Hydrogeologic Exploration and Tunneling in a Karstified and Fractured Limestone Aquifer (Lötschberg Base Tunnel, Switzerland)

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1. Introduction and Summary
1.1 Abstract

The Lötschberg Base Tunnel (LBT) is a major tunnel construction in Switzerland and will be completed in 2007. The tunnel is a double tube railway tunnel with a total length of 34.5 km. One of the most critical tunnel sections was a potentially karstified and fractured 3.2 km long section in the Doldenhorn Nappe, consisting of limestones and marls. Because large water inflows into the tunnel through open karst pipes and fractures could not be excluded, this section was intensively explored during the excavation process. The exploration program consisted mainly of two horizontal boreholes per tunnel tube drilled through the tunnel face with a length of approx. 300 m each. The boreholes were performed as cored or as destructive boreholes. In total, 63 horizontal boreholes with a total length of 14853 m were successfully performed during excavation of the Doldenhorn Nappe.

During the drilling process, inflows into the borehole were continuously monitored and core was inspected in detail with respect to transmissive features. After reaching the target depth of the borehole, open hole pressure tests and a few packer tests were successfully performed in these drillholes. An open hole hydrottest consisted of a pressure drawdown phase of approx. 1.5 h duration and a recovery phase of approx. 1 h duration. Outflow from the borehole during the drawdown phase was controlled by a partly opened gate valve. The pressure response was continuously logged with a highly sensitive pressure transmitter mounted on the borehole head. Single and crosshole pressure responses gave valuable indications for local and far field hydraulic transmissivity, storativity, connectivity of permeable features and formation pressure distributions. Based on an on-site “quick look” analysis of the hydrottest data, zones of high risk for the tunnel excavation could be identified and decisions for the ongoing excavation process could be successfully taken. Comparing detected inflows into the exploration boreholes with inflows into the later excavated tunnel allowed us to study the detection efficiency of the horizontal exploration boreholes with respect to conductive structures. It could be demonstrated that the detection efficiency is strongly dependent on the flow rate and the location and number of the
exploration boreholes. Open hole transmissivity derived from “quick look” analysis indicated a relative homogeneous rock mass over the distance of the excavated limestone (i.e. values ranging between 3.3E-4 m²/s and 1.2E-5 m²/s). Small scale storativity values determined from crosshole responses in the same limestone formation are between 9.6E-5 and 4.3E-8.

Analysis of the tunnel and borehole inflows showed that two sets of brittle faults control about 50% of the fluid flux within the limestones of the Doldenhorn Nappe. Palaeokarstification at the level of the Base Tunnel could be observed, but not as major water conductors, because the karst channels were filled with fine to coarse grained sediments.

Detailed analysis of the hydrotests with diagnostic plots indicated complex flow conditions. Approx. 60% of the pressure test reactions could be explained with storage and skin effects, infinite acting radial flow and boundary effects for the early mid and late time pressure responses. 30% of the pressure reactions showed clear indications for bilinear fracture flow in the early time pressure response and 10% of the pressure reactions could not be explained with classical well test flow models. An analysis of the late time boundary effects visible on the hydrotest pressure reaction showed that the short hydrotests with small flow rates (2–6 l/s) characterized permeable structures over distances of up to 300–1200 m. Constant pressure boundaries seen in the test reactions are related to valleys deeply eroded by glaciers and filled with fluvial sediments having a ground water table a few meters below the surface (Gastere and Kander Valleys). In a sensitivity study it was demonstrated that a reliable test analysis is strongly dependent on the borehole history. Time events and corresponding flow rates after completing the borehole – removing drilling rods – or any other manipulation on the borehole influence the pressure reaction in the subsequently performed hydrotest. Pressure recovery phases before a hydrotest should last at least 2 h.

During tunnel excavation in the Doldenhorn Nappe a monitoring program of hydraulic heads in selected limestone formations and the overlying gravel aquifers was performed. Hydraulic heads in the limestone aquifer were determined in deep,
vertical monitoring boreholes drilled from the ground surface. Due to construction of
the Lötschberg Base Tunnel the hydraulic head in the limestones below the Gastere
Valley was irreversibly lowered by approx. 26 m, while the head in the gravel aquifer,
located above the limestones remained unaffected. Flow from the horizontal
exploration boreholes created reversible pressure pulses which were clearly
identifiable in the deep sections of the vertical monitoring boreholes. A detailed
analysis of the time differences between crossing a conductive structure with a
horizontal exploration borehole and the pressure reaction in the distant monitoring
wells allowed estimating large scale storativity values of the Doldenhorn limestone
formation (2.3E-7 to 8.9E-8). Large scale storativity values determined from distant
boundary effects visible on transient pressure reactions of hydrotests in the
exploration boreholes are in a similar interval of 1.2E-6 to 3.6E-8.

The steady state discharge rates in the limestones of the Doldenhorn Nappe to the
LBT (on a level of 820 m a.s.l.) differ significantly from the rates reported for the old
and shallow Lötschberg Crest Tunnel (LCT) crossing the Doldenhorn Nappe on a
level of 1230 m a.s.l. While the discharge rates to the LBT show no significant annual
variations, a highly variable rate is observed at the tunnel portal of the LCT. The latter
discharge behavior is typical for an active phreatic karst aquifer with highly variable
hydraulic heads related to seasonal variations in recharge rate. Karst systems on the
level of the Base Tunnel are much older, not active and filled with clay, silt, sand or
gravel.

A 3D steady state hydrodynamic continuum model was built to simulate the impact of
the tunnel excavations. The model extension was 3.5 x 8.0 kilometers (km) in
horizontal and 3.0 km in vertical direction. The model area covered two major
limestone units of the Doldenhorn Nappe and the gravel aquifer of the Gastere Valley.
Evaporitic rocks and crystalline rocks located below the limestone units were assumed
to be impermeable. Spatially variable groundwater recharge rates were determined
from the back analysis of stream hydrograph data. The observed discharge rates of the
two tunnels could be modeled successfully with depth dependent hydraulic
conductivities in the limestone aquifers.
The impact of the shallow LCT on the ground water flow system is massive and hydraulic heads within the limestone aquifers are lowered up to 180 m. The groundwater table within the limestones is lowered nearly down to the level of the Crest Tunnel. The additional impact caused by the excavation of the deep LBT is less strong, hydraulic heads are additionally lowered by up to 50 m in the limestones. According to this model the inflow to the LCT (76 to 101 l/s) prior to the construction of the LBT comes from distributed recharge at ground surface (approx. 50%) and from the gravel aquifer of the Gastere Valley (approx. 50%). The LBT inflow (103 to 107 l/s) comes mainly from the gravel aquifer of the Gastere Valley. This gravel aquifer is fed by the Kanderfirn Glacier and has an estimate annual mean discharge of approx. 3.7 m³/s. Therefore the discharge of the LBT represents only approx. 3% of the total flow of this aquifer and the environmental impact of the LBT in this section is small.

1.2 Zusammenfassung

Der Lötschberg Basistunnel ist eine der beiden Hauptachsen des neuen Eisenbahntransitkorridors durch die Schweiz. Der Basistunnel ist ein doppelspurig geführter Eisenbahntunnel mit einer Gesamtlänge von 34.5 km. Einer der kritischsten zu bewältigenden Tunnelabschnitte waren die potentiell verkarsteten und geklüfteten Kalk- und Mergelgesteine der Doldenhorndecke auf einer Länge von 3.2 km. Da grosse Wassereinbrüche in den Tunnel nicht ausgeschlossen werden konnten, wurde dieser Tunnelabschnitt während des Auffahrens intensiv mittels eines Vorauserkundungsprogrammes exploriert. Das Vorauserkundungsprogramm bestand aus horizontalen, langen Vorausbohrungen (ca. 300 m), die durch die Tunnelbrust ausgeführt wurden. Die Bohrungen wurden als Seilkernbohrungen oder als zerstörende Bohrungen durchgeführt. Total wurden 63 Horizontalbohrungen mit einer Gesamtlänge von 14853 m erfolgreich ausgeführt.

Während des Bohrprozesses wurden Zuflüsse zum Bohrloch kontinuierlich überwacht und die gewonnenen Bohrkerne wurden detailliert bezüglich transmissiven Merkmalen inspiziert. Nachdem die Endteufe der Bohrung erreicht war, wurden

Eine Analyse von Tunnel- und Bohrlochzuflüssen zeigte, dass zwei Sets von spröden Störzonen den Grundwasserfluss (ca. 50%) in den Kalksteinen der Doldenhorndecke massgeblich bestimmen. Paläokarstsysteme konnten auf Niveau des Basistunnels zwar beobachtet werden, jedoch bilden diese nicht den Hauptgrundwasserleiter, da die Karströhren mit feinen bis grobkörnigen Sedimenten verfüllt waren.

Analyse der Zeitdifferenzen vom Zeitpunkt des Anbohrens einer wasserführenden Struktur durch eine Horizontalbohrung im Basistunnel bis zur gemessenen Druckreaktion im vertikalen Bohrloch mit offener Filterstrecke im Kalkgestein der Doldenhorndecke konnte eine grossräumige Abschätzung der Gebirgspeicherkapazität (über ca. 1 km) gemacht werden. Die grossräumige Speicherkapazität im Kalkgestein liegt bei 2.3E-7 bis 8.9E-8. Grossräumige Speicherkapazitäten bestimmt aus Randeffekten, sichtbar in transienten Druckreaktionen in horizontalen Bohrungen liegen in einem Intervall zwischen 1.2E-6 und 3.6E-8.


Um die Auswirkungen des Basistunnels und des darüberliegenden, alten Scheiteltunnels auf die hydraulischen Potentiale und die Fliesssysteme abzuschätzen, wurde ein dreidimensionales Kontinuum Grundwassermodell für die Region erstellt. Die Grösse des Modells ist 3.5 x 8.0 Kilometer (km) in horizontaler Richtung und 3.0 km in vertikaler Richtung. Im Modell wurden zwei wichtige hydraulische Kalkgesteinseinheiten der Doldenhorndecke, sowie der Schotteraquifer des Gasteretals berücksichtigt. Kristallines Gestein sowie Evaporite unterhalb der Kalkgesteine der Doldenhorndecke wurden als hydraulisch undurchlässig angenommen. Räumlich variable Grundwasserneubildungsraten wurden mittels Rückwärtsanalyse von Abflussganglinien bestimmt. Die beobachteten Tunnelzuflussraten konnten erfolgreich mit tiefenabhängigen hydraulischen Durchlässigkeiten innerhalb der Kalkgesteine modelliert werden.
Objective and scientific approach

The objective of this thesis is the development of a hydrological testing method to prevent underground excavations under high overburden crossing potentially karstified limestones from large water inflows, to characterize a fractured and potentially karstified limestone aquifer structurally and hydrologically on several scales with various methods and to simulate the hydrological impact of a large tunnel excavation on the regional flow system of a karstified limestone aquifer.

During crossing of a 3.2 km long potentially karstified and fractured limestone section in the Lötschberg Base Tunnel (Switzerland) in 2002 until spring 2003 a worldwide unique exploration program consisting of long, horizontal boreholes drilled through the tunnel face – in total 63 boreholes – along the tunnel axis was initiated by the construction company of the tunnel to prevent the tunnel excavation from large water inflows. During this drilling program open hole hydrotests were performed in many of the boreholes. It was one of the aims of this drilling and testing program to provide tunnel engineers with so called “Quick Look Reports” (QLR’s) which consisted of a hydrological characterization of the formation explored by the horizontal borehole
including estimated hydrological parameters such as transmissivity, storativity and formation pressure $p_i$. The open hole hydrotests were performed as constant rate tests and pressure reaction of the aquifer was determined with highly sensitive piezoelectric pressure transmitters. As pressure reactions from the constant rate tests were analyzed for the QLR’s within 12 h, a simple, fast and reliable method – Jacob’s straight line semi – log method – was applied to estimate main aquifer parameters. The decision of a continuation of the excavation or intensifying the exploration program was mainly dependent on this delivered dataset.

Despite the importance of an in situ characterization of an aquifer crossed by a tunnel and the prediction of water inflows into underground excavations – considering the various large tunnel projects which are currently in the planning or already in the construction phase in alpine regions – the corresponding literature is very restricted. Most of the work is related to a simulation of a tunnel inflow rate calibrated on hydrotests performed in vertical boreholes drilled from the surface. The dataset and our experiences made in the tunnel during performing the hydrotests lead to an increase in know how for tunnel constructors, engineers and geologists.

After the potentially and karstified limestone section was successfully excavated, it was decided to analyze the huge hydrotest dataset with more sophisticated methods. It was the aim to determine aquifer parameters such as transmissivity, storativity and initial formation pressure precisely along the tunnel section within the limestones. Furthermore, possible boundary effects in the late time pressure response of the hydrotests should be characterized and different flow regimes during the hydrotests should be determined. These aims were successfully fulfilled by analyzing the hydrotest data with a method developed by the oil industry – so called diagnostic log – log plots – which are not commonly applied in hydrogeology. Non linear fitting algorithms related to various aquifer models were applied to determine the aquifer properties. The model required the input of two major base parameters – formation compressibility and effective porosity. Both input parameters were first derived from literature studies of comparable formations and then adjusted for the limestone aquifer.
From hydrotest analysis with diagnostic plots various aquifer models for the near, mid and far field pressure reaction could be derived. To verify the predictions made for the flow field in the aquifer (bilinear flow, radial flow etc.) the orientation and shape of conductive structures was mapped at the locations where hydrotests were performed and the determined orientation and shape of conductive structures was compared to predictions derived from the hydrotests. In literature, no article was found in which a similar comparison is presented. This analysis and the corresponding dataset can therefore be regarded as unique. Late time pressure responses were analyzed and non linear fitting algorithms were successfully used to determine the distance to boundaries visible in the pressure reactions of the hydrotests.

Large scale impacts on the limestone aquifer were monitored by equipping two vertical deep boreholes with piezoelectric pressure transmitters to determine continuously the water table in the boreholes. Reversible water table reactions could be related to the horizontal drilling program which took place during that time in the tunnel. Large scale storativities were determined based on the determination of the pressure wave travel time triggered by the horizontal exploration borehole and the water table reaction in the vertical deep borehole under the assumption of a homogenous porous model. After the excavation of a clearly defined brittle fault within the limestones, the hydraulic head in the monitored boreholes dropped irreversible by approx. 25 m. To simulate large scale impacts caused by the excavation of the tunnel a fully 3D – model was built. As simulator a finite differences porous media model was selected. Boundaries of the model were selected based on geological and / or topographical features regarding impermeable boundaries. Recharge into the model was determined using a sophisticated simulator, especially built for determining recharge and runoff in alpine regions. Calibration of the model was preformed on various tunnel inflows in several underground excavations in the region.
1.4 Geological and hydrogeological outline

Our study site is a section of the new Lötschberg Base Tunnel - a 34.5 km long double tube railway tunnel which will be in fully operation in 2007. The tunnel intersects from its north portal located at the town of Frutigen, central Switzerland, towards the South, the Helvetic Nappes with the sub units of the Wildhorn Nappe - consisting of limestones and shists in the north and sandstones (named “Flysch”) in the southern section and the Doldenhorn Nappe consisting of limestones and marls. Towards the South the tunnel crosses a short interval of Triassic sediments named Autochthonous North (Autochthonous sediment cover of the Aar - Massif) consisting of sandstones, anhydrites and shists and enters finally the crystalline rocks (granites and gneisses) of the Aar Massif. One section of the tunnel project - the 3.2 km long Doldenhorn Nappe - was intensively explored during the excavation of the tunnel and is the study site of this thesis. The rocks of the Doldenhorn Nappe are of Jurassic and Cretaceous age deposited in a large marine basin. Major lithologic units of the Doldenhorn Nappe are (from north to south): the Kiesel – Limestone (limestone with typical silicified bands); the Öhrli – Limestone (limestone with low Quarz content); the Öhrli - Marl (dark, partly clay rich limestone); the Quintner – Limestone (dense, massive limestone with clear bedding). The actual position of these sediments does not represent the location of the original deposition as the end phase of the alpine orogenesis (early Miocene) resulted in heavy folding and over thrusting of the Helvetic Nappe – including the Doldenhorn Nappe. Large, U – shaped and gravel filled valleys (Kander – and Gastere – Valley) dominate the topography of the region and are the result of the erosion of many (approx. 21) glaciation periods during the last 2.3 million years. The base tunnel crosses both valleys in solid rock under an overburden of 400 and 600 m respectively. In the Kander – as well as in the Gastere – Valley several large karst springs can be found – an indication of potentially karstified limestone rocks. Tracer tests on various locations near our study site showed that hydrologic conditions and flow paths in the area are extremely complex. Several studies were performed to determine the elevation of the receiving stream in the Kander – Valley during the last glaciation period – this level is supposed to be equal to the level of karstification of the limestone rocks during the galciation period. Before the tunnel excavation was started
studies demonstrated that on the level of the base tunnel an inactive, probably sealed (with gravel, sand, silt or clay) karst system besides do to solution voids expanded fractures might exist. If karstified structures are directly connected to the water filled gravel aquifers of the valleys, the tunneling crew would be brought into great danger because of large water inflows into the tunnel. Both features – a palaeo karst system and due to solution voids expanded fractures were later intersected by the base tunnel during excavation.

1.5 Contents of the thesis

This work consists of 3 major parts, Chapters 2, 3 and 4. The chapters are written in manuscript form for later submission to scientific journals.

Chapter 2 discusses the exploration program performed with horizontal boreholes and the related hydrotests performed during the excavation phase of the Lötschberg Base Tunnel while crossing the limestones of the Doldenhorn Nappe. We present the excavation concept of the tunnel in this section and the world wide unique horizontal drilling program regarding tunnel projects. As the flow rate and the exact location of water inflows into the horizontal boreholes were logged by the drilling crew and later, during tunnel excavation location and inflows into the excavation zone of the tunnel were determined likewise, we were able to compare determined locations of borehole inflows with later excavated locations of tunnel inflows. Based on this dataset we were able to quantify the detection efficiency regarding conductive structures intersected by horizontal boreholes. In most of the performed boreholes, open hole hydrotests (constant rate) were performed. We will present our low cost, but highly precise measuring equipment consisting of piezoelectric pressure transmitters. Further we will discuss the testing methods in detail and we will present results of the quick on – site test analysis. The drawdown pressure reactions of the hydrotests were analyzed with Jacob’s straight line method, while the recovery pressure data were analyzed with the method of Theis. Important aquifer parameters such as transmissivity, storativity and initial formation pressure pᵢ could be derived from the hydrotests. To demonstrate the reliability of the testing method, a dataset preformed
with the open hole test equipment was compared to a test performed with a highly
sophisticated packer test equipment. It could be shown, that the results regarding the
determination of the aquifer parameters is equal. Based on the performed hydrotests
we were able to show a profile of determined aquifer parameters along the tunnel axis
including a distribution of K – values for hydrotests performed in boreholes with
similar borehole length. We are closing the chapter with a discussion of the
limitations of our method and presenting recommendations for tunnel engineers and
hydrogeologists who have to perform hydrotests in a similar environment, based on
our experience.

Chapter 3 discusses the analysis of hydrotest data with a sophisticated method, so
called diagnostic plots, developed by the oil industry to evaluate pump tests in oil
bearing formations. In the first Paragraph, we present a detailed structural description
of conductive and non conductive structures, intersected by the horizontal boreholes
and later by the tunnel. Structures described on a borehole scale (core recovery) were
compared with structures described in the later excavated tunnel. It could be shown
that the regional flow system is controlled by two major sets of brittle faults which are
responsible for 50 % of the tunnel inflows and we tested mainly those brittle faults
with the hydrotests. The hydrotests were analyzed in two stages; first, the pressure
tests were analyzed with Jacob’s straight line method, but in contrast to the analysis
presented in Chapter 2, diagnostic log – log and derivative plots were used to
determine the correct straight line on the semi – log plot. Based on the diagnostic plot
analysis we could show that the assumption of early time radial flow towards a tunnel
is not always valid and pressure response data have to be analyzed with great care
with respect to the applied model. Results (transmissivity, large scale storativity and
initial formation pressure) derived from this analysis were comparable to results
determined with a manual fitting presented in Chapter 2. In a second stage selected
hydrotests were analyzed with non – linear fitting algorithms to derive more aquifer
parameters than the basic ones described above, e.g. distances to constant pressure
boundaries were determined and interpreted as the distance to a large gravel aquifer of
a valley, located above the tunnel. Based on this observation, we concluded that the
radius of investigation of our hydrotests is large, at least 300 – 400 m. In a sensitivity
study we showed that the borehole history (manipulations in the borehole before the
(hydrotest) is very important for a correct simulation of the hydrotests with non linear fitting algorithms and all manipulations on the borehole with respect to the flow rate from the borehole should be recorded up to 4 h before the hydrotest is started.

In *Chapter 4* we present the regional impact of the Base tunnel to the limestone aquifers. Based on the monitoring of the water table in deep vertical boreholes an irreversible drop in the hydraulic head in the limestone aquifer of approx. -26 m could be determined. The water table in a gravel aquifer which is important with respect to environmental protection was not affected by the base tunnel. Small, reversible reactions of the hydraulic head in the vertical deep boreholes could be related in a detailed analysis to the horizontal drilling program in the base tunnel. Time differences between crossing a conductive structure by a horizontal borehole in the base tunnel and hydraulic head reactions in a vertical deep borehole, in more than 1 km horizontal distance from the horizontal borehole in the tunnel were used to determine large a scale storativity of the limestone aquifer. This large scale storativity value is comparable to storativities determined in *Chapter 3* and *Chapter 4*. To simulate the large scale impact of the base tunnel on the regional aquifers, a fully 3D hydrodynamic steady state continuum model was built. Recharge as one of the major boundary conditions of the model was simulated with sophisticated software designed to model runoff and recharge in alpine catchments. The 3D – hydrodynamic model showed that major differences between the discharge rate (amount and variations) of the shallow crest tunnel and of the deep base tunnel can be explained with elevation dependent K – values. Major environmental impact of the regional aquifers regarding the distribution of the hydraulic head compared to natural conditions could be related to the excavation of the shallow crest tunnel, while the impact of the deep base tunnel less strong. Flow paths of the region are affected heavily by the excavation of both tunnel systems.
2.

Hydrogeologic Exploration during Excavation of a deep Tunnel in Fractured and Karstified Limestone (Lötschberg Base Tunnel, Switzerland)

M. Pesendorfer and S. Löw
2.1 Introduction

The aim of this article is to demonstrate the utility of horizontal, long boreholes drilled through the face of a tunnel under high overburden and located in potentially karstified limestone. The boreholes were performed along the tunnel axis to explore water conductive structures and possible karst pipes and to prevent the tunnel excavation from dangerous and unexpected water inflows. We will describe a simple and new technique to perform hydraulic tests in the horizontal boreholes and to hydraulically characterize conductive structures within a short amount of time. Decisions, regarding the future tunnel excavation can be relied on this characterization and accurate action e.g. grouting can be planned. Further, we were able to study the efficiency of horizontal boreholes regarding their efficiency in detecting conductive structures.

Karstification of limestones and dolomites can lead to various types of solution voids, among which many can lead to preferential pathways with very large hydraulic conductance. An underground excavation intersecting such structures in the saturated part of an aquifer can be confronted with extreme water inflows. Besides karst structures water conductive fractures and fracture networks with high hydraulic transmissivities can cause great problems during tunnel excavation in carbonate rocks. If these fractures are hydraulically connected to karstified structures or deep quaternary gravel infillings of valleys above the tunnel, tunnel inflows can maintain high for very long periods of time.

Many tunnels that are currently being built through the Alps have to cross such formations at great depth and many hundred meters below the regional ground water table. Therefore the detection and characterization of karstified zones and water conductive fractures ahead of the advancing tunnel face is vital for these projects. The determination of the spatial distribution of pressures, transmissivities and storativities along the tunnel axes is of great practical interest especially in complex hydrogeologic situations. Marinos (2005) presents a summary of experiences made in tunnels driven through karstified formations.
The estimation and prediction of possible inflows into a tunnel excavated in hard fractured rocks is a difficult topic, mainly due to extreme spatial variability and range of hydraulic properties. Loew (2002) describes different conceptual and analytical models for tunnel inflows in homogeneous media. Raymer (2001) presents a statistical method to determine water inflow into an underground excavation which takes into account permeability distributions, measured from packer tests performed in exploration boreholes drilled from the ground surface during preliminary investigation phases.

For long and deep tunnels it might not be feasible to explore the detailed hydrogeological conditions from ground surface. In such a situation, drilling and testing from the advancing tunnel face (or adjacent caverns) is often more appropriate. However hydraulic testing in horizontal boreholes is not commonly used in underground excavations and the corresponding literature is very restricted. Fransson and Gustafson (2000) present results of an exploration campaign with horizontal short boreholes (length approx. 16 m) performed through the tunnel face with hydraulic tests in water conductive zones. The authors were able to detect and characterize the major hydraulic conductors successfully.

On the other side horizontal well testing is very common in the petroleum industry. Interpretation methods have been developed by Kuchuk (1990), Kuchuk (1995) and others. Horne (2000) summarizes their papers in his well test analysis book. Kawecki (2000) presented an interpretation method for hydraulic testing in horizontal boreholes which is based on theories developed in the petroleum industry.

In this paper, we present analysis methods and hydrogeologic test results from horizontal boreholes of a deep alpine tunnel in Switzerland, the double tube Lötschberg Base Tunnel (LBT) of the Swiss AlpTransit project (Loew, 2000). This tunnel has crossed 3.2 kilometers of limestones (karstified and fractured) under an overburden of up to 1000 meters. The excavation of these limestones was accompanied by an intensive exploration program consisting of 63 horizontal and 200 – 300 m long exploration boreholes drilled through the tunnel face with a total length of 14’853 meters.
As with this test exploration setup, locations and flow rate of water inflows into the boreholes could be compared to locations and flow rate of water inflows into the later excavated tunnel, we were able to present results of this comparison – named the “Detection Efficiency” of the exploration boreholes. Probably for the first time in tunnel excavation history such a dataset has been analyzed systematically in two parallel tunnel tubes over a distance of more than 3000 m. Based on this dataset we are able to provide tunnel engineers and geologists with reasonable values how effective the detection of water conductive structures with a horizontal borehole drilled along the axis of a future excavated tunnel in fractured rock is.

In 43 of these boreholes systematic open hole hydraulic tests were performed after drilling had been completed. Because of the amount of tests performed and the high data quality of all tests the gained data set can be regarded as unique. Most hydrogeologic characterizations of a rock mass are usually related to a relatively restricted area. The systematic dataset gained during the exploration program characterized not only a few hundred meters of a fractured rock mass, but more than 3 km of later excavated rock.

2.2 Geological and Hydrogeological Setting

All hydraulic measurements were performed during excavation of the Lötschberg Base Tunnel (LBT). Figure 2.1 shows the location of the tunnel including a simplified geological map. The tunnel crosses from north to south the Helvetic Nappes with the sub units of the Wildhorn Nappe - consisting of limestones and shists in the north and sandstones (named “Flysch”) in the southern section and the Doldenhorn Nappe consisting of limestones and marls. Towards the south the tunnel crosses a short interval of Triassic sediments named Autochthonous North (Autochthonous sediment cover of the Aar - Massif) consisting of sandstones, anhydrites and shists and enters finally the crystalline rocks (granites and gneisses) of the Aar Massif. The Penninic Nappes consisting of high grade metamorphic rocks are not crossed by the Base Tunnel.
A vertical simplified geological cross section of the study area is presented in Figure 2.2. The Doldenhorn Nappe is built of several sub units namely (from north to south) the Kiesel - Limestone (limestone with typical silicified bands), the Öhrli - Limestone (limestone with low quartz content), the Öhrli - Marl (dark, partly clay rich limestone) and the Quintner - Limestone (dense, massive limestone with clear bedding). Buxtorf and Trunninger (1909), Buxtorf (1910), Hugi and Trunninger (1914), Krebs (1925), Tavel (1936), Brueckner (1943), Furrer (1962), Hügi et al. (1988), describe in detail the geology, lithology and tectonics of the Lötschberg area. A detailed geological description of the complete LBT project is presented by Kellerhals and Isler (1998) or Loew (2000).

During the 1990’s several detailed studies related to the hydrogeology of the Helvetic Nappes were performed including deep borehole drilling, detailed water chemistry analysis, tracer tests, monitoring of karst springs and numerical modeling. The results of these studies are summed in Kellerhals and Isler (1998).

These studies showed that the crossing of the Doldenhorn Nappe with its phreatic limestone aquifers included the risk of intersecting deep paleokarst structures on the level of the base tunnel. The limestones and marls of the Doldenhorn Nappe which occur over 3200 m on Base Tunnel level are heavily folded and truncated by several fault zones. Northward plunging thrust planes exist and are potentially connected with the Gastere Valley and the Kander Valley. Both valleys are filled with gravel and other quaternary infills. The Base Tunnel has to cross these valleys with a water level located 400 m (Kander Valley) and 600 m (Gastere Valley) above the tunnel level, respectively.

