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Determination of the sustainable yield of tunnel water inflows for a hydrogeological and environmental sensitive metacarbonatic succession at the Brenner Base Tunnel – Italy/Austria

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Crossing hydrogeological and ecological sensitive aquifers, water ingress can occur, which can lead to irreversible damage to hydrogeological and ecological systems. In order to avoid this, the rock mass surrounding these hydrogeological sensitive tunnel sections is sealed by injections to reduce the hydraulic permeability, the water inflows and consequently the regional water level drawdowns. In deep tunnels, complete sealing is not possible due to the high water pressures. Residual water volumes will continue to enter the tunnel. The magnitude of these water inflows must be such that irreversible damage to the systems does not occur. These allowed water inputs inflows are called sustainable yield. The aim of the article is to explain the concept and determination of sustainable yield for a sensitive aquifer, the Hochstegen marble, in the Brenner Base Tunnel project. After determining the water resources and their complex relationships, calibrated, regional and local hydrogeological numerical models are used. The analysis shows that water inlets in order of 35 l/s lead to regional water level drawdowns in the shallow aquifers hydrogeological and ecological still acceptable.

Keywords: *tunnel, water inflow, hydrogeological numerical model, cone of depression, impact.*

1. Introduction

Tunnel water inflows can cause impacts on hydrogeological systems relevant for the water resources and the environment (Loew at al. 2007, Gargini *et al*. 2008, Kværner and Snilsberg 2008, Kværner and Snilsberg (2013). These impacts can appear in very short times, attributed to early transient water inflows, or late, when tunnel water inflows reach stationary conditions and the cone of depression its maximum extension.

Therefore in hydrogeological and environmental sensitive project areas a control of tunnel water inflows is necessary to avoid these impacts. Usually, these controls are performed by applying permeability reduction techniques to the rock mass surrounding the tunnel, based on high pressure injections of different materials, mostly cements. In deep tunnel systems these injections have to be executed from the tunnel face inside sub-horizontal boreholes, due to the high overburden. But since in these tunnels prevail high natural water pressures a complete impermeabilization of the rock mass is not possible. Even after intense injection measures a certain amount of water still flows into the tunnel. This amount of tunnel water inflows should have such magnitudes, which not cause irreversible impacts on water resources and the environment. Therefore a sustainable yield of tunnel water inflows has to be defined before crossing the sensitive aquifer.

For the Brenner Base Tunnel this concept of sustainable yield for tunnel water inflows for avoiding impacts to the hydrogeological and environmental system was developed and followed during different project stages. In the environmental impact assessment (EIA) stage, hydrogeologists evaluated in cooperation with environment specialists sensitive areas, usually wetland areas. One of these wetland areas is the Valsertal biotope, which is also classified as a protected Nature 2000 area in the central section of the Brenner Base Tunnel project. In this area the flora and fauna depend on water resources stored in porous aquifers of Quaternary deposits located in alpine valleys and with shallow lying groundwater tables. These porous aquifers are hydraulically connected to metacarbonatic rock aquifers in mountainous regime.

These hard rock aquifers are referred to the so called Subpenninic unit with the Hochstegen Marble as the main lithology and has to be crossed by the deep lying tunnel system. To avoid undesired impacts in this sensitive area a maximum of drawdown of the water table in these shallow lying soft rock aquifers was defined on the base of ecological judgement during the EIA. In this specific case the maximum allowed drawdown of the shallow-lying groundwater table was quantitatively fixed at 30cm from the natural minimum water level measured in the last 20 years. A higher drawdown of the groundwater levels would be considered dangerous for the protected fauna as the roots of these sensitive plants wouldn't reach the water table.

Due to the time scale of the construction of the long tunnel system it was finally possible to carry out detailed and time consuming hydrogeological investigations in this specific project area with the aim to determine the amount of tunnel water inflows without hydrogeological and environmental impacts, the so called sustainable yield of tunnel water inflows.

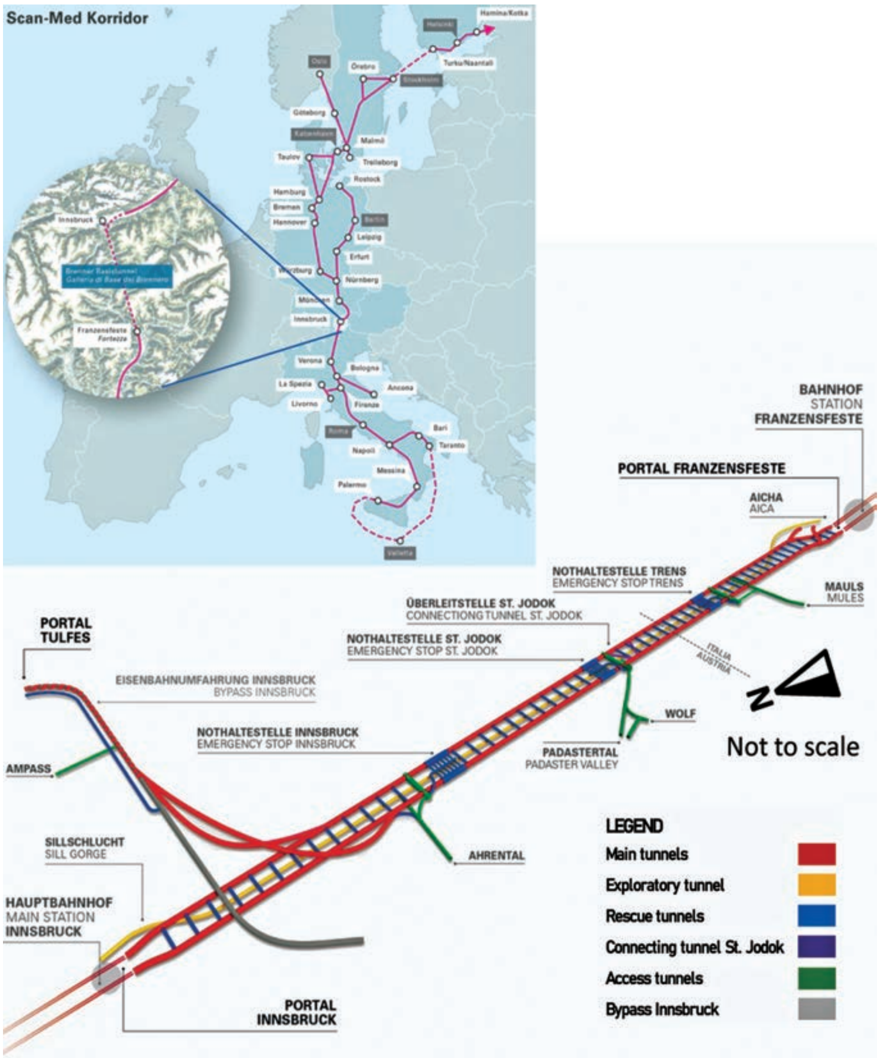

Fig. 1a – The Brenner Base Tunnel (BBT) system as a part of the transnational European Main Corridor Scandinavia (Helsinki) to Mediterranean (Valletta), called TEN-Korridor SCAN-MED. Additional project details are available on www.bbt-se.com.

2. The tunnel project and the specific project area

2.1. The Brenner Base Tunnel project

The Brenner Base Tunnel (BBT) is a 55 km long railway tunnel through the Alps connecting Innsbruck (Austria) to the North with Franzensfeste-Fortezza (Italy) to the South. The complex tunnel system as shown in Fig. 1a has a total tunnel length of 230 km. The standard cross section of the BBT consists of two main railway tunnels and a central lying exploratory tunnel situated 12 m deeper than the main tunnels. In addition, four access tunnels and several logistical tunnels have already been built for the construction and the operation phase. Starting the excavation on the Italian side in 2007 and on the Austrian side in 2010, approximately 154 km of the total 230 km long tunnel system have already been excavated at December 2022 (Fig. 1b).

2.2. The Hochstegen zone

The Hochstegen zone is a mountainous, transboundary area close to the Brenner pass, where the metacarbonatic rocks, the so called Hochstegen marbles, are exposed at the surface. The western boundary of the study area is the central section of the North-South trending main valley, the Wipptal valley, to the North and South of the Brenner pass (1.370 m). The Brenner Pass is a natural water divide and the main rivers originate in this area: the Sill on the Austrian side and the Eisack – Isarco on the Italian side. The northern and southern boundaries are East – West trending lateral valleys of the main Wipptal valley: the Valsertal valley (approximately 1.100 m in the West and 1.400 m to the East) to the North and the Pfitsch-Val di Vizze valley (approximately 950 m to the West and 1.450

