intermediate measurement stations inside the tunnel, in order to quantify the inflows of water in distinct sectors of the tunnel.

The choice of monitoring points depends on several factors, explained below:

– a first criterion is that of proximity to the underground work to be monitored. All the surveyed points falling within the area where an impact and a risk of impoverishment are deemed possible are identified;
– analysis of the risk of impact on surface and underground water points must be carried out in the design phase, before the start of construction. The risk analysis is identified through a geological-structural and hydrogeological study, in the sector underlying the tunnel route. The risk analysis must include analysis of the probability of water entering the tunnel. This has already been extensively discussed in Chapter 4;
– the choice of points to be monitored on the surface can be extended to include areas of outstanding environmental importance and natural beauty, even if outside the area of potential impact;
– the density of the monitoring network and the general layout of the points are further important parameters to consider. The points should be equidistant in order to guarantee they provide information on the dynamics of the system, with increased density where potential problems require it. For example, points in the tunnel consistent with points on the surface at risk of impact, but also points at increasing distances starting from the axis of a tunnel, to ensure that any piezometric reduction over space and time is recorded.

DOI 10.7343/as-2022-592

8.4.3 Monitoring parameters

The monitoring parameters are chosen according to the type of point and water body to be monitored. For some specific water points which are particularly important or vulnerable, specific monitoring indicators can be defined.

Monitoring indicators can be divided into the following categories:

- physical quantities: flow rate (from a spring or stream), piezometric level (in a well or piezometer), bathymetric level (in a lake);
- chemical-physical parameters (measurable in situ and/ or in the laboratory): specific electrical conductivity, temperature, pH, redox potential, dissolved oxygen, turbidity;
- analytical concentrations of dissolved substances (measurable only in the laboratory using certified methodologies):
    - principal ions;
    - minor ions;
    - metals;
    - pollutants, depending on the specific impact risks identified;
- isotope concentrations;
- radiometric analyses;
- bacteriological analysis (to verify any biological pollution);
- ecological analyses (for the monitoring of GDEs).

The choice of analysis type depends on:

- endemic characteristics of the sector;
- characteristics of the planned work;
- potential impact risks.
–

8.4.4 Measurement methodologies

For each indicator, the method of measurement in the field, or of laboratory analysis, must be precisely defined, as should the type of instrumentation to be used, so the different measurements performed over time are comparable, and instrumental/methodological errors can be checked for.

This information should be included in the monitoring reports, detailing the procedures and methodologies used for sampling and storage of samples, sample pretreatment, the list of laboratories involved, with references for the analysis methods used.

In the case of in situ measurements, for some parameters a subjective component is unavoidable in the execution of certain measurements (for example, measurements of flow rate in water with current meter); in these cases it is also important to archive the description of the surrounding conditions, such as climatic and orographic conditions, and the name of the person carrying out the survey, as well as to attach photographic documentation.

8.4.5 Frequency of monitoring

The frequency of monitoring (in situ measurements and laboratory analyses) is determined by several factors, the main ones being listed below:

- the phase of the project, with higher frequency during excavation of underground works (fortnightly, weekly) and more infrequent during earlier phases (information gathering, before construction) or later (after construction);
- seasonal trend of the flow rates in the project area;
- hydrodynamic parameters of aquifers. For example, in sectors where there are aquifers with high hydraulic conductivity, higher monitoring frequencies are required, because the water flows that occur in the tunnel at the excavation face can generate impacts on the surface more quickly;
- excavation advancement speed. Measurement rates need to be higher as the excavation approaches the monitoring point.

Some typical basic monitoring frequencies can be cited as examples:

- six-monthly/annual: these frequencies should be avoided as they cannot in any way permit assessment of seasonal processes affecting surface and underground water points;
- quarterly: this is the minimum frequency that permits monitoring of seasonal effects; to be evaluated only for points with limited variations over time or complementary to other nearby points;
- monthly;
- fortnightly;
- weekly;
- daily or lower (hourly): for these high frequencies it is advisable to install suitable continuous monitoring instruments.

For water flows in the tunnel which remain active over time, it is important to differentiate between peak, transitory and stabilized flows, as defined in Paragraph 2.2.1.