From detailed studies of the development of karst systems during the last glaciation period, Lützenkirchen and Loew (2000) concluded that on the level of the base tunnel within the section of the Doldenhorn Nappe karst structures of various opening and shape can be expected. The most common type of karst was expected to appear as karstified fault zones on a small scale while karst systems with the shape of a network in great depth would represent a non common – but not excludable type. Conductive structures were expected to occur along lithologic boundaries towards clay rich beds
and cataclastic fault zones under high inclination. The karst structures on the level of
the base tunnel can be open or filled with sediments (gravel, clay).

The study could not exclude, based on detailed geochemical and hydrological
analysis, that karst systems (with circulating groundwater) are recently still active on
the level of the base tunnel. Because of uncertain hydraulic parameters of the karst
aquifer (opening, roughness, storativity, etc.) the inflows into the tunnel out of karst
pipes could only be estimated (initial inflow rate of several m³/s). An initial inflow
rate stands here for an inflow which occurs immediately (seconds to minutes) after
miners were blasting (accidentally) into a karst pipe.

In addition, a “worst case” scenario was established consisting of karst pipes in intact
limestones with an effective pipe diameter of approx. 1 meter. The worst case inflow
from such a system was estimated for a vertical pipe and a pipe with 30 ° inclination
generating a maximum inflow of 8 m³/s and 5 m³/s into the base tunnel, respectively.
Based on these assessments the tunnel implementer decided to support the excavation
of the Doldenhorn Nappe with an extensive exploration program.

2.3 Excavation and Exploration Concept

2.3.1 Excavation Concept

As a fully automatic excavation method, performed by a TBM, was found to be not
flexible enough to react on unexpected situations such as crossing water filled karst
pipes under high pressure, the tunnel engineers decided to excavate the critical tunnel
section with the drill and blast method. The tunnel was built of two parallel tubes,
with an approx. diameter of 8 m, constructed in a horse shoe profile. The distance
between the two parallel tunnel tubes is 40 m. Every 330 meters the tunnels are
connected through small diameter (approx. 5 m) transversal galleries. During the
excavation phase the mean daily rate amounted to be approx. 10 meters.

Both tunnel tubes (named East and West tunnel subsequently) were surveyed in a
separate metric system. To be able to compare events between the tunnel tubes, all
locations discussed in this paper (those from the East - and the West – tunnel) were normalized to the metric system of the East tunnel. Locations are indicated with the prefix “TM” which represents “TunnelMeters”.

During tunnel excavation the tunnel face and tunnel walls (approx. interval length 3 m behind the tunnel face) were mapped by the site geologist normally once a day. Additional to the geological mapping, water inflows into the excavation zone of approx. 10 m length were determined by measurements with a watch and a tub or, if not accessible or diffusive, by estimation. Experience showed that the error of determining a flow rate with tub and watch is approx. ± 0.1 l/s for a flow rate of 5 l/s, the error of determining a flow rate by sight is ± 100 % for a comparable rate. Water inflows into the excavation zone occurred mostly from conductive fractures and shear zones, blast holes drilled into the tunnel face (depth approx. 3.5 m) and anchor holes (depth approx. 3.5 m) drilled into the crown and into the side walls. Therefore, an exact location of the tunnel inflows is not always possible.

2.3.2 Exploration Program

2.3.2.1 Drilling

Based on the results of preliminary studies (Lützenkirchen and Loew, 2000; Kellerhals et al., 1998) it was decided to support the crossing of the last meters (towards the South) of the Wildhorn Nappe and the complete Doldenhorn Nappe (approx. 3.2 km of tunnel) with horizontal boreholes drilled through the tunnel face.

In a first concept it was planned to perform long (up to 1000 m) directional horizontal boreholes from a transversal gallery in between the two tunnels. This concept was disregarded after one completed bore hole (K1Z, between TM 25361 and TM 25902) mainly because of hydraulic short circuits in between the advancing tunnels and the borehole.

In Figure 2.3 the final exploration borehole concept is shown in plan view. One or two drill rigs mounted on truck trailers were driven to the tunnel face and standpipes of 20 m length were simultaneously drilled into the tunnel face. After testing the
standpipes for pressures of approx. 100 bar the drillholes were performed as cored (cable drilling) or destructive (in hole hammer) boreholes. On average drilling of two parallel boreholes of approximately 250 m length was completed within 4 days (day: 24 h) using two drilling rigs. In case of encountering permeable structures, the borehole density was increased.

Within the marl sections (Öhrli - Marl) of the Doldenhorn Nappe exploration during tunnel driving consisted of 1 horizontal cored directional borehole per tunnel tube. In potentially karstified limestone sections (Öhrli - Limestone and Quintner Limestone) the exploration included at least two boreholes. Table 2.1 and Table 2.2 give a summary of all boreholes drilled during the exploration program. On Figure 2.2 the start and the end point of the tunnel section, explored with horizontal boreholes is indicated including the lithostraphical units of the Doldenhorn Nappe mentioned above.

In total, 30 boreholes, 21 cored and 9 destructive with a total length of 7347 m were drilled from the East – tunnel and 32 boreholes, 28 cored and 4 destructive with a total length of 6964.5 m were drilled from the West – tunnel. One cored borehole (at the start of the exploration campaign at TM 25361) was drilled from a niche between the tunnels with a total length of 541 m.

**2.3.2.2 Borehole Inflow Logging**

During drilling, water inflows into the borehole were systematically surveyed and logged by the drilling crew. The determination of the flow rate was always performed after one drilling cycle, i.e. after reaching an additional depth of 3 m (length of the core catcher). The location of an inflow into the borehole is therefore only known on a precision of 3 m. The measurement of the flow rate was always performed with the drill string inside the borehole, but without core catcher; i.e. water flows from a water bearing structure along the annulus (open space approx. 1 mm) and through the drill bit into the drilling rods. Water flow was not only determined in cored boreholes, but also in destructive boreholes. As in cored boreholes, water flows along the annulus
(open space approx. 7 mm) and enters the drill string through flush holes in the inhole hammer.

A major inflow into the borehole is reduced because of friction in the annulus, especially in the cored boreholes (smaller annulus). The outflow from the borehole was measured at the end of the drill string with a normalized tub and a watch (error: ± 0.1 l/s at a flow rate of 5 l/s). One has to keep in mind that a measured flow rate at the borehole head is always the sum of all flow rates up to the actual borehole depth. From the difference of the flow rate between two logged inflow points the flow rate of a single inflow point can be determined. Additional to the technical detection of an inflow into the borehole one might also consider the increase of experience (sensitivity to a water inflow into the borehole) of the drilling crew. Because of no possibility to quantify this “increase of experience” it was not considered in the analysis.

Figure 2.4 presents the monitored inflow rate into the borehole for the East – and West exploration drillholes including free outflow measurements after reaching target depth without drill string. Horizontal bars indicate the open borehole length during the free outflow rate determination. In most cases, the measured borehole outflow after the drill string has been removed is higher than measured with the drill string in the borehole. The heavily reduced outflow is due to friction losses in the annulus. For interpreting the water inflows into the boreholes correctly, it is vital that one knows the exact position of the tunnel faces relative to each other because of possible drainage effects.

Inflow rates into the boreholes were analyzed with care regarding a possible reduction in the flow rate because of horizontal drilling in the lagging tunnel. Between Tm 25’000 and TM 30’000 the West – tunnel was leading on 65.4% of the distance. The position of the tunnel faces is shown in Attachment A of this thesis. No relation between flow rate determination in the lagging tunnel and a reduction in the flow rate was found.
It was found that normally one inflow was dominant over the entire borehole length (dominant: one inflow was at least twice as big as every other inflow encountered in the same borehole). From total 63 drilled boreholes, 60 could be analyzed for comparing inflow rates into the borehole (2 boreholes were dry after the target depth was reached – K7EA and K7EB – and the borehole drilled between the tunnels – K1Z – was not taken into the analysis because of hydraulic short circuits between the tunnels and the borehole). 49 of the analyzed boreholes showed one dominant inflow, on 11 boreholes more than two inflow rates differed less than 50 %.

Depending on the results of the first boreholes, additional drillings were subsequently carried out in zones showing indications for karstification and / or conductive fracturing. Strongly karstified or fractured sections were tested with at least 4 boreholes before any decision regarding continuation of tunnel driving was taken.

2.3.2.3 Permeable Structures

The 3200 m long intensively explored tunnel section consisted of 2500 m of massive, hard limestones and 330 m of marls, both showing high RQD – values (> 80) and a mean fracture density of 2 fractures per m. At the start of the exploration program 370 m were drilled in hard sandstones (Flysch). Usually, water inflows occurred from non-karstified fractures. In most cases, it was not possible to directly relate a detected water flow in the borehole to a specific structure in the core, because water conducting fractures were generally not differentiable from dry fractures (80% of the water containing fractures showed no sign of alteration due to flowing water). Only at three locations fractures showed strong widening and corrosion due to karst processes. A karst system with sediment filled karst pipes of 0.75 m width and 1.5 m height was encountered in the West tunnel at TM 26876. Figure 2.5 shows one of the karstholes. The maximum outflow from a borehole crossing this karst system was 4.0 l/s (measured with rods but without core catcher) and approx. 16 l/s initial flow rate into the tunnel. “Initial Flow” represents in this relation a flow rate which was determined between 1 and 10 hours after the excavation of the karst structure. The exact time difference between excavation of the karst system and determination of the flow rate is not known. Another karst system was found in the West tunnel at TM 27172. The
maximum borehole flow (with rods but without core catcher) was 7 l/s, the initial tunnel inflow was approx. 14.5 l/s. Also here, the exact time difference between excavation of the karst system and the determination of the flow rate is not known, but is between 1 and 10 hours after excavation.

During a detailed structural mapping campaign of Scan Windows (Size approx 10 x 7 m) on 18 different locations in the East – tunnel (from TM 25530 to TM 28385) around conductive structures it was found that two fracture sets are dominant; one set has a dip direction of approx. NW – SE with a steep dip angle (> 60°) and one set has a dip direction of approx. N – S with a shallow dip angle (20 – 30°). In this study mainly dry mesoscale fractures with no indication of water flow in the structure and conductive mesoscale fractures with clear indication of water flow in the structure (microcrystalline calcite cover, due to water flow bleached rock etc.) were described. The mesoscale fractures have an assumed extension of 10’s of meters (Pesendorfer and Loew, 2006).

Brittle faults were studied in the East tunnel (between TM 26970 and 28425) and the West tunnel (between TM 26744 and 28565) in detail. It was found that the orientation of the brittle faults is dominated by two major sets. One with a dip direction NW – SE and a dip of approx. 80° and a second set with a dip direction SW – NE and a dip angle of approx. 30°. Especially the orientation of the steep set is compatible to a set of mesoscale fractures mapped in the East – tunnel.

Approx. 80% of the described brittle faults occur as isolated single structure. The distance between single brittle faults was usually > 50 m. No infill (sand, mud, gravel) was found within single faults. Few faults were strongly altered due to fluid flow or showed a crystalline calcite cover. Few small fractures or brittle faults were usually connected to the single brittle fault, but the total extension of the conductive fracture network was usually not more than 10 m.

20 % of the brittle faults were part of a system of more than two ± parallel faults. In total, three systems consisting of more than one fault could be identified in the intervals described in detail in the East – and West tunnel. These systems consisted of
one major fault, strongly altered and bleached due to fluid flow. The major fault was filled with sand, gravel or mud and had an extension perpendicular to the fault of up to 250 mm. Along two major fault planes karst systems were encountered during tunnel excavation (at TM 26876 and TM 27172, both in West tunnel). Several minor faults, altered and slightly widened were found to be in connection with the major fault. *Figure 2.6* shows a brittle fault, encountered in the West – tunnel at TM 27183 (*Pesendorfer and Loew, 2006*). In *Attachment H* of this thesis we present a detailed tunnel map of all geological structures.

## 2.3.3 A Comparison of Borehole and Tunnel Inflows

During the exploration program and the later tunnel excavation we compared locations of inflows into the boreholes detected during drilling with locations of inflows to the excavation zone of the tunnel. The analysis was only performed with inflows of a rate \( \geq 0.1 \, \text{l/s} \). This comparison allows evaluating the success of the exploration boreholes with respect to the identification and localization of permeable structures along the tunnel axes. In a first step, a permeable structure was defined as correctly identified if an inflow mapped in the tunnel excavation zone could be correlated to an inflow into a borehole within an interval of \( \pm 20 \, \text{m} \).

As described earlier, a section was usually explored with two boreholes. In the case of large water inflows into these boreholes, the exploration drilling was intensified to three or more boreholes. While excavating the Doldenhorn Nappe, this was the case on three locations. Only one borehole (Start: TM 25361) was drilled between the tunnel tubes.

Considering the different drilling campaigns following observations were made:

- With one borehole, drilled between the tunnels, 6 inflows with \( > 4 \, \text{l/s} \) are missed; huge inflows of 10 l/s, 15 l/s and 40 l/s are missed in the West – tunnel

- the biggest inflow missed with one borehole along the tunnel axis is 6 l/s
- the biggest inflow missed with two boreholes along the tunnel axis is 3 l/s, but ~80% of all inflows missed are ≤0.1 l/s.

- with more than two boreholes along the tunnel axis only two small inflows are not detected; 1 x 1 l/s and 1 x 0.1 l/s

77% of the occurrences (139 out of 180) of the tunnel inflows greater than 0.1 l/s were properly identified by the exploration program. 80% of the not detected inflows into the tunnel are ≤1 l/s. These results refer to all boreholes drilled within a given tunnel section.

In a second step it was analyzed if tunnel inflows could be localized reliable by the exploration boreholes. For that purpose the inflow locations in the tunnel within an interval of ±5 m were compared to inflow locations of the exploration boreholes. This analysis was also done only for inflows with a rate > 0.1 l/s. In Attachment B of this thesis all results comparing tunnel inflows and borehole inflows are presented graphically.

Table 2.3 shows the results of this analysis with the localization of the inflows in the exploration boreholes. The table is separated into results from the East and West – tunnel and also into “leading” and “lagging” tunnel. “Leading” indicates, that at the time of the measurement the tunnel (exactly: tunnel face) was leading compared to the other (“lagging”) tunnel. Table 2.3 shows, that for the assumed 5 – m criterion 52% to 73% of the inflows are localized correctly.

In a scatter plot, the rate of tunnel inflow is plotted vs. the rate of borehole inflow determined at the same location for the East – and West – tunnel (Figure 2.7 and Figure 2.8) is shown. Values are separated into measurements preformed in the leading and in the lagging tunnel. This separation corresponds only to the relative position of the tunnel faces and not to the effective inflow location with respect to the tunnel faces. Values which are plotting directly on the X – Axis represent inflow points which were not detected at all by the exploration drilling program; values which plot on the Y – Axis represent values which were detected during the exploration drilling program, but generated no inflows into the tunnel. We are aware
that comparing tunnel inflows with borehole inflows in such a way is problematic; first because the tunnel inflow rate was determined from a conductive structure not reduced by friction losses as the flow rate determined at the borehole head was and, second because the correct time of the determination of a flow rate is not precisely known. If the fact is neglected that the flow rate determined at the borehole head is reduced by friction losses in the annulus we are able to present a theoretical span width of tunnel inflow rates compared to borehole inflow rates related to a homogenous and isotropic aquifer. This ratio can be derived from the model introduced by Jacob and Lohmann (1952) or Lei (1999) for constant head tests. It is assumed that a tunnel crosses a homogenous, isotropic, confined fault zone of a given thickness. The time dependent inflow rate into the tunnel can be determined after

\[
Q(t) = \frac{4 \cdot \pi \cdot T \cdot s}{2.3 \cdot \log \left( \frac{2.25 \cdot T \cdot t}{S \cdot r_w^2} \right)}
\]  

Whereas \(Q(t)\) is the inflow rate as a function of time, \(T\) the transmissivity of the fault zone, \(s\) the hydraulic head (600 m if the head difference between LBT and ground water level of the Gastere Valley is assumed), \(t\) the time, \(S\) the storativity of the fault zone and \(r_w\) the tunnel radius (4m) and the borehole radius (0.05 m) respectively. We assume that the inflow rate of a conductive structure intersected by the borehole was determined after 10 minutes (neglecting friction losses) and we assume that a tunnel inflow was determined between 1 and 10 h after being intersected by the tunnel. For \(T\) and \(S\) we assume a range of parameters which are realistic (supported by hydrotests) for the LBT – aquifer:

\[
1E-6 \text{ m}^2/\text{s} \leq T \leq 1E-4 \text{ m}^2/\text{s}
\]

\[
1E-8 \leq S \leq 1E-6
\]

The range of parameters applied to (1) results in a simulated comparison of tunnel inflow rates and borehole inflow rates (hatched area) presented in Figure 2.7 and Figure 2.8. We are aware that this comparison is only a rough approximation of the
conditions in the LBT - aquifer but it can be seen that only few data points plot within the simulated area. This is an indication that the aquifer is rather heterogeneous than homogeneous on a local scale around the excavated tunnel.

2.4 Equipment and Testing Methods

After completing the borehole, systematic borehole georadar measurements for detecting karst cavities or large water containing fractures around the borehole were performed in at least one borehole per tunnel tube. The detectability of karst structures in limestones with single hole georadar measurements was extensively studied in a feasibility study by Maurer (2000) and Maurer et al. (2000). In a detailed numerical study could be shown that isolated 1 x 1 m karst – pipes within a solid limestone matrix should be detectable with tomographic run time inversion methods. Models of the radar reflection (single hole) method showed that the detectability of open karst caves is limited and their localization is restricted. Because of restricted time, only single hole borehole radar was applied in the LBT. Results of this application are discussed elsewhere.

Hydraulic open hole tests were subsequently performed after the georadar measurements in most of the boreholes. In addition, a few single packer tests were used for hydraulic characterization in case that several important inflows occurred. In Table 2.1 and Table 2.2 a compilation of all open hole and packer hydrotests is presented.

2.4.1 Open Hole Test Equipment

One of the most important objectives during the evaluation phase of the testing tools was to find hydrological test equipment which was reliable, simple to use, cost effective and ready for operation in a short time. The main devices finally used for the open hole hydrotests consisted of piezoelectric high accuracy pressure sensors with data logger, a Laptop for reading out and controlling the pressure measurements (via
RS232 port), a calibrated tank and a stop watch for measuring the outflow from the borehole.

Two KELLER® pressure sensors with a range of 0.8 to 35 bar (max. error ± 0.07 bar) and two sensors with a range 0.8 to 50 bar (max. error ± 0.1 bar) were used to survey the pressure reaction in the boreholes. It was found by experiments that the sensitivity of the sensors was at least one order of magnitude more precise than the error specified by the manufacturer. The pressure sensor was mounted in connection with ball valves, an analog pressure gauge, reducers and connectors directly to the stand pipe. An explosion drawing of the set up including a parts list is shown in Figure 2.9.

2.4.2 Downhole Equipment

For packer tests a newly designed system that could be pumped through the drill string including downhole pressure and temperature sensors and a flow meter at the borehole head was used. Delouvrier and Buehler (2003) give a detailed description of the packer system.

2.4.3 Testing Methods

When the target depth of the borehole was reached, georadar reflection measurements were systematically accomplished in one of the boreholes.

After a phase of pressure stabilization (all gate valves closed) which was allowed to last for about 1.5 hours, transient open hole tests were started, which consisted of a constant rate outflow (pressure drawdown) phase followed by pressure recovery. Figure 2.10 shows a schematic overview of the test phases and the corresponding durations of such a standard hydrotest.

Most of the open hole tests were performed as interference tests (only one well is produced and pressure is observed in all the other closed boreholes). Open hole tests over the complete borehole length could only be performed systematically and successfully, because only a limited number of discrete and closely spaced conductive
structures were crossed by the borehole. Otherwise packer tests for separating highly transmissive zones would have had to be used more often.

In most cases pressure was recorded with the piezoelectric pressure transmitters at intervals of 1 second. Only few tests (K4W and K7W) were executed with simple manual pressure readings from the analog pressure gauges.

As shown on Figure 2.9 the flow phase of the hydrotest was controlled by opening a ball valve connected directly to a flange welded on the stand pipe. As with this test setup a complete opening of the ball valve would result in an instantaneous pressure drop followed by a strongly decreasing flow rate, it was decided to open the valve during the drawdown phase only partly. The outflow was continuously monitored with a normalized barrel and a watch (error: ± 0.1 l/s at a flow rate of 5 l/s). It was found empirically that the flow rate should be approx. 1/5 of the initial open hole flow rate but, because of disturbances of the pressure sensor and strongly decreasing flow rates during the drawdown phase, maximum 6 l/s. With this reduced flow rate, the outflow rate is nearly constant during the pressure drawdown phase, as shown in Figure 2.11, Figure 2.12, Figure 2.14 and Figure 2.15. Once the ball valve is opened partly, manipulations on the valve during the drawdown phase are unfavorable, resulting in stepwise pressure reactions. The interpretation of hydrotests performed in this manner is more difficult to analyze than the interpretation of a constant rate test (e.g. Krusemann and de Ridder, 1994). A compilation of all performed open hole hydrotests is presented in Attachment C of this thesis.

2.5 On – Site Test Analysis

2.5.1 Test Interpretation Method – Linear Approximation

The tunnel responsibilities were interested mainly in an estimation of the important aquifer parameters transmissivity T, storativity S and the initial formation pressure $p_i$ to decide if the excavation of the tunnel after a drilling campaign was finished can be continued, or, if additional action such as increasing the amount of exploration
boreholes, preparation for a grouting campaign etc. has to be taken. This decision relied mainly on the determination of the transmissivity $T$ together with a detailed inspection of the core recovery. As the hydrotest interpretation had to be accomplished on site within 12 h an interpretation method had to be applied which was simple and fast and which considered the following characteristics of the aquifer:

- Fractured and faulted limestone. The water flow in the Doldenhorn Nappe is controlled by two sets of brittle faults. One set with a dip direction to NW – SE and a dip of approx. 80° and one set with a dip direction SW – NE and a dip of approx. 30°. A detailed description of the aquifer properties is given by Pesendorfer and Loew (2006).

- Confined. It was assumed that during the drawdown phase no significant lowering of a free water table in the fractured aquifer occurred. Additionally, it was assumed that flow takes place only in the planar fault zones and the fluid stored in the matrix does not strongly interact with these fractures during the drawdown and build up phase of the hydrotest.

For a rough estimation of hydraulic properties it was assumed that a confined, homogenous and isotropic fracture zone of uniform transmissivity intersected the borehole at a large angle generating radial flows towards the well. This assumption is equal to the aquifer assumptions made by Theis (1935) to solve the diffusion equation. If it is assumed that a lowering of the free aquifer table can be neglected during a test with a horizontal borehole crossing a conductive fracture approx. perpendicular to the exploration borehole the only major difference between a “Theis” – Aquifer and a horizontally crossed fracture is the angle between the borehole and the fracture. If the fracture is crossed parallel by the borehole, the flow field during the hydrotest is not radial flow but linear flow (Horne, 2000). Pesendorfer and Loew (2006) describe in detail with examples pressure reactions following linear flow in the LBT aquifer. The study also showed that there is no major difference in the resulting parameters of $T$ and $S$ compared to the Theis method.

The extent of the permeable faults could not be determined during exploration drilling. From transient pressure reactions rough estimations of the vertical extent of
the permeable faults could be derived ranging in the order of several hundred meters to several kilometers. The extent of permeable faults is discussed in detail in Pesendorfer and Loew (2006).

Figure 2.10 shows the idealized flow rate and pressure reactions for an idealized constant flow rate and pressure build up phase. First estimations of the hydraulic parameters based on the drawdown data transmissivity (active and observation boreholes) and storativity (observation boreholes) were derived with the method of Jacob (Cooper and Jacob, 1946). For the ideal aquifer of the type described above the log of time vs. drawdown during production leads to a straight line in which the slope is proportional to fracture transmissivity.

With Jacob’s method the transmissivity \( T \) [m²/s] can be calculated:

\[
T = \frac{2.3 \cdot Q}{4 \cdot \pi \cdot \Delta s}
\] (2)

Where \( Q \) is the flow rate and \( \Delta s \) is the drawdown during a decade of time. The method can be applied in active as well as in observation boreholes. As Jacob’s method is a straight line approximation of the pressure reaction the validity of the approximation has to be checked. Todd (1959) states that Jacob’s semilog method is valid for \( u < 0.01 \) whereas

\[
u = \frac{r^2 \cdot S}{4 \cdot T \cdot t}
\] (3)

Krusemann and de Ridder (1990) state that \( u < 0.01 \) is a rather rigid condition for the applicability of Jacob’s method and suggest to use \( u < 0.1 \) as a practical condition. The error introduced in the result of using \( u < 0.1 \) is less than 5% compared to \( u < 0.01 \). For the LBT hydrotest analysis the restriction \( u < 0.1 \) always was fulfilled.

If the fracture zone in between the active and observation boreholes can be treated as homogenous a storativity value \( S \) can be estimated from the observation borehole
pressure reaction with a simple straight line method after Jacob (Cooper and Jacob, 1946):

\[ S = \frac{2.25 \cdot T \cdot t_0}{r^2} \]  

(4)

Where T is determined with (2), \( t_0 \) is the point where the Jacob regression line of the drawdown intersects the time axis at \( s = 0 \). The distance \( r \) between water inflows into the boreholes was roughly estimated from the geometry of the boreholes. In Pesendorfer and Loew (2006) a more precise method based on vector geometry to determine the distance between water inflows into the boreholes is presented.

Based on the build up pressure data, transmissivity could be derived from active as well as from observation wells. The build up pressure data were analyzed with the Theis recovery method Theis (1935), (e.g. in Krusemann and de Ridder, 1990). For the ideal aquifer type the log of \( t/t' \) (\( t \): time since the start of the drawdown phase; \( t' \): time since the end of the drawdown phase) vs. build up during pressure recovery leads to a straight line which the slope is proportional to fracture transmissivity. For determining aquifer parameters on the base of a pressure recovery, sometimes it is suggested to use an analysis method developed by Agarwal (Agarwal, 1980). This method was introduced mainly to apply type curves for analyzing pressure drawdown reactions directly on recovery data. As type curve analysis was not considered, determined transmissivities based on the Theis and on the Agarwal method were equal, and the Theis method is slightly simpler to apply, we choose this analysis method.

Figure 2.11, Figure 2.12, Figure 2.13, Figure 2.14, and Figure 2.15 show 5 pressure reactions of tests performed in boreholes K10WA, K15EA, K15EB, K13EA and K13WB. All figures show the complete pressure reaction (drawdown and build up phase), the flow rate during the drawdown phase (except Figure 2.13) and the corresponding semi – log plot of the drawdown phase. In Figure 2.11, Figure 2.12, Figure 2.14, and Figure 2.15 the pressure reactions of the active borehole is shown while Figure 2.13 presents the pressure reaction of the observation borehole (active borehole shown in Figure 2.12). As seen in Figure 2.12, Figure 2.13, Figure 2.14,
and Figure 2.15 the semi–log plot of time versus drawdown has a strong deviation to the straight line. This deviation was observed in many other tests. Under such conditions it can be difficult to find the correct straight line in the semi–log plot and it can often not be pointed out exactly, where the straight line begins and where it ends. First estimate T and S values were determined by fitting a straight line manually through the selected points. Therefore the determined T and S values can be regarded as rough estimate values only.

In Pesendorfer and Loew (2006) we present a more sophisticated analysis method – so called diagnostic plots – for determining the straight line section in curved semi–log plots.

First estimate initial formation pressures $p_i$ were determined from analogue pressure gauge readings during drilling and from piezoelectric transmitter data from the end of the pressure build up phase before gate valves were opened to initiate the pressure drawdown phase of the hydrotest (Figure 2.10). Equilibrated $p_i$ was assumed when pressure was changing for less than 0.05 bar during an interval of 200 seconds.

### 2.5.2 Results

#### 2.5.2.1 Selected Examples of Transient Pressure Tests

With 5 selected examples (Figure 2.11, Figure 2.12, Figure 2.13, Figure 2.14, and Figure 2.15) we will demonstrate the analysis method of the hydraulic tests.

Figure 2.11 shows the pressure test results of the active borehole K10WA. Based on the straight line fit of the drawdown phase a transmissivity of 2.50E-5 m$^2$/s is determined, $T$ determined based on the build up phase (not shown in the figure) is 2.3E-5 m$^2$/s. The determined storativity of the observation borehole (K10WB) is 2.60E-7. Initial pressure estimates are 24.8 bar, based on manual pressure gauge readings at the start of the hydrotest.

