Tunnelling and groundwater interaction: the role of the hydrogeological monitoring

Tunnelling and groundwater interaction: the role of the hydrogeological monitoring

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The interaction between tunnelling and groundwater is an important factor to be considered in any underground work. Groundwater can represent a major constraint for many technical decisions related to the tunnel construction and, at the same time, a fundamental valuable natural resource to be preserved quantitatively and qualitatively during and after the tunnel completion. The knowledge of the geological subsurface conditions, the hydrogeological mechanisms of groundwater infiltration and circulation, the degree of the aquifers connection with the river network as well as the chemical composition of the circulating groundwater are some of the more important topics that should be analysed in the early phase of the tunnel design. Moreover the numerical modelling of the tunnel-groundwater system requires a large amount of suitable data derived by field investigation. The hydrogeological monitoring represents a fundamental tool for the tunnel design, construction and functioning and has to be developed in a program which includes surface and subsurface data in an integrated geo-referred way. The system needs the continuous uploading of the environmental data coming form the tunnel and the surface environment in order to check the short and long-term interactions, verify the modelling hypothesis and monitor the dynamic behaviour of the whole system and the compliance with the local environmental regulations.
Keywords: *tunneling, groundwater, monitoring.*

Interazione tra acque sotterranee e gallerie: il ruolo del monitoraggio idrogeologico. *Tra le principali problematiche che devono essere analizzate nella realizzazione di un'opera in sotterraneo vi è l'interferenza con i sistemi acquiferi. Le acque sotterranee possono condizionare notevolmente le scelte tecnologiche nella costruzione di un tunnel e costituiscono contemporaneamente una fondamentale risorsa naturale che deve essere preservata quantitativamente e qualitativamente durante l'esecuzione dei lavori e dopo il completamento dell'opera.*
La conoscenza geologica del sottosuolo, i meccanismi di infiltrazione e di circolazione delle acque sotterranee nell'ammasso roccioso, il grado di connessione tra l'acquifero e la rete idrica superficiale così come la composizione chimica delle acque sotterranee sono alcuni degli elementi più importanti che devono essere analizzati sin dalla prima fase del progetto. Anche la modellazione numerica del sistema acquifero-tunnel necessita per definizione di una grande quantità di dati derivanti dal monitoraggio delle variabili ambientali. In questo quadro, il monitoraggio idrogeologico rappresenta uno strumento fondamentale per la progettazione e la realizzazione del tunnel: il sistema deve essere capace di integrare in modo georiferito dati provenienti dalla galleria e dall'ambiente esterno in modo dinamico e deve permettere un continuo aggiornamento dei dati ambientali. Tale aggiornamento permette infatti la verifica delle interazioni tra acquifero e tunnel sia a breve che a lungo termine.
Parole chiave: *gallerie, acque sotterranee, monitoraggio.*

L'interaction entre les galeries et les eaux souteraines: le rôle de la surveillance des eaux souteraines. *L'interaction entre les galeries et les eaux souterraines est un facteur important à considérer dans tout les travaux souterrain. L'eau souterraine peut représenter une contrainte majeure pour nombreuses techniques liées à la construction du tunnel et, dans le même temps, une ressource naturelle précieuse fondamentale à être préservé, quantitativement et qualitativement, pendant et après l'achèvement du tunnel. La connaissance des conditions souterraines géologiques, les mécanismes hydrogéologiques de infiltration des eaux souterraines et leur circulation, le degré de la connexion des aquifères avec le réseau des rivières, ainsi que la composition chimique de l'eau souterraine circulant, sont certains des sujets les plus importants qui devraient être analysés dans la phase précoce de la conception du tunnel. En outre, la modélisation numérique du système eaux souterraines-tunnel nécessite grande quantité de données dérivés par une surveillance des variables environnementales. Le suivi hydrogéologique représente un outil fondamental pour la conception, la construction et le fonctionnement du tunnel. Le système a besoin de mise à jour des données provenant du tunnel et de l'environnement de surface afin de vérifier les interactions à court et à long terme, vérifier l'hypothèse de modélisation, surveiller le comportement dynamique de l'ensemble du système et le respect de règlements locaux de l'environnement.*
Mots-clés: *tunnels, eaux souterraines, surveillance.*

1. Introduction

Underground works involve the resolution of technical problems whose complexity depends on the geological and environmental context. International experience (Gattinoni *et al.*, 2012) has proved that the occurrence of an "unforeseen geologic event" can produce a relevant increase in time and costs, in the order of 30% of the whole tunnel cost.