8.4.6 Continuous monitoring

Probes available on the market for the measurement of the main hydrogeological parameters (for example the water level in a catchment point or a well or piezometer, the flow rate of a spring/ stream/drain/discharge, the electrical conductivity of the water, pH, temperature) are equipped with long-lasting batteries and a data logger inside a small, watertight case. This allows for high-frequency monitoring, which in the case of tunnels typically ranges from hourly to daily.

Monitoring probes are highly recommended for tunnels, since the data collected, being more numerous, better describe the hydrological functioning of water bodies, greatly facilitating the interpretation of the phenomena studied and the prediction of impacts. The monitoring data stored in the probe data recorder can be downloaded manually by someone going to the site at regular intervals, or transmitted by radio link or by GSM/GPRS, ADSL or satellite repeater networks. Data transmission is generally used to activate real-time alarm systems calibrated to alert limit thresholds, as for example for landslides and floods. When monitoring water resources in underground excavations, data transmission is used more rarely. The most typical reasons for generally opting for manual data collection are the general lack of the need for immediate information, the number of monitoring points and the risk of vandalism, especially in the case of urban areas. In some cases, it is however necessary to set up these systems to verify the efficiency and effectiveness of mitigation or compensation systems in real time, including automatic alert systems, (for example, the correct functioning of groups of intake and yield wells for mitigation of the barrier effect).

8.5 Data storage

The monitoring network is the set of all monitoring points. The monitoring database is the set of all monitored indicators.

The setting up of a georeferenced monitoring database (*Geo-Data-Base*) which brings together all the points of the monitoring network and then serves as a continually updated container for all monitoring data is of fundamental importance. In addition to being an archive tool, it is also valuable when consulting, processing and analyzing data.

GIS (*Geographic Information System*) software, now widely used, is available in both open-source and proprietary versions for setting up the *Geo-Data-Base*.

DOI 10.7343/as-2022-592

9. COMMUNICATION

Guido Ruffinatto, Sergio Vazzoler, Antonio Dematteis

The construction of a large infrastructure should envisage channels of communication with and participation by the population, with particular reference to the relationship with local areas and communities. In the case of tunnel excavation, which can potentially have an impact on groundwater and surface water, this aspect is often a priority with respect to the technical design aspects of the work.

The decision to carry out large infrastructure works must respect procedures outlined in the Aarhus Convention (and Law 108/2001, which embodies it in Italy). This communication process must start at a preliminary stage of project analysis, and can be combined with the "public investigation" that art. 24bis of Legislative Decree 152/2006 states can be ordered by the responsible authority.

The process must be coordinated by staff comprising the project management and public authorities and based on shared awareness and sustainability of the project and its monitoring, such as to sustain a constructive dialogue with the local inhabitants.

Communication includes raising awareness, training, support for decision makers, advertising, perception of impacts and opportunities for enhancement, and also listening to and dialogue with the communities concerned.

9.1 Communication experiences from large infrastructures

There have been some very informative experiences **at the Italian level** regarding the usefulness of communication and the methods to be adopted. A case in point is that of the Turin-Lyon railway line, where different view-points were recognized ex post, following full-blown conflict, and which was the focus of a complex extraordinary structure (Institutional Board of the Presidency of the Council of Ministers, Technical Observatory, Government Commissioner) which joined the standard organization and related ordinary procedures (Intergovernmental Commission, Environmental Impact Assessment Commission, Services Conference, etc.). The experience gained on that project draws attention to some essential points in the field of communication.

A method already tested at an international level is that of **creative confrontation** (public consensus building), which consists in listening to points of view and exploring together new ideas and possibilities, to establish common guidelines that avoid blocking decision-making and/or conflict escalation. This approach is all the more valuable the more issues of divergence on non-negotiable underlying values there are. It makes it possible to find convergences on other levels by improving ethical and intellectual coexistence.

In the USA it has been used by the Federal government since the 1990s (Negotiated Rulemaking Act 1990, Administrative Dispute Resolution Act 1996) for participated drafting of the implementing regulations of the most controversial laws. In South Africa it is used in trade union negotiations in very fragmented and complex productive sectors.

Creative confrontation includes a process of dialogue aimed at exploring interests underlying the various positions in order to build new proposals judged "best" by the largest possible number of participants; it involves a number of stakeholders able to represent all the concerns and points of view relating to the topic under discussion; it is led by a mediator and facilitator independent of the parties; it follows a structure agreed with the participants in which the objective of the dialogue and its rules are clarified and it aims to elaborate the guidelines of a "common project".