On Figure 2.12 and Figure 2.13 the pressure reaction of an active borehole (K15EA) and of an observation borehole (K15EB) can be compared. Before the pressure
disturbance due to the blasting event in the other tunnel occurs, borehole K15EA shows a total drawdown of 236.7 m while K15EB shows only 72.2 m. The shape of the drawdown curves in the semi – log plot differs but the slope of the radial flow period (for determining the transmissivity) is comparable. T determined based on the drawdown of the active borehole is 1.65E-5 m²/s, based on the drawdown of the observation borehole it is 1.24E-5 m²/s. The transmissivity determined based on the build up curves is 3.90E-5 m²/s and 1.10E-5 m²/s respectively. The determined storativity is 3.70E-6. Initial pressures were estimated from manual pressure gauge readings at the start of the hydrotest to be 48 bars for both boreholes.

While a straight line on the semi – log plot of the drawdown phase of the pressure test in borehole K13EA (Figure 2.14) can be determined between 6 and 80 seconds, the determination of a straight line on the semi – log plot in Figure 2.15 (borehole K13WA) is not clearly defined. If radial flow is assumed between 120 and 600 seconds, the transmissivity is 1.30E-5 m²/s. A straight line fit based on the build up curve where the radial flow period is clearly definable, results in a transmissivity of 1.05E-5 [m²/s]. Further analysis with diagnostic plots (Pesendorfer and Loew, 2006) indicated that the pressure reaction in borehole K13WA is strongly influenced by a constant pressure boundary and shows a radial flow period (= straight line) only in a narrow transition interval.

2.5.2.2 Comparison of Open Hole & Packer Test Results

To demonstrate the reliability of the open hole test analysis, results from an open hole test performed in borehole K12EB were compared to a packer test performed in the same borehole. K12EB showed two inflows into the borehole: at a depth of 50 m with 0.5 l/s (measured through the drill string, without core catcher) and at a depth of 75 m with 4 l/s. The measuring interval of the open hole test was from 20 m depth to 242 m while the single packer tested an interval from a depth of 61 m to 242 m. Therefore, the structure with the inflow of 0.5 l/s was not included by the packer test setup. Figure 2.16 shows a comparison between two pressure reactions (drawdown and build up phase) performed in borehole K12EB. Because of different outflow rates during the two hydrotests, the drawdown pressure reactions were normalized by the
flow rate (drawdown divided by flow rate). Similar to the drawdown phase, the build up phase was normalized by the arithmetic mean of the flow rate, measured during the drawdown phase.

It can be recognized, that the slope of the “straight line” section of both pressure reactions (drawdown and build up phase) is nearly identical. The drawdown difference in the two normalized datasets is based on a not exactly determined flow rate. If the flow rate of the packer system is decreased by 20 %, the drawdown pressure reactions match good. The flow rate of the open hole hydrotest was determined with a normalized barrel and a stop watch in intervals of approx. 10 minutes while the flow rate of the packer test was determined with an inductive flow meter in intervals of 5 seconds. The accuracy of the flow meter is not known, but both flow rate determination systems surely contain an error (guess: approx. 10 %).

As is derived from the slope of the straight line, values of both tests must be comparable. Results from the open hole test were $T = 3.90E-5 \text{ m}^2/\text{s}$ for the drawdown phase and $T = 4.20E-5 \text{ m}^2/\text{s}$ for the build up phase. Best fit values from the packer test were $T = 4.65E-5 \text{ m}^2/\text{s}$ for the drawdown phase and $T = 3.61E-5 \text{ m}^2/\text{s}$ for the build up phase (values given by the contractor). Therefore, taking into account the inherent uncertainties in transmissivity estimation, the $T$ – values, determined by two completely different measurement systems, lead to a nearly equal dataset with no significant differences. The storativity was not compared in this study as only pressure reaction data of an active borehole was taken into account where only transmissivities were determined.

Based on these findings, we concluded that the transient open hole tests performed over the whole length of the borehole can be applied to the test the aquifer at the LBT accurately if only one or two inflows dominate the inflows along the borehole length. The results are comparable to values determined from much more complicated and costly packer tests.
2.5.2.3 Transmissivity, Hydraulic Conductivity, Storativity and Formation Pressure Estimates

*Figure 2.17* shows a compilation of all first estimated formation pressures and straight line determined transmissivity and storativity values for the West – and East – tunnel. In another study (*Pesendorfer and Loew, 2006*) it could be demonstrated that determined formation pressures are “real” pressures and not influenced due to tunnel excavation or other activity in the tunnel.

Horizontal bars in *Figure 2.17* represent the open borehole interval corresponding to the determined values. If drawdown and build up phases of hydraulic tests could be analyzed or, if more than one drawdown and build up phase were performed in one borehole (e.g. hydrotests in boreholes K8Wx) transmissivity values in *Figure 2.17* represent the arithmetic mean values of all determined values.

To determine a mean hydraulic conductivity $K$ of a specific tunnel interval length, the determined transmissivity $T$ in a hydrotest can be divided by the borehole length $l$. Despite of a possible application of this simple method to all borehole tests, it was decided to only compare $K$ – values of hydrotests with approx. equal borehole lengths. For selecting the most occurring borehole length of reliable hydrotests (K11E to K16E in the East – tunnel and K8W to K14W in the West – tunnel) a histogram with an interval length of 25 m was plotted resulting in an outstanding peak of 12 borehole lengths for an interval of 287.5 to 312.5 m. $K$ – values were determined from boreholes K14EA & B, K15EA & B, K8WA & B, K10WA, K11WB, K12WA & B, K13WB and K14WA. Resulting $K$ – values are plotted along the tunnel axis in a semilog diagram together with a geological cross section in *Figure 2.18*. 
2.6 Discussion

2.6.1 Discussion and Interpretation of the Calculated Hydraulic Parameters

Inflow rates measured during drilling (with drilling rods in the borehole, but without core catcher) range from 0.1 l/s to 25 l/s. Inflow rates measured after drilling in open hole conditions yielded outflow rates which were systematically higher (Figure 2.4). This implies that clogging and friction losses in the annulus and drill bit can often not be neglected.

Several tunnel intervals up to 750 m length showed no or very few borehole inflows corresponding mostly to no or very few tunnel inflows.

These intervals are not related to zones which were predicted as zones of low permeability (e.g. Öhrli – Marl in the East – tunnel between TM 26900 and 27090 and TM 27204 and 27420).

Regarding the relative position of the tunnel faces of the two tunnels, one tunnel was the leading and one the lagging tunnel. Based on this fact, one could assume that water inflows into the lagging tunnel were generally smaller than into the leading tunnel because of the excavation process performed in an already drained rock mass. First, this assumption is not valid for inflows into the exploration boreholes. No systematic reduction in the borehole outflow was observed when performing a borehole from the lagging tunnel. E.g. inflows into boreholes drilled from the lagging West – tunnel between TM 25978 and TM 27446 are significantly higher than into boreholes drilled from the leading East – tunnel in the same interval (Figure 2.4). As the horizontal borehole drilled from the lagging tunnel usually was longer than the distance between the two tunnel faces, inflows were still measured in non affected or only weakly drained locations of the rock mass. Second, the same observation was made for inflows into the tunnels. In the same interval discussed above, inflows into the lagging West – tunnel were significantly higher than into the (sometimes more than 100 m) leading East – tunnel. A simple explanation of drainage effects of the
tunnels is therefore not possible probably because of water inflows related to a complex and heterogeneous fracture network on a local scale.

The **pressure reaction** during the hydrotest can be influenced by dissolving gas. Only during two tests (K9WA, K9WC) this phenomenon has been observed. *Pesendorfer and Loew (2006)* discuss in detail the effect of dissolving gas during a hydrotest. Pressure reactions are also influenced by a non–constant outflow rate and a non equilibrated system.

Comparing **Fluid Pressures** with the local topography clearly shows that the pressure distribution at tunnel elevation does not follow the overburden. Conspicuous low pressures in both tunnels between TM 26500 and TM 27600 can only partly be explained due to a lowering of the hydraulic head in this interval caused by the old Lütschberg Crest Tunnel (built: 1908). This old tunnel is located in the interval of low pressure head in a vertical distance 400 m above the base tunnel with a horizontal distance of 300 to 400 m. With increasing horizontal distance from the base tunnel to the crest tunnel caused due to a curve in the crest tunnel to the South East, hydraulic heads determined in the base tunnel are approaching the elevation of the topography (Gastere Valley).

Relating fluid pressure values to the relative positions of the two tunnel faces show that estimations of fluid pressures can also be performed in the lagging tunnel yielding similar values as measurements performed at the same locations in the leading tunnel. A detailed explanation is presented in *Pesendorfer and Loew (2006)*.

For both tunnels, **transmissivity** values range from 2.8E-4 m²/s to 4.5E-6 m²/s. This narrow range of T - values is related to the long length of the test intervals in relationship to the spacing of conductive fractures. *Ostrowski et al., 1992*, present T - values from double packer tests at the Wellenberg Site, Switzerland (*NAGRA, 1997*) having a test interval length of 2.2 to 178.9 meters. Here 42 packer tests in 3 vertical boreholes were performed in the Valanginian Marls. These marls can be compared, under restrictions (the Valanginian Marls are more dense and less fractured) to the
Öhrli – Marls of the Doldenhorn Nappe. T - values in the 42 tests range from 1.7E-5 m²/s to 2.8E-13 m²/s.

Storativity values range for both tunnels from 1.7E-5 to 8.7E-8. Based on the analysis method, these values must be regarded as estimation only. In Pesendorfer and Loew (2006) we will present more reliable S – values based on a more sophisticated analysis method.

Comparing selected hydraulic conductivity values along the tunnel axis (Figure 2.18) shows a variation of the K – values of only approx. one order of magnitude along an interval of approx. 2 km of tunnel. As these selected values are dependent mainly on the determined transmissivities – which remain in a quite narrow interval – it is no surprise that the K – values do not vary over orders of magnitude. The range of the K – values is 2.65E-7 to 1.48E-8 m/s. As will be shown in Pesendorfer and Loew (2006) the transmissivities determined during this study do not show great variation when determined with more advanced methods. The K – values can therefore be regarded as reliable. No significant difference in the K – values between the formation of the Quinter Limestone and the Öhrli – Marl can be observed. As mainly major structures are tested by the hydrotests (see Pesendorfer and Loew, 2006) the determined K – values are related to these major structures which are similar regarding their hydraulic conductivity.

Comparing tunnel inflows with borehole inflows indicates that mainly – but not only – structures of low permeability were not detected by the exploration program. The not detected maximum inflows of 40, 15 and 10 l/s in the West – tunnel are based on the fact that in this section only one central borehole was drilled from a niche in between the tunnels.

The detection efficiency of a water bearing structure is increasing with its inflow rate: With only one borehole along the tunnel axis the biggest inflow missed had a flow rate of 6 l/s, with two parallel boreholes 3 l/s, 80% of the missed inflows were smaller than 1.0 l/s.
Based on the analysis of the detection efficiency it can be concluded that performing a long, central borehole between the tunnels is probably not an accurate measure to detect water containing structures. The detection efficiency increased significantly with the number of boreholes drilled. With two parallel boreholes in only one case a water bearing structure with an initial inflow rate bigger than 5 l/s was missed completely; with only one borehole at several locations (TM 25500 – 25550 West – tunnel). With more than two exploration boreholes the detection efficiency again increases strongly.

The exact prediction of the locality of an inflow into the tunnel was in many cases not possible with the applied exploration program. Due to hydraulic heterogeneity 52 % - 78 % of the tunnel inflows were detected properly within ± 5 m with the exploration boreholes. If the orientation of the conductive fractures and fault zones would rotate from a dip angle of 20° - 30° to a steeper angle (> 60°) the localization of such structures would have been better.

2.6.1.1 Limitations of the method

Although many important results could be gained through the application of these open hole pressure tests, the method applied in this exploration program also has its limitations, discussed in the following paragraphs.

2.6.1.2 Range of Possible Borehole Outflow Rates

If the water flow into the borehole is smaller than 0.1 l/s, no constant outflow rate can be controlled through the gate valve. Such small open hole outflow rates can be caused by fracture zones of limited extent, or low transmissivity.

If the open hole water flow is in the range of 0.1 l/s to about 0.02 l/s the aquifer properties can be determined e.g. by a slug test. Cooper et al. (1967) present a method for analyzing slug tests. The disadvantage of all slug tests is that they generally cannot be analyzed with simple straight line analysis methods similar to constant rate tests but require a curve – matching procedure.
It has been observed during several flow tests that an outflow rate > 10 l/s through the gate valve is difficult to control. Equipment (e.g. hoses, gaskets) can be damaged through a highly turbulent flow probably mixed with sand and rocks. An outflow rate of 10 l/s can therefore be regarded as the upper limit of constant rate outflow tests possible with the equipment used at the Lötschberg Base Tunnel. In practice because of increasing noise and shaking of the logger during the hydrotest no flow rate during the drawdown phase > 8 l/s has been applied.

2.6.1.3 Multiple Inflows of Similar Size

For an open-hole hydrotest it has to be kept in mind, that the aquifer parameters calculated from the test represent a complex weighted mean of all the water bearing structures intersected by the exploration borehole. At the LBT test program 80% of the tested boreholes showed one dominant structure, hydraulic parameters derived from the open hole hydrotest are therefore dominated by this structure. If more than one comparable inflow is encountered during the drilling process the open hole test can still be performed as long as the static heads (or pressures) in these structures do not differ much and the structures do not interfere. The determined T value from such a test is an estimation of the summed transmissivity. In this case packer tests to separate transmissive intervals would lead to clearer results.

2.6.1.4 Outflow Tests in Sediment Filled Structures

If a water bearing structure is filled with coarse sediment (Ø > 5 mm) such as in karstified pipes the production phase of the hydrotest can flush out rocky material which can plug the borehole or the gate valve. In that case the outflow rate can no longer be kept constant; a strongly pulsating pressure signal is the consequence. In such a case usually only the pressure build up phase can be used for an analysis.
2.6.2  Recommendations for Tunnel Site Engineers and Geologists

In this paragraph we present some recommendations to tunnel site engineers or geologists who have to perform hydraulic tests in fractured rocks under high overburden based on our experience in the Lötschberg Base Tunnel.

2.6.2.1  Pre Test Phase

- All water inflows into the borehole have to be recorded by the drilling crew quantitatively (flow rate, position of inflow). *Reason:* Determine dominant inflows along the borehole; decide if open hole tests are accurate to perform or if packer tests have to be used.

- A free outflow rate has to be determined before the hydrotest. During the measurement one has to make sure that no drilling material (drill string, core catcher etc.) remains in the borehole. The gate valve has to be opened completely for a few minutes. Flow rates can be determined with a barrel and a stop watch. *Reason:* A determined free outflow rate is necessary to estimate an outflow rate during the drawdown phase of the hydrotest.

- All boreholes have to be kept closed during the pressure build up phase before the test for at least 2 h. A test in a non equilibrated hydraulic system (still increasing pressure at the beginning of the drawdown phase) is difficult to interpret. *Reason:* when the aquifer is in equilibrium, a subsequently performed hydrotests is much easier to interpret.

- All manipulations to the boreholes have to be recorded (exact time to the second) at least 4 h before starting the hydrotest. *Reason:* the borehole history is important for an advanced analysis of a hydrotest.

2.6.2.2  Drawdown Phase

- All other boreholes, except the active one, have to be kept closed during the test. *Reason:* a hydrotest, disturbed by occurring outflow from other boreholes than the active one is difficult if not impossible to interpret.
• The gate valve has to be opened rapidly. *Reason:* the first minute in a hydrotest in an aquifer with hydraulic parameters as ours contains crucial information about the formation around the borehole. If the gate valve is opened slowly, the first pressure response from the aquifer is overlain by a non constant flow rate which can result in a very complex pressure response.

• The flow rate should be approx 1/5 of the open hole flow rate but max. 6 l/s. *Reason:* empirically determined values; min. 1/5 of the open hole flow rate to guarantee a constant flow rate and a drawdown which is large enough to analyze, max. 6 l/s because of disturbance of the pressure signal by highly turbulent flow and a non constant outflow during the hydrotest if the flow rate is too large.

• A constant outflow rate is more important than reaching the exact flow rate planned previously. *Reason:* manipulations on the gate valve (open / close) during the hydrotest result in a non constant outflow rate which affect the pressure reaction of the aquifer. Such hydrotests are more difficult to analyze than hydrotests with a constant flow rate.

• Flow rate measurements are best to be performed in an interval of 5 minutes in the first ½ h of the drawdown phase, later, intervals of 10 minutes are sufficient. *Reason:* As aquifer pressure response data are analyzed mostly with semi – log plots, early time data close to the start of the drawdown phase are more important than late time data.

• Fluid pressures should be recorded in short time intervals of one second during the first 2 minutes of the drawdown phase. During later times the measurement frequency can be increased. *Reason:* as above

• All disturbances due to manipulations in the tunnel (e.g. blasting events in the other tunnel etc.) have to be, if possible, avoided, or the time has to be recorded down to the second. *Reason:* conspicuous pressure reactions can probably be related to an event in the tunnel, if the time of a certain event is known.
2.6.2.3 Build Up Phase

- As in the drawdown phase, the first two minutes after shut in require very high frequency pressure measurements. *Reason:* as above

- Record all disturbances down to the second. *Reason:* as above

2.6.2.4 Equipment

- Fluid pressures in the active (and eventually passive) borehole should be recorded with a high precision digital pressure transducer, during all three test phases.

2.7 Summary

During tunnel excavation of the Lötschberg Base Tunnel, while crossing the Limestones of the Doldenhorn Nappe, we were able to gain unique hydrogeological data sets from a large number of hydrotests performed in horizontal exploration boreholes drilled through the tunnel face. The equipment used was simple and low cost (one pressure transmitter ≈ 700 Euro) but lead to a dataset of equal or better quality than determined with costly packer tests. As normally only one, two or maximum three closely spaced and discrete transmissive zones were intersected by boreholes of approx. 300 m length, open hole pressure tests could be successfully performed in most of the drilled boreholes. For characterizing individual transmissive or complex zones, packer tests were used.

Single and crosshole pressure responses gave very valuable indications for local and far field hydraulic transmissivity, storativity, connectivity of permeable features and static pressure head distributions. Based on a careful and on site quick – look analysis of the hydrogeological dataset, zones of potential high hydraulical risk, e.g. highly conductive fractures or open karst holes, could be identified. Decisions taken by the tunnel engineers for the ongoing excavation process were successfully based on these hydraulical data.
Already simplified data analysis could demonstrate that only few transient pressure reactions can be explained with radial flow in a homogenous aquifer of infinite extent.

It could be demonstrated that formation pressures do not follow the overburden. Low pressure heads can be partly explained with the influence of the old Lötschberg crest tunnel on the regional aquifer. It could be shown that the excavated tunnel tubes of the LBT do not interfere with measurements of the hydraulic heads in the exploration boreholes.

Comparing detected inflows into the exploration boreholes with inflows in the later excavated tunnel allowed conclusions with respect to the detection efficiency of transmissive structures in different types of exploration borehole setups.

It could be demonstrated that the detection efficiency is strongly dependent on the flow rates and location and number of exploration boreholes.

Selected determined K – values based on transmissivities show only a variation of one order of magnitude along a distance of approx. 2 km of excavated tunnel. This narrow interval of K – values is an indicator of a ± homogenous fractured rock mass on a large scale.

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2.10 Figures

Figure 2.1 Location including simplified geological surface map with main lithostratigraphical units (after Kellerhals and Isler, 1998) of the Lötschberg Base Tunnel with indicated study area.
Figure 2.2  Detailed geological cross section of the study area including lithostratigraphical sub – units, tunnel axis and start as well as end point of the exploration program.
Figure 2.3  Ground plan of the tunnel (East – and West – tube) with transversal gallery and exploration concept
Figure 2.4  Initial inflow rates for the East – and West tunnel. Squares represent the location of a flow rate determined during the drilling phase, i.e. measured with drill string in the borehole, but without core catcher. Crosses, including horizontal bars, which indicate the open borehole length, represent the flow rate measured at the borehole head, without drill string.
Figure 2.5  Karst hole, excavated in the West – tunnel at TM 26900 (normalized to the East – tunnel). The structure has a height of 1.5 m and a width of 0.5 m.

Figure 2.6  Brittle fault zone in the West – tunnel in direct connection to a karst system at TM 27183 (normalized to the East – tunnel. The picture has a height of approx. 2 m and a width of approx. 3m.
Figure 2.7 Tunnel inflow rates vs. borehole inflow rates, determined in the East–tunnel, divided into values measured in the leading and the lagging tunnel. The hatched area represents the simulated water inflow into a tunnel / borehole from a homogenous, isotropic aquifer with realistic parameter assumptions comparable to the LBT limestone aquifer.
Figure 2.8  Tunnel inflow rates vs. borehole inflow rates, determined in the West–tunnel, divided into values measured in the leading and the lagging tunnel. The hatched area represents the simulated water inflow into a tunnel / borehole from a homogenous, isotropic aquifer with realistic parameter assumptions comparable to the LBT limestone aquifer.
Figure 2.9 Explosion drawing of the equipment mounted on the stand pipe. Partslist: 1) Standpipe 2) Reducer (G3/4" to G1/4") 3) Pressure Sensor and Data Logger 4) T – Piece (G3/4") 5) Pressure Gauge 6) Flange with two G3/4” outlets 7) Cap for sealing the standpipe 8) Pipe with two G3/4” threads 9) Ball Valve G3/4” 10) Nut G3/4”, connection to hose 11) Hose
Figure 2.10  Idealized pressure reaction of a hydrotest with pressure stabilization -, drawdown – and build up phase including corresponding time durations applied in the test campaign
Figure 2.11  Pressure reaction incl. flow rate of active borehole K10WA in a linear plot (upper diagram). For clarification only every 20’sest point of the pressure reaction was plotted. The corresponding drawdown incl. straight line fit (semi – log plot) is shown in the lower diagram.
Figure 2.12 Pressure reaction incl. flow rate of active borehole K15EA in a linear plot (upper diagram). For clarification only every 20’iest point of the pressure reaction was plotted. A blasting event in the other tunnel can be seen clearly in the pressure reaction. The corresponding drawdown incl. straight line fit (semi – log plot) is shown in the lower diagram.
Figure 2.13  Pressure reaction incl. flow rate of observation borehole K15EB in a linear plot (upper diagram). For clarification only every 20’iest point of the pressure reaction was plotted. The corresponding borehole (active borehole) of borehole K15EB is K15EA. The corresponding drawdown incl. straight line fit (semi – log plot) is shown in the lower diagram.
Figure 2.14 Pressure reaction incl. flow rate of active borehole K13EA in a linear plot (upper diagram). For clarification only every 20’iest point of the pressure reaction was plotted. The corresponding drawdown incl. straight line fit (semi – log plot) is shown in the lower diagram.
Figure 2.15  Pressure reaction incl. flow rate of active borehole K13WB in a linear plot (upper diagram). For clarification only every 20’iest point of the pressure reaction was plotted. The corresponding drawdown incl. (doubtful) straight line fit (semi – log plot) is shown in the lower diagram.
Figure 2.16  Comparison between a packer test and an open hole hydrotest performed in borehole K12EB. The drawdown phase is plotted in the upper diagram, the build-up phase in the lower diagram.
Figure 2.17  T and S values determined based on the straight line analysis. Initial fluid pressures represent mostly values which were determined by manual pressure gauge reading before the start of the hydrotest. Horizontal bars indicate the open borehole length.
Figure 2.18  Selected K – values plotted along the tunnel axis.
### Table 2.1

Exploration boreholes performed from the East – Tunnel. **Name:** Bohrehole Identification; **TM-S:** Start location of borehole (Tunnel meter); **TM-E:** End location of borehole (Tunnel meter); **L:** length of borehole [m]; **CB:** Cored borehole; **DB:** destructive borehole (with inhole hammer); **Ø:** diameter of borehole (NQ = 76 mm; HQ = 96 mm); **OH-A:** No. of open hole hydrotests in active borehole; **OH-O:** No. of open hole hydrotests in observation borehole; **PT:** No. of packer tests.

* Tests performed without electronic logging equipment; pressure reaction measured with analogue pressure gauges.

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Table 2.2  Exploration boreholes performed from the West – Tunnel. **Name:** Bohrehole Identification; **TM-S:** Start location of borehole (Tunnel meter); **TM-E:** End location of borehole (Tunnel meter); **L:** length of borehole [m]; **CB:** Cored borehole; **DB:** destructive borehole (with inhole hammer); **Ø:** diameter of borehole (NQ = 76 mm; HQ = 96 mm); **OH-A:** No. of open hole hydrotests in active borehole; **OH-O:** No. of open hole hydrotests in observation borehole; **PT:** No. of packer tests.

* Tests performed without electronic logging equipment; pressure reaction measured with analogue pressure gauges.

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*Table 2.3* Statistical analysis of the location of determined initial tunnel inflows to the excavation zone and the location of borehole inflows.
3.

Transient Pressure Testing in Horizontal Boreholes Drilled from a Deep Alpine Tunnel (Lötschberg Base Tunnel, Switzerland)

M. Pesendorfer and S. Löw
3.1 Introduction

The aim of this article is to present hydrological test data from horizontal boreholes drilled from a deep tunnel which were used to characterize a limestone aquifer over a length of 3.2 km. It will be shown that major aquifer parameters such as transmissivity, storativity and undisturbed formation pressures determined with simple methods are similar to parameters determined with advanced analysis methods. An analysis method, developed in the oil industry for pump tests will be used to define various flow phases in the pressure reaction of the aquifer during a hydrotest, from early time flow characterization to late time boundary effects. As conductive structures characterized by a hydrotest could be described in detail in the later excavated tunnel, we were able to check predictions regarding the orientation of a conductive structure based on the hydrotest. This worldwide unique dataset is discussed in detail in this paper.

Many tunnels that are currently being built through the Alps have to cross fractured or karstified rocks at great depth and many hundred meters below the regional groundwater table. The detection and characterization of karstified zones, karst pipes and water-containing fractures ahead of the advancing tunnel face is vital for these projects. The determination of the spatial distribution of water pressures, transmissivities and storativities along the tunnel axes is of great practical interest especially in complex hydrogeologic situations.

In one of these tunnel projects, the partly double tube Lötschberg Base Tunnel (LBT), an intensive exploration program was executed during the excavation of a 3.2 kilometer (km) long section in fractured and potentially karstified limestone with a groundwater table located 400 to 600 meters (m) above the tunnel axis. The exploration program consisted of horizontal boreholes drilled from the tunnel faces along the tunnel axis with a length of approx. 250 to 300 m. Pesendorfer and Loew (2006a) describe in detail this drilling and testing program. Drilling took place in both tunnels, named West – and East – tunnel subsequently. Both tunnel tubes were surveyed in a separate metric system. To be able to compare structures between the
tunnel tubes, all locations discussed in this paper (those from the East - and the West –
tunnel) were normalized to the metric system of the East – tunnel. Locations are
indicated with the prefix “TM” which represents “Tunnel Meters”.

In total, 30 boreholes, 21 cored and 9 destructive with a total length of 7347 m were
drilled from the East – Tunnel and 32 boreholes, 28 cored and 4 destructive with a
total length of 6964.5 m were drilled from the West – Tunnel. One directional
borehole executed at the start of the exploration campaign was drilled from a niche
between the tunnels (distance from the tunnel axis: 20 m) with a length of 541 m.

In many boreholes hydraulic tests (mostly interference tests, between two or more
boreholes) were performed after completing the drillhole. In Table 3.1 and Table 3.2
an overview of the drilling program and the hydraulic tests is presented. The hydraulic
tests were generally performed as open hole constant rate tests, i.e. the test was
performed over the total open borehole length excluding a 20 m long standpipe
section. In some boreholes single packer tests were used to separate highly
transmissive zones from each other.

In the reviewed literature there are relatively few discussions about the utility of
horizontal boreholes preformed from underground excavations. Many of these focus
on in situ stress determination (e.g. Warren and Smith, 1985) or on geophysical
investigations (e.g. Carroll and Cunningham, 1980). There are even fewer studies that
discuss the application of hydraulic tests in horizontal boreholes performed from
underground excavations. Fransson and Gustafson (2000) describe hydraulic tests
executed in short (30 m) horizontal boreholes at the Äspö underground laboratory.
The target of the study was to identify conductive structures that require grouting. It
could be shown, that the major hydraulic conductors which required repeated grouting
were identified well. Gnirk (1993) presents an overview about hydraulic crosshole
and single-borehole tests preformed from horizontal, inclined and vertical boreholes
in the Stripa Mine, located in granite, Sweden. It could be shown that crosshole
hydraulic – interference tests are most valuable for locating highly conductive zones
in the rock mass between the boreholes, and for assessing directional hydraulic
conductivity over large distances. Vomvoris et al. (1992) summarize hydraulic
crosshole and single-hole results from the Grimsel research underground laboratory, located in fractured granite, Switzerland. Pressure – recovery and constant – head injection tests were performed in inclined boreholes (-10° to -90°). Strong evidence was found that the flow system is complex and hydraulic boundaries affect the pressure response.