The interaction between tunneling and groundwater is a very relevant problem not only due to the need to safeguard water resources from impoverishment and pollution risk, but also to guarantee the safety of workers during the construction, the long-term stability of the underground works and the effectiveness of the draining towards the external environment after the tunnel construction. In the tunneling activities groundwater should be therefore considered at the same time a natural valuable asset to be defended and a source of risk to be prevented during the underground construction works (fig. 1).

Moreover the dynamic interaction between the surface water and groundwater should be considered and analyzed to prevent alterations of natural eco-systems which are related to surface water environment due to the excavations works (fig. 2).

An example can be represented by Mompantero tunnel, part of the highway linking Turin (Italy) to Frejus Tunnel (France). According to Cresco A. *et al*ii (1992), during the excavation un unexpected problem occurred when a tectonic lineament,

IMPACT ON	EFFECTS	ACTIONS		
		Design	Construction	Operating
WATER	**POLLUTION** (physical, chemical, biological) -direct - groundwater interconnection		-mud treatment -pollutants control -decontamination and cleaning water	
	GROUNDWATER FLOW OBSTACLE (dam effects)			-under and upper special ways of longitudinal flow
	DRAINAGE -breakage to the hydraulic systems -groundwater lowering -drying up springs and wells -water flow in surface pauperization -hydrotermal cycles disturbance	-ground tinning	-digging techniques adoption for the water control -temporary alternative supply	-ground tinning -permanent alternative supply -water preservation and transport outside
EXCAVATION	**WORK INCONVENIENCE**		-drainage -local protection	
	FLOODING	-portal location and protection		
			-counterslope excavation	
	INFLOW OF PARTICLES SOLID AND CHEMICAL AND PHYSICAL DEPOSITS		-surveys and drainages	-adequate drainage of the impermeabilization system
	EXCAVATION INSTABILITY (front and walls) **EARTH PRESSURE** **COLLAPSES** **SOIL WEATHERING**		-drainage -active drainage -groundwater lowering through extraction wells	-adequate permanent supports
	WATER LEVEL		-pre-consolidation grouting -water table lowering through pumping wells and drainage	
	WATER HEAD ON THE LINING			-drainage -adequate structures
	EXCAVATION TEMPERATURE (cold-hot)		-drainage -insulated pipes	
	KARST		-progress investigations	-avoid extrados circulation -monitoring
	DRAIN		-drainage grooves	
	CONCRETE AGEING -chemical and aggressive water		-water chemical verification	-waterproofing -special cements and concretes

Fig. 1. Water-excavation interaction: consequences and related actions (updated after Pelizza 1999).
Interazione fra acqua ed opere in sotterraneo: impatti e relative azioni (aggiornato dopo Pellizza 1999).