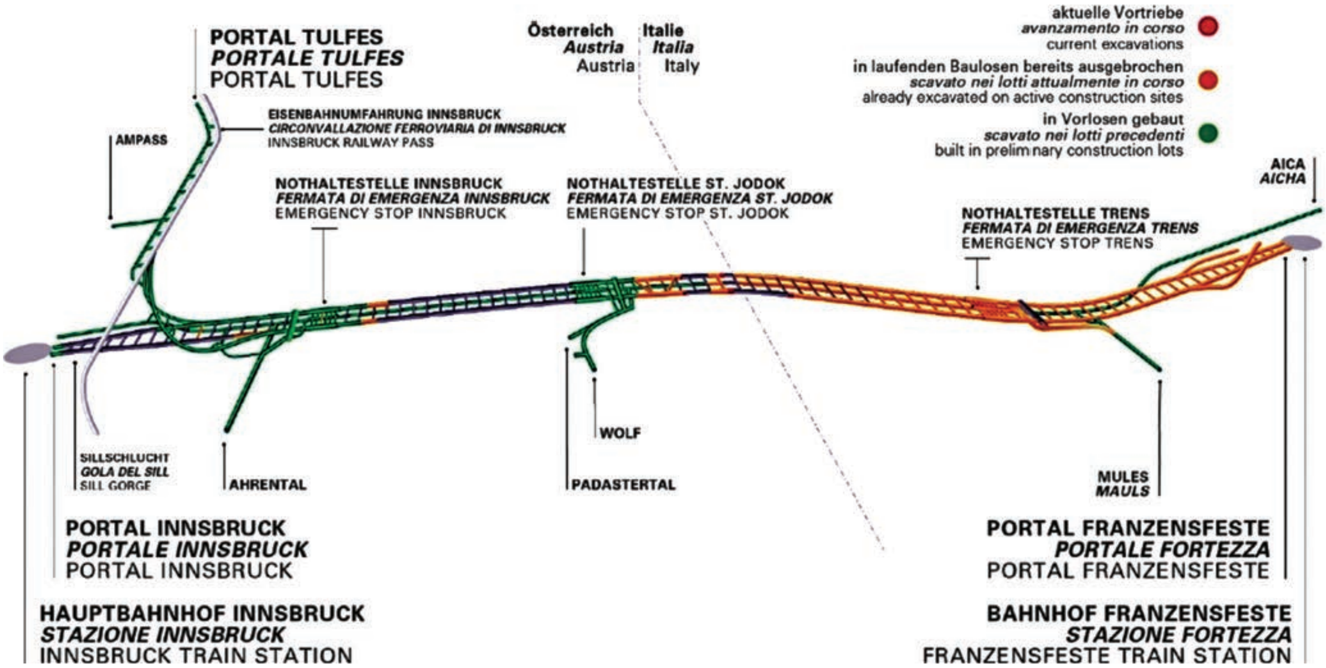

Fig. 1b – The status of excavation works (project status December 2022).

m to the East) to the South. These valleys are surrounded by mountains reaching altitudes between 2.000 to 3.500 m. The eastern boundary corresponds to the eastern outcrop line of the Hochstegen Marbles, in detail the contact between the Hochstegen Marbles at the top and the Central Gneiss at the basis.

The annual mean precipitation varies from 1.000 mm to 1.800 mm, depending from the topography. Several rivers drain the study area, the Sill (to the North) and the Eisack-Isarco (to the South) in the Wipptal valley. The river Valserbach drain the valley Valsertal and the river Pfitschbach – Rio Val di Vizze flows in the valley Pfitschtal-Val di Vizze. In the centre of the study area flows from East to West the river Vennbach, which is the main water resource for the lake Brenner See, lying in the main valley close to the Brenner Pass. Snow melting from April to June represents the main groundwater recharge period for the different aquifers, but even some precipitation events in the summer and autumn contribute to groundwater recharge.

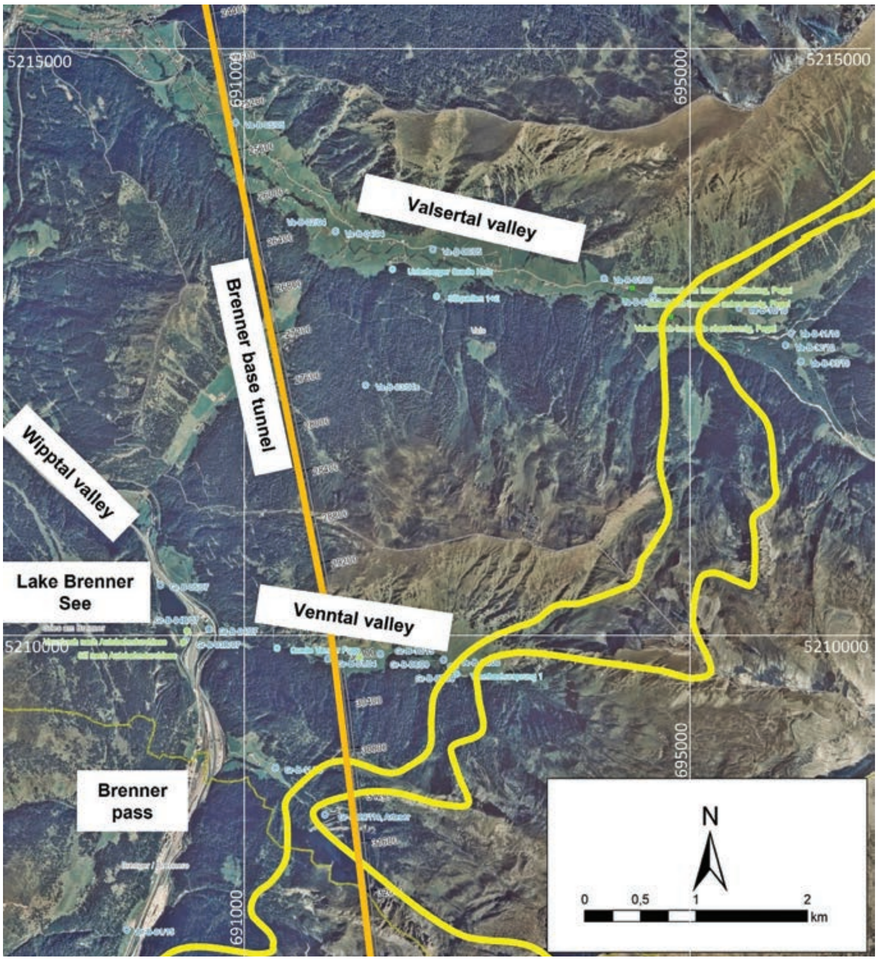

Fig. 2 – Orthophoto of the study area Hochstegen zone with the main, North South trending valley Wipptal to the west and the East-West trending, lateral valleys Valsertal and Venntal. The white line is the Circumference of the Hochstegen marble exposed at the surface (coordinates WGS1984 UTM32N).

3. Geology of the Hochstegen zone

3.1. The Tauernwindow

The entire study area is part of the so-called Tauern Window. The Tauern Window represents a tectonic window in the Eastern Alps, in detail the Zillertaler Alps. In the Tauern window rocks of the Sub-Penninic domain, belonging to the former southern European continental margin, and the Penninic domain, originating from the Penninic ocean, are exposed on the surface and are framed by eastern Alpine units, which, outside of the Tauern window, cover these deeper tectonic units.

The development of the Tauern Window is due to the alpine orogenesis and in detail to a Oligocene duplex development of the deepest geological units (the central gneiss cores) and to the Miocene doming with lateral extension due to the penetration of the rigid southern Alpine indenter (Schmid *et al*. 2013).

The Sub-Penninic domain refers to the pre-Alpidic, distal continental margin of Europe, more precisely the crystalline basement and its Permo-Mesozoic cover. The crystalline basement consists predominantly of post-Variscan intrusiv and polymetamorphic sequences. The intrusive rocks intruded in several phases (Veselá *et al*. 2011), starting in the Early Carboniferous, until the early Permian into the existing sequence ("Old Roof") of shists, gneisses, amphibolites and meta-ophiolites, which at least already experienced a Variscan metamorphosis in the greenschist to amphibolite facies.

After the Variscan orogeny, during the Permian to the Triassic elongated basins formed due to continental extension and rifting tectonic (Veselá and Lammerer 2008; Veselá *et al*. 2022). Clastica, volcanic rocks and later shallow marine deposits were deposited in ENE-WSW stretched basins. The Hochstegen limestone covered finally in the Jurassic as thick carbonate deposites this shaped, southern European margin covering the basin sediments and even horst structures transgressing on the post-Variscian intrusive rocks.

The post-Variscian sediment cover of the Sub-Penninic domain was – like the intrusives – shaped only by the Alpine metamorphosis.

3.2. The main lithologies of the Hochstegen zone

The main lithologies of the Hochstegen zone consist of Triassic, heterogeneous metasediments and the Jurassic Hochstegen marble.

The Triassic metasediments contain quartzite, quartz-bearing limestone marbles, shales and evaporitic rocks like anhydrites (Frisch 1978). These metasediments cover in their autochtonous position the central gneiss, an orthogneis and are situated therefor at the base of the Hochstegen marbles. In their allochtonous position these metasediments are situated at the base of a tectonic nappe overlying the Hochstegen marbles. The thickness of these metasediments varies between several meters and decameters.

Due to its thickness, the Hochstegen marble is the main lithology of the Hochstegen zone. The Hochstegen marbles are carbonatic metasediments deposited as shallow marine sediments on the south-Europe shelf which is equivalent to the Helvetic shelf region. The Hochstegenmarble is placed by Klebelsberg (1940) in the Upper Jurassic, Oxfordian.

The Hochstegen marble is a uniform, gray to blue-gray, crystalline marble. The predominant rock is a fairly pure marble consisting mostly of calcite. Depending on the degree of purity, largely subordinate quantities of quartz and light

Fig. 3 – Marble with partly solution-extended fissures, e.g. 772.3 to 772.8 m.