On the other side, well tests in oil fields performed in boreholes drilled vertically from the surface and re-directed into flat lying oil bearing formations are commonly used in the oil industry. Interpretation methods for horizontal well tests in petroleum engineering are based on the assumption that a horizontal well penetrates a flat lying aquifer over a certain limited length and that the aquifer is limited by an upper and a lower confined or semi-confined boundary. Ozkan et al. (1987), Odeh and Babu (1990) developed methods to interpret horizontal well tests in oil fields. Kuchuk (1995) presented an overview of interpretation methods for horizontal well tests; Horne (2000) summarizes the methods in his book. Kawecki (2000) applies equations that relate the transient head in a horizontal well to a constant well discharge selected from the petroleum literature and converts them from the notation and eclectic system of units used in the oil industry to groundwater notation with consistent units.

The flow geometry of an upper and a lower confined or semi-confined boundary is not obvious for the LBT limestone aquifers. Here the individual marine formations are isoclinally folded, dissected by shear planes and rotated into North-plunging thrust sheets and folds. Most tunnel inflows are related to brittle faults crosscutting the exploration boreholes in two sets. One set crosses the exploration borehole at an angle of 20 – 30 °, the other set at an angle 60 – 90 °. These faults are sometimes karstified and have various thickness and lateral extent. Some of them penetrate the aquifer over more than 1 kilometer and reach ground surface. It was therefore assumed that also radial flow models derived for vertical boreholes could be applied to determine aquifer parameters and aquifer geometries.

The basic interpretation methods for well tests in vertical boreholes have been developed by Theis (1935), Cooper and Jacob (1946), Jacob and Lohmann (1952),
Horner (1951) and others. Streltsova (1988) presents an overview of the performance and interpretation of hydraulic well tests in heterogeneous and fractured aquifers.

In the second part of this paper we present the geological setting, the preferential groundwater pathways and the technical details of the hydraulic exploration program. In the third paragraph we present and discuss the conditions, in terms of experimental setup and hydraulic system properties of the hydraulic tests.

In Paragraph 3.4 we present the results of forward and inverse modeling of the hydraulic tests, taking into account wellbore storage, borehole history, fracture flow and various types of outer boundary conditions. For this rigorous analysis the code SAPHIR was applied to 18 hydrotests consisting of a constant rate outflow and a pressure build up phase. Sensitivity studies are related to pre – test flow events (borehole history) and the effect of a non constant flow rate during the drawdown phase. It will be shown that only 11 of the performed tests could be explained with a classical model approach such as storage and skin effects for the early time pressure response and an infinite acting radial flow period for the mid time response. 5 tests showed clear indications of a fracture dominated flow in the early time response and 2 pressure reactions could not be explained with a simple model approach.

3.2 Hydrogeological Setting and Pathways for Preferential Groundwater Flow

3.2.1 Hydrogeological Setting

Figure 3.1 shows the location of the Lötschberg Base Tunnel and a simplified geologic map. The tunnel crosses from north to south the Wildhorn Nappe, consisting of limestones, shists and sandstones (named “Flysch”) and the Doldenhorn Nappe consisting of limestones and marls (study area). Towards the south the tunnel crosses a short interval of autochthonous Triassic sediments consisting of sandstones anhydrites and shists. Further south the LBT enters the crystalline rocks (granites and gneisses) of the Aar Massif. Kellerhals and Isler (1998) present a detailed overview
about the area and the tunnel geology. In Pesendorfer and Loew (2006a) more literature references about the geology of the Lötschberg area are listed.

A longitudinal geological cross section of the study area is presented in Figure 3.2. The Doldenhorn Nappe consists of several lithostratigraphic sub units, which are (from north to south) the Kiesel - Limestone (limestone with silicified bands), the Öhrli - Limestone (limestone with low quartz content), the Öhrli - Marl (dark, partly clay rich limestone) and the Quintner - Limestone (dense, massive limestone with clear bedding).

Several catchments in the Doldenhorn Nappe have no or only reduced surface runoff. In the area “Filfalle” south of Kandersteg 13 karst springs can be identified. Except one, all these springs discharge at the elevation of the gravel filled valley floor. The flow rate of these springs is highly variable; some of them are only active during summertime. Kellerhals (1996) concludes that the strongly karstifiable Öhrli – Limestone is the main aquifer of these springs.

Many of these springs are located just above (zero to several m) the valley floor of the Kander valley. This valley was deeply incised by glaciers during the last glaciation period and subsequently filled with fluvial sediments and landslide material. In periods of high precipitation, it is thought that the water level in the Öhrli - Limestone increases, similar to a phreatic aquifer and the karst springs start to release water. The total flow rate of all springs in the Filfalle area varies between 350 and 2000 l/s. Another important spring in the Doldenhorn Nappe is the “Geltenbachquelle” in the Gastere Valley, a karst spring at the boundary Öhrli – Marl and Quintner Limestone. The flow rate of this spring (approx. 3000 l/s maximum) is highly variable in a daily and a yearly cycle. The Geltenbachquelle is part of a not completely explored karst system and described in detail in Gerber and Rouiller (1990).

During the 1990’s several detailed studies related to the hydrogeology of the Doldenhorn Nappe were performed including deep borehole drilling, detailed water chemistry analysis, tracer tests, monitoring of karst springs and numerical modeling.
The results of these studies are summed in Kellerhals and Isler (1998) and Lützenkirchen and Loew (2000).

These studies showed that the crossing of the Doldenhorn Nappe with its phreatic limestone aquifers included the risk of intersecting deep paleokarst structures at the level of the base tunnel. The potentially karstified limestones and marls of the Doldenhorn Nappe occur over a length of 2800 m on Base Tunnel level and are heavily folded and truncated by several fault zones. Northward plunging thrust planes exist which are potentially connected with the Gastere Valley and the Kander Valley (Figure 3.2). The Base Tunnel has to cross these valleys with a water level located 400 m (Kander Valley) and 600 m (Gastere Valley) above the tunnel level, respectively.

### 3.2.2 Observations during Drilling

During drilling, water inflows into the boreholes were continuously monitored by the drilling crew. Flow during core and destructive drilling into the borehole was measured with the drill string in the borehole but without core catcher. Pesendorfer and Loew (2006a) give detailed information about flow rate determination during the drilling process. It was found that flow rates determined with the drill string can be heavily reduced. The reduction is caused by friction losses in the annulus and the amount of reduction is dependent on the free outflow rate.

First detectable inflows into the borehole were usually observed in a certain distance (approx. 40 m) from the tunnel face, but could also occur as in one case, during drilling of the stand pipe. In only 4 boreholes four and more inflow locations were detected during the drilling period. Most of these inflows were clearly separated from each other, with distances > 10 m. In Pesendorfer and Loew (2006a) it could be shown that the influence (drainage) of the tunnel pipes to the location of water conductive structures can be neglected because water conductive structures crossed by the long horizontal drillholes had enough distance to the tunnel faces. From a total of 63 drilled boreholes, 60 could be analyzed semi quantitatively for early time inflow
rates into the boreholes. It was found that 49 boreholes showed only one dominant inflow, on 11 boreholes more than two inflows differed less than 50%.

In most cases formation water observed at the borehole head during drilling was clear. On two locations (TM 26876 and TM 27172) a karst system was crossed by several exploration drillholes under a dip angle of approx. 80°. The initial flow rate (measured with drill string, but without core catcher) at these locations was 12 and 5 l/s, respectively. Water from the karst system was mixed with sediments such as clay, silt, sand and/or gravel and was of slightly brown or red color. At TM 26037 an overthrusting fault with widened fractures due to rock solution was encountered in the West – tunnel. At that location, only sediments of small grain size (silt, clay) were flushed out and the water was of red color. In general it was observed that colored water is a strong indicator for higher conductive (widened) fractures or faults and that water mixed with clay, silt, sand or gravel is an indicator for (major) fault zones of a lateral extent of probably several km and/or karst cavities.

3.2.3 Observations on Core

While a new inflow could usually be located within 3 meters during the drilling phase by flow measurements, this inflow could only be related to a specific structure (fault, fracture) in the core recovery for 20% of all inflows identified during drilling. A correct determination of the orientation of the fractures was not possible as cores were recovered non-oriented. Additional to these restrictions, a structure identified in the core recovery which indicates fluid flow (e.g. alteration, infill etc.) is not necessarily a recently conductive structure. It is therefore more accurate to distinguish between potentially conductive fractures (fractures with alteration, infill etc.) and potentially dry fractures. Because of simplification terms as “potentially conductive fracture” will not be used subsequently and are replaced by “conductive structures” and “dry structures”.

For 80% of all encountered structures in the core recovery potentially related to an inflow location the borehole one could not distinguish between non conductive and conductive structures. These structures had no infill of clay, silt or sand, slickensides
were missing and a brown – red crystalline cover of the structures which could indicate paleo-fluid flow was not observed. Most of these structures were crossed by the exploration borehole under an inclination of 20° - 30°. It is assumed that these conductive structures have extensions of ten’s of meters and are rather mesoscale fractures than fault zones.

20% of the conductive structures could clearly be identified in the core recovery because of a red colored microcrystalline coverage of the fractures. This coverage consisted of micro-crystalline calcite and hematite of rusty color with a thickness of approx. 1 – 2 mm. No widening or solution voids were observed. These altered structures were crossed under the same inclination angle as non altered ones. Water flowing out from these structures was of a red color with few fine grained (clay, silt) additives. The structures were occurring rather in small networks (enlargement: several meters along the drilling axis) than as isolated single structures. In general, an increasing flow rate was observed at locations with conductive structures showing alteration.

Widening (mm – cm) due to rock solution was observed in 5% of all crossed conductive structures. Small karts caves (diameter approx. 2 – 3 cm) were observed in the core around these structures. In widened structures slickenside indicating overthrusting usually could be observed. Infill of clay, silt, sand or gravel was common. The limestone rock was bleached on some locations to a maximum depth of 5 cm. The inclination of these structures was comparable to previously described structures. Widened structures were highly conductive, with initial flow rates > 10 l/s. It is assumed that widened structures with slickenside and infill are brittle faults on a regional scale, probably in connection with the surface.

3.2.4 Observations during Tunnel Excavation

Kellerhals and Isler (1998) describe and name in their report 3 major fracture systems mapped on the surface. These systems are:
K1: Dip direction NW – SE, steep dip angle of approx. 80°. These structures represent
the regional major fracture set. It can be identified on the maps drawn by Furrer et al.
(1993) and Hügi et al. (1985).

K2: Dip direction NE – SW until WNW – ESE with variable dip angle (accumulated
structures with dip angles of approx. 30°).

K3: Dip Direction N – S, with steep dip angle. Often widely opened (dm – m) on the
surface.

After tunnel excavation, a detailed structural mapping campaign of the tunnel floor
was performed at selected locations in the East – tunnel. The East – tunnel was chosen
for the mapping campaign because the rock was not covered with concrete in contrast
to the West – tunnel. In total, 31 scanning windows of different size, mostly 10 m x 7
m between TM 25530 and TM 28385 were mapped in detail. 649 structures were
mapped and described during the campaign. 569 structures were “dry” i.e. did not
show any alteration or rusty cover due to fluid flow and were classified as “dry
mesoscale fractures”. Structures, where a microcrystalline calcite cover with hematite
(brown – red color) was visible, but which showed no widening or infill of clay, silt or
sand were classified as “conductive mesoscale fractures”. In probably more than 99 %
of the mapped structures no direct water outflow could be observed. Flow from
structures located on the tunnel floor was extremely seldom and only observed in one
or two cases. On most locations, water flow was observed on an undefined location
somewhere on the tunnel profile below the shotcrete. Equal to the explanations given
in Paragraph 3.2.3, the classification of conductive mesoscale fractures is based on
indirect observations such as fault gauge or alteration of a certain structure. It would
therefore be more accurate to describe the structures as “potentially conductive
mesoscale fractures” or “potentially dry mesoscale fractures” but equal to Paragraph
3.2.3 this description was abandoned because of simplification reasons. Figure 3.3
shows a stereographic plot of all mapped mesoscale fractures. Grey squares indicate
dry mesoscale fractures; black triangles indicate conductive mesoscale fractures.
Although scattering is large on the dry mesoscale fractures, two major sets can be
identified on the plot. One set with a dip direction to NW – SE and a steep dip
This mesoscale fracture set is parallel to the set K1 described by Kellerhals and Isler (1998). A second identified set shows a dip direction towards SW – NE with a dip angle of approx. 30°. It is parallel to the set K2. If the orientation of only conductive mesoscale fractures is considered in the analysis, scattering of the orientation of the fractures is even larger and no statistical relevant trend of orientation can be identified.

Based on the tunnel mapping and the geological description given by the site geologists, 25 brittle faults were described in the West – tunnel (between TM 26744 and TM 28565) and 17 in the East – tunnel (between TM 26970 and TM 28425). 80% of the described brittle faults occur as isolated single structure. The distance between single brittle faults was usually > 50 m. Only few single brittle faults showed a clear evidence of fluid flow. A map of geological structures, water inflows into the boreholes and the tunnels including the location of the horizontal drillholes is shown in Attachment H of this thesis.

Few small mesoscale fractures or brittle faults were usually connected to the single brittle fault, but the total extension of the conductive fracture network was usually not more than 10 m. 20% of the described brittle faults were part of a fault system of more than two ± parallel faults. These systems consisted of several minor faults and one major fault, strongly altered and bleached due to fluid flow with a fault gauge or fault breccia core of up to 250 mm thickness. Along two major fault planes karst systems were encountered during tunnel excavation (at TM 26876 and TM 27172, both in West - tunnel). The observation that major karst structures follow fracture structures is compatible with the approach developed by Grillot (1977) and Razack (1980). These authors assumed in hydrogeological models that the karst network should be organized in the same way as fractures are distributed. The karst caves in the LBT had a maximum diameter of 0.75 m and were filled with clay, silt, sand and gravel. The total outflow of the karst systems (including a surrounding conductive fracture network) was approx. 16 and 20 l/s, respectively. On some caves macro scale calcite crystals (approx. 0.5 cm long) were observed. Pesendorfer and Loew (2006a) show example pictures of karst caves and major fault planes in their article.
In the interval, where brittle faults were described in detail, summed initial inflow rates to the excavated tunnel (excavation zone) were compared to summed initial inflow rates from brittle fault zones. The expression “initial” stands here for a flow rate which was determined within 10 hours after a water conductive structure was blasted by the miners. For this calculation it is assumed that every inflow location mapped in the excavated tunnel can be related to exactly one structure producing water. In total, 176 inflows were located in the interval (East – and West – tunnel), producing a total initial inflow of 244 l/s. 25 (14%) of these structures are brittle faults producing 117 l/s (48%) initial flow, i.e. only few structures (brittle faults) in the Doldenhorn Nappe are responsible for ½ of the total determined flow rate.

*Figure 3.4* presents the orientation of all described brittle faults. The size of the plotted points is dependent on the initial flow rate from that structure. The orientation of the brittle faults is clearly divided into two major sets. These sets are parallel to the sets previously described for mesoscale fractures. It seems that the initial water inflow rate is smaller in the steep faults than in the shallow ones. The orientation of the shallow brittle faults is parallel to major overthrust planes, as indicated in *Figure 3.2*. In *Attachment H* we present a detailed description of all identified brittle faults.

Tunnel inflows from brittle faults in the West – tunnel (between TM 26744 and TM 28565) were monitored during a period of approx. 2 years after excavation (measurement interval approx. 2 weeks). It was observed that inflow rates showed a general decrease in the flow rate and stabilized independent from seasonal fluctuations in the hydraulic head, after approx. 2 – 3 months on a lower level. No brittle fault was observed that fell dry during the monitoring period. Determined water temperature and electrical conductivity were decreasing parallel to the flow rate. In *Attachment H* of this thesis the location of the long term tunnel inflows including the long term behavior of the flow rate, temperature and electrical conductivity of the water is shown.
3.3 Transient Pressure Test Conditions

3.3.1 Experimental Set Up

After reaching the target depth of the borehole, georadar reflection measurements were systematically accomplished in one of the boreholes. During the Radar reflection measurement, the drill string made of steel was changed to a PVC drill string. Open hole flow measurements were performed either after removing the drill string from the borehole or, if flow rates had to be assumed > 10 l/s, after the hydrotest.

A phase of pressure stabilization (all gate valves closed) followed the Radar test. This pressure stabilization phase was allowed to last for about 1.5 hours. After the pressure stabilization phase, the gate valve was carefully opened partly during approx. 2 h to generate a constant outflow. After the gate valve was shut in the pressure build up phase was monitored for approx 1 – 2 h. In most cases pressure was recorded with sensitive piezoelectric pressure transmitters at intervals of 1 second. Only few tests (K4W, K4E and K7W) were executed with manual pressure readings from pressure gauges. These tests were not included in the further analysis (Paragraph 3.3.2 and 3.4). As shown in Table 3.1 and in Table 3.2 most of the open hole tests were performed as interference tests (only one well is produced and pressure is observed in all the other closed boreholes). Details of the set – up are described in Pesendorfer and Loew (2006a).

3.3.2 Analysis of Diagnostic Plots

Selected pressure reactions from the drawdown phases of the active and observation wells were analyzed with the straight – line method of Jacob and Lohmann (1952). Static formation pressures (p_i) were determined from the build up analysis only, and storativity values (S) were determined from selected drawdowns and build up’s of observation boreholes.

The method of Jacob and Lohmann is based on a straight line approximation in semi – log space. De Marsily (1986) mentions that “It may thus be doubtful which is the
“right” straight line.” For determining the “right” straight line and evaluating the flow model assumptions diagnostic plots as introduced by Bourdet et al. (1983) and further developed by Bourdet et al. (1989) were created.

Figure 3.5 shows idealized diagnostic plots of drawdown or build up phases of a constant rate hydrotest. Logarithmic time since start of drawdown (build up) is plotted vs. the difference in pressure since start of drawdown (build up). Additional to the drawdown (build up) its derivative is displayed in the same plot. General characteristics of a Log – Log diagnostic plot including derivative are a unit slope line caused by - if observed - early time wellbore storage and skin effects followed by a transition period (1.5 log cycle rule, see Horne, 2000). After the transition period, the borehole pressure response is dominated by radial flow represented on the derivative plot by a slope of zero. At late time, the pressure response can be affected by the influence of reservoir boundaries. Although several different types of flow can be identified during the intermediate period, one of the most common and easily identified is radial flow, named Infinite Acting Radial Flow (IARF).

As the geometry of a classical porous media reaction (borehole storage and skin effect– IARF – boundary) needs no further explanation, the concept of fracture flow requires some geometrical thoughts. Cinco et al. (1978) and Cinco and Samaniego (1981) introduced a general concept for the pressure response of a finite conductivity fracture. Figure 3.6 shows the basic concept of a fracture flow including the different time phases of the pressure responses. A vertical fracture fully penetrating the formation is crossed by a vertical borehole (Figure 3.6 a). The pressure response at early time is dominated by linear flow within the fracture and linear flow into the fracture from the formation named bilinear flow period (Figure 3.6 b). This interval of the pressure response is characterized by a straight line with a slope of ¼ on the log – log pressure response as on the derivative plot (Figure 3.5 d). The separation factor between log – log pressure and derivative is 4. Following the bilinear flow period a linear flow period (Figure 3.6 c) is only observed if the fracture conductivity tends to infinite. The linear flow response would be observable on the log – log derivative plot in a ½ slope. Usually, bilinear flow is followed by a radial flow (Figure 3.6 d) without ever achieving a linear flow period.
A classical IARF behavior of the hydrotest performed in borehole K14WA is presented in Figure 3.7. In general, the pressure data of the build up phase were of higher quality due to less pressure disturbance caused by the outflow. In this pressure reaction, no borehole storage or skin effects can be identified; the IARF period begins approx. 5 seconds after the gate valve is closed. In this particular example, the IARF period is followed by a constant pressure boundary effect.

IARF periods of the drawdown phase of all performed hydrotests (active boreholes) were identified and, if existing, used to determine reliable transmissivity values.

*Horner (1951)* developed a straight line method to determine the transmissivity (T) from a build up test. The method is based on a “Horner – Plot” which is described in detail e.g. in *Streltsova (1988)*. In a Semi-Log plot the Horner Time Y is plotted vs. the difference in pressure from shut in on.

\[
Y = \frac{t_f + \Delta t}{\Delta t}
\]  

(1)

Whereas \(t_f\) represents the time since the start of the drawdown phase and \(\Delta t\) the time since shut in. Equal to the drawdown phase, T can be determined from the slope of the straight line fitted through the data points during the IARF phase. The “right” straight line and the applicability of the method were evaluated similarly to the drawdown phase with diagnostic Log – Log plots. As described in Paragraph 3.2 the LBT intersected highly heterogeneous formations. This is why many of the log – log diagnostic plots do not correspond to the flow models shown in Figure 3.5. In many cases, the 1.5 log cycle rule was not fulfilled or even no clear radial flow period could be identified on the plot. Some tests showed flow phases which were superimposed by the previous pressure reactions of the hydrotest, or, other flow models e.g. fracture flow dominated the pressure reaction.

If the formation is homogenous and of infinite extent, the straight line of the Horner Plot extrapolates to \(p_i\) at \(Y=1\). IARF intervals in the build up phase were extrapolated
in the Horner plot by a straight line to $Y=1$. Only one pressure reaction of the hydrotests showing a clear IARF period was not affected by a late time boundary effect (K10WA). Most build up pressure reactions plotted in Horner space were of curved shape, indicating another reservoir type behavior than IARF. Therefore, all other determined $p_i$ on the basis of the IARF period can be regarded as an estimate value only.

Pressure reactions of observation boreholes can also be analyzed with diagnostic plots. Horne (2000) describes in his book some of the methods. Rahm and Enachescu (2004) report 5 constant rate pump tests with total interference testing of 13 boreholes to determine transmissivity values of conductive fractures in granite at the Oskashamn Site, Sweden. Diagnostic log – log and derivative plots were used for a successful interpretation of the data.

As the geometry of the flow is different at the location of the observation borehole, the pressure reaction can not directly be compared to the pressure reaction of the active borehole. For identifying flow periods, preliminary the period of IARF, synthetic plots with parameters of the limestone aquifer determined through pressure analysis in the active borehole were created with the software code SAPHIR and compared to the measured pressure reaction of the observation borehole. Attachment $E$ of this thesis presents synthetic examples of diagnostic plots from observation boreholes and selected pressure test examples for diagnostic analysis. The applied software is described later in this article. $T$ and $p_i$ values were determined, equal to the active boreholes with a straight line analysis. In the pressure reactions of the observation boreholes, only borehole K8WB did show no late time boundary effect. All other determined $p_i$’s are estimate values only. Table 3.3 shows all determined $T$ and $p_i$’s under the assumption of an IARF model.
3.3.3 Formation Storativity, Total Compressibility and Effective Porosity

For a detailed numerical analysis of the hydrotests, estimations of key variables such as formation storativity (S), total system compressibility (ct), effective porosity (\(\Phi\)) and wellbore storage (C) are required.

Values of S on a macroscopic scale determined in fractured limestones are not commonly found in the literature. Guyonnet et al. (1993) estimates S for the Valanginian Marls at the Wellenberg Site (NAGRA, 1996), Switzerland, a formation with similar prospects like the Öhrli Marls, at the LBT. The range of S, 3.3E-7 to 5E-5, is based on through stress – strain determined rock compressibility and an assumed matrix porosity. The given range can be regarded as estimation value only, as no crosshole hydrotests have been performed to determine S. Shapiro et al. (1998) reports an S value of 9.0 E-06 in fractured limestone of the Madison Limestone, South Dakota determined from single hole pressure response. It can therefore be regarded as rough estimation value only (e.g. Carrera et al. 1989).

For this project S values were estimated from crosshole pressure reactions with the method of Jacob and Lohmann (1952). Equal to T or \(p_r\), the determination of S is based on a straight line analysis. Determining S – values in observation boreholes based on the build – up pressure data requires a more sophisticated method, developed e.g. by Ballukraya and Sharma (1991). Both methods require the knowledge of the distance \(r\) between the observation borehole and the active borehole. For determining \(r\) between the boreholes it was assumed that the boreholes were connected through the inflow points determined during drilling. As it is not known through which inflow points the boreholes are connected, several combinations are possible. Based on the borehole geometry the shortest possible distance and the longest possible distance between the inflow points were calculated applying vector geometry under assumption of a straight connection between the inflow points. As the geometry of the fracture network is unknown, the effective distance of the flow path could not be determined. Applying a maximum and a minimum \(r\) to the model of Jacob and Lohmann, results in a maximum and minimum S.
Table 3.3 shows the results of the determined S in the observation boreholes. With determined minimum and maximum distances between the boreholes and the determined T during the drawdown and the build up phase of the hydrotest S ranges between 9.7 E-5 and 4.3 E-8.

A Storativity S can also be estimated from total system compressibility \( c_t \) and effective porosity \( \Phi \) (e.g. Streltsova, 1988).

\[
S = \phi \cdot c_t \cdot h
\]

In the case of the LBT Limestone aquifer, h was assumed to be the open borehole length (total borehole length minus standpipe length). The open borehole length for reliable determined S values ranges between 79 and 268 m.

As the LBT aquifer is not a porous medium, it is more convenient to describe the total porosity as fracture porosity. The fracture porosity results from the presence of openings produced by the breaking or shattering of brittle rocks. Weber and Bakker (1981) collected in a literature study many values of fracture porosities mostly determined in petroleum bearing limestone and dolomite rocks. Most of the fracture porosities were determined on counting fracture densities on cores crossing carbon baring reservoirs. Weber and Bakker (1981) reviewed more than 500 articles for their study. Many of those are internal reports from the oil industry and are not available to public. Exact locations of the measurements and an exact description of the rocks are therefore not available but it can be assumed that the collected data relate to formations located approx. > 500 m below surface.

Porosity values were divided into genetically related groups:

- Monoclines and low-dip anticlines \( \Phi = 0.01 – 0.1 \% \)
- Strongly folded anticlines \( \Phi = 0.01 – 0.75 \% \)
- Fracture porosity enhanced by leaching \( \Phi = 0.08 – 0.9 \% \)
Karst aquifers, surface to shallow $\Phi = 0.2 - 3.0 \%$
Deeply buried brecciated karst, collapsed breccias $\Phi = 0.33 - 2.8 \%$
Fractured chert $\Phi = 5.0 - 8.0 \%$
Fractured tuff, igneous rocks $\Phi = 0.5 - 2.0 \%$

Fracture opening measurements e.g. for “Strongly folded anticlines” are reported to be 0.1 mm for joints restricted to a single bed and 0.2 – 0.5 mm for the larger fractures intersecting several beds.

A representative fracture porosity for the LBT limestone is difficult to determine. Fracture openings were determined (roughly estimated) in the East – tunnel after excavation, preliminary on mesoscale fractures where fluid flow was clearly visible due to rusty alteration of the fracture (see Paragraph 3.2.4). On 95 % on these mapped fractures, the opening was less than 1 mm. Baker et al. (2001), determined fracture openings based on the analysis of pressure build up data in the Puerto Escondido oil field Cuba, consisting of limestone. It was found that 97 % of the conductive fractures have an opening of less than 0.33 mm. Based on the observations in the tunnel compared to values given by Weber and Bakker (1981) we assume a minimum fracture porosity of 0.01 %. The fracture porosity might be substantially higher (one order of magnitude) in highly conductive zones, such as brittle faults. A fracture porosity range of 0.1 % to 0.01 % seems to be a reasonable assumption for the LBT aquifer.

The total compressibility $c_t$ is the sum of appropriately weighted fluid, gas, formation and tool compressibilities (e.g. described in Streltsova, 1988).

$$c_t = S_g \cdot c_g + S_w \cdot c_w + c_f + c_p \quad \text{[Pa}^{-1}] \quad (3)$$

Enachescu et al. (1997) present in a report about packer testing at the Wellenberg Site, Switzerland, the value of $c_t = 2.0 \text{E-9} \text{[Pa}^{-1}]$. For determining a total compressibility value for the LBT aquifer following assumptions were made:
as in only 2 tests (K9WA, K9WC) degassing was observed (bubbles in tub during outflow measurements) and the amount of solved gas in the water could not be determined, a value of $S_g = 0$ was assumed.

The compressibility of water at the temperature of 20°C is $4.6 \times 10^{-10}$ [Pa$^{-1}$] (e.g. De Marsily, 1986); a fracture saturation of 100% was assumed.