Examples of participatory creative confrontation processes adopted in Italy are: the former foundries in Modena (2007) and the "Cisternino" in Livorno (2008), the site for the Ponte Buggianese sewage treatment plant (2009-2010) and the site and technology for the TMB (Mechanical Biological Treatment) plant in Reggio Emilia (2011). In other cases, only some parts of the creative confrontation process have been adopted, for example the "No Dal Molin" negotiation in Vicenza (2006-2011) and the aforementioned Turin-Lyon Observatory (from 2006, ongoing).

9.2 Indications

In practical terms, the communication of hydrogeological aspects must be based on **indications drawn from the project**.

Results from the hydrogeological surveys highlight the probability of interfering with or impacting water resources of significant interest. It is therefore necessary to identify **methods of sharing hydrogeological design issues** with the different experts involved in the implementation of the project, at least by providing for a technical interface between hydrogeologists and engineers to jointly evaluate tunnel drainage methods and system types, for example.

Based on these indications, the content of the communication must come from the design team, which transmits it to the proponent and/or owner of the work. From here, communication must be directed towards responsible local bodies, the local water resource managers and population through the media, with different levels of technicality to meet the different competences of the public. This phase must be aimed at accurate **information on and perception of hydrogeological risk and impacts** on the water resource and on the ecosystems dependent on groundwater (GDE), as well as covering possible mitigation and enhancement.

Communication with those "external" to the design phase must take place within a **planned and coordinated process**, as for the examples in the previous Paragraph. An important issue in this sense is accessibility, open to all, through the organization and presentation of data of interest, for example through the web.

Communication must include a review of **opportunities for exploiting** the water drained from the tunnels and the real positive impact on the population, as far as possible accompanied by examples of similar achievements previously developed for other projects.

9.3 Work method

The framework of a communication activity in support of a public work, large or small, must include some preliminary aspects. These include **accurate identification of the stakeholders involved**, the analysis of their **influence** on the project (which will generate different approaches and require different tools and contents), the **definition of content** to communicate and its **scheduling** for specific times and, finally, the **channeling** of the content to the most suitable media format (local media, social media, direct newsletters).

This action, which requires specific professional skills, is all the more necessary since the environment (taken in its broadest sense) is an **area of conflict on multiple levels**, of polarized positions/difficulty in confronting different opinions. In this sense, communication awareness, direct and consistent with the decisions adopted, is an effective and irreplaceable deterrent to the emergence of opposition syndromes that risk creating a breakdown in social cohesion (as mentioned above with regard to the Turin-Lyon railway line).

Finally, it is always good practice to bear in mind the importance of **"non-technical" aspects**, which together with the more specifically technical ones, lie at the heart of communication. Non-technical aspects are essential, especially when (as in most cases) the target audience does not possess specific technical competences. Effective communication should not exclude such issues.

9.4 Stakeholders

Stakeholders are those who for various reasons are involved in or by the infrastructure. A fairly full list of the categories into which it is possible to divide them is as follows (although it is not uncommon for one stakeholder to fall into several categories simultaneously):

- citizens and public opinion;
- third party and control bodies;
- public and local committees;
- businesses;
- institutions;
- schools;
- environmental associations;
- scientists;
- new mediaforms;
- skeptics and antagonists.

Each of the previous categories requires a different approach, a specific language, and can be reached through different media. At the same time, not all the stakeholders listed above have the same importance (and influence) regarding the project. In other words, not everyone acts in the same way for or against the realization of the work. For this reason, once the reference stakeholders have been identified, they should be analyzed and the kind of influence/link they have with the work in question established.

On the basis of the criteria used, a diagram, shown in Figure 11, can be constructed that expresses stakeholder position regarding the project or work, which allows the following types to be differentiated:

Key stakeholder: the stakeholder on whom the main activities of analysis, communication and involvement must be concentrated. Strategy → manage carefully.

Secondary stakeholder: a stakeholder who can potentially become key but whose role is yet to be defined. Strategy → monitor and engage.

Influential stakeholder: has a strong influence on key players but does not show particular interest in the project because it is remote from his own field of activity. Strategy → increase interest.

Interested stakeholder: is not able to influence the key stakeholders but can provide knowledge, resources and useful ideas for the development of the project. Strategy → involve and listen to him/her.

Marginal stakeholder: to be taken into account but does not represent a determinant of the process. Strategy →monitor.