Fig. 4 – Drill core from the Hochstegen marble with RQD equal to 100%, no dissolution and discontinuities.

and dark mica can be present. The very pure marbles are massive. The mica and quartz-bearing types of marble usually show a banky appearance.

3.3. Distribution of the Hochstegen marble

The Hochstegen marble, as main lithology of the study area, at the regional scale crops out on the eastern flank of the main Wipptal valley (see fig. 5). In detail the Hochstegen marbles are mostly exposed at surface close to the Brenner pass and on the Italian side of the study area. Due to the dipping of the lithologies to the West and North-West the marbles are locally exposed even on the Austrian side.

In the subsurface the Hochstegen marble envelope the Central Gneiss core of the western Tauern window with a North to South striking along the Wipptal valley and a South-West to Noth-East striking in the Venntal to Valsertal region. Due to the strike of the Hochstegen marbles they cross different lateral valleys and connect them from a hydrogeological point of view.

As can be seen by the geological section in figure 6 the Hochstegen Formation is crossed by the Brenner Base tunnel at depths always greater than 600 m. This deep part of the Formation is connected to the shallow lying formation which is covered especially in the valleys by thick quaternary coarse grained sedimentary rocks.

4. Hydrogeological conceptual model of the study area

4.1. Main flow systems in the study area

In the study area four main flow system types can be identified:

a. Flow systems in shallow porous aquifers

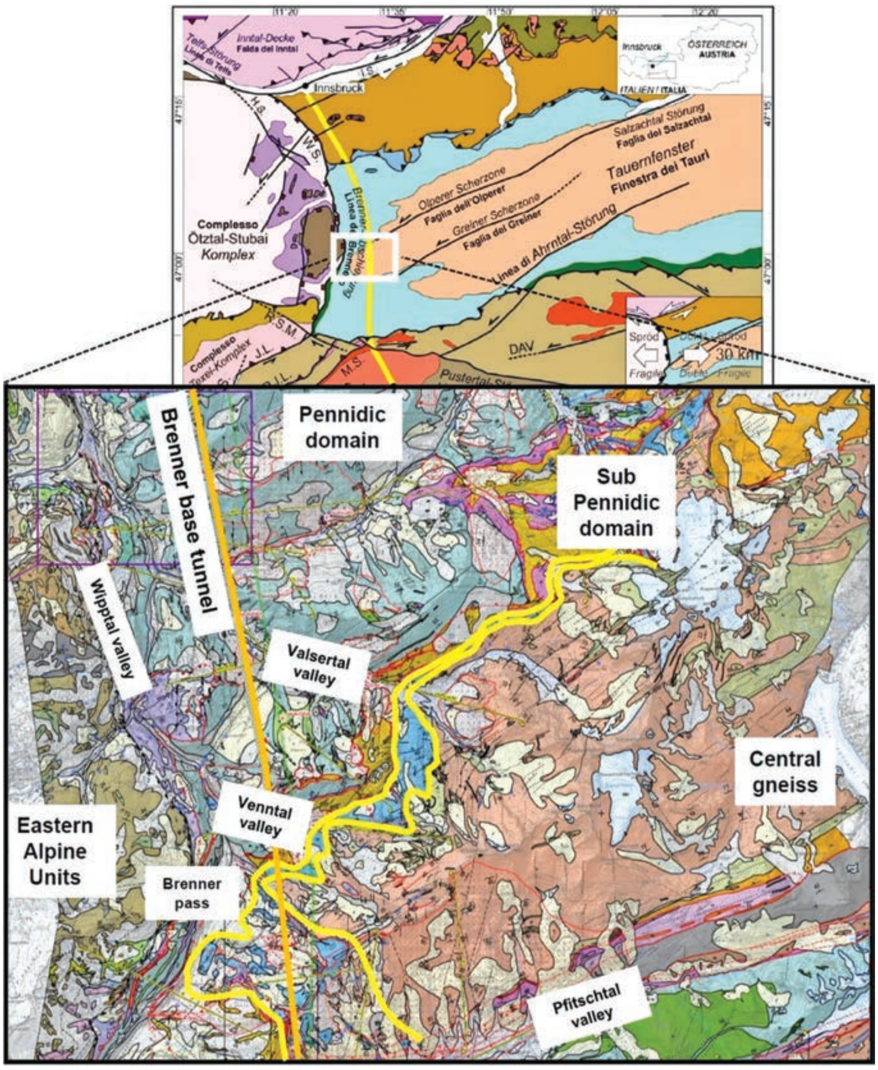

Fig. 5 – Simplifies geological map of the study area; the white line is the Circumference of the Hochstegen marble exposed at the surface.

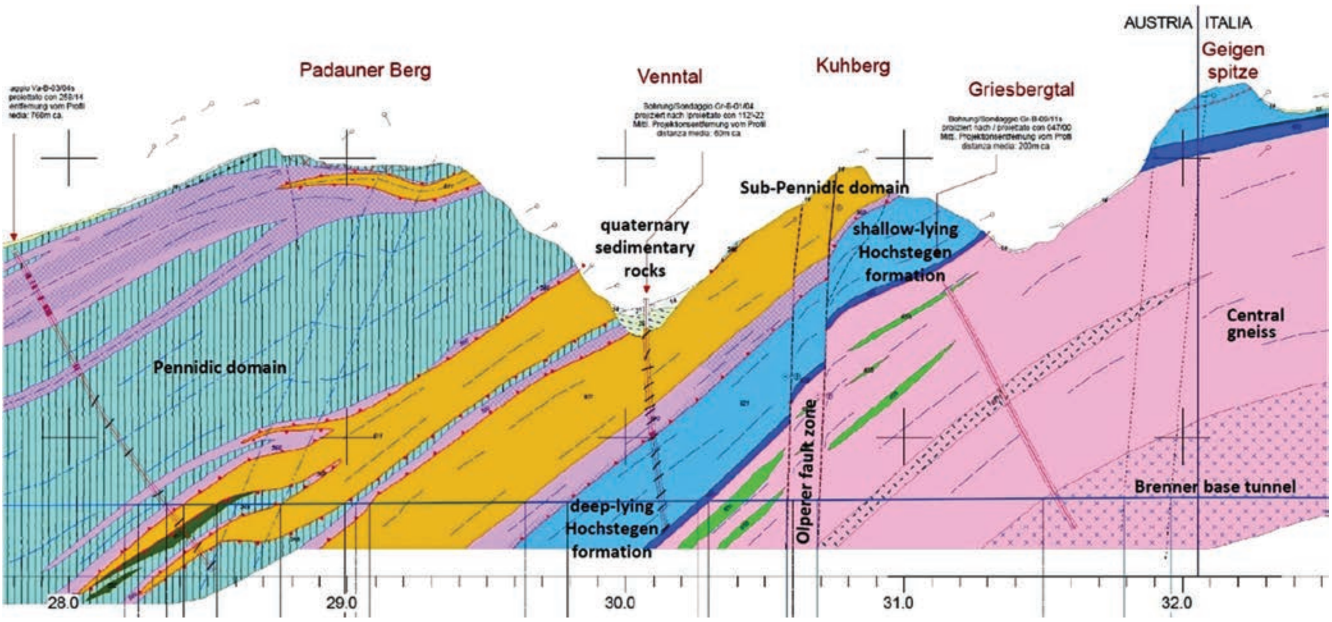

Fig. 6 – Geological section along the Brenner Base Tunnel in the study area.

b. Flow systems in the Hochstegen marbles (see fig. 7)
c. Flow systems in the Triassic metasediments
d. Flow systems in cataclastic fault portions of the Central Gneiss

The flow systems in shallow porous aquifers are situated in the alluvial fillings of the valleys, especially the Valsertal valley which contains 200 m thick quaternary deposits with unconfined and several confined (sometime artesian) porous aquifers. These aquifers consist mainly of gravels and sands and are separated by several meter thick silty-sandy aquitards and aquicludes.

Soft rock aquifers of coarse grained sediments are also present in the Venntal valley, with a mean thickness of approximately 100 m and in the Wipptal valley to the North and South of the Brenner Pass. Especially in the Brenner lake region quaternary sediments have thicknesses of around 100 m.