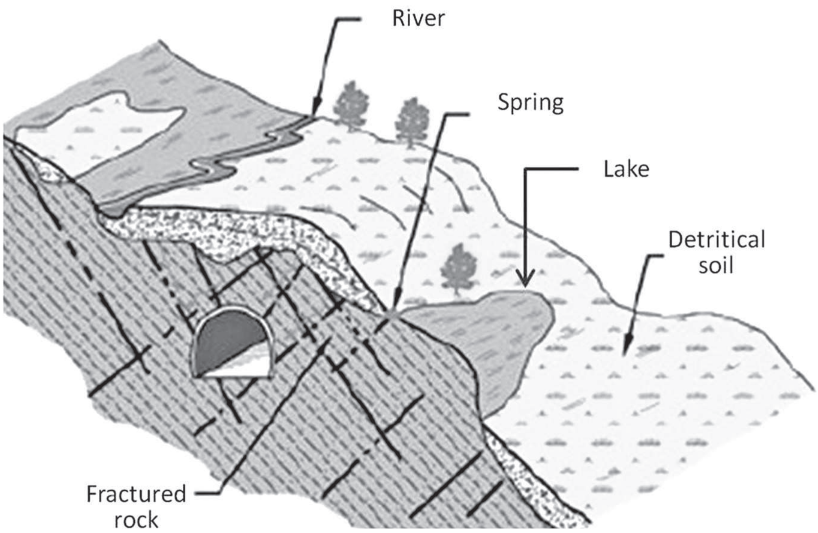

Fig. 2. Conceptual scheme of the potential interaction between a tunnel and the aquifers (Gattinoni, *et al.*, 2014).
Schema concettuale delle potenziali interazioni tra gallerie e acquiferi.

associated with a paleo creek was intercepted just below Mompantero village. This finding coincided with a drastic reduction of the self-supporting capability of the excavation face and the collapse of several tens of cubic meters of alluvial and glacial deposits with heavy inflow of water. This heavy water inflow was also associated with hydrologic changes that occurred on the surface, namely reduced flow in Giandula stream and near drying-up of the "Fontana Maria"spring which was the main source of water supply to all the surrounding villages. It was obviously necessary to proceed with water proofing of the ground around the tunnel with chemical injections, to gradually recover the original hydro-

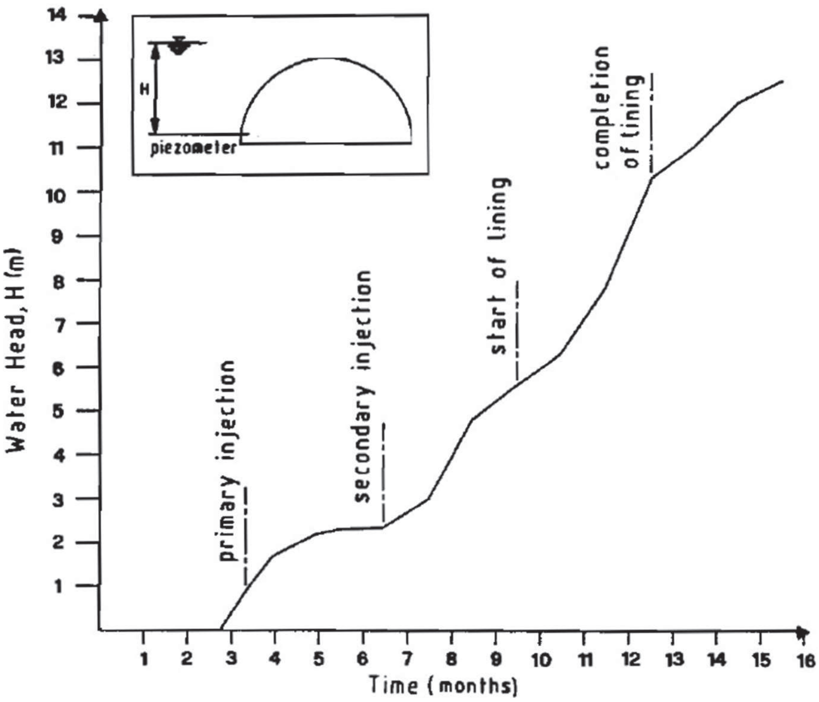

Fig. 3. Results of water proofing on water level, monitored by piezometer during tunnel construction (Crespo 1992).
Risultati dell'impermeabilizzazione sul livello di falda, monitorato tramite piezometri durante lo scavo di una galleria (Crespo 1992).

geological conditions. The gradually recovery of the original water level, measured by piezometric monitoring, was achieved in two steps of injection and finally with the concrete lining of the tunnel (fig. 3).