*Kellerhals (1998)* reports values of rock compressibilities based on uniaxial compression tests of $2.8 \times 10^{-11}$ [Pa$^{-1}$] for Öhrli - Limestone and $1.5 \times 10^{-11}$ [Pa$^{-1}$] for Quintner Limestone. Lab determined rock compressibilities do not represent large scale formation compressibilities and can be several orders of magnitude lower than the formation compressibility on a macroscopic scale (e.g. Hoek, 2000), especially in a fractured rock mass. After Serafim and Pereira (1983), a jointed rock mass compressibility can be estimated by relating in an empirical formula the geological strength index (GSI), the uniaxial compressive strength of the intact rock piece and the elasticity modulus. Applying determined values of the uniaxial compressive strength (*Kellerhals, 1998*) to the equation with a GSI of 60 – 80 (estimate value for limestone rocks in the LBT) would result in a rock compressibility of $5.3 \times 10^{-8}$ [Pa$^{-1}$] (Quinter Limestone, GSI 60) to $1.3 \times 10^{-8}$ [Pa$^{-1}$] (Öhrli – Limestone, GSI 80). Serafim’s model is based on the back analysis of dam foundation deformations and is therefore valid for fractured rocks exposed on the surface. For fractured rocks under high overburden one can assume total compressibilities which are orders of magnitude higher than determined with Serafim’s model. *Zangerl (2003)* collected in a literature study many values of the fracture stiffness (directly related to the compressibility of a fractured rock mass) in granites. Based on laboratory experiments on fractures in granite rock it could be shown that the closure of fractures above an effective normal stress of approx. 20 MPa is very small. All locations in the Doldenhorn Nappe have an effective normal stress $> 20$ MPa (determined from overburden calculations). From these observations it can be concluded that the compressibility of a fractured rock mass
under high effective normal stress is probably close to the compressibility values determined on non-fRACTured samples.

\( c_p \)  

*Enachescu et al. (1997)* report a tool compressibility range of 5.7 E-10 [Pa\(^{-1}\)] to 1.5 E-9 [Pa\(^{-1}\)]. These values represent the compressibility of an inflatable packer system. At the LBT no packer system was used, the short standpipes and valves were fabricated of steel resulting in much lower tool compressibility. It was therefore assumed that \( c_p < 5.7 \) E-10 [Pa\(^{-1}\)].

For determining an estimate value of the total compressibility \( c_t \), it is assumed, based on the thoughts presented above that \( c_w \) is substantially larger than all other \( c \)'s presented in (3).

Applying values of porosity (0.1 % to 0.01 %), total compressibility (4.6E-10 [Pa-1]) and a formation thickness - equal to the open borehole length (79 – 268 [m]) results in a range for the storativity of 1.2 E-6 to 3.6 E-8. This estimated range is nearly compatible with the range of storativity given by the crosshole hydrotests.

### 3.3.4 Wellbore Storage Coefficient C

Wellbore storage effects in horizontal boreholes drilled into a confined aquifer can be caused by fluid expansion and volume change of the equipment. The wellbore storage coefficient \( C \) caused by fluid expansion can be determined after the equation (see e.g. *Horne, 2000*):

\[
C = c_w \cdot V
\]

(4)

with \( c_w = 4.591 \text{E}-10 \text{ m}^3\text{ Pa}^{-1} \) at 20° (see e.g. *De Marsily, 1986*) and \( V = 2.17 \text{ m}^3 \) (assuming a borehole diameter of 0.096 m and a borehole length of 300 m) results in \( C = 1.0 \text{ E}-10 \text{ m}^3\text{ Pa}^{-1} \).
Discussed already under Paragraph 3.3.3, it is assumed that the test equipment applied is very stiff (only short steel components, no inflatable packer) and causes volume changes which are at least one order of magnitude smaller than $c_w$. It is therefore assumed that the tool compressibility can be neglected in further calculations.

Based on the pressure reactions in the active borehole during the outflow and the build up phase, the wellbore storage effect can also be analyzed with diagnostic plots (early time unit slope, Bourdet et al. 1983, Bourdet et al. 1989). Because of a small $C$, caused by fluid expansion (assuming no free gas in the borehole) and a relatively high $T$, in the exploration boreholes of the LBT, this effect is most probably of very short duration and often not visible on the log – log plots.

The analysis in log – log space showed that most of the drawdown and build up pressure data show a non existing or very unclear unit slope line at the start of the hydrotest. The unit slope line, is existent maximum for 20 seconds. The arithmetic mean of the length of all determined unit slope lines is 6.4 seconds. Even tests where degassing was visible during the drawdown phase (K9WA, K9WC) do not show any storage effects. Degassing is supposed to happen only outside the borehole.

The only drawdown curve with a clearly visible unit slope line at the beginning of the drawdown phase was found in drillhole K10WA. No unit slope line was found on the corresponding build up pressure data.

Based on the nearly non detectability of a unit slope line no reliable value for the wellbore storage coefficient $C$ could be determined based on the log – log diagnostic plot. Comparing synthetic model results for $C = 1.2 \times 10^{-9}$ [m$^3$Pa$^{-1}$] (pure fluid compressibility) to one with $C = 0$ showed a difference in the resulting hydraulic parameters of less than 1%. It was therefore decided to apply $C = 0$ to all further analytical models.
3.4 Transient Pressure Test Simulation

3.4.1 Methods

Modern well test simulation software is able to optimize free aquifer parameters for a given aquifer model based on a given pressure dataset (e.g. drawdown and build up pressure) and input values about the formation (e.g. porosity, aquifer compressibility, wellbore storage, etc.).

The well test simulation software selected for this project (SAPHIR) allows the user to simulate a sequence of events regarding the pressure defined by a flow history in the active well. The pressure sequence can be simulated in an active well as well as in an observation well. The software SAPHIR is a pressure transient interpretation package using the methodology of the Bourdet derivative (Bourdet et al. 1983, Bourdet et al. 1989), coupled with a library of analytical and numerical reservoir models. From the measured rate history, and a model and parameter selection, SAPHIR generates the convolved pressure response, which may be compared with the acquired data. A non-linear optimization routine adjusts the model parameters in order to obtain a match.

In the case of the transient pressure tests at LBT usually three flow phases can be identified:

a) Pre test phase before the drawdown phase
b) Drawdown phase
c) Build Up Phase

The simulator can also be used for automated and confidence interval estimation. If a simulation of a pressure reaction is performed on the base of the drawdown phase, free aquifer parameters are optimized for this phase, while the pressure is simulated for all other phases (pre test, build up). Equal simulations can be done on the base of a build up phase. Deviations between modeled and measured pressure responses can be related to

a) Inappropriate aquifer model type
b) Differences between real and assumed outflow rate during the drawdown phase

c) Borehole history effects and non–equilibrated pressures at the start of the hydrotest

d) Hydromechanically coupled processes

The appropriateness of the flow model, selected from diagnostic plot analysis was evaluated by comparing the inverse modeling results with the experimental data sets.

An overview about different aquifer models available in the code SAPHIR is presented in Bourdet et al. (1989) or Horne (2000).

Impacts of non–steady borehole outflow rates are discussed under Paragraph 3.4.3. The drilling process and other manipulations at the borehole before the hydrotest (e.g. geophysical testing, rod change etc.) disturb the pressure in the aquifer. Paragraph 3.4.2 describes a sensitivity study where different flow scenarios during the pre test phase of the hydrotest are assumed and the effects on the simulated hydrotest and estimated formation parameters are investigated. The validity of the fundamental assumptions (flow model, process) is discussed in Paragraph 3.5.

### 3.4.2 Sensitivity Studies of Borehole History

The borehole history in the case of the exploration drilling at the LBT is complex. Additional to the reconstruction of the drilling phase (based on drilling protocols on which time events and the corresponding flow rate is recorded), other events (e.g. geophysical measurements in the borehole etc.) also have to be considered. Generally the pre–test history can be split in up to 6 phases with different flow rates.

Phase 1) **Drilling Phase;** Outflow from the borehole is occurring after every drill–cycle, i.e. after reaching an additional depth of 3 m. Measurements of these flow rates were determined with rods in the borehole, but without core catcher. High flows are strongly reduced due to friction in the annulus. An average duration of this flow phase between two drilling cycles is 120 seconds (personal note S. Brisson, Boart Longyear
Inc.). During the rest of the drilling phase it was assumed that no fluid from the formation enters the borehole. Fluid injection into the formation during the drilling phase can also occur.

Phase 2) **Drill String Removal**: the duration of removing the drill string at the end of the drilling was usually not recorded. It was therefore generally assumed, that the removal takes one hour for 300 m of string. A free outflow of the borehole occurred during removing the drill string during 40 to 70 minutes (dependent on the borehole length).

Phase 3) and Phase 5) **Inserting and removing PVC – Liner**: in some boreholes geophysical measurements with a Radar probe were preformed (Maurer et al. 2000). For performing a successful Radar – Test, a PVC – tube had to be inserted into the open hole. As the PVC – string could be pushed / pulled for a long distance manually in contrast to the steel string, a depth of 300 m was generally reached after 2000 seconds. During push and pull of the PVC – string, a free outflow based on measurements taken with no drill string in the borehole was assumed.

Phase 4) **Radar Measurements**: on average, the duration of the complete (push and pull) Radar test was finished after 5000 seconds for a borehole length of 300 m. During the Radar test a reduced outflow was assumed equal to the last measured flow rate during the drilling process.

Phase 6) **Pre – test Pressure recovery**: the closing of all gate valves was recorded on the drilling protocol. Usually the gate valves were closed immediately after the drill string was removed from the borehole. The outflow during the relaxation phase is zero.

The reconstruction of the durations and flow rates of the different phases is not unique and uncertain even though we had access to all drilling and testing protocols.

For determining the effects of different rate histories before starting the drawdown phase, the code SAPHIR was used to optimize pressure reactions (drawdown or build
up phase) and to simulate the pressure reaction based on the given rate history. For the fit of a flow phase (e.g. drawdown or build up) SAPHIR is able to consider all flow phases that took place before the fitted pressure reaction. All simulations are performed and optimized for the pressure reactions of borehole K10WA. Based on the Log – Log diagnostic plot an IARF model with no borehole storage but skin effect and no influence of a boundary was chosen. Fixed input parameters for the model were:

Well radius \( r_w \): \( 0.048 \) m  
Borehole length \( h \): \( 274 \) m  
Porosity \( \Phi \): \( 0.01 \% \)  
Total compressibility \( c_t \): \( 4.6E-10 \text{ Pa}^{-1} \)

As free modeling parameters the skin factor \( s \) and the transmissivity \( T \) were chosen. For the corresponding model, additional the initial pressure \( p_i \) and the radius of investigation \( R_{inv} \) are determined. The constant flow rate during the drawdown phase is \( 0.004 \text{ m}^3/\text{s} \) (arithmetic mean of the measured flow rates during the hydrotest). The modeled results for a best fit solution without implementing a borehole history are presented subsequently with 95% confidence intervals in brackets. Because of a better data quality only results of the fitted build up phase are compared during this study.

**Build Up Phase:**

Skin Factor \( s \): \( -6.94 \) (4.2 %)  
Initial Pressure \( p_i \) [bar]: \( 25.58 \)  
Transmissivity \( T \) [\( \text{m}^2/\text{s} \)]: \( 2.25E-5 \) (21 %)  
Radius of Investigation \( R_{inv} \) [m]: \( 1070 \)

Simulations with the implementation of a borehole history were divided into two categories:

1) Demonstrating the effects of different flow and injection rates during Phase 1 of the pre test history
2) Demonstrating the effects of different flow rates and durations of Phase 2 – 6 (assumed flow rate of zero during Phase 1)

3.4.2.1 Category 1): Flow and Injection during Phase 1

For Category 1) first the Phase 2 – 6 were defined based on drilling protocols and determined outflow rates. Subsequently, the corresponding Phase, the duration in seconds and the outflow in m³/s are presented.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration [s]</th>
<th>Outflow [m³/s]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 2</td>
<td>3547</td>
<td>0.008</td>
<td>(Pull steel rods)</td>
</tr>
<tr>
<td>Phase 3</td>
<td>1940</td>
<td>0.008</td>
<td>(Insert PVC – Liner)</td>
</tr>
<tr>
<td>Phase 4</td>
<td>4480</td>
<td>0.0033</td>
<td>(Radar test)</td>
</tr>
<tr>
<td>Phase 5</td>
<td>1940</td>
<td>0.008</td>
<td>(Pull PVC – liner)</td>
</tr>
<tr>
<td>Phase 6</td>
<td>7200</td>
<td>0.0</td>
<td>(Relaxation)</td>
</tr>
</tbody>
</table>

For Phase 1 of Category 1 six different scenarios were proposed. Outflow measurements and corresponding points in time were determined based on drilling protocols. The different scenarios are described subsequently.

a) Outflow from the borehole was assumed to occur only between two drilling cycles (duration dependent on drilling speed) during an interval of 120 seconds. This scenario results in approx. 100 flow pulses with a duration of 120 seconds each during the whole drilling process. *Figure 3.8* shows the concept of the flow pulses of 120 seconds duration.

b) Determining the sum (volume) of water released during Scenario a) and distributing this volume as a constant outflow rate during the whole drilling process (no more flow pulses)

c) No outflow from the borehole during Phase 1

d) Equal flow history as Scenario a), but between flow pulses constant rate injection of fluid into the formation (constant rate). Total volume injected during Phase 1: 1 m³. This injection volume is distributed continuously during the total duration of Phase 1 resulting in a constant injection rate, except for intervals with a outflow flow rate (120 s). The injection scenarios are shown schematically in *Figure 3.8*.

e) Equal to Scenario d) but total injection volume: 10m³
f) Equal to Scenario d) but total injection volume: 100m$^3$

Comparing Scenario a), b) and c) to the modeling results without borehole history shows that

- All simulated parameters and confidence intervals do not differ significantly from the results based on the simulation without a history, except the initial pressure $p_i$ which is significantly higher (6%) than for the model without history.
- The simulated phases (drawdown) are visually better represented by the fitted parameters of the build up phase than without a borehole history.

Comparing Scenario d), e) f) to the simulation without borehole history shows

- The confidence intervals are equal to scenarios a), b) and c), all modeled parameters for d) e) and f) do not differ significantly from the model without borehole history, except the modeled initial pressures. $P_i$ is approx. 6% higher than for the model without borehole history.
- The simulated phases (drawdown) are visually better represented by the fitted parameters of the build up phase, but not as accurate as without injection.

**Conclusion for Phase 1:**

No significant difference in the fitted parameters can be identified, but the simulated pressure reaction (drawdown) is better represented by a model with a borehole history than one without. It therefore can be concluded that

- A flow history during Phase 1 can be neglected and the flow rate can be set to zero.
- Injection up to 100 m$^3$ of fluid during Phase 1 of the borehole history has no significant effect on the modeled parameters and can therefore be neglected.

The scenario c) is now defined as the reference history. All changes in the flow history performed subsequently are compared to this history.
3.4.2.2 Category 2) Flow and Duration of Phase 2 – 6

Further simulations for determining the impact of the flow history were, based on the conclusions in Paragraph 3.4.2.1, performed with assuming a flow rate of 0 during Phase 1.

First it was analyzed, how sensitive the simulation reacts on different durations of the Pre – test Pressure recovery (Phase 6) compared to scenario c) of the previous paragraph.

In a first simulation, Phase 6 was shortened by 3600 s (duration of reference simulation: 7200 s), so the “new” duration of Phase 6 was 3600 seconds. It was found that the fitted parameters and the corresponding confidence intervals for the build up phase do not differ significantly (transmissivity increases approx. 7 %, skin factor decreases approx. 5%). The simulated initial pressure is 27.42 bars instead of 27.04 bars, which represents a significant increase of 1.4 %. A good fit based on the build up data with narrow confidence intervals is produced, but the simulated drawdown phase of the hydrotest based on the parameters fitted on the build up, differs significantly from the pressure reaction which has been observed.

In a second simulation, the Phase 6 was expanded by 3600 seconds, so the new duration of Phase 6 was 10800 seconds. Neither a difference in the determined parameters, nor in the confidence intervals could be observed. Only the simulated initial pressure was 26.84 bars than 27.05 bars in the reference model. The fit based on the build up visually represented the drawdown well, but not as good as the reference model.

From these observations can be concluded that an assumed too short relaxation phase (Phase 6) has a larger effect on the simulation than a too long one. It is therefore necessary to determine all time events before the hydrotest is started, especially those which are close in time to the test start, as accurate as possible.
**Second** it was analyzed how sensitive the simulation reacts on different flow rates close to the hydrotest. For this analysis, Phase 5 (flow during removing the PVC – liner) was edited.

In a first simulation, the flow rate during Phase 5 was decreased from 0.008 m$^3$/s (flow rate of the reference model) to 0.006 m$^3$/s. Again, the most sensitive parameter of the fit is the initial pressure $p_i$. With the lower flow rate the determined $p_i$ decreases by 0.27 bars. All other parameters are only affected in a negligible way. The fit based on the buildup represents the data of the drawdown very well.

In a second simulation, the flow rate during Phase 5 was increased to 0.01 m$^3$/s (compared to 0.008 m$^3$/s). Equal to the example discussed before, $p_i$ is the most sensitive parameter. With the higher flow rate, the determined $p_i$ increases by 0.1 bars. All other parameters are only affected in a negligible way. The fit based on the buildup represents the data of the drawdown very well.

**Conclusion for Phase 2 - 6:**

As changes in the flow rate (± 33%) of Phase 5 result not in a change of parameters $(T, s)$ but in a significant change of the initial pressure $p_i$, it is crucial to determine the flow rate of Phase 5 exactly. As a change in the flow rate of Phase 5 (closest flow phase in time in respect to the hydrotest) induces only a minor effect (except on $p_i$) to the parameters, the sensitivity of the other flow phases was not determined.

**Third**, the effects of a non constant flow rate during the drawdown phase of the hydrotest with a given flow rate during Phase 2 – 6 and zero flow during Phase 1 were analyzed.

### 3.4.3 Non – Constant Flow Rate during the Drawdown Phase

In this study results of a non constant flow rate during the drawdown phase with a given flow rate during Phase 2 – 6 (equal to Paragraph 3.4.2.1) and zero flow during Phase 1 of the hydrotest are discussed. First, measured points of the flow rate were
fitted continuously with an exponential function. As the software code is not able to handle continuous changes in the flow rate the exponential function was discretized to intervals of 1 second, resulting in a step – drawdown phase of a total duration of 2268 seconds. All in all, representing the outflow with a non continuous flow rate is complex and for simulations of this kind of flow rate a lot of CPU power is needed. Compared to the fitted build up parameters of the reference history no significant differences, neither in the parameters nor in the confidence intervals are observed. The initial pressure \( p_i \) is reacting most sensitive on the non – constant outflow rate, resulting in an increase of 0.088 bars compared to the reference history c) in Paragraph 3.4.2.1. The drawdown phase is visually not represented very well by the parameters fitted based on the build up phase.

**Conclusion:**

For the considered flow history and the corresponding pressure reaction there is no improvement in representing a continuous flow rate during the drawdown phase by a non continuous, complex function. This conclusion is strictly only valid for the test case in the LBT and a generalization to other situations must be performed with care.

General conclusions on the sensitivity of the borehole history based on the build up fit:

- The most sensitive parameter that reacts on a change in the history is the initial pressure \( p_i \).
- The exact determination of events regarding the flow (time and corresponding rate) is crucial to simulate accurately the initial pressure \( p_i \).
- With a borehole history applied, the simulated phases (e.g. drawdown phase) are represented better by the fitted parameters of another phase (e.g. build up phase).
- The flow history during the drilling phase (outflow and injection) has no significant effect on the fitted parameters.
3.4.4 Flow Models and Formation Properties

In total, 18 hydrotests from 16 different boreholes were selected for a detailed analysis with the software code SAPHIR. On 13 hydrotests, the drawdown and the build up phase could be analyzed, on the remaining 5 tests, only the build up phase was analyzable because of disturbed pressure signals during the drawdown phase.

3.4.4.1 Modeling Procedure

First, based on the log–log diagnostic plot of the test phase (drawdown or build up) an analytical model was chosen. If both phases were analyzable, the selected model had to be equal for both phases, otherwise only the build up phase was analyzed. This was the case on one test (K8WD, second test), where the drawdown phase showed a complete different shape in log–log space than the build up phase. The reason for this pressure reaction is not known.

The flow model was divided into three phases, based on examples given by Horne (2000). Subsequently the flow phases including the selected models for the corresponding phases including the defining parameters are listed.

- Early time response; Pressure reaction dominated by effects of the well and its nearest surroundings
  - Borehole Storage (Storage C) and Skin Effects (Skin Factor $s$)
  - Fracture Flow (Fracture Length $X_f$, Fracture Transmissivity $FT$)

- Intermediate time response; Pressure reaction dominated by effects of the formation
  - IARF

- Late time response; Pressure reaction dominated by boundary effects
  - Infinite acting reservoir
  - Linear Constant Pressure Boundary (Distance to the boundary $L$)
  - Linear No Flow Boundary (Distance to the boundary $L$)

After selecting conceptual models for the three phases, the build up phase, because of a better data quality, was analyzed first. Pressure data of the build up phase were fitted
and confidence intervals of the free parameters were minimized by an automatic algorithm. Additional, an initial pressure $p_i$ was determined automatically. Measured pressure reactions of the other phases (e.g. drawdown) were compared to the simulated phase given by the software. The drawdown phase was fitted equal to the build up phase, except that $p_i$ cannot be determined automatically and has to be entered manually. $p_i$ was estimated based on the build up phase and on the pressure record before the drawdown phase of the hydrotests was initiated.

For two hydrotests (K13EA and K16EB) the model for the pressure reaction could not be explained with an approach listed above. The pressure reactions were dominated by not clearly identifiable flow periods.

### 3.4.4.2 Results

As described under Paragraph 3.4.4.1 only few models were selected to describe the pressure reactions. No evidence was found in the diagnostic plots, as one could probably expect, for a double porosity behavior of the intermediate flow response.

Based on the log – log diagnostic plots following models were selected:

- **Early time response**
  - $11 \times$ Borehole Storage and Skin effect
  - $5 \times$ Fracture Flow

- **Intermediate time response**
  - $16 \times$ IARF (homogenous reservoir)

- **Late time response**
  - $2 \times$ Infinite acting reservoir
  - $10 \times$ Linear Constant Pressure Boundary
  - $4 \times$ Linear No Flow Boundary

*Figure 3.9* shows the complete model of the hydrotest performed in borehole K14WA, including flow history, pressure reaction, derivative plots and analytical model. In this case the pressure reaction was modeled with Borehole Storage and Skin effect, IARF and Linear Constant Pressure Boundary. *Figure 3.10* shows an example
of a typical fracture flow model described under *Paragraph 3.3.2*. The slope of $\frac{1}{4}$ indicates the bilinear flow period for the early time response. As proposed by the conceptual model for a finite conductive fracture, no linear flow period can be identified. The proposed IARF – period following bilinear flow is short and influenced strongly by a linear constant pressure boundary. In *Attachment D* all for modeling selected hydrotests (active borehole) are presented.

*Table 3.4* shows the modeling results including 95% confidence intervals of all selected hydrotests in the West – tunnel, *Table 3.5* shows the results of the East – tunnel.

Despite of the conclusions made in *Paragraph 3.3.4*, where a borehole storage coefficient of 0 is assumed for all the hydrotests, 4 tests showed a transition period from a borehole storage effect to the IARF period of up to 100 seconds. This kind of pressure reaction will be discussed later in this paper and these tests (K11WA, K13WB, K12EC, K15EA) are first excluded from the analysis. Following observations are made for the remaining 12 tests:

- The quality of the fit is significantly better in 70 % of the modeled build up phase than for the corresponding drawdown phase
- 90% of the early time pressure response represented by a “Borehole Storage and Skin” model showed (highly) negative skin factors, ranging between -0.2 and -7.9
- The largest difference between determined $T$ – values by a “best fit model” and $T$ – values determined by the method of Jacob and Lohman (see *Paragraph 3.3.2*) was 21 %
- Confidence intervals are mostly wide for determined distances to linear constant pressure or linear no flow boundaries.
- Modeled initial pressures $p_i$ based on the build up phase differed maximum 2.6 % from determined formation pressures with the Horner Method (see *Paragraph 3.3.2*)
The remaining 4 tests showing indications for Borehole Storage Coefficient \( C \neq 0 \) were first modeled and fitted with \( C = 0 \). The pressure reactions, build up and drawdown phase were poorly represented by the model and confidence intervals remained large. In a second approach, equal models were selected to represent the pressure reactions, but the Borehole Storage Coefficient \( C \) was selected as a free parameter (\( C \neq 0 \)). Following observations were made:

- Visually, the model represented better the fitted data with the additional free parameter \( C \)
- Comparing confidence intervals, the intervals of some parameters, especially those of the transmissivity \( T \), were narrower after introduction of the additional free parameter \( C \), but confidence intervals of other parameters (e.g. skin factor, distance to linear boundaries etc.) remained large or did not even show an improvement.

### 3.5 Discussion of the Results

#### 3.5.1 Hydraulic Head Distribution in the Base Tunnel

*Figure 3.11* presents determined initial formation pressures (*Table 3.3*) along the tunnel axis of the LBT. The determined formation pressures in bars are presented in the same scale as the vertical cross section. The rectangle represents the pressure test on which no late time boundary could be identified and is therefore the most reliable value. Circles represent determined initial formation pressures with late time boundary effects. Additional to the geology, the projected tunnel axis of the Lötschberg Crest Tunnel (LCT) built in 1908 is shown. This tunnel is located in a lateral distance of approx. 400 m of the LBT and between TM 26500 and TM 27200 both tunnel axis are approx. parallel. At this location the LCT axis dilates in a large curve to the east. Heavily reduced formation pressures are observed between TM 26500 and TM 27700. As a drainage effect of the tunnel tubes to the pressure measured in the borehole is excluded, the determined pressures can be regarded as real formation pressures. Formation pressures are at least partly lowered by the influence of the LCT. Outflow measurements from the LCT show approx. 141 l/s
averaged over a ten year period period. Unfortunately, no determination about the
distribution of the hydraulic head is available for the LCT. As discharge from the LCT
is strongly variable in a seasonal cycle one must also assume a strong variation in the
hydraulic head. *Pesendorfer and Loew (2006b)* presented in a numerical model
hydraulic head distribution for the area of the Gastere Valley. The numerical model
was calibrated on discharge measurements of the Base as well as of the Crest Tunnel.
It could be shown that only hydraulic heads presented in *Figure 3.11* between TM
27500 and TM 28500 and between TM 27000 and TM 27250 are ± in accordance
with the proposed numerical model. All other determined hydraulic heads in the LBT
are on a significantly lower level than proposed. Especially the hydraulic head
determined in borehole K10WA (1075 m) at TM 27400 and in borehole K11WB
(1010 m) at TM 27645 are 125 m and 190 m below the proposed hydraulic head of
the model. A lowering of the hydraulic head due to tunnel excavation of the LBT can
be excluded, mainly based on the following observations:

- Major conductive locations, dominating the water flow of the borehole were
  usually encountered in a distance > 50 m from the tunnel face

- Comparing determined formation pressures derived from equal structures in
  the leading or in the lagging tunnel leads to similar results. Formation
  pressures are therefore not influenced – as one could assume – by drainage
  effects of the leading to the lagging tunnel. Again, this is mainly based on the
  fact that conductive structures were usually detected in a certain distance from
  the tunnel face.

Based on these essential observations it is accurate to assume that observed formation
pressures are “real” pressures representing the hydraulic head of the Doldenhorn
Nappe and not a product of a drainage effect.

### 3.5.2 Flow Models

Many analytical models e.g. developed by *Jacob and Lohmann (1952), Goodman
(1965), Lei (1999)* to determine transient inflow into a tunnel section of a certain
length assume a radial flow field around the tunnel excavation as one of the basic
assumptions. Comparing this assumption to 18 with log – log diagnostic plots analyzed hydrotests shows that this assumption is not generally valid. Only 11 hydrotests show a classical flow behavior with Storage and Skin effects in the early time pressure response, IARF in the mid time response and boundary effects at late time. 5 tests were clearly dominated by fracture flow and 2 tests could not be analyzed with classical models and were dominated through several not clearly identifiable transition periods. The assumption of radial flow would therefore be valid in only 61% of the cases.

3.5.3 Orientation of Conductive Structures and Comparison with Predictions made by Hydraulic Pressure Tests

As described in Paragraph 3.2.4 major inflows into the LBT were dominated by two major conductive brittle fault sets. It can therefore be assumed that mostly the geometry of these two brittle fault sets were tested with the open hole hydrotest. Geologically the sets could be divided into one with an orientation NW – SE and a dip angle of approx. 80° and one with an orientation of NE - SW and a dip angle of approx. 30 °. The steep set represents one of the regional fracture systems of the Kandersteg area and in connection with this set karst caves of larger diameter (approx. 75 cm) with infills of clay, silt, sand or gravel were found on the level of the base tunnel. The other set is parallel to major shallow overthrust structures as shown on Figure 3.2. On this set no particular large karst caves were found but overthrust structure were sometimes widened by solution voids.