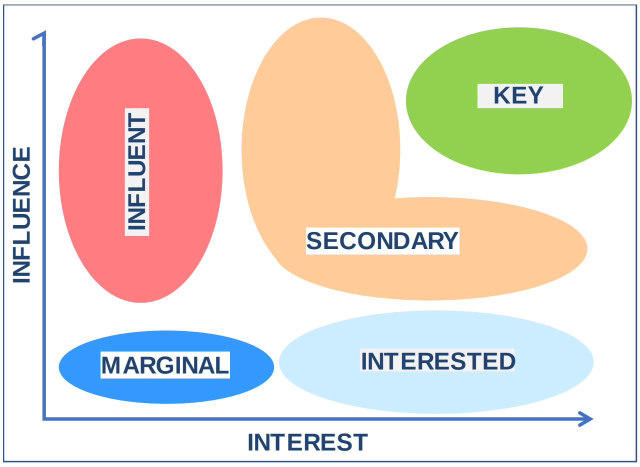

Fig. 11 - Stakeholder classification diagram according to the parameters "interest" and "influence".

9.5 What to communicate

We emphasized the importance of dealing with non-technical aspects within the communication flow as an essential part of engaging an audience that is not vertically competent on the effects of the work. Here it is useful to specify some **cornerstones of communication**. It must comply with certain criteria of clarity and accessibility to maximize stakeholder engagement. Too often, we have witnessed the use of difficult, ultra-technical terminology by the decision maker and the executor, at times even repelling users.

Good communication complies with the criteria of:

- clarity;
- transparency;
- simplicity;
- consistency (between what is said and what takes place);
- ability to give concrete examples.

This last point is particularly delicate, as one of the most frequently encountered defects in environmental communication today is that of generating distance (often unbridgeable) between the communication and the recipient's

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daily experiences. For example: describing the effects of climate change by showing images of the Arctic ice pack melting touches the emotions and captures the attention of the recipient of the message. But the exotic setting (and the remoteness of the scenario described from direct experience) are powerful deterrents to identification, and an ability to transform emotional involvement into actionable behavior. This communication is unable render a direct experience to the recipient of my message, so it does not generate resulting behavior in him. Therefore, the effectiveness of the communication has no value (at least partially) since it is limited to informing and not to getting the listener to adopt a position and a certain behavior.

Relating this example to the context of groundwater works (the subject of these guidelines), from the point of view of communication the effects that the work will have on the daily lives of our stakeholders, on their quality of life and the environment in which they reside, generate the most suitable message. By way of example, it can be explained how it will be ensured that there will be no water shortages, or that it will be possible to continue to enjoy river environments.

9.6 Good rules and practical advice: the toolkit

Experience (and successful cases of effective environmental communication) suggest some tricks that are valid for both online and offline communication. Good environmental communication tries to respect these precepts:

Avoid technicalities and incomprehensible initials. We can never repeat this enough: clarity is the first ingredient of the recipe.

Avoid shortcuts regarding 'image'. Green washing and phony comparative analyses are to be avoided. As are ignoring and omitting important elements of the process of building the work. Hoping that our stakeholders will not notice the "flaw" is counterproductive. Good environmental communication anticipates uncomfortable questions and does not bypass problems arising along the way.

Avoid sensationalism and exoticism. Media especially use ever more frequently topics and tones to trigger a negative emotional response. Or, as exemplified above with regard to the need to bring direct experience to life, they resort to distant scenarios, not relevant to everyday lives, capable only of creating further distancing with respect to the communication.

Interact with your stakeholders in order to understand them, satisfy them and at the same time make them responsible for shared commitments.

Adapt the 'tone of voice' and get to know the stakeholders' communication channel. It is above all companies and organized groups (with a complex structure) that struggle to communicate with their stakeholders (committees, associations, citizens). They fail to intercept their movements, are not able to respond in a timely manner to pressure/input (due to their typically complex structure). Spontaneous committees especially, which bring together the "no's" regarding the infrastructure in progress, move quickly on the network, communicate frequently in a typical tone and have a widespread base. Trying to reach these stakeholders by resorting solely to traditional communication based on press releases, conferences, billboards, risks being highly ineffective.

Give specific significance to relations with local communities while at the same time seizing opportunities offered by digital communications and social media to reduce distances and establish a channel for communication that is always active and monitored.