In any case, the relationships between water and tunneling have to be assessed and controlled through suitable monitoring activities. A complete program of groundwater monitoring should be designed as a fundamental component of the tunnel project and a relevant effort in the design phases has to be definite also in terms of financials in order to assess the short and long-term effects of tunneling on the natural undisturbed groundwater subsurface environment.

In this paper we highlight the necessity to consider the surface and groundwater monitoring programs as a fundamental task of the whole process of the tunneling activity. In detailed we discuss about the need to design a comprehensive monitoring program that should be developed in the design, construction and operating phases of the tunnels considering the groundwater as a natural valuable resource to be preserved and, at the same time, as a source of potential risk for the construction, maintenance and operation of tunnels.

2. Tunneling and Water Monitoring

Today, the cost of delays and impact compensations that may result from inadequate understanding of the environment, fully justify investigating and evaluating the conditions, as well as establishing a monitoring system to measure possible impacts. The most effective response to environmental concerns is based on an understanding of the respective environment, accompanied by adequate supporting data.

Cotecchia V. (1993) suggests how investigating and evaluating geological and hydrogeological conditions during the phase design of a tunnel construction can, in some cases, turn a difficult situation in a opportunity to be seized. An example is represented by Monte La Mula Tunnel – Cosenza , where the draining effect of the tunnel was not mitigated but used to collect several springs characterized by a flow rate too small to be exploited by direct capitation. This water has in fact been utilized for the water supply of Provincia di Cosenza.

The approach begins with developing a good understanding of the water resources, collecting a database with which to establish the hydrologic characteristics before the construction, and early establishment of a resource monitoring program. With this completed prior to construction, the resource monitoring program can be organized to provide early detection of an impact during construction (Premadasa *et al.*, 2006).

The monitoring program must begin before the opening of the tunnel and must continue after the end of the construction. In the tunneling activities we can distinguish three important phases:

– design
– construction
– operating (post-construction)

A suitable surface and groundwater monitoring program should include in any phase the study of wells, springs, and streams in the project area that might be affected by the construction of the tunnel. The monitoring program should consider not only the surface area which overlays the tunnel track but also the suitable external water monitoring points that can be considered as a useful control of undisturbed conditions (Nebbia *et al.*, 2006). In fact, especially for deep tunnels, the long-term phenomena which characterize the groundwater infiltration and flow can be developed very slowly and at a great distance from the area interested by the excavation, and therefore cannot immediately be detected during the normal hydrogeological investigation in the proximity of the tunnel.

Monitoring and conservation of water quality is an important goal both during and after the construction phase. Contamination may occur in the construction phase as well as in the operation phase. In the construction phase, pollution could result from acidic rocks, nitrogen from rubble, particle runoff and spills of fuel or chemicals. In the operation phase the watercourses may be affected by traffic-polluted runoff water and emissions from road accidents. In the last few years some topic as tunnel washing and its effect on water quality (Stotz and Holldorb, 2008) have gained in importance.

Understanding the interaction between groundwater and surface water can be important for water resources management, and in the determination of migration pathways for contaminants. The degree of interaction can depend on a number of factors including topography, underlying geology, subsurface hydraulic properties, temporal variation in precipitation, and local groundwater flow patterns (Cey *et al.*, 1998). Seepage meters and mini-piezometers are simple devices that allow for the collection of hydraulic data directly from the streambed (Lee, 1978;). Minipiezometers provide information on the hydraulic gradient, while seepage meters allow for the direct measurement of seepage flux between the groundwater system and the overlying surface water. Both instruments provide a means for collecting samples for electrical conductivity and isotopic analysis. (Oxtobee *et al.*, 2002). For this purpose tracer test could be also useful. In many study areas, groundwater displays a distinctive isotopic signature compared to surface water (Jacobson *et al.*, 1991).The tracer tests can also provide data on ground-surface water interaction but also data on flow and transport parameter. Finally stream discharge measurements are also useful to identify areas of large-scale water loss, or gain within the area of interest.