The flow systems in the porous aquifers are hydraulically connected with flow systems in the basement aquifers as follows:

- The basement flow system in the Triassic metasediments are known in the valleys Valsertal and Venntal. The flow system has a SO4-HCO3-Ca chemistry, attesting circulations in evaporitic rocks.
- The basement flow system in the Hochstegen Marbles, which give origin to main springs in the Venntal valley and in the Wipptal valley, have to be subdivided into shallow and deep flow systems. The shallow flow systems discharge to several huge springs with karstic character and a hydrochemistry of HCO3-Ca waters. The discharges of the deeper flow systems are not known, but it is assumed that they are located in the thick

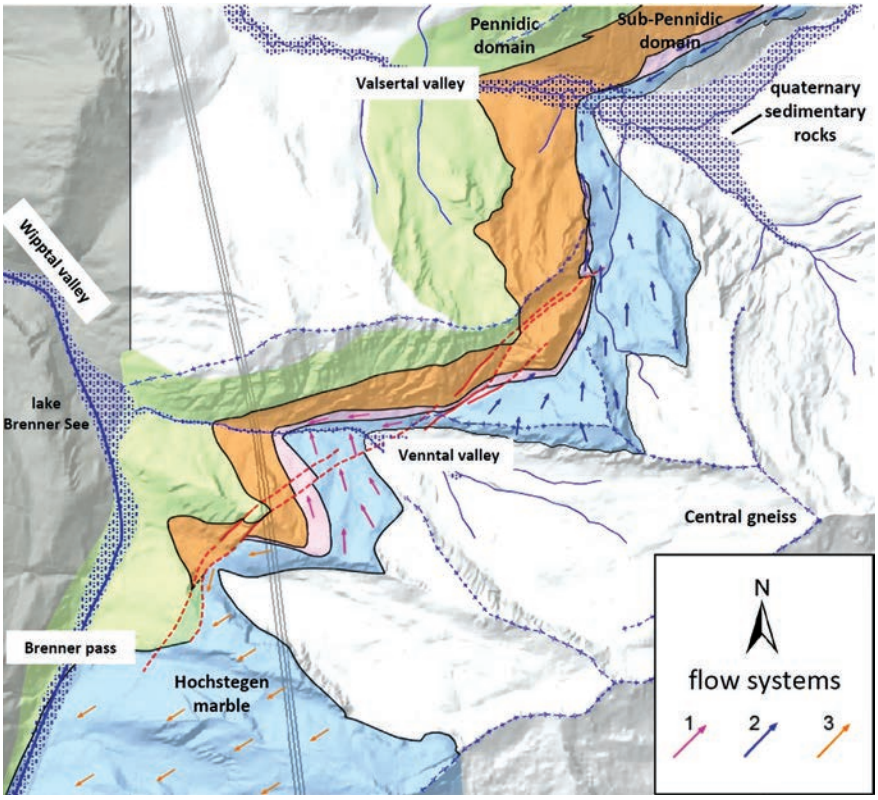

Fig. 7 – Illustration of the main flow systems in the Hochstegen marble of the project area.

quaternary fillings of the different valleys. The waters are of a SO4-HCO3-Ca-Na type.
- The Central Gneiss is mainly a lithology with a low hydraulic conductivity except in fault zones, especially in their damage zones. These flow systems follow the strike of the main faults. The main fault zone in the study area is the Olperer fault system with deep flow system of SO4-Cl-HCO3-Ca-Na-K hydrochemistry.

4.2. Interactions of the hard and soft rock aquifers

Of specific interest is the interaction of the basement and deposits flow systems, especially in the Alpine valleys of the study area. As an example the Valsertal valley is discussed.

In this region the flow system in the quaternary porous aquifer is in hydraulic equilibrium with the basement flow system of the Hochstegen Marble. This basement aquifer has discharge zones along the Valsertal valley floor; the waters flow from basement to porous aquifers and originate springs at the foot of the two slopes which feed the two main rivers in the area, namely the river Valserbach and the Giessenbach stream. It is estimated that in low flow conditions, about 25% of these two surface waters (about 50 l / s) come from the basement flow systems, while the remaining 75% (about 150 l / s) come from the Quaternary aquifer. The basement aquifers are an important contribution for the porous deposits aquifers in this area. Therefore, the possible drainage of these basement flow systems by the tunnel may decrease the groundwater flow to the porous aquifers and its surface waters, with perturbations of the different water heads, the groundwater head of the shallow lying porous aquifers and the water heads of the surface streams that are in hydraulic equilibrium with these aquifers.

5. Study method

5.1. Mapping

The basis for the geological and hydrogeological model is a detailed geological and hydrogeological map of the study area at a 1:5.000 scale. The map included the different basement lithologies with their fault systems and the different Quaternary deposits, covering the hard rocks. Of main interest are the grain size distribution and the genetic development of these deposits. Especially the quaternary valley fills, their lateral extension and characteristics are complex, but of main interest

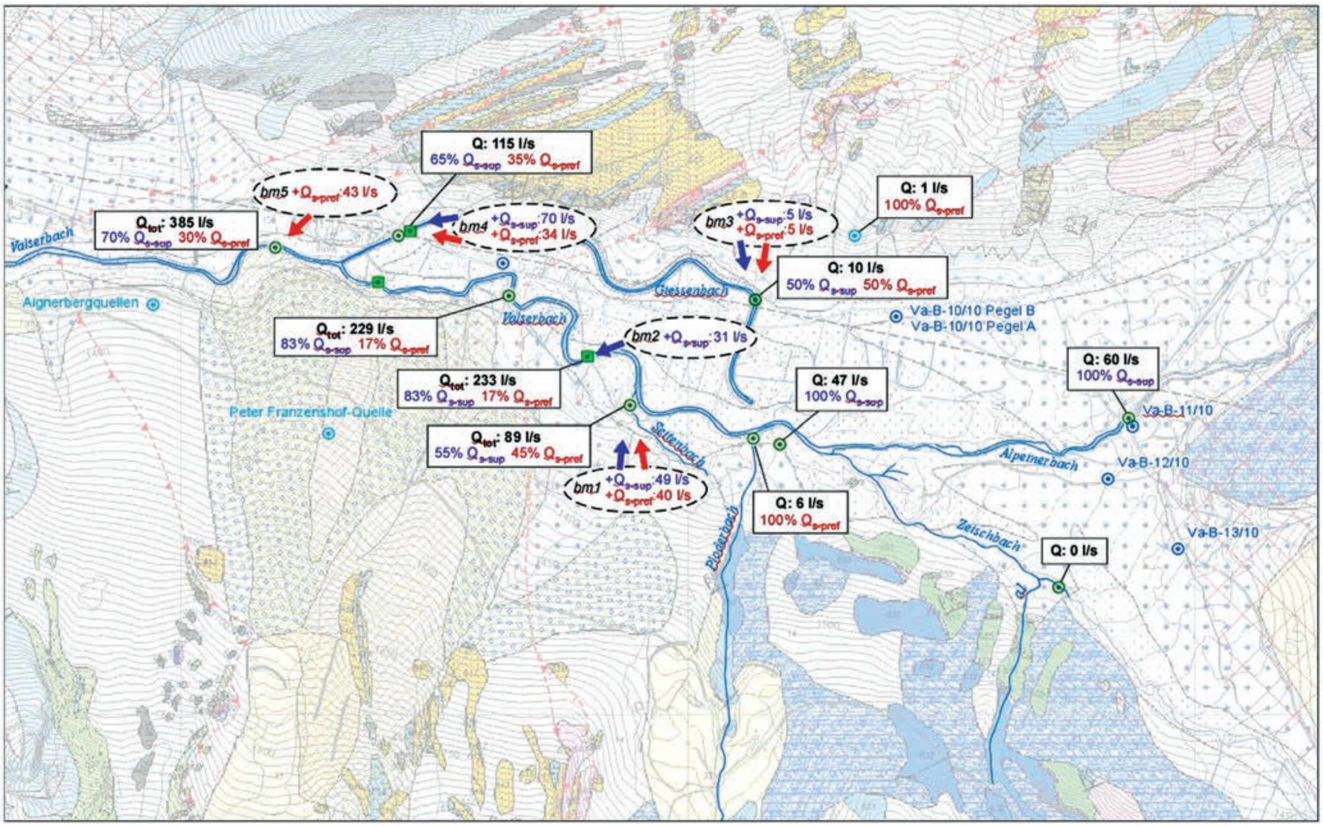

Fig. 8 – Estimates of the basement flow systems and the flow systems of porous aquifers using mass balance calculations. In blue the values referring to the aquifer in porous aquifers and in red the values referring to the basement flow systems.

for the evaluation of the hydraulic interaction with the hard rock aquifers.

The shallow lying porous aquifers are the origin of ecologically important wetlands, springs and small rivers. A detailed mapping of the hydraulic water elements like springs, rivers, lakes and wetlands have been executed in an early stage of the project. River mapping included even a sistematic monitoring of the quantity of flow at different points including the electric conductivity and the temperature of the water to characterise the infiltrating or exfiltrating behaviour of the rivers.

5.2. Monitoring of the water resources

Already in an early stage of the project the rivers, the springs, lakes and wetlands were included in a hydraulic monitoring program. In the first years, monthly measurements of the main physical parameters were executed. On the base of a hydraulic understanding of the flow conditions, some monitoring points were selected and equipped with continuous measuring data logger systems with a measuring frequency from 15 min up to 2 h. The knowledge of the behaviour of the physical parameters were necessary to associate the elements to flow systems, especially their flow depths.

5.3. Drillings and in situ testing

To explore the geological and hydrogeological conditions of the subsurface several core drillings and deep wells were performed in the study area (see table 1).

In the feasibility study (2000-2002) first, even deep drillings, were performed to get a first image of the subsurface and to work out a more detailed investigation program.

In the second, main investigation program (2004 to 2007), additional core drillings were executed for the procedure study phase. In this project phase the extension and hydraulic characteristics of the main hard rock and soft rock aquifers had to be recognized and even their hydraulic interconnection.

For monitoring the different aquifers an additional drilling program (2009 to 2010) was carried out installing several groundwater wells in hard and soft rock aquifers and to start at an early stage to monitor the groundwater conditions before starting the tunnel excavation works.