Based on the open hole hydrotests and the analysis of the log – log diagnostic plots predictions should be possible about the geometry of the conductive structures tested. Two major pressure reactions - early time fracture dominated flow and early time storage and skin effects followed by an IARF period and late time boundary effects - were compared to the geometry of later excavated major brittle faults. Equal to the conceptual model discussed under Paragraph 3.3.2, the pressure response of fracture flow was observed in 5 selected hydrotests (Figure 3.10).
Example 1:

The hydrotests in boreholes K8WC and K8WD showed a clear fracture dominated flow reaction, on the drawdown as on the build up phase each. The data can therefore be regarded as reliable. This pressure reaction would correspond after Horne (2000) to a single fracture that completely penetrates the thickness of the productive formation and which extends some distance from the well. Comparing this proposed geometry to structures mapped in the excavated tunnel shows that these pressure reactions was encountered where several steep brittle faults ± perpendicular to the borehole axis were crossed. Along strike of the brittle faults, several karst caves (Size: approx. 0.75 m) were observed. These major brittle faults were in connection with a network of conductive overthrust faults, crossed by the borehole with a dip angle of approx. 30°. Despite of the major outflows observed from the steep structures, the pressure reaction indicated a fracture crossed parallel to the borehole axis. On all analyzed pressure reactions a bilinear flow period dominates the early time pressure reaction followed by an IARF – Period which is strongly influenced by late time linear constant pressure boundary effects. It must therefore be suggested that the network of shallow dipping overthrust faults control the fluid flow and therefore the pressure reaction.

Example 2:

The hydrotest in borehole K15EA shows an IARF pressure reaction for the mid time pressure response with a late time linear constant pressure boundary effect. One major inflow of 4 l/s was dominant over the borehole length (another inflow of 0.6 l/s might be negligible compared to the dominant inflow). Based on the diagnostic log – log analyses a conductive structure crossed perpendicular to the borehole axis is proposed. During excavation one steep brittle fault, opening width approx. 2 mm with slickenside, partly with thin microcrystalline calcite cover of red - rusty color was encountered. This geometry of the brittle fault is in perfect agreement with the geometry proposed based on the pressure reaction of the hydrotest.
**Example 3:**

Borehole K12EB shows a typical fracture flow pressure reaction in the early time response. One major inflow of 4 l/s was dominant over the borehole length. The pressure response indicates a fracture, crossed on a certain length parallel to the borehole axis. In the excavated tunnel, a nearly vertical brittle fault, with an angle of approx. 5 – 10 ° to the borehole (tunnel) axis was found. The brittle fault was filled with fault gauge and the size of the structure was variable between 2 mm and 250 mm. The rock around the fault (up to 50 cm) was strongly bleached due to fluid flow. The proposed geometry based on the analysis in log – log space of the hydrotests was therefore encountered in the tunnel.

Predictions of the orientation of conductive structures based on the analysis of hydrotests in log – log space is possible but requires some care. As shown in Example 1, even with several clear pressure reactions in two boreholes indicating fracture flow the proposed structure is not necessarily (and obviously) found in the later excavated tunnel. The borehole crossed several overthrust faults under a shallow angle including steep major brittle faults with high initial flow rates in the later excavated tunnel. Based on the geometry and the water flow observed, one would assume as dominating structure (regarding the pressure reaction of the hydrotest) the steep brittle faults. But, comparing the predicted geometry of the fractures with the geometry of the fractures in the later excavated tunnel, also a non dominating fracture system (shallow overthrust faults) can dominate the pressure reaction. Even if the pressure reaction indicates one well defined conductive structure, the particular pressure reaction can also represent a complicated pressure reaction of several conductive structures.

In the other discussed examples, the pressure reaction can be related to one single structure and represents therefore not a complex mix of different conductive structures. One single conductive structure was tested with only few hydrotests. Two examples are presented above. If only one structure is tested, the analyzed pressure in log – log space can be used to predict the orientation of conductive structures. In other hydrotests, where the borehole crossed several parallel conductive overthrust structures in a dip angle of approx. 30 °, the pressure reaction is not, as one would
expect, dominated by fracture flow, but represents a complex reaction of the total fracture network.

### 3.5.4 Storativities on Local and Regional Scale

In many hydrotests late time pressure responses showed indications of linear constant pressure boundaries. A linear constant pressure boundary is represented by a river or a lake. With basic aquifer parameters determined under Paragraph 3.3.3, the distance to constant pressure boundaries could be determined with SAPHIR. To include only the most reliable hydrotests in the analysis, only tests

- a) showing a classical IARF behavior with no fracture flow
- b) showing a clearly identifiable downward slope at the late time pressure response
- c) which could be modeled without the implementation of a borehole storage coefficient unequal 0
- d) with a narrow confidence interval (< 50%) regarding the quality of the determination of the distance \( L \) to the boundary

were selected. With the above listed rigorous criteria, only one hydrotest – K14WA – can be used to determine a distance to a linear constant pressure boundary. K14WA shows distance of 423 m (95% confidence interval 21%) for the drawdown phase and 306 m (95% confidence interval 26 %) for the build up phase to a linear constant pressure boundary. As can be seen on Figure 3.2 the tunnel crosses at the location of exploration borehole K14WA the Gastere Valley, filled with fluvial sediments and a ground water table 600 m above the tunnel axis. The Gastere Valley can be regarded as a linear constant pressure boundary equal to a lake. The minimum linear distance between the major water inflow locations in the borehole and the basin of the Gastere Valley with a 3D Model (GOCAD) was determined to 270 m. The values – effective linear distance and distance determined by the hydrotest – are in a good agreement.

One might suggest that, as the distance to a linear constant pressure boundary is dependent on the parameters of the total aquifer compressibility \( c_t \) and the porosity \( \Phi \), these parameters are doubtful and only estimated. Additional, the determined values
of the distance to the linear constant pressure boundary implement a large radius of investigation of a hydrotest which releases only 2 – 6 l/s of water during the drawdown phase.

In another study *Pesendorfer and Loew (2006b)* showed that the drilling of exploration boreholes in the tunnel has an effect on the hydraulic head in vertical deep boreholes drilled from the surface. The distance between the horizontal exploration boreholes and the deep vertical boreholes is more than a km. Time delays between drilling into a certain structure with a horizontal borehole and the head reaction in the vertical borehole was used to determine storativity values and therefore $c_c$. The parameters determined were in the same range as determined in Paragraph 3.3.3. Based on these findings it is assumed that hydrotests preformed in the LBT horizontal exploration boreholes have a large radius of investigation and that linear constant pressure boundaries seen in the log – log diagnostic plots represent the gravel and water filled Gastere Valley.

### 3.5.5 Skin Factors and Borehole Storage

Strongly negative skin factors based on the fit of log – log diagnostic plots are observed throughout nearly all hydrotests fitted with the model of borehole storage and skin effect. If a zone around the well is higher transmissive than the formation the skin factor becomes negative. The higher transmissive zone around the well results in a lower pressure drop than from a homogenous reservoir (e.g. *Horne, 2000*).

With a simple equation the “effective wellbore radius” can be determined (e.g. *Horne, 2000*) based on the skin factor $s$. This is the larger radius that the well appears to have due to the increase in flow caused by the skin effect.

$$r_{w_{\text{eff}}} = r_w \cdot e^{-s}$$ (5)
Whereas $r_{\text{w eff}}$ is the effective wellbore radius, $r_w$ is the wellbore radius and $s$ is the skin factor. Applying a skin factor of -6.81 (determined in borehole K10WA on the build up phase) results in a $r_{\text{w eff}}$ of 43.5 m with a borehole radius of 0.048 m.

As drilling was performed in hard limestone rock it is implausible that the drilling process affected the conductive fractures in such a way around the borehole. Generally, no effects (wash out of material etc.) of the drilling process could be found in conductive fractures in the tunnel. Horne (2000) describes in his book that skin factors less than -5 are rarely seen. Ostrowski et al. (1992) observed in many packer tests performed in boreholes in Valanginian Marls at the Wellenberg Site, Switzerland also strongly negative skin factors. Ostrowski et al. (1992) explain the negative skin factors with the application of a “Double Porosity” aquifer model for the mid time response and concludes that undamaged wells showing a skin factor of zero shift toward skin factors of -2 to -3 if a double porosity model is used. As many tests in the Valanginian Marls were interpreted with a “Double Porosity” Model, the results are not directly comparable to the hydrotests in the LBT. Synthetically generated models with highly negative skin factors and comparable aquifer parameters determined with the hydrotests show comparable pressure reactions as observed in the LBT. The highly negative skin factors are therefore not an effect of inconsistent fitting etc. These factors are real. A general valid explanation for the negative skin factors can not be given here.

As described in Paragraph 3.4.4.2, 4 out of 18 selected hydrotests could not be fitted satisfactorily with an assumed borehole storage coefficient $C=0$. In Paragraph 3.3.4 it was described that nearly no borehole storage effects were observed (unit slope straight line in log – log space at the beginning of the test) in the hydrotests performed. Despite of these findings, large transition periods of up to 100 seconds between a (non visible) borehole storage effect and the IARF phase were observed. With a synthetic model, based on the fitted aquifer parameters, an equal shape of the pressure drawdown and the derivative curve could be reproduced in log – log space. In these models, borehole storage effects with $C = 5E-9 \text{ m}^3/\text{Pa}$ showed an identifiable unit slope straight line for 0.5 seconds followed by a transition period of 100 seconds to the IARF period. As the time interval between two pressure points is 1 second,
given by the pressure transmitter, it is obvious that no borehole storage effect can be identified in such a case. Nevertheless, the reason for the appearance of borehole storage effects in some boreholes remains not clear.

If solved gas is present in the fluid, borehole storage effects can be observed during a hydrotest. Enachescu et al. (1997) show in their report that a 1% gas saturation of the fluid rises 0.5 by half order of magnitude. No solved gas could be observed in the particular tests and it is difficult to explain why gas should be solved on some tests while on other tests, testing same formations, no gas should be present. It is therefore implausible that the effect is caused by solved gas in the fluid. An explanation might given by Ostrowski et al. (1992) who analyzed many packer tests in the Valanginian Marls at the Wellenberg site. In their report C values which are one order of magnitude higher than previously suggested by theoretical calculations were found on some of the performed hydrotests. Ostrowski et al. (1992) suggest that at least part of the higher C value is due to larger wellbore storage volume resulting from fissures. As the wellbore storage coefficient C in a horizontal borehole is determined after Equation (4) under the assumption of no solved gas in the fluid, the storage volume V has to be known exactly. In this report it was suggested that V is equal to the borehole volume. If it is assumed that the borehole volume is larger due to conductive fissures, C increases significantly. Despite this explanation, it cannot be explained why on some tests the effect is present and on some not. A mix of several effects (small amounts of solved gas, borehole volume larger than on other tests etc.) might be a possible answer.

3.6 Summary and Conclusions

Two conductive sets of brittle faults and fractures control the fluid flux in the Doldenhorn Nappe. The flow conditions are complex in many of the cases, only 11 tests out of 18 could be explained with a simple storage and skin, IARF and boundary effects for the early, mid and late time pressure response. 5 tests showed clear indications for finite conductivity “fractures” with bilinear flow in the early time pressure response. Most late time pressure responses of the hydrotests showed clearly
identifiable boundary effects as linear constant pressure or linear no flow boundaries. Some tests could not be interpreted with simple flow models.

The hydrotests, even with small flow rates during the drawdown phase of 2 – 6 l/s characterize the brittle faults over great distances up to 300 – 400 m. It could be shown that constant pressure boundaries are related to the Gastere Valley, a valley eroded by glaciers during the last ice age and filled with fluvial sediments. The ground water table in the valley is located few meters below the surface of the valley floor and therefore the valley acts equal to a lake or a constant pressure boundary.

Transmissivities of the brittle faults could be determined in a narrow interval between 3.32E-4 and 1.23E-5 m²/s. Large scale storativity values could be determined in an interval of 9.67E-5 and 4.27E-8. The determination of the initial formation pressures showed that the old Lötschberg Crest Tunnel lowers the hydraulic potential in parts of our study site.

It was found that a reliable test analysis is not only dependent on the selected flow model but also on the borehole history. It could be shown that the flow history from finishing drilling and taking out the drilling rods from the borehole should be recorded in time and related fluid flow. The pressure recovery phase after drilling should be at least 2 hours.

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### 3.8 Nomenclature

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3.9 Figures

Figure 3.1 Location including simplified geological surface map with main lithostratigraphical units (after Kellerhals and Isler, 1998) of the Lötschberg Base Tunnel with indicated study area
Figure 3.2  Detailed geological cross section of the study area including lithostratigraphical sub – units, tunnel axis and start as well as end point of the exploration program
Figure 3.3  Stereographic Pole – Plot (lower hemisphere) of conductive (black triangles) and dry (grey rectangles) mesoscale fractures.
Figure 3.4  Stereographic Pole – Plot (lower hemisphere) of brittle faults and fault zones. The size of the rectangles is dependent on the initial fluid flow rate determined during the excavation.
Figure 3.5 Synthetic log – log plots with pressure (crosses) and corresponding derivative (open circles). a) pressure reaction with skin but no borehole storage and IARF – period and no boundary effect b) pressure reaction with no skin but borehole storage and IARF – period and no boundary effect c) pressure reaction with skin and borehole storage and IARF – period and linear constant pressure boundary d) pressure reaction with bilinear (fracture) flow, IARF – period and no boundary effect
Figure 3.6 Conceptual Model of Fracture Flow. a) conceptual geometry of a fracture crossed by a borehole. b) early time bilinear flow period followed by c) linear flow period (rarely observed). At late time the flow field reacts as d) - radial flow.
Figure 3.7  Log – Log diagnostic plot of the build up pressure reaction in borehole K14WA. The IARF period begins approx. 5 seconds after shut in, lasting for approx. 140 seconds and followed by a linear constant pressure boundary effect. Legend: Rotated squares: Pressure Build up; Open Circles: Derivative
Figure 3.8 Schematic detail of the flow scenarios a) – f) during Phase 1 of the pre test history. For scenario a) – c) no injection rate is assumed; the hatched area reduces to a flow rate of 0. A positive flow rate (flow pulse) represents the assumed outflow during 120 s between two drilling cycles. The grey hatched area represents an assumed constant rate fluid injection for scenario d) – f) during drilling of a total volume of 1, 10 or 100 m³, respectively.
Figure 3.9  Flow history, pressure reaction, log – log derivative and analytical SAPHIR model of the hydrotest performed in borehole K14WA
Figure 3.10  Flow history, pressure reaction, log – log derivative and analytical SAPHIR model of the hydrotest performed in borehole K8WC
Figure 3.11  Distribution of initial formation pressures $p_i$ along the tunnel axis determined from reliable hydrotests
3.10 Tables

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Table 3.1 Exploration boreholes performed from the East – Tunnel. Name: Bohrehole Identification; TM-S: Start location of borehole (Tunnel meter); TM-E: End location of borehole (Tunnel meter); L: length of borehole [m]; CB: Cored borehole; DB: destructive borehole (with inhole hammer); Ø: diameter of borehole (NQ = 76 mm; HQ = 96 mm); OH-A: No. of open hole hydrotests in active borehole; OH-O: No. of open hole hydrotests in observation borehole; PT: No. of packer tests.

* Tests performed without electronic logging equipment; pressure reaction measured with analogue pressure gauges.
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Table 3.2 Exploration boreholes performed from the West – Tunnel. **Name:** Bohrhole Identification; **TM-S:** Start location of borehole (Tunnel meter); **TM-E:** End location of borehole (Tunnel meter); **L:** length of borehole [m]; **CB:** Cored borehole; **DB:** destructive borehole (with inhole hammer); **Ø:** diameter of borehole (NQ = 76 mm; HQ = 96 mm); **OH-A:** No. of open hole hydrotests in active borehole; **OH-O:** No. of open hole hydrotests in observation borehole; **PT:** No. of packer tests.

* Tests performed without electronic logging equipment; pressure reaction measured with analogue pressure gauges.

** Borehole performed between tunnels
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*Table 3.3* Through straight line analysis determined reliable values of transmissivity T (active and observation boreholes), storativity S (observation boreholes) and initial pressures $\pi$ (active and observation boreholes)

() represents Observation boreholes

(( )) represents active boreholes
Table 3.4  Compilation of the results of all for advanced modeling (SAPHIR) selected hydrotests in the West – tunnel. The compilation includes also the tests which could not be modeled with the assumption of a borehole storage coefficient $C = 0$ (Tests K11WA and K13WB).
Table 3.5  Compilation of the results of all for advanced modeling (SAPHIR) selected hydrottests in the East – tunnel. The compilation includes also the tests which could not be modeled with the assumption of a borehole storage coefficient C = 0 (Tests K12EC and K15EA). For the tests K13EA and K16EB no reliable analytical model was found.
4.

Groundwater Flow and Environmental Impacts of the Lötschberg Base and Crest Tunnels (Switzerland)

Marc Pesendorfer, Simon Löw and Massimiliano Zappa
4.1 Introduction

Studies about the regional impacts of large underground excavations on aquifers in alpine catchments are not commonly found in the literature. Ofterdinger (2001) applied a numerical finite element model to simulate groundwater flow to an underground gallery in the Gotthard Massif, Switzerland. Stable isotopes were used to verify successfully the flow paths to the underground galleries. Zangerl (2003) used a numerical model to simulate subsidence above the Gotthard road tunnel and calibrated the model on discharge measurements of the road tunnel. Loew et al. (1996) and Kitterod et al. (2000) investigated groundwater flow systems within fractured crystalline rocks on a regional scale from observations in underground excavations.

In this study we will present results from a ground water monitoring and exploration program around a selected section of the Lötschberg Base Tunnel, Switzerland. The Lötschberg Base Tunnel (LBT) is a double tube railway tunnel in central Switzerland with a total length of 34.5 km, driven from the city of Frutigen to the city of Raron (Figure 4.1). In one part of the tunnel project – the 3.2 km long limestone and marl dominated section of the Doldenhorn Nappe - an intensive exploration program was performed with long (~300 m) horizontal exploration holes drilled through the tunnel face to explore possible large water inflows into the tunnel from karstified sections within the limestones. After completing the drillholes, systematic hydrotests were performed in many of the boreholes. Pesendorfer and Loew (2006a) and Pesendorfer and Loew (2006b) describe in detail this exploration and testing program and present results from detailed hydrotest analysis.

Two major valleys, the Kander – and the Gastere Valley – filled with deep gravel deposits and storing large volumes of ground water are crossed by the tunnel in solid limestone at depths of 400 and 600 m below ground surface, respectively. To monitor the impact of the tunnel excavation on the aquifers (fractured and karstified limestones as well as gravel aquifers) deep surface drillholes completed during the
1990’s were equipped with piezoelectric pressure transmitters and water tables in the boreholes were monitored with electric light gauges.

To understand the impact of the LBT and of the shallow crest tunnel (LCT), located above the LBT (vertical distance approx. 400 m) on the regional ground water flow system and its impact on the regional hydraulic heads especially on a selected unit within the Doldenhorn Nappe, a numerical simulation following a finite differences continuum approach was carried out. Karstified and fractured rocks present a great challenge for numerical ground water simulation. White (2003) presents basic concepts and required parameters for hydrodynamic modeling in karst environments. Kiraly (2003) and Bakalowicz (2004) review the complex mathematical background and numerical approaches for simulation models. Scanlon et al. (2003) present a case study where regional groundwater flow in a karst system was approached with an equivalent porous media model. Besides the numerical difficulty in representing a karst system and modeling the flow, karst systems in high alpine catchments are even more challenging to model. Regional flow systems are strongly influenced by the topography (e.g. Zijl, 1999). Fault zones and other structural elements have a strong influence on the flow in the system (e.g. López and Smith, 1995). The determination of the groundwater recharge in an alpine catchment which is dependent on numerous factors such as topography, geology, soil cover, vegetation, glacial coverage etc. represents another challenge for a hydrodynamic model. Kattelmann and Elder (1991) studied the recharge in an alpine catchment in the Sierra Nevada. Zappa et al. (2003), Gurtz et al. (2003), Verbunt et al. (2006) presented studies about the strong spatial variability of the recharge in high alpine catchment areas. Spatially distributed recharge rates were extracted from a sophisticated hydrological simulator and imported into the hydrodynamic model.

Key questions addressed with the ground water flow model are scale effects in hydraulic conductivity, the interactions between surface recharge rates and discharge of the base tunnel and finally the impact of the excavation of the base tunnel and flow systems within the limestone aquifer. Additional to the model results we will present data of a detailed environmental monitoring program addressing hydraulic heads in
deep vertical boreholes and impacts of the horizontal exploration drilling performed in the base tunnel on the hydraulic heads in the limestone aquifer.

4.2 Geologic and Hydrogeologic Setting

4.2.1 Geologic Setting and Exploration Program

Figure 4.1 shows the location of the Lötschberg Base Tunnel and a simplified geologic map. The tunnel crosses from north to south the Wildhorn Nappe, consisting of limestones, shists and sandstones (named “Flysch”) and the Doldenhorn Nappe consisting of limestones and marls (study area). Towards the south the tunnel crosses a short interval of autochthonous Triassic sediments consisting of sandstones anhydrites and shists. Further south the LBT enters the crystalline rocks (granites and gneisses) of the Aar Massif. Hügi et al. (1988), Furrer (1962), Furrer et al. (1993) and Kellerhals (1996) studied the geologic setting of the region extensively. Kellerhals and Isler (1998) present a detailed overview about the area and the tunnel geology. In Pesendorfer and Loew (2006a) more literature references about the geology of the Lötschberg area are listed.

A longitudinal geological cross section of the study area along the tunnel axis of the base tunnel is presented in Figure 4.2. The Doldenhorn Nappe consists of several lithostratigraphic sub units, which are (from north to south) the Kiesel - Limestone (limestone with silicified bands), the Öhrli - Limestone (limestone with low quartz content), the Öhrli - Marl (dark, partly clay rich limestone) and the Quintner - Limestone (dense, massive limestone with clear bedding). Overthrusting, folding and faulting during the major alpine development resulted in a very complex geology. As it is clearly indicated on the Figure 4.2, the tunnel crosses two deeply incised valleys, the Kander – and the Gastere Valley. Both valleys were incised during the last glaciation period and are mainly filled with fluvial sediments such as gravel, sand and silt.
The research area of this study is shown in a detailed topographical map in Figure 4.3 on which topographical locations, important karst springs, the tunnel axis of the Lötschberg Base Tunnel (LBT), the Lötschberg Crest Tunnel (LCT) and of the Lötschberg Accident Tunnel (LAT) are indicated. The LCT / LAT are on a level of 1220 m a.s.l. while the LBT is on a level of 830 m a.s.l. The topographical elevation of the area ranges from 1200 (Kander Valley) to 3698 m a.s.l. (Balmhorn).

Between 1991 and 1994 several deep drilling boreholes were performed onto the level of the LBT from the Gastere Valley. Figure 4.4 shows the detailed view indicated in Figure 4.3 with the axis of the three tunnels and the location of the deep boreholes 91/2, 92/7 and 94/19. Borehole GA20 is a piezometer pipe for monitoring the hydraulic head in the gravel aquifer of the Gastere Valley.

The lithology of the deep boreholes (borehole axis projected onto cross – section) is presented in Figure 4.2. As the boreholes are only in a marginal horizontal distance from the tunnel axis, the change in the lithology caused by the projection is negligible. All boreholes cross first the Quaternary sediments of the Gastere Valley followed by the Quinter Limestone of various thicknesses, the Triassic sediments and ending in crystalline rocks. Detailed lithological profiles of the deep boreholes are shown in Attachment F.

The Doldenhorn Nappe was intensively explored during tunnel excavation with up to 300 m long, horizontal boreholes drilled along the tunnel axis of the base tunnel. Pesendorfer and Loew (2006a) and Pesendorfer and Loew (2006b) describe in detail this exploration program. Only a summary of this program will be presented in this article. In total, 30 boreholes, 21 cored and 9 destructive with a total length of 7347 m were drilled from the East – Tunnel and 32 boreholes, 28 cored and 4 destructive, with a total length of 6964.5 m were drilled from the West – Tunnel. Table 4.1 presents an overview of the relevant boreholes for this article with start and end location. All locations are normalized to the metric system of the East – Tunnel and are indicated with the Prefix “TM” which represents “Tunnel Meters”. The Tunnel Meters are shown on Figure 4.2, Figure 4.3 and Figure 4.4.
During drilling, the outflow from the borehole was continuously monitored by the drilling crew and recorded on a drilling protocol. In many boreholes hydraulic open hole tests (mostly interference tests, between two or more boreholes) were preformed to characterize the hydraulic formation properties.

4.2.2 Hydrogeologic Setting

Based on the complex geology with fractured and karstified overthrusted and folded lithological units the hydrogeological setting is very complex. Furrer (1962) and Furrer et al. (1993) describe the general hydrological setting of the region Kandersteg – Leukerbad – Adelboden (locations see Figure 4.1) and conclude that karstification of limestones in several lithologic units dominate the regional ground water flow systems. Based on several detailed studies performed during the preliminary investigation phases of the base tunnel project Kellerhals and Isler (1998) present a comprehensive hydrologic overview of the Doldenhorn Nappe area.

4.2.2.1 Karst Springs

During phases of high precipitation several karst springs in the Kander Valley and Gastere Valley increase instantaneously their flow rate or become activated by a precipitation event. Two major karst springs are located in the area of the Doldenhorn Nappe (Figure 4.3):

- **Doldenhorn Spring**: The “Doldenhorn Springs” are 5 larger karst springs within an area of approx. 1000 m². The flow rate of all springs is highly variable within a yearly cycle and ranges between approx. 150 l/s in January / February and approx. 650 l/s in July / August (Figure 4.5–a). All springs are located from zero to several meters above the floor of the Kander Valley and originate in the lithological unit of the Öhrli – Limestone. The location of the Doldenhorn Springs is shown on the cross section in Figure 4.2. Since 16.02.2000 the total flow rate of the Doldenhorn Spring is regularly measured in intervals of approx. 30 days. The strong variation in the flow rate is typical for a karst aquifer. In 1957 several tracer tests were performed for the exploration of a hydropower plant in the Gastere Valley, but a connection
between ground water in the gravel aquifer of the Gastere Valley and the Doldenhorn Spring could not be shown. This might be an indication for a karst system fed only by the Öhrli – Limestones.

- **Geltenbach Spring**: This karst spring is located in the Gastere Valley on 1560 m a.s.l., approx. 160 m above the valley floor. The karst spring has is located at the boundary of the low conductive Öhrli – Marl and the higher conductive Quintner Limestone. *Gerber and Rouiller (1990)* describe in detail the shape and the geometry of explored section of this karst system. The flow rate of the spring is highly variable in a daily as well as in a yearly cycle ranging between 0 l/s during winter time and approx. 3000 l/s in summertime. The strong daily variation (variation of flow rate unknown) correlates to the snow melt during the afternoon in summertime. *Kellerhals and Isler (1998)* conclude that based on the strong daily variation of this spring, the catchment area might be rather local and located on the northern flank of the Tatlishorn (Location see *Figure 4.3*).

### 4.2.2.2 Ground Water in Gravel Aquifers

Two gravel filled and deeply incised valleys – the Kander – and the Gastere Valley are crossed by the base tunnel (*Figure 4.2* and *Figure 4.3*). In both valleys, the ground water level is located close to the ground surface (approx. 1200 m a.s.l. for the Kander Valley and approx. 1400 m a.s.l. for the Gastere Valley). In the Gastere Valley the level of the ground water shows a variation with a yearly cycle of approx. 25 m with a maximum level in the months of July and August and a minimum in January and February. The total discharge of the gravel aquifer can be monitored at the valley outlet near “Chluse” (*Figure 4.3*) where the bedrock surface forms the river bed.

### 4.2.2.3 Preferential Groundwater Pathways in Underground Excavations

The dominating conductive structures in the limestones of the Doldenhorn Nappe at the level of the LBT are described in detail in *Pesendorfer and Loew (2006b)*. A detailed map of the geological structures found during excavation of the LBT is presented in *Attachment H*. Here only a summary of the observations is presented.
During excavation of the Base Tunnel in the section of the Doldenhorn Nappe, water inflow into the tunnel was mainly related to brittle fault zones which showed two major orientations: one set with a strike direction NW – SE and a steep dip angle (approx. 80°) and a second set with a strike direction to SW – NE and a dip angle of approx. 30°. A stereographic projection of the brittle faults is presented in Pesendorfer and Loew (2006b). The brittle fault zones can also be seen on the geological cross-section of Figure 4.2.