2.1 Design phase monitoring

The first task of the monitoring program is to collect preconstruction data on the resource features of the area and on hydrologic control variables that are independent of any impact by underground excavation (Premadasa *et al.*, 2006).

Correlations established between these data will be the reference ("baseline" conditions) for determining seasonal and annual fluctuations unaffected by construction activities.

Because of this, effective detection of impacts cannot be made by comparing measurements during construction to a reference simply expressed as average conditions, or even as average seasonal conditions. The correlation under baseline conditions needs to provide a measure of the response of features to natural climatic fluctuations. (Premadasa *et al.*, 2006).

Typically, the data show seasonal and yearly fluctuations and the monitoring times are often very long to evaluate environment and hydrogeological impacts in very long term.

The purpose of the prognosis includes gaining an understanding of the hydrogeological situation of the entire rock mass covered by the works, in order to foresee both problems that may arise during construction due to the presence of water and also the possible effects that excavations may have on the important water resource that is tapped from the tunnel below (Banzato *et al.*, 2011).

According to Gargini *et al.*, (2008) hydrologic recession analysis of undisturbed conditions is a key tool in studying aquifer hydrogeology, allow the discrimination of groundwater flow systems (GFS), the estimation of recharge relative to the upstream reach portion and the identification of springs most vulnerable to tunnel drainage impacts. Using data flow monitoring it possible to evaluate the vulnerability of different springs (Civita 2008). Meteoric precipitation is another fundamental parameter that has to be considered. Additionally, in mountainous areas where winter precipitation is usually present as snowfall, the temporary delay between precipitation and infiltration, due to the amount of time taken for snow to melt in the spring season, can further complicate predictions of the dynamics of water infiltration (Lo Russo *et al.*, 2013).

2.2 Construction phase monitoring

The means and speed with which a construction-related impact could be detected is largely governed by the magnitude of the impact. Detecting possible impacts begins by defining baseline conditions, with statistical correlations between the resource features and the control variables, using the preconstruction data. Periodic monitoring of the resource

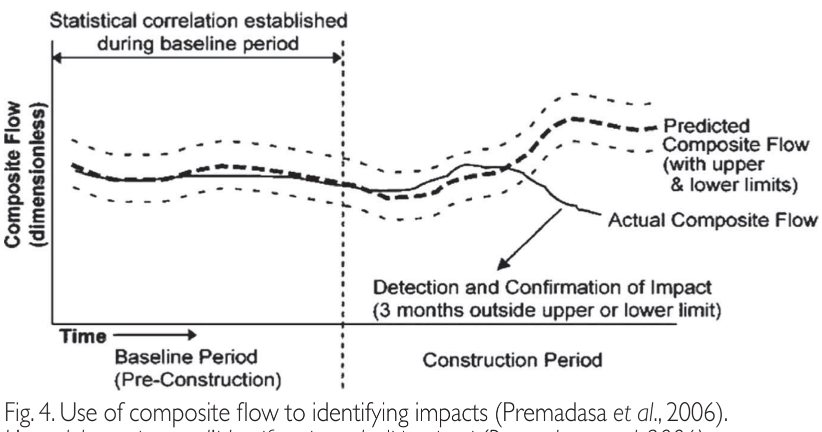

Fig. 4. Use of composite flow to identifying impacts (Premadasa *et al.*, 2006).
L'uso del grouting per l'identificazione degli impianti (Premadasa et al. 2006)

features during construction is then evaluated against that correlation, and if the measurements indicate fluctuations beyond what can be attributed to "normal" conditions, an alert is established, and related features are more closely monitored to confirm whether or not remediation is justified. (Premadasa *et al.*, 2006).

The monitoring during construction phase should involves not only springs, wells and streams but also water inlets in the tunnel. Inlets discharge measures at the face during the excavation and measures of the total discharge at the tunnel outlets should be provided.

Multi-tracer test inside the tunnels can be also useful to assess the main groundwater-water inlet or stream-water inlets connection.