The last drilling program were performed in 2015 during the tendering phase. In this case additional deep boreholes and even 2 deep wells were built. With these deep wells in the Venntal valley the draining tunnel was simulated and the impact on the hydraulic system monitored with the groundwater wells. These data were the base for calibrating the numerical hydraulic models.

5.4. Hydrogeological numerical modelling

The modelling study was done in two phases:

During the procedure project phase (2004-2008) a regional 3-dimensional hydrogeological numerical model was created to simulate in a first step the natural hydraulic conditions in the study area. In a second step the model was used to simulate the draining tunnel system and its regional impact on the groundwater. On the base of this knowledge, technical solutions composed of injection programs to reduce the hydraulic conductivity of the rock mass surrounding the tunnel in a hydrogeological sensitive section for reducing the water inflows and therefore the impacts on the groundwater were conceptually designed.

For the tendering design (2015) the regional model was actualized based on the data of the drilling campaigns carried out in 2009 and 2015, data of additional hydraulic in situ tests and of the continued water monitoring program. Additional to the regional model a local, numerical 2d-model for the valley Venntal was developed. This model was used to simulate in detail the effects of measures to reduce the hydraulic conductivity in the rock mass surrounding the tunnel.

These two models are finally used during the construction phase to prove the in situ conditions and the sustainability of the determined allowed water inflows.

6. Determination of the sustainable yield of tunnel water inflows

6.1. Concept of determination of the sustainable yield of tunnel water inflows

The sustainable yield of tunnel water inflows is the amount of water drained by a tunnel section from a hydrogeological and ecological important aquifer without damaging the hydrogeological and ecological system in an irreversible way.

Actually the water inflow rate is determined by the allowed drawdown of water tables in shallow lying basement and porous aquifers which are hydraulically interconnected.

Therefore the main aim of the hydrogeological studies was the determination of the tunnel water inflow rate which cause groundwater table drawdowns on a regional scale and in different aquifers still sustainable for the hydrogeological and ecological system. This

Tab. 1 – The different drilling programs executed in the study area including the names of the boreholes/wells, their length, filter section and the monitored aquifer.

Drilling programm	Name of the borehole/well	Length [m]	Filter section [m]		Monitored aquifer
			from	to	
2000-2002	Va-B-01/00	560,00	260,70	560,00	Hochstegen, deep section
	Ve-B-01/00	718,00	103,40	718,00	Hochstegen, deep section
2004-2007	Gr-B-01/04	806,33	100,00	806,33	Hochstegen, deep section
	Gr-B-03/07	26,51	18,51	26,51	quaternary sediments, deep section
	Gr-B-03B/07	0,83	0,00	0,83	quaternary sediments, shallow section
	Gr-B-04/07 Pegel A	188,03	93,03	188,03	scists
	Gr-B-04/07 Pegel B	25,80	19,80	25,80	quaternary sediments, deep section
	Gr-B-04B/07	12,84	5,84	12,84	quaternary sediments, shallow section
	Gr-B-05/07 Pegel A	169,73	100,73	169,73	scists (Bundnerschiefer)
	Gr-B-05/07 Pegel B	58,92	39,92	58,92	quaternary sediments, deep section
	Gr-B-05B/07	7,09	4,09	7,09	quaternary sediments, shallow section
2009-2010	Gr-B-06/09	69,78	23,78	69,78	quaternary sediments, deep section
	Gr-B-07/09 Pegel A	58,00	53,00	58,00	quaternary sediments, deep section
	Gr-B-07/09 Pegel B	11,40	2,40	11,40	quaternary sediments, shallow section
	Gr-B-08/09 Pegel A	4,73	2,73	4,73	quaternary sediments, shallow section
	Gr-B-08/09 Pegel B	38,73	30,73	36,73	quaternary sediments, deep section
	Gr-B-08B/09	15,73	6,73	15,73	quaternary sediments, shallow section
	Va-B-07/10	23,03	15,03	23,03	quaternary sediments, deep section
	Va-B-07B/10	7,76	1,76	7,76	quaternary sediments, shallow section
	Va-B-09/10 Pegel A	63,84	51,84	63,84	quaternary sediments, deep section
	Va-B-09/10 Pegel B	22,81	13,81	22,81	quaternary sediments, shallow section
	Va-B-09B/10	5,77	2,77	5,77	quaternary sediments, shallow section
	Va-B-10/10 Pegel A	54,84	39,84	54,84	quaternary sediments, deep section
	Va-B-10/10 Pegel B	15,84	2,84	15,84	quaternary sediments, shallow section
	Va-B-11/10	46,00	19,00	46,00	quaternary sediments, shallow section
	Va-B-12/10	59,83	14,83	59,83	quaternary sediments, shallow section
	Va-B-13/10	29,91	19,91	29,91	quaternary sediments, shallow section
	Gr-B-09/11s	1002,15	702,15	1002,15	central gneiss
2015	Br-B-01/15	501,01	129,81	500,81	Hochstegen marbles, shallow section
	Gr-B-10/15	218,02	82,02	218,02	Hochstegen marbles, shallow section
	Gr-B-11/15s	561,90	270,90	561,90	Hochstegen marbles, deep section
	Gr-Br-01/15	333,00	315,00	333,00	triassic rocks on the top of the Hochstegen marble, deep section
	Gr-Br-02/16	664,00	362,00	664,00	Hochstegen marbles, deep section

determination was done using calibrated, hydrogeological, numerical models.

A regional hydrogeological numerical model was developed to study the regional groundwater flow systems, the hydraulic interaction between the different aquifers and the groundwater discharges to springs and wetlands. The model was finally used to quantify and illustrate the regional groundwater table drawdown in the different aquifers caused by a free draining tunnel system.

As the extension and even the magnitude of the regional drawdown under freely drained conditions are too high, decreased hydraulic conductivities in the rock mass around the tunnel were simulated to decrease the tunnel water inflows and the drawdowns of the groundwater tables in different aquifers. The simulation of the effect of reduced rockmass conductivities close to the tunnel on the drawdown of the groundwater table in the valley Venntal was done with a local 2d, hydrogeological, numerical model.

The hydraulic conductivity which induces a maximum water table drawdown without impacts on local water resources, especially springs, rivers and wetlands was the basis for the technical design of the rock mass injection project.

This specific hydraulic conductivity of the rock mass induces a tunnel water inflow rate which doesn't cause impacts on the hydrogeological and ecological system and is therefore the sustainable yield of tunnel water inflows.

6.2. The regional hydrogeological numerical model

The purpose of the regional hydrogeological numerical model is to analyse the hydraulic conditions of the study area and the hydraulic variations due to the draining tunnel system, especially in the valleys Venntal and Valsertal. The numerical simulations were set up as sensitivity analysis for material properties and hydraulic boundary conditions which may affect the expected impacts. In fact it must be noted that, despite a high number of hydrogeological investigations was performed in the BBT project, the high heterogeneity of basement properties and the large variety of context to test left high margins of uncertainties about material properties. In this framework, a dozen models were produced, in each of which a different scenario of properties and hydraulic boundary conditions are examined. The main modelled scenarios are:

- Scenario with one discrete main permeable horizon in the Hochstegen zone versus scenario with several permeable horizons in the Hochstegen zone
- Scenario with low/very low permeability of the Olperer Fault zone versus scenario with medium/high permeability of the fault zone
- Scenario of high permeability of alluvial deposits in the Venntal valley versus scenario with low permeability of these alluvial quaternary sediments.

The regional model was carried out using the Feflow finite element code, version 6.3.

The geometric boundaries of the regional model are based on the geological model:

- To the north, the boundary coincides with the Valsertal valley, which constitutes an area