The excavation of the double tube LBT showed mainly few well developed karst structures such as open karst pipes. Pesendorfer and Loew (2006a) describe two locations (at TM 26878 and TM 27172) in the base tunnel where significant karst structures were found. Both karst caves were filled with sediments (gravel, sand, silt and clay). The total outflow of these karst systems (including a surrounding conductive fracture network) was approx. 16 and 20 l/s, respectively (determined approx. 10 h after the excavation). While the system at TM 26878 showed a strong decrease in the flow rate to approx. 5 l/s over 3 years, the karst system at TM 27172 showed a decrease to approx. 12 l/s over 3 years. Based on the sediments found in the systems and the general decrease in the flow rate of 60 % and 30 %, respectively, we can assume that on the level on the base tunnel only sediment filled palaeokarst structures exist and no active karst systems. These findings are in agreement to the predictions made by Lützenkirchen and Loew (2000).

During the excavation of the Lötschberg Crest Tunnel in 1908 which is located on a level of approx. 1220 m a.s.l. several inflows into the tunnel occurred (Hugi and Trunninger, 1914). Based on the observations made by the tunnel geologists and the tunnel outflow monitoring discussed in Paragraph 4.2.3, we must assume that inflows occurred from karstified fractures or karst caves.

4.2.3 Tunnel Inflows

In Figure 4.5–a–b–c we compare the flow rate of the Doldenhorn Spring with the total discharge from the Lötschberg Crest Tunnel and the summed inflow from major
conductive structures into the base tunnel between 22.05.1995 and 01.01.2006. Details of the flow rates are discussed subsequently:

Since October 1991 the total tunnel discharge from the Lötschberg Crest Tunnel is regularly monitored at the tunnel portal in Kandersteg in intervals of approx. 30 days. The outflow from the LCT represents a sum of all tunnel inflows from the portal up to the crest point (located in crystalline rock) of the tunnel. The tunnel inflows show strong annual fluctuations and also strong inter-annual differences.

During a study performed in 1992 and 1993 Haefeli et al. (1994) determined the discharge from individual hydrological units along the tunnel axis (Limestones, autochthonous sediments and crystalline rocks). As the flow rates of corresponding lithologic units were very difficult to determine in the tunnel, an error of the flow measurements of at least ± 20% must be assumed. Figure 4.6–a shows the measured discharge rates in l/s from individual hydrologic units along the LCT in 1992 and 1993, while Figure 4.6–b presents the percentage of the flow rate of the individual formations compared to the total tunnel discharge. Time dependent flow rates of selected brittle faults are shown in Attachment H. Three major units are responsible for more than 70% of the total tunnel discharge rate: the formation boundary between the Quintner Limestones and the Öhrli–Marls, the formation boundary between the crystalline rocks and the autochthonous sediments, and the formation of the Öhrli–Marls. Mainly in the discharge rate related to the Öhrli–Marls a strong time dependent variability is observed. This is an indicator that the discharge from the Öhrli–Marls is controlled by a phreatic zone with highly variable hydraulic heads which is typical for karst- and jointed rock aquifers.

Haefeli et al. (1994) reports that a flow rate of approx. 35 l/s is determined from the Lötischberg Accident Tunnel (LAT), which is part of the flow rate of the Öhrli–Marl units. Unfortunately no time dependent measurements of the discharge rate of the LAT are available. Determining the percentage of the annual mean discharge rates based on Haefeli’s measurements showed that 69% of the total tunnel discharge is related to the limestone units of the Doldenhorn Nappe: Quintner Limestone: 2%,
For determining the yearly mean discharge rate of the LCT/LAT we selected the manual measurements at the tunnel portal from 1995 until 2006 which results in 141 l/s. The measurements determined before 1995 were not included in this analysis, as major construction work was performed in the tunnel in 1993 and 1994. Based on the measurements performed by Haefeli et al. (1994) we can derive a total annual mean discharge rate of approx. 90 l/s related to the Öhrli – Marls (including LAT), the Quinter Limestone and the boundary between Quintner Limestone and Öhrli – Marl. Considering the determined mean distribution of inflows in the years 1992 and 1993 into the LCT given by Haefeli et al. (1994) and observations on the level of the Base Tunnel showing that the inflows at the formation boundary Quintner Limestone / Öhrli Limestone are mainly related to the Quintner Limestone, following mean flow rates can be hypothesized:

- Yearly mean flow rate Quintner Limestones: 40 l/s (incl. boundary Quintner Limestone / Öhrli – Limestone)
- Yearly mean flow rate LAT: 35 l/s
- Yearly mean flow rate Öhrli – Marl: 15 l/s

In February 2002 the miners started to excavate the limestone units of the Doldenhorn Nappe in the Lütschberg Base Tunnel. During this excavation several major water inflows (up to 20 l/s), mostly related to brittle fault zones were crossed. All major inflows were continuously measured in intervals of approx. 14 days by the tunnel geologists. These flow rate measurements of major inflows usually started 1 – 2 days after the tunnel had crossed the structure, but could take up to 20 days after the excavation in some cases. Only inflows into the West – Tunnel were monitored. Figure 4.5–c shows the summed inflows from major brittle faults into the West -tunnel. In April 2003 the excavation of the Doldenhorn Nappe was completed and the summed flow rate stabilized on a level of approx. 46 l/s. Compared to the flow rates of the Doldenhorn Spring and to the LCT, no yearly variation in the flow rate of the base tunnel can be observed. In September 2003 the total tunnel outflow from the
Doldenhorn Nappe in the Base tunnel was determined using salt concentration measurements in tunnel water collector channels (Error in the flow rate: approx. ± 20 %). The total discharge rate was 91 l/s in the West – Tunnel and 58 l/s in the East – Tunnel. The total discharge rate of the West – Tunnel is about twice as high as the rate determined from major monitored inflow locations. This observation is in agreement with Pesendorfer and Loew (2006b) showing that the major conductive structures on the level of the Base Tunnel are producing about 50% of the total tunnel flow rate.

The distribution of the discharge within the Öhrli – Limestone and the Quintner Limestone determined in September 2003 is presented in Figure 4.7-a-b. The water collector channels are located every 330 m in the tunnel tubes resulting in the measurement interval length shown in Figure 4.7-a-b. On the level of the LBT, the Öhrli – Marls were mostly dry; an inflow from a brittle fault zone of approx. 11.2 l/s at the formation boundary Öhrli – Limestone and Öhrli – Marl was included based on observations during the excavation process in the Öhrli – Marls. The discharge from the Quintner Limestones in the West – Tunnel is 41.8 l/s. The strong difference between the two tunnels regarding the discharge is most probably related to heterogeneity in the major water conductors which are the brittle faults.

The total discharge rate from monitored brittle faults in the West – Tunnel of the LBT within the later discussed model domain (southward of TM 27’000) is shown in Figure 4.7-c. After finishing the excavation of the Doldenhorn Nappe on 02.04.2003 the discharge rate stabilizes around 30 l/s. The decreasing discharge rate from September 2004 on is related to the shut down of several monitoring locations in the LBT.

4.2.4 Hydraulic Head in Deep Boreholes

Three deep surface boreholes have been instrumented for long term pressure head monitoring (Figure 4.2 and Figure 4.3). Borehole 91/2 has an open filter section (between 1100 and 1080 m a.s.l.) in the Quintner Limestone, in borehole 92/7 the filter section (between 1120 and 1060 m a.s.l.) is also open in the Quintner Limestone,
while in borehole 94/19 the filter section (between 670 and 710 m a.s.l.) is open in the Triassic sediments and in the Crystalline. The hydraulic head monitored in borehole 91/2 and borehole 92/7 is therefore related to the Quintner Limestone while the hydraulic head in borehole 94/19 is related to the Triassic Sediments as the sediments are approx. one order of magnitude more conductive than the crystalline rocks (Kellerhals, 1996). The hydraulic head in the deep borehole 91/2 and borehole 92/7 was determined in irregular intervals with an electric light gauge since 1992. A detailed description of the deep boreholes including manually determined hydraulic heads in the boreholes between 1992 and 2002 is presented in Attachment F of this thesis. As during this study borehole 92/7 was equipped with a piezoelectric pressure transmitter the focus will be on this borehole subsequently. Figure 4.8–a presents two multi – year determined hydraulic head records, one for piezometer GA 20 and one for the deep borehole 92/7. From March 2000 to November 2005 the hydraulic head in the piezometer GA20 was determined manually. For later comparison between boreholes with non equal measurement intervals the measurement points (symbols in Figure 4.8) were interpolated using a spline function (dashed line in Figure 4.8–a). Manually measured hydraulic heads in borehole 92/7 between March 2000 and August 2002 were processed equally. On August 2nd 2002 borehole 92/7 was equipped with a piezoelectric pressure transmitter which recorded the hydraulic head in the borehole in intervals of 10 min. The hydraulic head determined between August 2002 and May 2005, when the transmitter broke down, are air pressure corrected. Figure 4.8–a shows daily arithmetic mean values represented by a continuous line. After the breakdown of the pressure transmitter in May 2005 the hydraulic head was determined manually on three more dates. As can be seen clearly on Figure 4.8–a, the hydraulic head of the piezometer GA 20 and the borehole 92/7 is nearly equal. The levels in piezometer GA 20 as well as the borehole 92/7 show a clear variation in a yearly cycle.
4.3 Pressure Changes Induced by Base Tunnel Excavation

4.3.1 Permanent Pressure Reductions

In this paragraph we will describe the observed influence of the LBT excavation on the hydraulic heads in the Quintner Limestone and in the gravel aquifer of the Gastere Valley as shown in Figure 4.8-b. In January 2003 the level of the deep borehole 92/7 drops and stabilizes (with an annual cyclic variation) on a lower level. To determine the effective drop in the water level without the influence of the cyclic variations we subtracted the level determined in piezometer GA 20 from the level determined in borehole 92/7. Additional to the difference of the water levels, the summed initial inflows into the LBT (both tubes) in l/s (determined between 1 and 10 h after a conductive structure was excavated) are shown Figure 4.8-b with a continuous thin line. It is obvious that the water level in borehole 92/7 is not irreversible influenced by the base tunnel until 20.02.2003. At this date a brittle fault zone at TM 28287 (West – Tunnel) with a major inflow (9 l/s) into the tunnel is excavated resulting in a permanent drop of the hydraulic head in the Quintner Limestones around borehole 92/7. To determine the effective drop of the hydraulic head, the arithmetic mean of the difference in the hydraulic heads was determined between March 2000 and January 2003 and between May 2004 and November 2005. As data are partly missing between June 2003 and May 2004 and / or – are only based on spline interpolation of the piezometer GA 20, this interval was not considered in the analysis. The difference between the non influenced hydraulic head and the influenced head is –26.5 m or - 2.7 bar. This hydraulic head drop in the Quintner Limestones at borehole 92/7 is irreversible.

The hydraulic head in borehole 91/2 was continuously determined in irregular intervals since 1992. The hydraulic head in borehole 91/2 dropped between 10.12.2002 and 23.01.2003 and stabilized, similar to borehole 92/7 on a lower level. The exact date of the hydraulic head drop is not known, as this borehole was not equipped with a piezoelectric pressure transmitter. No sophisticated analysis as on the
borehole 92/7 was performed on this borehole but an estimation of the drop of the hydraulic head is approx. -20 m or -2.0 bar in the Quintner Limestone.

4.3.2 Reversible Pressure Reactions

In this paragraph, observed pressure reactions caused by the disturbance of the horizontal exploration boreholes in the limestone aquifer are discussed.

The hydraulic head curve of borehole 92/7 between November 2002 and March 2003 (Figure 4.8–a) shows several irregularities. A detailed view of this time interval is shown in Figure 4.9–a. Additional to the hydraulic head the summed initial inflows (determined between 1 and 10 hours after a conductive structure was excavated) into the excavation zone (tunnel face minus 12 m) are shown. Also shown on Figure 4.9–b and -c are inflows to small destructive drillholes (amount: approx. 6) with a diameter of 5 cm and a depth of 24 m which were continuously performed along the tunnel axis to detect karst pipes probably missed by the exploration drilling program. And finally Figure 4.9–b and –c shows the inflows to the horizontal exploration boreholes discussed in Paragraph 4.2.1. In the interval between November 2002 and February 2003 eight horizontal exploration boreholes in four drilling campaigns were performed: four in the East – Tunnel (K15EA and B, K16EA and B) and four in the West – Tunnel (K13WA and B, K14WA and B). In Figure 4.9–b and –c the summed inflow rates for each drilling campaign (K15E, K16E, K13W and K14W) are presented. The location of the horizontal drillings is shown in Figure 4.4. In this excavation section the West – tunnel was always ahead of the East – tunnel.

Figure 4.9–a shows the superposition of several stresses acting on the pressure monitored in 92/7:


- Tide effects of variable frequency creating small scale reversible signals in the hydraulic head record.
Inflows to the long exploration drillholes during drilling and subsequently testing cause reversible pressure reactions in borehole 92/7 lasting several days. Horizontal exploration boreholes, performed from the lagging tunnel have the similar effects on the hydraulic head as boreholes drilled from the leading tunnel. The closer the distance between borehole 92/7 and the horizontal exploration boreholes, the stronger the induced head change (e.g. the horizontal distance between borehole 92/7 and borehole K16E is approx. 1000 m).

Under the assumption of a radial flow in a homogenous, isotropic aquifer of infinite extent, the time difference between the first appearance of an outflow from a horizontal drillhole (recorded on drilling protocols) and the head reaction in the deep borehole 92/7 can be used to determine an equivalent aquifer storativity (see e.g. Jacob, 1940, De Marsily, 1986):

\[
S = \frac{2.25 \cdot T \cdot t}{R^2}
\]

(1)

where T is transmissivity, S is storativity, R is the radius of action of the exploration borehole, i.e. the distance inside which the borehole outflow is felt, t is the response time.

For determining an aquifer storativity the head reaction related to the outflow in borehole K16EA/K16EB was selected because of a rather sharp response signal in borehole 92/7. Unfortunately, no reliable transmissivity values are available for borehole K16EA / B, but as presented in Pesendorfer and Loew (2006b), borehole transmissivity values in the limestone aquifer are relatively uniform. It was therefore decided to apply a reliable maximum (3.8E-5 m²/s – borehole K14WA) and minimum (1.5E-5 m²/s – borehole K15EA) transmissivity value determined from hydrotests performed in the boreholes located next to the borehole K16EA/B. The radius of action was determined to be 1000 m (Figure 4.4). The maximum time difference between the earliest occurrence of a flow out of the borehole K16EB and the latest head reaction in borehole 92/7 was determined taking into account the error of the
internal timer of the pressure transmitter and possible errors of the watches used by
the drilling crew. Taking into account the possible time shift errors the maximum
reaction time was determined to 45 min. The determination of the pressure reaction
time is shown in detail in Attachment G. Applying the range of transmissivities, the
range of response times \( t \) and the radius of action to Jacob’s equation results in a
range of storativity of the Quintner Limestone of between \( 2.3E-7 \) and \( 8.9E-8 \). Small scale storativity – values determined with a straight line method from crosshole
pressure responses between exploration boreholes in the Quintner Limestones are
between \( 9.6E-5 \) and \( 4.3E-8 \) (Pesendorfer and Loew, 2006b). Large scale
storativity – values from distant boundary effects visible on transient pressure
reactions of hydrotests in the exploration boreholes are in an interval of \( 1.2E-6 \) to
\( 3.6E-8 \) (Pesendorfer and Loew, 2006b).

4.4 Hydrodynamic Model Set – up

4.4.1 Model Objectives

To help understand flow systems on a larger scale in the Doldenhorn Nappe,
especially in the Quintner Limestones, a hydrodynamic model was created for the area
of the Gastere – Valley. Key questions addressed with the ground water flow model
are:

a) Understand / explore the difference in tunnel inflows (space and time) of the
   shallow LCT and the deep LBT

b) Understand / quantify environmental impacts (changes in flow systems) of the
   LCT and the LBT in the Quinter Limestone section

c) Explain / understand pressure heads measured in the exploration boreholes

d) Explain / understand significance of hydrotest results from the exploration
   boreholes with respect to the regional hydrodynamic system properties and
   long term tunnel inflows.
4.4.2 Conceptual Hydrogeological Model

Simulating a flow system in a fractured and karstified rock mass with complex geology is a difficult task. Many approaches are currently available each corresponding to a different conceptualization of the medium. The medium can be viewed as an equivalent single porosity, multiple or stochastic continuum (e.g. Carrera et al., 1990, Reeves et al. 1991, Pruess and Narasimhan, 1988, Neumann and Depner, 1988), or, flow can be associated to fractures (e.g. Dershowitz et al. 1991, Long et al. 1992) where a knowledge about the geometry of the fracture network is required. An even more complex approach is the combination of the two, so called hybrid models (e.g. Cacas et al., 1990, Oda et al., 1987). A combination between a fractured and potentially karstified rock mass is even more challenging to simulate. Maloszewski et al., (2002) represent an alpine karst aquifer with a “triple porosity” model – porous matrix – conductive fractures – and conductive drainage channels. Scanlon et al., (2003) represent a karst aquifer with an equivalent porous media model while Bakalowicz (2005) discusses many approaches for modeling a karst aquifer and compares the advantages and disadvantages of the models.

As this study is focused on the ground water flow systems on the scale of the Doldenhorn Nappe (several km) and its interactions with several subsurface structures (LCT, LAT and LBT), we have chosen a continuum approach. Due to the fact that many brittle faults of similar hydraulic properties (quite uniform K – values over more than 3.2 km of tunnel) and the “matrix” dominate the hydraulic behavior of the rock mass it was decided to not include the fault zones explicitly and to introduce effective hydraulic conductivities into the model to characterize large scale hydrogeologic units.

As field data of a possible hydraulic anisotropy of the hydrogeologic units were not available, isotropic conditions of the rock mass were assumed. A steady state fully three – dimensional model was chosen to simulate the influence of the complex topography and the subsurface galleries on the flow systems. The effect of spatially distributed ground water recharge rates (common in high alpine areas) is studied by assigning a free and movable water table.
The model domain is a high alpine area with very steep topography and a complex geology with thrust faults and folding. Major geological units within the model are the limestones and marls of the Doldenhorn Nappe. Boundaries of the model were selected with respect to impermeable geologic units and/or topographical features such as valleys or crests. The focus was kept on modeling the flow within the Quinter Limestones of the Doldenhorn Nappe.

### 4.4.3 Numerical Model

The simulations were carried out with the code Modflow Pro – PMWIN (Chiang and Kinzelbach, 1993; Chiang et al., 1998). PMWIN is an extension of the modular three-dimensional finite-difference groundwater model originally developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996a, Harbaugh and McDonald, 1996b). The model was built as a block model, with each layer representing the effective elevation above sea level. A “cube”, 8000m (NE-SW) x 3500m (NW-SE) x 2850m (vertical) is the result with a model base at 0 m a.s.l. The elevations of the layers including layer height are presented in Table 4.2. Topography was represented by deactivating selected cells in the upper layers of the model. The mesh consists of 158 columns and 52 rows of various sizes distributed in 41 layers (Figure 4.10) with a total of 336’856 cells. As indicated on Figure 4.10 the mesh was densified along the both tunnel traces and around the location of the deep borehole 92/7.

### 4.4.4 Model Parameters

#### 4.4.4.1 Topography and Geology

As shown on Figure 4.3, the model area is a high-alpine region with elevations ranging from 1200 m a.s.l. (Kander Valley) to 3676 m a.s.l. (Balmhorn). Several areas are glaciated. A deeply, during the last glaciation period incised valley, the Gastere Valley dominates the topography with extremely steep walls.

A simplified geological surface map of the area is shown in Figure 4.11-a. The following geologic units occur in the model:
- **Quaternary**: Embraces all quaternary sediments, such as fluvial sediments (valley infills), morains, rock falls, landslides etc.

- **Flysch (Gellihorn Nappe)**: Tertiary sediments, of turbiditic facies, mostly consisting of fine grained and very dense sandstones.

- **Kiesel Limestone (Doldenhorn Nappe)**: Limestone with silicified bands

- **Öhrli – Limestone (Doldenhorn Nappe)**: Limestone with low quartz content

- **Öhrli – Marl (Doldenhorn Nappe)**: Dark, partly clay rich limestone

- **Quintner Limestone (Doldenhorn Nappe)**: Dense, massive limestone with clear bedding

- **Marl Shists (Doldenhorn Nappe)**: Dense marl with high clay content

- **Triassic Sediments (Autochthonous)**: Sandstones, gypsum, anhydrite

- **Aar – Massif (Crystalline)**: Granites and Gneisses

Based on the findings during tunnel excavation of the LCT, LAT and the LBT, and based on profiles presented by *Kellerhals and Haefeli, 1998, Furrer, 1962, Hügi et al., 1988*, two horizontal geologic cross-sections within the boundaries of the hydrodynamic model were drawn. *Figure 4.11-b* presents a geological map on the level of the Crest Tunnel on an elevation of 1220m a.s.l. *Figure 4.11-c* presents a geological map on the level of the Base Tunnel at an elevation of 830 m a.s.l. Two vertical geologic cross-sections (with projected axes of the LCT / LBT onto the section) are shown in *Figure 4.11-d* and *Figure 4.11-e*.

### 4.4.4.2 Hydraulic Conductivities

An approximation of the hydraulic conductivities of lithologic units crossed by the Base Tunnel can be made from hydraulic tests performed in the horizontal exploration boreholes. Only tests rated “reliable” (*Pesendorfer and Loew, 2006b*) were considered in the analysis. $K$ – values for the Öhrli – Limestones deduced from 4 selected tests range from 4.0E-6 m/s to 2.2E-7 m/s with a geometric mean of 1.4E-6 m/s and $K$ – values for the Quintner Limestone deduced from 9 selected tests range from 2.5E-7 m/s to 5.3E-8 m/s with a geometric mean of 1.2E-7 m/s. Unfortunately, only one
A reliable K-value is available for the Öhrli–Marls. This value (\(K = 1.6 \times 10^{-7} \text{ m/s}\)) was determined on a boundary between the Öhrli–Limestones and the Öhrli–Marls.

From a packer test performed within the Triassic sediments by an external contractor a K-value of \(2.0 \times 10^{-9} \text{ m/s}\) (Solexperts, 2003) could be deduced. For determining a hydraulic conductivity for the crystalline Aar–Massif determined steady state flow rates from conductive structures were considered. Tunnel geologists reported inflows of total 7 l/s over a length of 1500 m tunnel within the crystalline rocks. Assuming steady state conditions by using the well known solution described by Goodman et al. (1965) a hydraulic conductivity could be determined

\[
K = \frac{Q \cdot 2.3 \log \left( \frac{2 \cdot h_e - h_i}{r} \right)}{2 \cdot \pi \cdot l \cdot (h_e - h_i)}
\]

where K is the effective hydraulic conductivity in the (vertical) plane of flow, \(h_e-h_i\) is the tunnel drawdown (~2000 m), r is the tunnel radius (4 m), l is the length of the investigated tunnel section (1500 m) and Q the discharge rate along the investigated section (7E-3 m³/s). This results in \(K = 2.6 \times 10^{-9} \text{ m/s}\). As tunnel geologists reported only very few conductive structures within the granite section of the tunnel, the K-value determined with Goodman’s solution seems reasonable.

Within the model outline (Figure 4.11-a) many Quaternary sediments are exposed. Only the fluvial sediments of the Gastere Valley have thicknesses which have to be considered in the model (all other Quaternary sediments are of minor importance). Freeze and Cherry (1979) present a hydraulic conductivity range for gravel between 1.0 m/s and 1E-3 m/s. As the walls of the trough are at least partly covered with glacial, consolidated sediments (probably ground morain) which were encountered e.g. in boreholes 91/2 and 92/7, the overall hydraulic conductivity of the sediments (gravel infill and morain) is certainly lower. Haefeli et al., 1994 estimated a value of 2.0E-4 m/s for the quaternary valley infills. Unfortunately no experimental K-values for the gravel Aquifer in the Gastere Valley are available.
The Marl – Shists of the Doldenhorn Nappe are thought to act as a formation of low conductivity compared to the northward adjacent Quintner Limestones. This assumption is supported by in situ observations of the East – face of the Balmhorn, which consists completely of Marl – Shists. No springs are observed on this huge face. Kellerhals (1996) concluded that the Marl – Shists form a separate hydrogeologic unit not connected to the Quintner Limestones.

4.4.4.3 Model Boundaries

All outline model boundaries were selected based on topographical elements or on hydrogeologic properties of the lithologic formations.

- **Boundary South East:** Indicated on Figure 4.11-a, the south east boundary was selected to follow the outcrops of the Quintner Limestone. As described above the Marl – Shists are thought to act as an impermeable boundary.

- **Boundary South West:** This boundary was selected along the valley of the Schwarzgletscher (Figure 4.3). It was assumed that no groundwater path lines cross the valley and therefore the valley acts as a groundwater divide and an impermeable boundary, respectively. This assumption is supported by Furrer (1962) who describes tracer tests which show that the complete region West – and Southwards of the summit “Kleines Rinderhorn” does not discharge to the Gastere – and the Kander Valley, respectively. The South West boundary does not match with the previous defined, straight outlines of the hydrodynamic model. Cells, between this assumed boundary and the model outline were selected inactive and not considered in the model runs.

- **Boundary North East:** This boundary was selected to follow the prominent exposed ridge between “Doldenhorn” and “Äusserer Fisistock”. Equal to hydrogeological impermeable boundaries within valleys, a ridge can also act as an impermeable boundary (Freeze and Cherry, 1979). Although this assumption is only strictly valid for a homogenous, isotropic aquifer, we assume this kind of boundary in this region of the model because no information about the ground water flow in this region is available and we
assume that this boundary is in enough distance to influence the hydrodynamics of the near tunnel region not significantly.

- **Boundary North West:** The North West boundary was the most difficult boundary to define. No topographical feature dominates this region and therefore a geological boundary had to be considered. A no flow boundary was selected for the part West – ward of the Gastere Valley (south of the Gällihorn) as a valley dominates the topography in this region (continuation of the Schwarzgletscher, *Figure 4.3*). For the part East – ward of the Gastere Valley the Öhrli Marls were selected as a low permeability hydrological boundary. In the West – Tunnel of the LBT, where major inflows from brittle faults were monitored after excavation during a period of 3 years, no inflow from brittle faults occurred in the Öhrli – Marls. All inflows were small (maximum 2 l/s) and were bleeding out soon after the excavation. As indicated on the cross section along the tunnel axis of the LBT presented in *Figure 4.2* the Öhrli – Marls are heavily folded and bedding is mostly steep, especially below the level of the crest tunnel. Flow in the Öhrli – Marls might therefore be perpendicular to the tunnel axis and parallel to the steep bedding. Within the Öhrli – Marls the hydraulic anisotropy might be high, with an increased conductivity in the bedding plane. In a first simulation we therefore assumed that the Öhrli – Marls form a steeply inclined hydrological barrier between the Quintner Limestones and the Öhrli – Limestones. The northward dipping (~30°) thrust faults (*Figure 4.2* and *Figure 4.11-d-e*) might form conductive structures and the North – West boundary might therefore be a leaky boundary. As the boundary conditions acting along such faults are difficult to implement into the model, model runs discussed in this article were performed with an impermeable North – West boundary. The possible effects of a leaky boundary are discussed under Paragraph 4.6. As indicated on *Figure 4.2* selecting the North – West model boundary at TM 27°000 results in a maximum length of the boundary within the Öhrli – Marls. We therefore have chosen the vertical North West boundary at TM 27°000.

- **Boundary Bottom:** As clearly indicated on the geological cross section in *Figure 4.2*, a northward plunging (approx. 20°) overthrust plane separates the
limestones of the Doldenhorn Nappe from the Triassic Sediments and the crystalline rocks. As described under Paragraph 4.4.4.2, the hydraulic conductivity of the Triassic Sediments and of the crystalline rocks is more than one order of magnitude lower than the one for the Quintner Limestone. We therefore assumed that the Triassic Sediments and the crystalline rocks can be represented by inactive cells. In a sensitivity run we compared a modeled free groundwater table surface with and without active cells in the crystalline and Triassic rocks. The difference between the two modeled free groundwater surfaces is marginal, resulting in a difference of max. 26 cm. It was concluded that the assumption of an impermeable boundary of the bottom of the model along the overthrust plane is valid.

- **Constant Head Boundaries:** Based on the large water volume stored within the fluvial infills of the Gastere Valley we assumed that the gravel aquifer of the valley acts as a constant head boundary equal to a lake or a river. This assumption is supported by the observation of the potentiometric surface in the valley which is not influenced by the base tunnel. Model cells exposed on the valley floor at an elevation of 1400 m a.s.l. were selected as constant head cells. Additional to the valley, all tunnel excavations (LCT, LAT and LBT) were selected as constant head cells with a head applied equal to the top elevation of the cell: LCT and LAT 1230 m and LBT 820 m. Table 4.2 shows the layers of the model with the location of the constant head cells. Generally, major flow through the Gastere Valley is controlled by recharge from the Kanderfirm (Figure 4.1) and the runoff at the location “Chluse” (Figure 4.3). Determination of the runoff from the Gastere Valley was performed with salt dilution measurements. Between 1991 and 2006, 116 runoff measurements were taken ranging between 13.7 m$^3$/s and 0.28 m$^3$/s with an arithmetic mean of 3.74 m$^3$/s. Recharge rates into the valley through the Kander river are assumed to be in the same range as the runoff rates. In the hydrodynamic model the flow through the valley is not considered.