2.3 Post-construction phase monitoring

Tunnels, although being built, may drain groundwater even after completion of their lining. In some instances, it is extremely difficult or impracticable to restore the original hydrodynamic equilibrium, with consequent risks of exhaustion of springs, change in the relations with adjacent hydrogeological structures, depletion of groundwater reserves and streams, appearance of inrush events, risks of exhaustion of wells, etc. For these reasons it is appropriate to apply a monitoring inside tunnel and external tunnel for a long period (tab. 1).

The monitoring data should be collected and integrated in a whole geo-referred database system in order

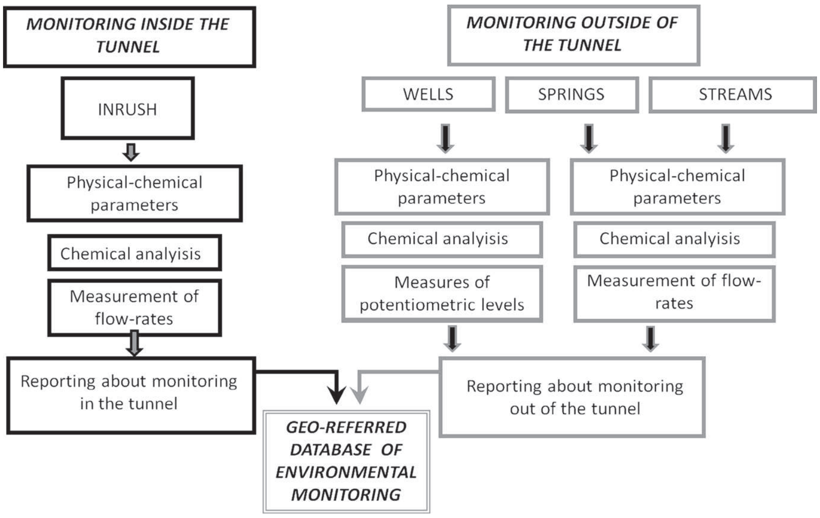

Fig. 5. Monitoring activities flow-chart. The scheme resumes the whole activities that should be developed in order to design a suitable monitoring program in the tunneling activity. Data should be collected and integrated in a geo-referred database. The continuous uploading permit to control in a dynamic way the different parameters and their evolution during time.
Schema di flusso delle attività di monitoraggio. Lo schema riassume tutte le attività necessarie per un programma di monitoraggio efficace durante le diverse fasi di realizzazione di un'opera in sotterraneo. I dati dovrebbero essere raccolti ed integrati in un database georiferito. L'aggiornamento in continuo dei dati permette il controllo dinamico dei diversi parametri e della loro evoluzione nel tempo.

Tab. 1. Monitoring activities that can be developed in relationship with different phases of the tunnel construction.
Le possibili attività di monitoraggio da sviluppare in relazione alle diverse fasi di costruzione della galleria.

	Monitoring Activity	Design	Construction	Post-Construction
Springs	Temperature, electrical conductivity, discharge rate and chemical testing; starting long time before design phase	x	x	x
Wells	Temperature, electrical conductivity, potentiometric level and chemical testing	x	x	x
Surface canal and rivers	Temperature, electrical conductivity, flow-rate and chemical testing	x	x	x
Main discharge outflow from the tunnel	Temperature, electrical conductivity, flow-rate and chemical analysis according to uses and quality local regulations. Presence of pollutants related to excavation machines (lubricating oil; fuel) and the excavation resulting in water lowering		x	x
Main inrush in the tunnel	Temperature, electrical conductivity, flow-rate and chemical testing		x	
Aggressive waters and interaction with the construction materials	Chemical analysis	x	x	x
Land subsidence and local ground movement	Control of ground movement by traditional topographic monitoring or automatic multipurpose stations (autolevel stations and/or precise leveling stations and/or SAR)	x	x	x

to facilitate the correlations between the different parameters of the tunnel-ground system, their time evolution during the construction and operating phase and, if necessary, in order to establish protocols of intervention in case of environmental risks.