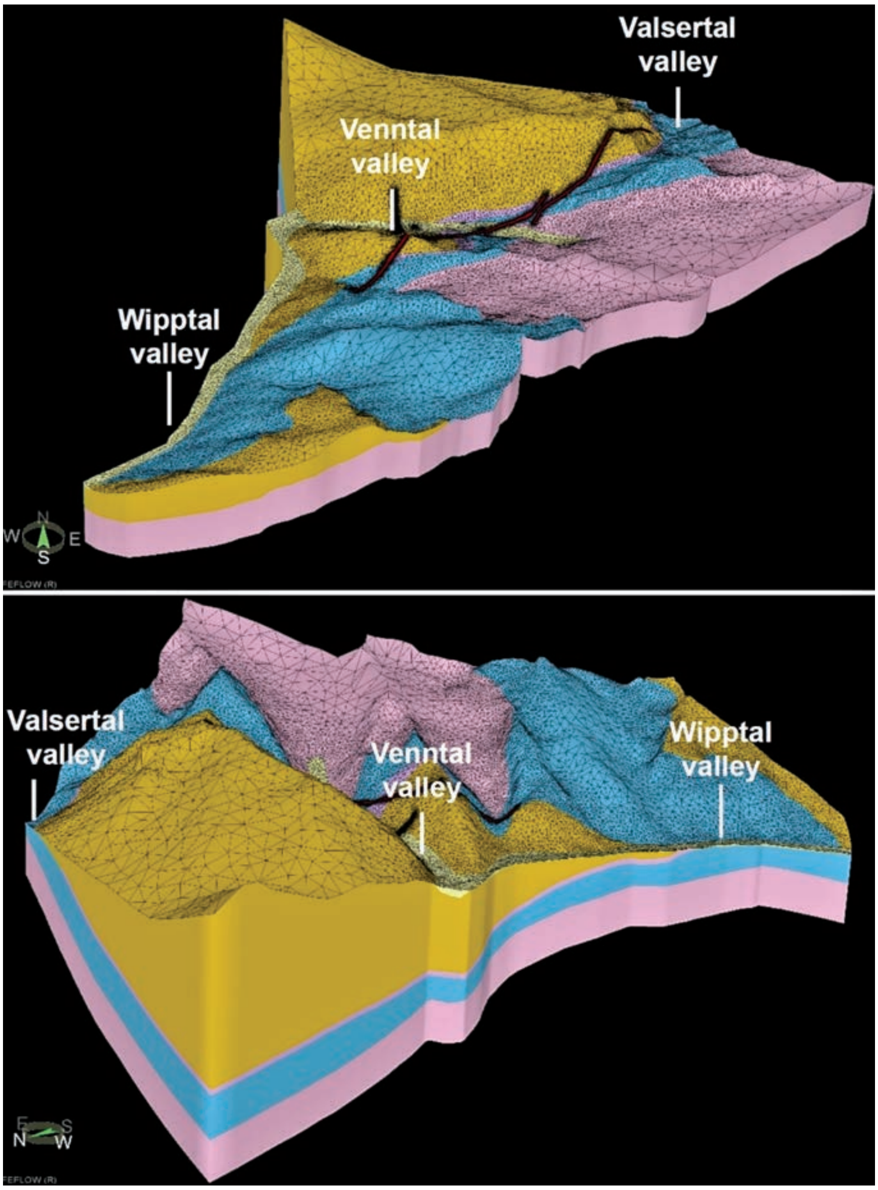

Fig. 9 – Visualizations of the 3D model geometry with triangular discretization mesh of elements.

of minimum hydraulic potential for the Hochstegen marble aquifer

- The boundary to the east corresponds with the intersection of the basis of the Hochstegen marble with the topographic surface
- To the west, the boundary corresponds with the Wipptal valley, which for the aquifers is an additional sector of minimum hydraulic potential
- To the south the boundary corresponds to the top of the Hochstegen marble and the Triassic metasediments which are overlain by impermeable rocks.

The vertical levels used in the regional model are 17, while the total number of finite elements is 1.23E+06. A refinement of the finite element meshes was carried out along the exploratory tunnel, the Olperer Fault and in the area of two deep wells in the valley Venntal.

Different hydraulic boundaries were used in the numerical model:

- Hydraulic loads (condition of I type – Dirichlet), applied at the Isarco River and along the valley Valsertal where the Hochstegen marbles intersect the valley floor.
- Recharge conditions (type II condition – Neumann), applied to the nodes of topography. The recharge values varies due to the different permeabilities of the outcropped geological formations. As example the Central Gneiss and additional lithologies with general low hydraulic conductivity values has a very low recharge rate (2.5 mm/y), average values for the Hochstegen marble vary between 200 and 500 mm/y. In some sectors with high hydraulic permeability zones higher values ranging from 500 and 1000 mm/y have also been taken into account.
- Hydraulic loads with transfer at the Venntal stream (type III condition – Cauchy), with transfer coefficients applied for the flow entering and leaving the riverbed.

The calibration of the regional model was done based on groundwater table data from different groundwater wells in the study area. In detail the calibration was carried out by varying the hydraulic conductivity and the recharge rate, verifying the simulated groundwater table values with the observed water levels.

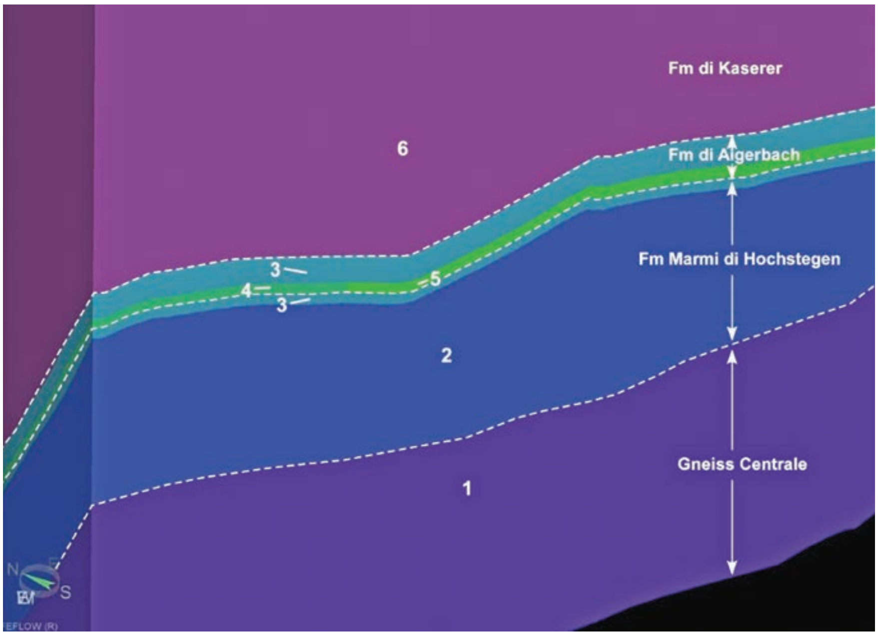

Fig. 10 – Schematization of the lithological units in the regional groundwater model: 1 Central Gneiss, 2 deeper part of the Hochstegen marble, 3 shallow part of the Hochstegen marbles and the Aigerbach formation, 4 deeper part of the interface between Hochstegen Marbles and Trias, 5 shallow part of the interface between Hochstegen Marbles and Trias, 6 Kaserer formation (part of the Sub-Pennidic domain).

The best fit between calculated and observed water table conditions were obtained with the following scenario: Very discrete zone as a permeable horizon between the Hochstegen marble at the base and the triassic metasediments at the top including rather low permeability for the rest of the lithologies in the study area except the quaternary deposits of the valleys. In detail:

Central gneiss K = 1E-08 m/s; deeper part of the Hochstegen marbles: K = 3E-07 m/s; shallow part of the Hochstegen marbles and the Aigerbach formation K = 5E-07 m/s, deeper part of the interface between Hochstegen Marbles and Trias K = 8E-07 m/s, shallow part of the interface between Hochstegen Marbles and Trias: K = 3E-06 m/s; Kaserer formation K = 1E-08 m/s; Olperer fault zone: K = 5E-08 m/s (3 m thickness), quaternary sediments of the Wipptal valley: K = 1E-04 m/s; quaternary sediments of the Venntal valley: K = 1E-04 m

In a first step the simulations were carried out in a transient regime until a stabilization of the distribution of the hydraulic heads in the modelled domain was obtained.

Simulations using the described boundary conditions and material properties resulted in the hydraulic head and flow configurations shown in fig. 11. The figure illustrates the intersection of the aquifer with the topographic surface: the blue areas represent the sectors in which there are groundwater transfers from the basement aquifers to the shallow porous aqui-

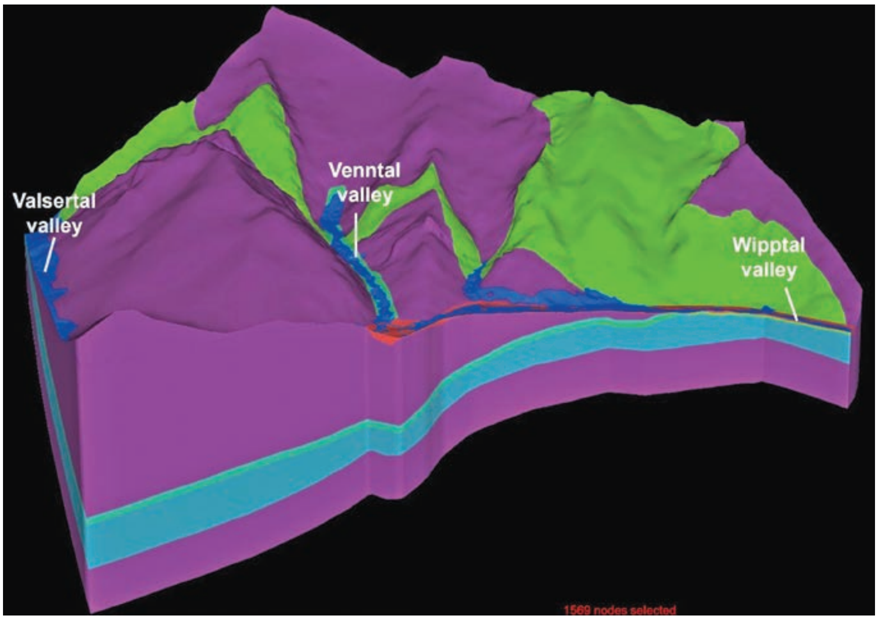

Fig. 11 – Visualisation of the intersection of the aquifer with the topographic surface. The blue areas represent the sectors in which there are outflows or water transfers from the hard rock aquifers to the most superficial aquifers.

fers. There is a general agreement between this output and the distribution of the main observed groundwater outflows.

6.3. *Simulation of the draining exploration tunnel with the regional model*

For the simulation of the drainage effect of the exploratory tunnel, a hydraulic head condition, type I, was imposed on the tunnel nodes, with a hydraulic head value equal to the node elevation and with an single flow discharge from the model, the so-called seepage condition.