Failure to respect these simple precepts will result in a real risk of fueling a climate of mistrust and suspicion capable of nullifying all the environmental technical skills (and careful attention) adopted by many companies as well as local bodies.

10. REGULATIONS FOR THE MANAGEMENT OF WATER IN TUNNELS

Maria Governa, Luca Ranfagni

10.1 Environmental Impact Assessment and requirements

Tunnels generally fall within the category of projects for which an environmental assessment is required:

"Environmental assessment is a procedure that ensures that the environmental implications of decisions are taken into account before the decisions are made."(https://ec.europa.eu/environment/eia/index_en.htm)

In the case of the EU EIA Directive (2011/92/EU), tunnels are not specifically named. However, they generally fall within the category of projects for which an environmental assessment is mandatory (for example: lines for long-distance railway traffic; motorways and express roads; new road of four or more lanes; transfer of water resources between river basins).

Tunnels can also fall within projects for which the EU directive provides that *"Member States shall determine whether the project shall be made subject to an assessment {...}. Member States shall make that determination through: a case-by-case examination; or thresholds or criteria set by the Member State"*. Of these: *"Urban development projects, including car parks; Construction of railways and roads (not included in the previous list), Tramways, elevated and underground railways, Installations of long-distance aqueducts"*.

Tunnels are in any case mentioned in "Guidance on the preparation of the Environmental Impact Assessment Report" (European Commission, 2017), in chapter 3 *"review checklist"*, article 1.6 *"For linear Projects, have the route corridor, the vertical and horizontal alignment and any tunnelling and earthworks been described?"*.

Especially in the absence of regulations or guidelines on tunnel interference at national or local levels, and/or in the case of projects of a certain complexity, a preparatory check with the body that will authorize the work may be useful, in order to better target the contents of the study, in particular regarding the content and details of the definition of hydrogeological dynamics and interferences.

10.2 DPSIR model

The study of the interaction between a work and the environment determines the need to outline as complete a picture as possible of the state of the environment in the area in which the project is planned and, subsequently, to identify and evaluate the possibility that the project in question will generate negative effects capable of compromising the original environmental quality or public health.

The reference scheme generally adopted is that of the DPSIR model (Driving forces, Pressures, States, Impacts, Responses), proposed by the European Environment Agency (EEA) in 1995.

According to this model (Fig. 15), developments of an economic and social nature (*Determinants*) exert *Pressures*, which produce alterations on the quality and quantity (*State*) of the environment and natural resources. The alteration of environmental conditions determines *Impacts* on human health, ecosystems and the economy, which require *Responses* from society.

The contents of these guidelines basically follows this philosophy, apart from some differences in terminology. In underground works, the concept of "Pressure" coincides with that of "Source of Danger" described in Chap. 4. The impact "Indicators", defined in the same Paragraph, quantify the