3. Monitoring and numerical modelling

Most of the modern tunneling activities developed an early-stage design numerical modelling in order to determine the potential interferences between the underground works and the aquifers. Commercial finite differences and/or finite elements numerical models such as MODFLOW (Mc Donald and Harbaugh, 2005) and FEFLOW (Diersch, 2010) respectively, are usually employed in order to assess the interferences between the aquifers and the tunnel especially for the porous media and also to predict the magnitude of the perturbation induced by the excavation works respect the undisturbed groundwater conditions. It is intuitive that in this modelling activity the monitoring data can assume a fundamental importance. In fact, the numerical modelling of groundwater systems usually follows a well-defined procedure through a series of interdependent stages with frequent feedback loops to earlier stages (fig. 6).

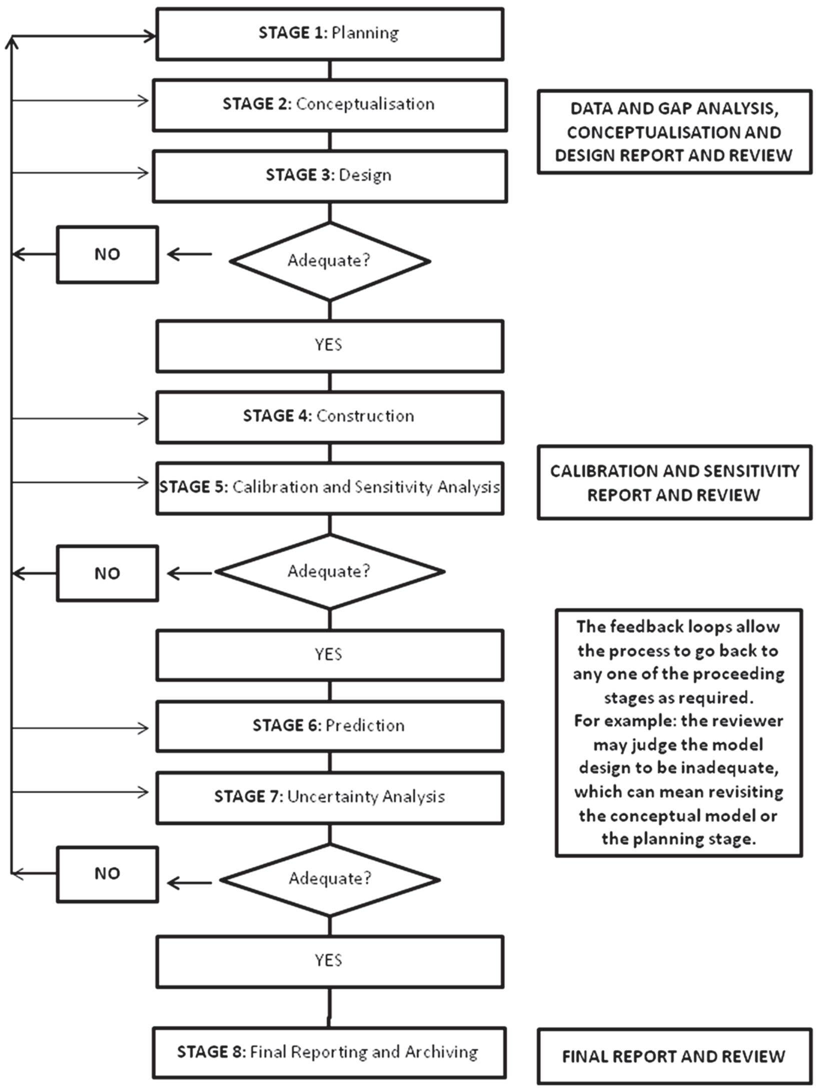

Fig. 6. Groundwater modeling process (modified after Barnett *et al.*, 2012).
Fasi per la modellazione di acque sotterranee (modificato dopo Barnett et al., 2012).