Figure 12 illustrates in a plan view the hydraulic head drawdown as an effect of the draining tunnel section crossing the Hochstegen marble after long drainage time (10 years).

Figure 13 illustrates in correspondence with a profile reconstructed along the Venntal track the lowered and stabilized hydraulic heads due to the draining effect of the tunnel section crossing the Hochstegen marble.

The catchment area of the drained tunnel water corresponds mainly to the Venntal and Griesbergtal hydrologic basins. A part of the contribution is even from a sector of the Wipptal valley.

To reduce these impacts the effects of measures to lower the hydraulic conductivity around the tunnel crossing the permeable horizons of the Hochstegen zone are studied by a 2d hydrogeological numerical model.

6.4. *The local 2d, hydrogeological, numerical model*

The main aim of the local 2d, hydrogeological, numerical model was to make a forecast assessment of the expected impacts on the shallow lying groundwater table along the Venntal, simulating a rockmass with reduced hydraulic conductivities around the tunnel section which crosses the permeable horizons of the Hochstegen Formations.

In the 2d model a necessary level of discretization along the tunnel to perform detailed evaluations was used. The alignment of the section was chosen along a flow line in the Venntal valley recovered by the 3d model. Even the hydraulic conditions of the rock masses and the boundary conditions were derivated by the calibrated regional model. Comparing the two profiles along the Venntal valley obtained by the 3d model and the 2d model similarities of the geometries of the hydraulic uni-

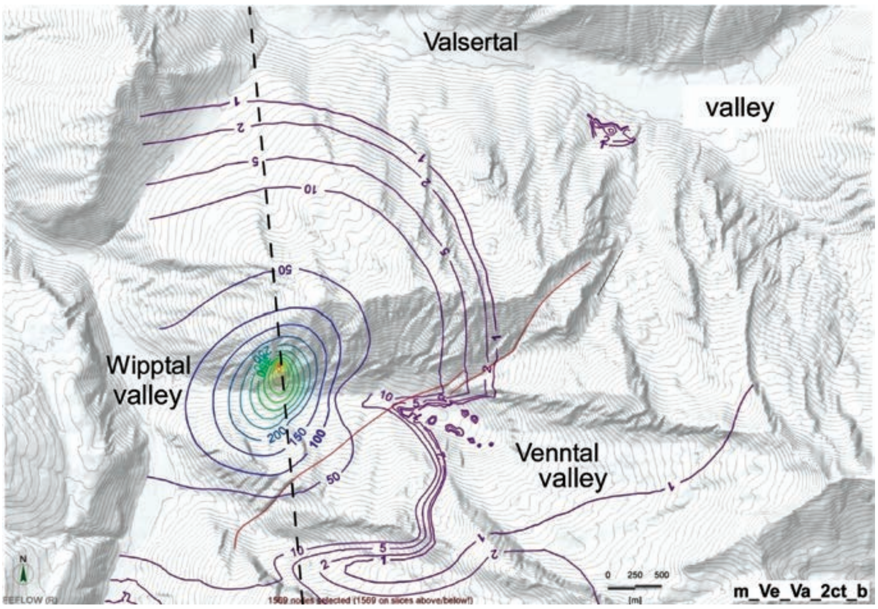

Fig. 12 – Simulated lowering of the water level heights in the bedrock due to the draining effect of the tunnel system (dashed line) in the area of the Venntal (Hochstegen zone).

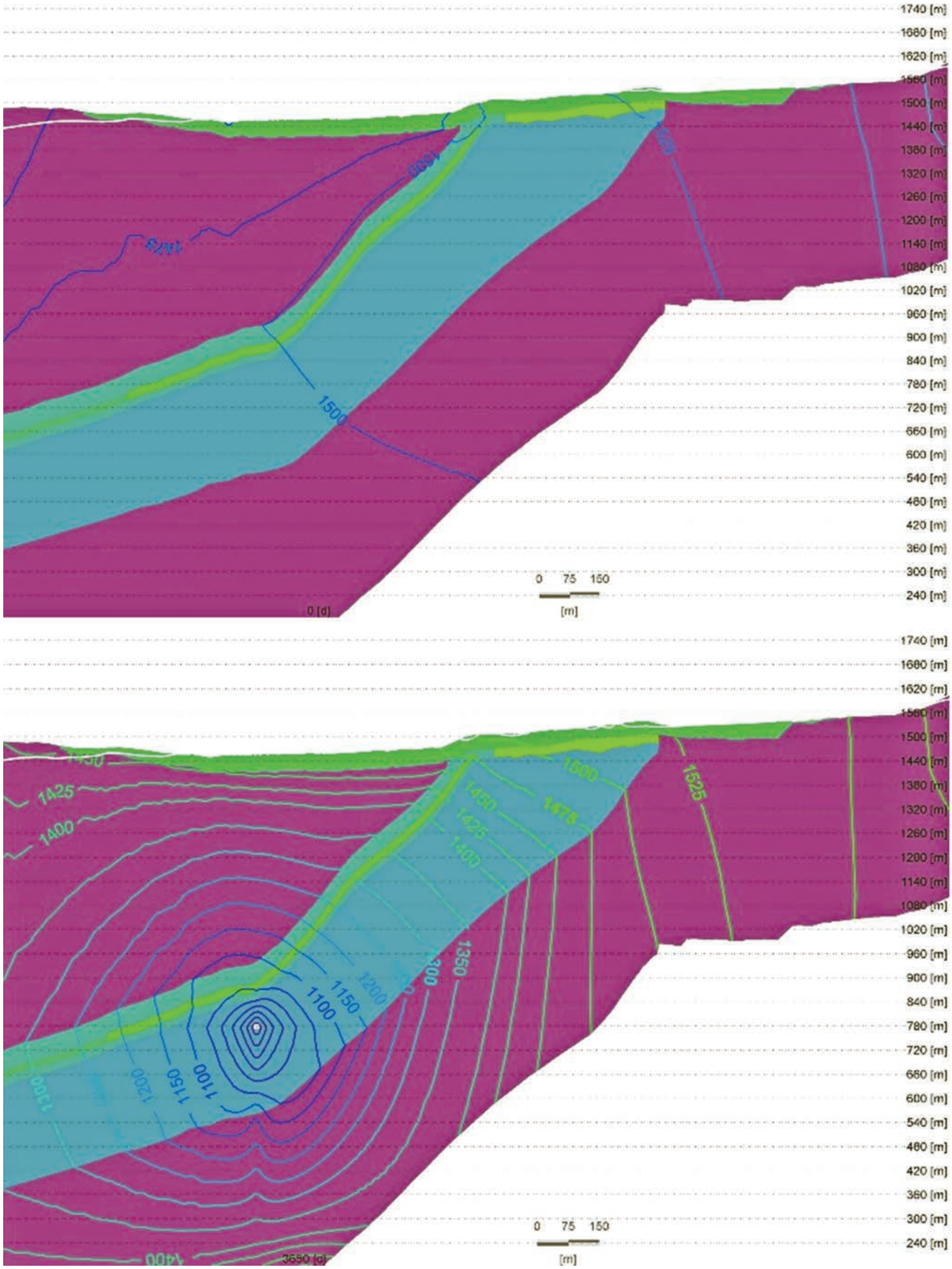

Fig. 13 – Profile along the Venntal valley, perpendicular to the exploration tunnel detailing the distribution of hydraulic heads in post-operam conditions with stabilized tunnel drainage conditions.

ts are visible but even the higher degree of discretisation in the 2d model especially for the triassic metasediments and the Hochstegen marble.

With the 2d model simulations were carried out on a section created along the Venntal varying the hydraulic conductivities of the rockmass surrounding the tunnel.

The flow rates for the tunnel inflows derived from the 2D models using different hydraulic conductivities for the rockmass around the tunnel sections were finally simulated in the 3D models in different runs to verify the regional effect of these different inflow rates. In this way, it was possible to determine the highest inflow rate still compatible with the specifications.

In a first modelling step the natural conditions of the aquifer were simulated. In a second step the free draining tunnel was simulated in the 2d model. Outputs of the 2d model for the first and second step were compared with outputs of the calibrated 3d model. In a last step simulations of a draining tunnel crossing rock masses with different hydraulic conductivities waterproofing treatments were carried out and studied.

In this last phase the model was used to evaluate the degree of reduction of the drained flow rates of the tunnel as a function of the waterproofing treatments applied around the tunnel. The treatments were applied to an annular portion surrounding the tunnel with a thickness of 8 m (see fig. 16).

Three simulations were carried out with the following hydraulic conductivities for the rock mass surrounding the tunnel: (i) K = 1 × 10-7 m/s, (ii) K = 5 × 10-8 m/s and (iii) K = 1 × 10-8 m/s. Fig. 17 shows the time dependent tunnel water inflow rates for the simulated rock masses with lowered hydraulic conductivities.