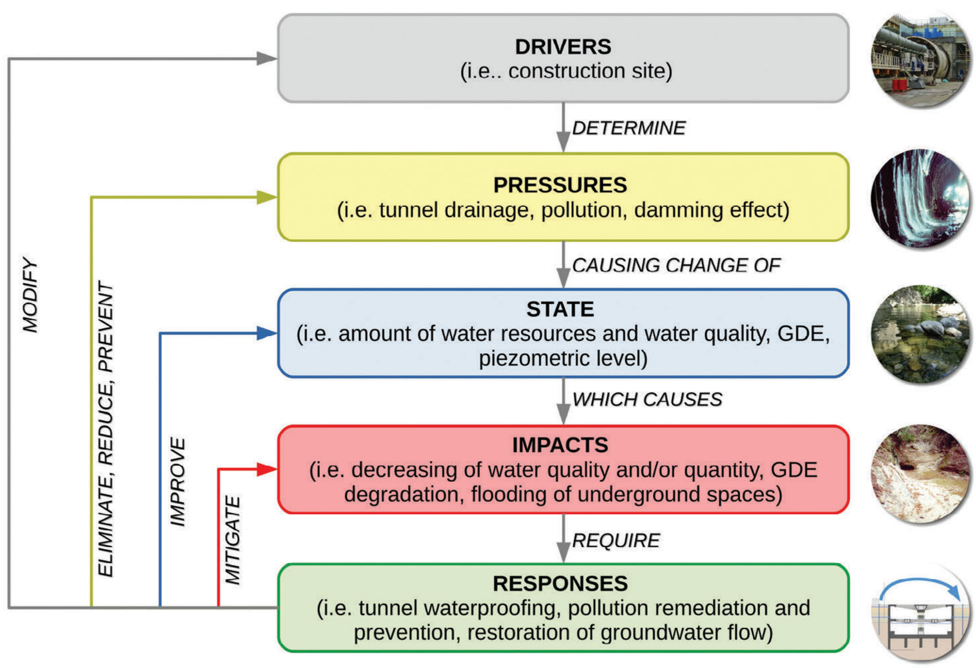

Fig. 12 - Example of DPSIR model application to the management of waters in tunnels.

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"State" of the environment, and consequently the presence or absence of an impact, and the effectiveness of the measures adopted (Response).

By way of example, the construction of a tunnel (*Driver*), can determine drainage (*Pressure*) with consequent lowering of the piezometric level (*State*) and subsequent drying of the source or well or watercourse (*Impact*), which can be mitigated by waterproofing the tunnel or compensated with other resources (*Response*).

As a result, monitoring is a fundamental and indispensable element in this process of analyzing the environment and evaluating the impacts of a work.

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Paragraph 11.1 reports the references cited in the text and paragraph 11.2 provides a collection of bibliographic suggestions on the topics covered, to which one or more numbers of chapters of the Guidelines are associated, to give a quick indication of the topics covered. Surely this is a non-exhaustive collection, but it is the result of the experience gained by the authors of the Guideline and can represent a good starting point for more targeted bibliographic research on specific topics.

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ABBREVIATIONS AND DEFINITIONS

The following abbreviations and definitions are used in the text.

AEA	European Environment Agency
ATS	Australasian Tunnelling Society
ARPA	Italian Regional Environmental Protection Agency
BEAM	Bore-tunnelling Electrical Ahead Monitoring
BHE	Borehole Heat Exchanger
BS	Bentonite Slurry
CA	Compressed Air
DF	Finite-Differences numerical model
DFN	Discrete Fracture Network
DHI	Drawdown Hazard Index
DPSIR	Determinants, Pressures, Status, Impacts, Responses
DQA	Water Framework Directive *(Direttiva Quadro sulle Acque)*
DSS	Decision Support System
EC50	Toxicity towards the crustacean Daphnia Magna according to OECD 202
EDF	Explicit Discrete Fracture
EIA	Environmental Impact Assessment
EPB	Earth Pressure Balance
EPM	Equivalent Porous Medium
FE	Finite-Elements numerical model
GDE	Groundwater Dependent Ecosystem
GESTAG	Sustainable Water Management in Tunnels Working Group
GFS	Groundwater Flow Systems
GIS	Geographic Information System
IAEA	International Association Environmental Agencies
IAH	International Association of Hydrogeologists
IPCC	Intergovernmental Panel on Climate Change
ISPRA	Italian Institute for Environmental Protection and Research *(Istituto Superiore per la Protezione e la Ricerca Ambientale)*
ISS	Italian Institute of Health *(Istituto Superiore di Sanità)*
ITA-AITES	International Tunneling and Underground Space Association
K	Hydraulic conductivity
LC50	Toxicity towards Danio Rerio fish according to the OECD 203
MATTM	Italian Ministry of the Environment, Land and Sea Protection *(Ministero dell'ambiente e della tutela del territorio e del mare)*
NWIS	National Water Information System
OCSE	Organization for Economic Cooperation and Development
PA	Public Administrations
PMA	Environmental Monitoring Plan *(Piano di Monitoraggio Ambientale)*
PP	Polypropilene
PVC-P	Polyvinyl chloride plasticized
REV	Representative Elementary Volume
RMR	Rock Mass Rating
RQD	Rock Quality Designation
SIA	Environmental Impact Study *(Studio di Impatto Ambientale)*
SNPA	Italian System for Environmental Protection *(Sistema Nazionale per le Protezione Ambientale)*
TBM	Tunnel Boring Machine
TH	Thermo-Hydraulic
THM	Thermo-Hydro-Mechanical
TRT	Thermal Response Test
USGS	United States Geological Service
VAS	Strategic Environmental Assessment *(Valutazione Ambientale Strategica)*
VIA	Environmental Impact Assessment *(Valutazione di Impatto Ambientale)*
WFD	Water Frame Directive