In the planning stage the modelers and key stakeholders should agree on various aspects of the model and the process leading to its development. The classification is a benchmark that illustrates the level of confidence in the model predictions and generally reflects the level of data available to support model development, the calibration process and the manner in which the predictions are formulated.

Conceptualization involves identifying and describing the processes that control or influence the movement and storage of groundwater and solutes in the hydrogeological system. In this regard it provides information on how the project is expected to impact on the groundwater and the surface water bodies that depend on groundwater. The conceptual model must explain (qualitatively and quantitatively) all observed groundwater behavior in the region. The design and construction stage involves a series of decisions on how to best implement the conceptualization in a mathematical and numerical modeling environment. The decisions required at this stage include selection of a numerical method and modeling software, selection of an appropriate model dimension, definition of a model domain and the spatial and temporal discretization to be used in the model.

Model calibration involves an iterative process to estimate parameters describing hydrogeological properties and boundary conditions so that the model's results closely match historical observations Predictive scenarios are designed to answer the questions posed in the modeling objectives. Because models simplify reality, their outputs are uncertain. Model outputs presented to decision-makers should include estimates of the goodness or uncertainty of the results. Model reporting encompasses documentation and communication of different stages of the model through a written technical document. The report should describe the model, all data collected and information created through the modeling process. The report should be accompanied by an archive of all the model files and all supporting data so the results presented in the report can, if necessary, be reproduced and the model used in future studies. Modeling of surface water–groundwater interaction requires knowledge of groundwater modeling, and an understanding of the exchange processes that occur between surface water and groundwater. The water monitoring activities can interact with the modelling phases providing useful data able to define a correct conceptual model and/or to help in the calibration. Therefore it is fundamental that the monitoring program design has to be developed in a close connection with the numerical modelling phases and, if necessary, adapted to the modelling requirements.

4. Water legislative framework

Some of the most commonly occurring contaminants in water are heavy metals, whose toxic behavior has been documented in many works (Kabata-Pendias and Mukherjee 2007). Low contents of metals such as Cd, Cr, Cu, Ni, Pb, Zn, Fe, and Mn are also required for suitable drinking water or for other uses. Hence, the concentrations of these metals is taken into account in most national and international water quality norms. Therefore the surface and groundwater chemical and physical parameters that have to be controlled through the monitoring around the tunnel construction, should be selected not only considering the soundness with the need to understand the impact of the tunnel on the hydrologic system, but also in order to guarantee the compliance with the local legislative framework. One of the key element of a suitable monitoring program is therefore related to the compliance of the controls with the (local) legislative framework. Such regulations can vary worldwide and during time. In general however the water regulations that should be verified and included in a monitoring program are related to:

– Quality parameters of water intended for human consumption (when the groundwater drained outside by the tunnel is used for the human supply and when the tunnel modifies the undisturbed conditions of some existing human water supply spring or well)
– Protection of water resources and eco-systems which are dependent by the water resources (regulations related to the surface and groundwater planning actions)
– Static protection of drinking water resources (wellhead and spring protection areas)
– Wastewater discharges (when the water drained outside by the tunnel is discharged in the natural environment)
– Mineral and thermal water (quality of water and temperature)

5. Conclusions

The main problems to be solved for any underground works is the interaction between groundwater system and tunneling. The hydrogeological monitoring, correctly designed, is a fundamental tool that consent to predict the potential interferences and thus to protect both the excavation and the water resource. Moreover a suitable monitoring program provides useful information to understand the short and long-term interferences between underground works, the aquifers and the interconnected surface eco-systems during the construction and operating phases.

It is important to emphasize that the hydrodynamic characteristics of aquifers and springs must be monitored from at least one year or more seasonal cycles before the beginning of the construction phase.

The modern automatic acquisition sensors helps to design a comprehensive monitoring network and facilitate the construction of a geo-referred database able to collect in a continuous way any interesting environmental data deriving from the tunnel and from outside. Such data are also fundamental to calibrate in real time the numerical modelling predictions and permit to verify the soundness of the model compliance with the physical hydrogeological reality

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