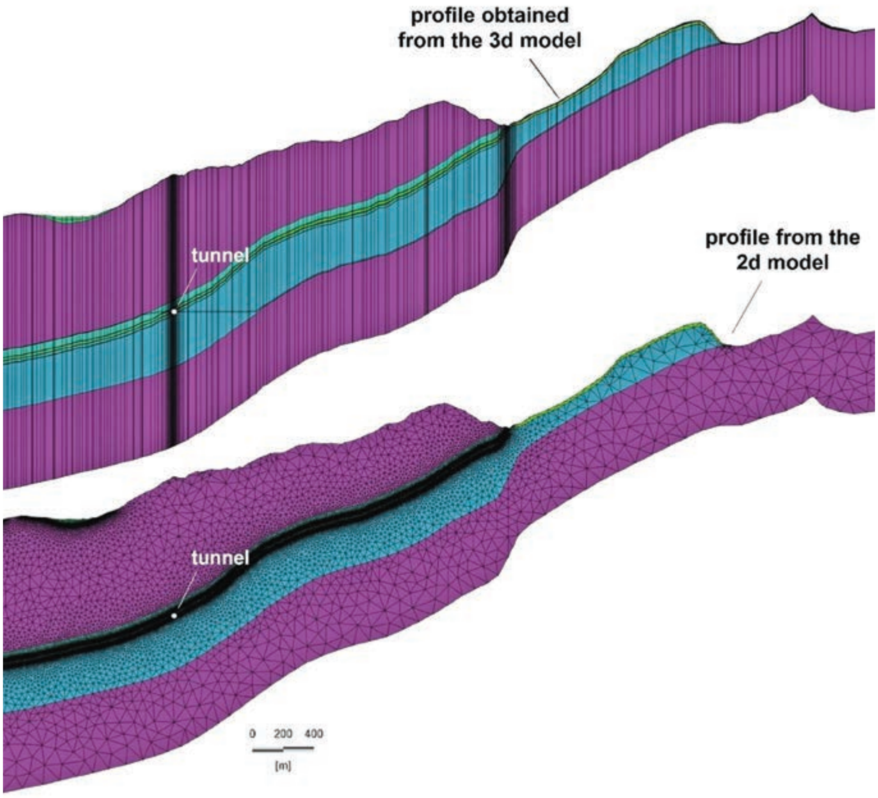

Fig. 14 – Comparison between the profile obtained from the 3d model and the reconstructed 2d model and the detail of the mesh of elements in the sector surrounding the exploratory tunnel.

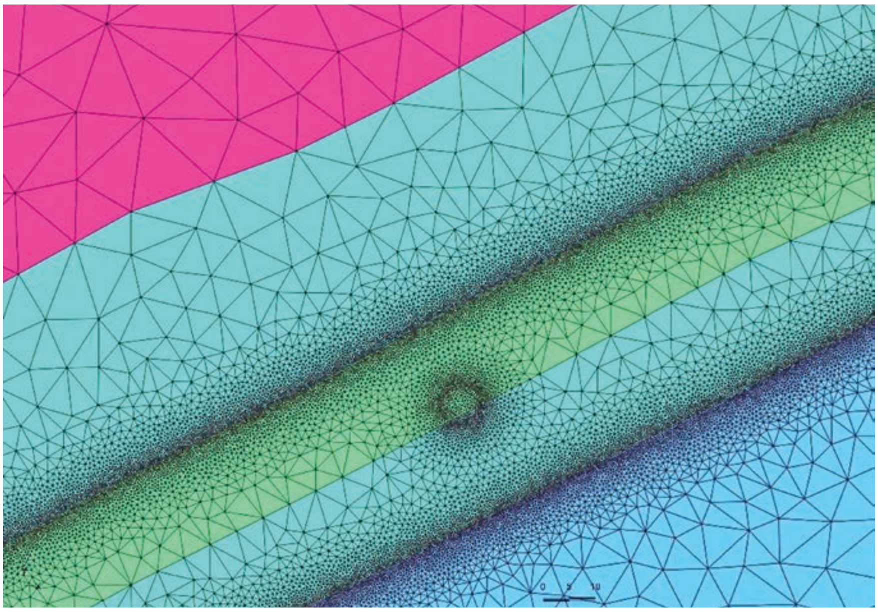

Fig. 15 – Detail of the mesh of elements in the sector surrounding the exploratory tunnel in the 2d model.

From the 2d model and the 3d model result that in the case of a rock mass with a reduced hydraulic conductivitiy surrounding the tunnel equal K = 1x10^{-8} m/s the inflow rate is 35l/s for tunnel section (500 m long) crossing the Hochstegen marble. In this case the extension of the impact area and the amount of groundwater lowering are of magnitudes lower than the prescribed limits. This flow rate

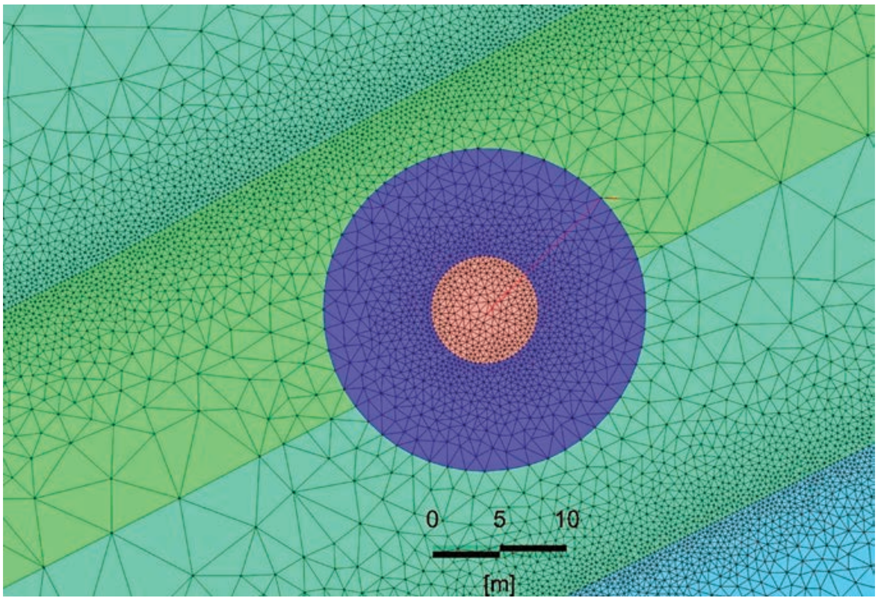

Fig. 16 – Detail of the 2d model with the central tunnel (light grey) surrounded by the outer ring (dark grey) where the rock mass has a reduced hydraulic conductivity due to injections.

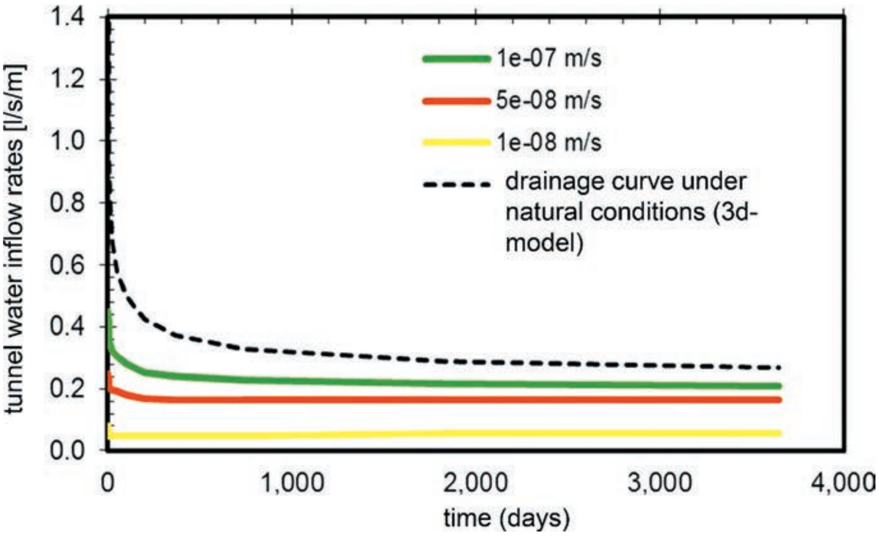

Fig. 17 – Diagramm with the time depending tunnel water inflow rates as a function of the hydraulic conductivity of the rock mass surrounding the tunnel and comparison with the drainage curve under natural conditions obtained by the 3d model.

of 35l/s was finally defined as sustainable yield of the exploratory tunnel section crossing the Hochstegen zone.

7. Outlook

A validation of the output of the models and therefore a validation of the sustainability of the recommended yield is possible during construction of the exploratory tunnel, monitoring the groundwater wells in the study area and comparing the simulated drawdown values with the observed values.

In general this validation is carried out comparing the simulated tunnel water inflows and groundwater table drawdowns with the observed values.

In detail the validation is performed in two main steps. At first horizontal boreholes equipped with a preventer system and with a maximum length of 150 m are drilled from the tunnel face in advance of the tunnel and used to simulate the draining tunnel and to test the in situ hydraulic rockmass conditions. On the base of the amount of the measured flow rates and the measured drawdown in groundwater monitoring wells the decision is made, whether the explored rock mass surrounding the tunnel has to be treated by measures reducing the hydraulic conductivity or not.

After the execution of these eventually necessary measures the exploration tunnel is excavated and the tunnel water inflow rate and the drawdowns of the groundwater tables continuous observed and compared with the simulated values. If the observed impacts on the groundwater table are not sustainable for the hydrological and ecological system additional injection measures are foreseen in the construction contract after construction of the tunnel.

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