### 4.4.4.4 Ground Water Recharge Rates

#### 4.4.4.4.1 Hydrological Model
For estimating the groundwater recharge in the investigated area hydrological modelling was applied to three basins (Figure 4.12 and Table 4.3). The distributed hydrological model PREVAH (Precipitation Runoff EVapotranspiration HRU Model, Gurtz et al., 1999) has been applied. PREVAH was applied in several Swiss basins (Zappa et al., 2003, Gurtz et al., 2003, Verbunt et al., 2006).

In this study we adopt hourly meteorological information obtained from the Swiss Meteorological Institute MeteoSwiss. More local information on precipitation was obtained from a dense network of daily pluviometers, also from MeteoSwiss. Similarly to the schemes adopted in Garen and Marks (2001) and Klok et al., (2001), the interpolation algorithms used here are simple and elevation de-trended inverse distance weighting.

The spatial discretization of PREVAH relies on the aggregation of gridded spatial information into clusters with similar hydrological response, the HRUs (Zappa, 2003). Hydrological similarity has been identified according to the elevation, land use, exposition and soil depth of the grid cells (Gurtz et al., 1999). The equilibrium line of the glacier was also considered in order to define if grid cells are part of either the accumulation or the ablation area of the glaciers. The model contains modules also for the simulation of snow and glacier melt (Klok et al., 2001 and Zappa et al., 2003) and for the estimation of soil water losses by evapotranspiration (Zappa and Gurtz, 2003). The implemented runoff generation module is based on the conception of the HBV-model (Lindström et al., 1997), adapted to a spatially distributed application. The HBV – Model (Hydrologiska Byråns Vattenbalansavdelning – Hydrological Bureau Water Balance Section) is a rainfall – runoff model which includes conceptual numerical distributions of hydrological processes at the catchment scale. Groundwater recharge is resulting from the percolation from the unsaturated zone of the soil. Detailed maps of the groundwater recharge at 100 x 100 meters resolution have been produced in order to provide inputs to the hydrodynamic continuum model.

4.4.4.4.2 Experimental Setup
PREVAH is a spatially distributed hydrological model and application requires thorough calibration and verification. The most sensitive tuneable parameters of PREVAH are the adjustment factors for scaling snowfall and rainfall (Zappa, 2002), the parameters of the snowmelt module (Zappa et al., 2003), the non-linearity factor controlling the soil moisture recharge (Zappa and Gurtz, 2003) and the parameters of the runoff generation module (Gurtz et al., 2003).

The calibration procedure relies on the monitored maximisation of an acceptability score based on nine different objective functions derived by the comparison between the observed and the simulated daily discharges (Sonderegger, 2004, Verbunt et al., 2006). The functions test the overall agreement between observation and simulation and combine equations from Nash and Sutcliffe (1970), Legates and McCabe (1999) and Zappa et al., (2003). To calibrate the PREVAH model in the investigated area two basins (Kander and Allenbach) with different area have been analyzed. The hydrology of the Gastere Valley was modeled based on these calibration runs and surveyed runoffs at the outlet of this basin at gorges of the Kander (Location “Chluse” see Figure 4.3). Here regular runoff observations by salt dilution technique were conducted. As shown in Figure 4.12 the two smaller basins are nested in the main basin of the Kander. An overview on the basic parameters of the catchments is given in Table 4.3.

The first year of all model runs (1990) was considered as initialization period and disregarded for evaluation purposes. The period 1991-2004 was split into calibration and verification periods as declared in Table 4.4.
4.4.4.3 Results

Figure 4.13 shows two observed and simulated hydrographs for the basins where calibration was done. The picture shows a three-year time series of the verification period. In both basins the automatic calibration procedure provided a set of parameters which allows a fairly good simulation of the verification period. The statistical values presented in Table 4.4 confirm that a good agreement is reached both in the smaller Allenbach basin and in the larger Kander basin. The agreement is slightly better in the calibration period as in the verification period, where results show a general underestimation of the discharge volumes. This is mostly evident for the Allenbach basin, where the model generates about 10% too few runoff in the period 1996 to 2004.

The results of the application of the calibrated parameters obtained for the Kander basin to the ungauged Gastere Valley basin for the period January 1991 to August 2005 are reported in Figure 4.14 and the corresponding statistical coefficients are given in Table 4.5. The correlation between observed and estimated values is 0.881 for the full range of observed discharge values. From this Figure we can estimate, that the runoff observed by the salt dilution technique for 116 cases in the investigated period is overpredicted by the model, when the observed value is smaller than 5 m$^3$/s. In such cases the correlation between model estimations and observed records is 0.888. For observed values exceeding 5 m$^3$/s there is no evidence for a systematic overestimation of the observed value by the model. The correlation in these cases is 0.442. In absolute numbers in low flow phases the observed value is about 1 m$^3$/s lower than the value estimated by the model, even if the model generally tends to underestimate runoff generation in this region (Table 4.4). This is rather good evidence that some water is diverted from the basin though a karst system.

The PREVAH determined recharge rate was applied to the hydrodynamic model, differentiating between three cases - a yearly mean recharge – a maximum recharge (arithmetic mean of the months May, June, July and August) – and a minimum recharge (arithmetic mean of the months November, December, January and February). The recharge distribution shows strong spatial variability especially in
regions of high altitude where steep bare rock slopes (low recharge) alternate with glaciated regions (high recharge). The recharge applied to the model area is shown in Figure 4.15-a (yearly mean recharge; \( \overline{Q_{\text{Model Domain}}} = 105.7 \text{ mm/y} \)), Figure 4.15-b (maximum recharge; \( \overline{Q_{\text{Model Domain}}} = 152.8 \text{ mm/y} \)) and Figure 4.15-c (minimum recharge; \( \overline{Q_{\text{Model Domain}}} = 51.6 \text{ mm/y} \)).

### 4.4.4.5 Excavations within the Model Domain

As shown in Figure 4.3, the orientation of the model was selected in a way that the model grid is parallel to the linear extent of the major excavations. The model area is dominated by the following major excavations:

- **Lötschberg Crest Tunnel (LCT):** the single tube tunnel was constructed in a horse shoe profile of approx. 8 m height and of approx. 6 m width. It was represented in the model with connecting cells of 10 x 10 m, all selected as constant head (1230 m) and a high conductivity (K = 1 m/s). Southward of the Öhrli – Marls (Figure 4.11-b) where the tunnel is no more parallel to the model grid, the tunnel is represented by single non connecting cells of constant head and high conductivity representing the same total volume as the true tunnel.

- **Lötschberg Accident Tunnel (LAT):** the tunnel is of equal size as the LCT and equally represented in the model. The tunnel runs parallel to the model grid.

- **Lötschberg Base Tunnel (LBT):** the double tube tunnel is constructed in a horse shoe profile with a height of 9 m, a width of 7 m and a distance between the tunnel axes of 40 m. Two tunnel tubes are represented in the model with connecting cells of 10 x 10 m, all selected as constant head (820 m) and a high conductivity (K = 1 m/s). The tunnel runs parallel to the model grid.

- **Secret military excavations:** A major excavation constructed by the army exists within the model domain. Unfortunately only marginal information about this excavation is available to us. Kellerhals and Isler, (1998) describe “a large underground excavation near Kandersteg, constructed during the project phase of the Lötschberg Base Tunnel”. As a surface entry exists in the
Gastere Valley, exactly above the tunnel axis of the LBT and a large army base is located in the Kander Valley likewise exactly above the tunnel axis of the LBT, westward of the tunnel portal of the LCT, we assume a direct connection along the axis of the LBT but on a level of 1230 m a.s.l. between those locations. The military access locations are shown in Figure 4.3. From a personal note given by one of the construction geologists it is known that the secret military excavation is not located below the level of the LCT (1230 m.a.s.l.). As the exact location and the shape of these military excavations is not known exactly, they were not included in the model.

### 4.4.4.6 Modeling Approach

Calibration of the model was done manually against the steady state tunnel inflows and focused on the hydraulic conductivities of the Quintner Limestone and on the vertical hydraulic conductivity of the Öhrli – Marl. The $K$ – values of the Öhrli – Limestones were not adjusted in the calibration procedure; instead the geometric mean $K$ – values of reliable hydrotests were applied to the model and not changed. Equal to the Öhrli – Limestones, the $K$ – value of the quaternary sediments in the trough of the Gastere Valley were not changed during the modeling process.

The model approach consisted of three steps for all simulations. Figure 4.16 shows the modeling process in a scheme. Yearly mean recharge rates and initial $K$ – values either estimated or selected from hydrotests were applied to the model. The first model run was started in fully saturated conditions.

In step 1 hydraulic heads and a free groundwater surface was determined for natural conditions (without any galleries). Hydraulic heads resulting from this first run were applied to the step 2 model with the LCT / LAT galleries applied. The $K$ – values for the model were adjusted manually until the simulation reproduced the LCT / LAT tunnel discharge from the formations of the Öhrli – Marl and the Quintner Limestone and the resulting free groundwater surface was compared to the spring level in the Gastere Valley and to hydraulic heads determined in deep boreholes. Resulting hydraulic heads were applied to the step 3 model with the double tube LBT applied to
the model. K-values again were manually adjusted until the simulation correctly reproduced the discharge of the limestone formations in all three underground excavations. Based on these results sensitivities to tunnel discharge was investigated by varying K-values of the limestone units by ± 20%, and surface recharge variations from yearly mean recharge to maximum and minimum values. Finally the impact of the secret military excavation was simulated.

After a first simulation run with uniform K-values related to the limestone units for the whole model domain, it became obvious that K-values on the level of the base tunnel differ from those on the level of the crest tunnel. Therefore, the model was split into two zones: an “active” karst zone with higher hydraulic conductivities located above 1200 m (level of the Kander Valley, including LCT / LAT) and a “palaeo” karst zone with lower hydraulic conductivities located below the level of the Kander Valley (including LBT).

4.5 Model Results

4.5.1 Simulation with Uniform K-values

The model results of the simulation with a yearly mean recharge rate and uniform K-values for the limestone formations (Öhrli – Marl and Quintner Limestone) are presented in Table 4.6. The simulation target was to reproduce the discharge rates of the limestone formations on the level of the base tunnel, which are represented well by the adjusted K-values. Applying the adjusted K-values for the base tunnel at the level of the LCT / LAT (without the LBT included in the model) only 54% of the observed total LCT / LAT tunnel discharge is simulated. These simulation results confirm that two depth dependent K-values have to be applied to the model to correctly simulate the discharge rates on the level of the LCT / LAT simultaneously with the LBT.
4.5.2 Simulations with Depth Dependent K – Values

4.5.2.1 Sensitivity of Tunnel Inflows

Model results for simulations with higher conductive limestone formations on the level of the LCT/LAT compared to the level of the LBT are presented in Table 4.7. First, yearly mean recharge rates were applied and K – values were adjusted until the tunnel discharge rates were comparable to the calibration target rates. The simulated discharge rates for the limestone formations on the level of the LCT/LAT match well with the simulation target, but decrease after the base tunnel is applied to 63 % of the previous calibrated values. This strong decrease in the discharge rate is not observed on the tunnel discharge rates measured at the portal of the LCT (Figure 4.5). In Table 4.7 the results of recharge variation (maximum and minimum compared to the yearly mean recharge) are presented. The variation of recharge does only affect the discharge rate of the LCT/LAT, while the discharge of the deep LBT remains constant. This is in accordance to the observations of continuous measurements of the discharge of both tunnels. The tunnel discharge of the LAT/LCT increases 12.6 % with maximum recharge applied compared to a yearly mean recharge, while it decreases by 15.8 % with minimum recharge applied to the model. This variation in discharge based on various recharge scenarios applied to the model strongly underestimates the variation in discharge in a yearly cycle measured at the tunnel portal of the LCT (variation up to 800 %, Figure 4.5). With a yearly mean recharge rate applied, the sensitivity of the discharge rates of the limestone formations was checked by varying the corresponding calibrated K – values ±20%. The discharge rates on the level of the deep base tunnel are directly coupled to the corresponding K – values, an increase of the K – values of 20 % results in an increase of the discharge rate of 20 % and vice versa. This is not observed on the level of the LCT. An increase of the K – value of 20 % increases the discharge rate of the corresponding formation of approx. 13 %.

4.5.2.2 Water Balances

In Table 4.8 we present a comparison of the water balances of three simulations with different recharge rates applied to the hydrodynamic model. The water balance of one simulation is divided between INflows representing flow into the model and
OUTflows representing flow out of the model. In general, the error of the water balance for all simulations was below 0.05% with respect to the total flow through the model. Because of different simulation stages – Natural Conditions, applying the LCT/LAT to the model and applying additionally the LBT to the model – the water balance was differentiated between those three stages. A change in recharge changes proportionally the water flow through the model. We therefore focus the description on the case with a yearly mean recharge applied. Including the LCT/LAT in the model, major flow into the model is determined by approx. 50% aerially distributed recharge and approx. 50% recharge from the constant head boundary of the Gastere Valley. With the LBT included in the model, this proportion changes to approx. 33% and 66%, respectively. The valley is therefore the major feeder of the LBT inflows. Considering the flow out of the model only with the LCT/LAT applied, the shallow crest tunnel becomes the major discharge unit within the model domain (approx. 80% of the total model outflow). After applying the LBT to the model, the outflows of the three units – Gastere Valley, LCT/LAT and LBT contribute 7.3%, 32.6% and 60.1% each to the total outflow of the model.

As shown in Paragraph 4.4.4.3 the flow through the Gastere Valley is approx. 3.8 m³/s (yearly mean). As shown in Table 4.8 including the LBT into the model “requires” 120 l/s from the assumed constant head boundary of the Gastere Valley. Compared to the total flow through the valley this additional amount of water represents only approx. 3% of the total flow. Regional recharge into the valley floor is not relevant.

4.5.2.3 Groundwater Table

In Figure 4.17 we present the water table isohypses within the model domain for yearly mean recharge rate applied. Figure 4.17-a shows the water table isohypses of the natural conditions without any gallery in the model, Figure 4.17-b the water table isohypses of the ground water table after application of the LCT/LAT and Figure 4.17-c the isohypses of the ground water table after additional application of the LBT. Compared to the water table determined for natural conditions the shallow LCT/LAT lowers the water table significantly (up to – 180 m compared to natural conditions)
and includes a major environmental impact (regarding flow in the regional aquifers). Indicated on Figure 4.17-b the LCT/LAT only affects the NE – area of the Gastere Valley, the SW – area remains unaffected. The construction of the double tube deep LBT additionally lowers the water table within the limestones only marginally (maximum approx. 50 m).

4.5.2.4 Flow Systems

The visualization of a three dimensional flow system is very complex. To visualize the impact of the LCT/LAT and the LBT on the hydraulic head distribution within the limestones of the Doldenhorn Nappe a cross section indicated in Figure 4.17-a (A – A’) was chosen. The cross section was selected with respect to a certain distance to the NW – boundary and at the intersection between LCT and LAT. The cross sections with topography, water table and isopotential lines are shown in Figure 4.18. Figure 4.18-a shows the isopotential lines for natural conditions, Figure 4.18-b after including the LCT/LAT in the model and Figure 4.18-b after including the LBT in the model. The major impact on the hydraulic head in the cross sections has its origin in the construction of the LCT/LAT, but the impact is mainly restricted to the NE – side of the Gastere Valley. The construction of the LBT changes the hydraulic potential around the new gallery strongly but major changes in the values in a distance more than 500 m away from the tunnel are not observed.

To visualize the regional flow system under natural conditions and the impact of the subsurface galleries on this flow system, particles were distributed on selected points along the cross section A – A’ (Figure 4.17-a) and were backtracked using the code MODPATH. Figure 4.19 shows the backtracking results in a map view and along the cross section A – A’ for natural conditions. Figure 4.20 after including the LCT/LAT in the model and Figure 4.21 after including the LBT. Regarding the Figures it has to be kept in mind that the resulting path lines are part of a highly complex, three dimensional flow system and the flow lines are projected onto the cross section or onto the map view of the Figure. Therefore it is possible that flow lines cross (visually) in these Figures. In natural conditions, the Gastere Valley with its constant head boundary controls the flow system of the area. After construction of the
LCT/LAT, the path lines are changed; in the SW of the Gastere Valley only areas close to the valley represent the recharge areas for the valley, while distant locations discharge into the LCT/LAT. In the NE part of the valley the complete area is discharging into the LCT/LAT. Applying the LBT to the model shows that the tunnel inflow to the LBT within this cross section is mainly controlled by the gravel aquifer of the Gastere Valley. The valley itself is still recharged from a flow system near the valley which is not affected by the LBT, and, as discussed in Paragraph 4.5.2.2 by the flow through the valley.

4.5.2.5 Hydraulic Pressure Heads

Locally very low static formation hydraulic heads were determined during the exploration program in the LBT. In Figure 4.22 simulated hydraulic heads along the LBT – axis (with yearly mean recharge applied to the model) are compared to the experimentally derived static hydraulic heads in horizontal exploration boreholes of the LBT. While hydraulic heads after TM 27750 towards south are simulated well by the model, a large discrepancy is observed for simulated hydraulic heads between TM 27000 and TM 27750. Applying other recharge scenarios to the model does not change hydraulic heads in the area of interest significantly.

Hydraulic heads including the measured head change after excavation of the LBT determined in the deep vertical boreholes (91/2, 92/7) could not be reproduced by the hydrodynamic model. As the boundary conditions of those boreholes are complex (open filter section in the Quintner Limestones, a free water table in the borehole and a cased section above, crossing the gravel aquifer of the Gastere Valley) it is thought, that the model failed mainly because we were unable to reproduce the boundary conditions of the boreholes correctly.
4.6 Discussion

4.6.1 Pore Pressure Changes induced by Subsurface Reconnaissance Drillings and Tunnel Excavations at Great Depth

During horizontal exploration drilling and the simultaneous survey of the hydraulic head in the Quintner limestone aquifer intersected by borehole 92/7, reversible head changes induced by exploration drilling were observed. The intensity of the changes in the hydraulic head induced by exploration drilling was increasing by approaching the head survey location. The “pressure pulse” induced by the open (flowing) exploration drillings traveled with high velocities through the fractured rock mass; 1000 m rock mass were crossed within maximum 45 minutes. The magnitude of induced pore pressure changes increased with decreasing distances. Pore pressure changes were induced from exploration drillings performed from the leading as well as from the lagging tunnel. Initial inflows into the tunnel had no measurable effect on the hydraulic head in borehole 92/7, even when same structures were excavated that induced reversible pressure reactions in exploration boreholes. Only after the excavation of one clearly defined brittle fault in the West – tunnel at TM 28287 the hydraulic head in borehole 92/7 became irreversible lowered by about 26 m.

In borehole 91/2 located in a horizontal distance of approx. 800 m from borehole 92/7 (Figure 4.4) the hydraulic head was lowered by about 20 m. Based on this observation it can be assumed that lowering of the hydraulic head in the Quintner Limestone caused by excavation of the LBT affected the aquifer of the Quintner Limestone on a larger scale and is not only bound to borehole 91/2 and 92/7. As the hydraulic head was lowered after the excavation of one clearly defined brittle fault, it can be concluded that flow systems within the Quinter Limestones are mainly related to the brittle faults. Head changes after including the LBT in the hydrodynamic model could not be reproduced at the locations of the deep boreholes, but as shown on Figure 4.17-d the construction of the LBT lowers the hydraulic head in the limestone aquifer on a regional scale.
Analyzing transient hydrotests in horizontal exploration boreholes with log – log diagnostic plots (Pesendorfer and Loew, 2006b) showed many tests with constant pressure boundaries affecting the late time test response. Using non linear regression procedures the distance to this boundary was determined and interpreted as the large gravel aquifer of the Gastere Valley. This interpretation indicated that hydrotests performed in deep tunnels can influence a large rock mass within short amounts time. Observations of reversible pore pressure reactions in distant deep vertical boreholes confirm this previous interpretation. When conductive structures were intersected and drained by the exploration boreholes in a certain distance from the tunnel faces the induced pore pressure disturbance occurred in a quasi undisturbed aquifer. As the horizontal boreholes performed in the lagging tunnel overlapped the excavation of the leading tunnel, similar pore pressure disturbance can be observed also from boreholes performed from the lagging tunnel. The question arises why hydrotests performed in small horizontal boreholes (Ø = 96 mm) induce a remarkable pressure drawdown in the limestone aquifer while two large tunnels (Ø ≈ 4.5 m) excavating the same conductive structures do not significantly change the hydraulic head until a clearly defined conductive brittle fault is excavated.

The inflow to the exploration boreholes is significantly bigger than to the tunnel tubes. This strong reduction in inflow is related to a reduced global impact of the pore pressure field. The strong reduction in inflow can not only be attributed to time. It could also be related to pressure dependant closure of initially conductive fractures around the tunnel excavation. The pressure drawdown induced by the tunnel is stronger than by the boreholes.

### 4.6.2 Transient Inflow behavior to Underground Excavations at Different Elevations in a Fractured / Karstified Limestone Aquifer

Comparing the tunnel discharge rates of the LCT/LAT and the LBT shows strong differences (Figure 4.5–b and –c). While the discharge rate at the LCT/LAT tunnel portal is similar to the discharge rate of the Doldenhorn Spring (Figure 4.5–a) – a typical karst spring with highly variable annually and inter-annually discharge rates -
the discharge rate of monitored conductive brittle faults in the LBT shows a stabilization after completing the excavation with no or only weak seasonal variations. In the hydrodynamic model, flow rates from the limestone formations could only be simulated satisfactorily with depth dependent hydraulic conductivities applied to the model. An active karst system was assumed above the elevation of the Kander Valley (≈ 1200 m a.s.l.) with open karst pipes and a phreatic zone with highly variable hydraulic heads. Simulations performed with the hydrodynamic model strongly underestimate the variations of the LCT/LAT tunnel discharge and therefore the variations of the hydraulic head in the phreatic zone. Only a small fraction of the observed discharge variations could be reproduced by the model.

On the level of the LBT, brittle faults dominate the groundwater flow. Only on two locations larger karst pipes (Ø ca. 75 cm) were encountered. These karst pipes were filled with clay, silt, sand and gravel and even initial flow rates from the crossed karst pipe did not exceed 20 l/s. The karst system on the level of the LBT is interpreted as a palaeo – karst system developed during Pleistocene when the level of the receiving stream was significantly lower than today. These observations are in agreement with the predictions made by Lützenkirchen and Loew (2000). Annual variation in recharge within the model domain do not significantly change the total discharge rate from the LBT. Therefore, the assumption of a continuum model approach for simulating discharge rates on the level of the LBT is reasonable.

4.6.3 Environmental Impacts caused by Shallow and Deep Tunnels in a Fractured and Karstified Limestone Aquifer

Under natural conditions, the phreatic ground water table within the model domain is expected to be rather flat, without high gradients and hydraulic heads are slightly increasing towards the Gastere Valley. In winter time this ground water table is expected to lay below level oft the Geltenbach Spring, which is only active during summertime. The impact of the construction of the shallow LCT/LAT on the ground water flow system is massive. The complete area NE of the Gastere Valley is influenced by the construction of this tunnel system and the water table is lowered by
up to - 180 m, while the SW area of the valley remains unaffected. Unfortunately no environmental monitoring program (e.g. springs, piezometers) was performed during construction of this tunnel system (built 1908), but it must be assumed that some springs fell dry during excavation.

The additional impact on the ground water system caused by the construction of the deep base tunnel is not as strong as caused by the LCT/LAT. Mainly the NE area of the Gastere Valley is influenced – the ground water table is lowered by less than 50 m – and compared to the construction of the LCT/LAT the SW area of the valley is affected only slightly (Figure 4.17-d).

As discussed in Paragraph 4.2.2.2 and Paragraph 4.5.2.4 major flow through the Gastere Valley is controlled by the melt water of the Kanderfirn glacier. More than 80% of the inflow into the deep LBT tunnel is controlled by the nearby gravel and water filled Gastere Valley. No drawdown of the water table in the valley is observed also the environmental impact is relatively low. This is remarkably different than the shallow LCT tunnel which drains a larger region nearby the tunnel creating a massive environmental impact.

As discussed under Paragraph 4.4.4.3, the NW – model boundary was assumed to be impermeable because of steep bedding within the Öhrli – Marls especially below the level of the LCT. Increased conductivity was assumed in the bedding plane. As presented in Figure 4.14 and Table 4.5 the runoff model indicates that approx. 10 – 15% of the determined runoff at the location “Chluse” (Figure 4.3) discharge subterraneous. This is an indication that the determined water balances do not represent exactly reality and the NW – model boundary is semi – permeable. Assuming a semi – permeable boundary, the hydraulic heads in the limestone aquifer are surely affected (lowered), but the effect might be marginal, as highly conductive brittle faults (Figure 4.2) cross the Öhrli – Marls and the Quintner Limestones and drain the gravel aquifer of the Gastere Valley.
4.6.4 Hydraulic Head Distributions along the Base Tunnel

In Figure 4.22 we present a comparison between static hydraulic heads extrapolated from hydrotests in exploration boreholes of the base tunnel and simulated hydraulic heads from the hydrodynamic model. Very low hydraulic heads are observed between TM 27’000 and 27’750. The following possible explanations for these low hydraulic heads are discussed subsequently:

a) Influence of drainage of the leading / lagging tunnel on the exploration borehole pressures
b) Leaky stand pipes of the exploration boreholes
c) Receiving streams with low hydraulic head in large distance from the tunnel
d) Under pressure zones caused by low permeability pressure seals
e) Unknown, deep excavations

a) Low hydraulic heads were determined in horizontal boreholes where major water conductive structures were intersected in a horizontal distance of more than 50 m from the tunnel face. Low hydraulic heads were determined continuously in five drilling campaigns - over a distance of more than 700 m of tunnel driving. The low hydraulic heads were determined in the lagging as well as in the leading tunnel. Testing the same structures with different drilling campaigns and from different tunnel tubes lead to equal results regarding static hydraulic head. Drilling and testing from the lagging tunnel is not coupled with a lowering of the hydraulic head caused by tunnel drainage. (E.g. in borehole K14EA when the explored tunnel tube (East) was lagging more than 80 m behind the leading West tunnel in which a previously performed drilling campaign resulted in an equal formation pressure of approx. 52 bars). Therefore this explanation for the low hydraulic heads determined in the LBT seems to be unlikely.

b) Great care has been taken to cement and seal the stand pipes. All drilled stand pipes of the boreholes were cemented and subsequently tested on pressures of 100 bars during 60 minutes under the survey of injection engineers. No outflow from the standpipes was allowed during this time, otherwise the pipes
were recemented. It is unlikely that in five successive drilling campaigns all stand pipes were leaky.

c) The nearest receiving stream with a hydraulic head comparable to the low hydraulic heads determined in the LBT is located in the Kander Valley near Mitholz (*Figure 4.1*), approx. 6 km north of the locations where low hydraulic heads have been determined in the LBT. The region in between is dominated by a complex geology with folding on regional scales, northward dipping, inclined thrust faults in various lithologic units of various hydraulic conductivities. This explanation cannot satisfactorily explain why hydraulic heads determined in the same formation (Quintner Limestone) should be affected by a distant receiving stream while others, just about 100 m horizontal distance away should be not. No geologic structure which separates the Quinter Limestones internally was found and which could probably explain such a zone of low hydraulic head.

d) A zone of anomalously low hydraulic head was encountered during an investigation program of a possible underground nuclear waste storage facility near Wellenberg, central Switzerland (*NAGRA, 1996*). The low hydraulic heads were encountered in the rock formation of the Valangingian Marls, a tight rock with low hydraulic conductivities (1E-14 m/s – 1E-12 m/s). As the values of the hydraulic heads were massively below the local and regional exfiltration zones (in extreme cases on the elevation of the sea level), the heads were interpreted as part of a large scale under pressure anomaly. This pressure anomaly is probably related to the end of the last glaciation period (approx. 14’000 years from now) when the melting glacier ice resulted in a decompaclion of the tight Valanginian – Marls building up low pressures within the rock mass. Mainly because of the strong difference of the hydraulic conductivity the Quintner Limestones cannot be compared to the Valanginian Marls. Another observation makes this explanation rather unlikely: in the borehole, showing the lowest hydraulic head of all the tested boreholes (K11EA, TM 27645, Head = 1020 m a.s.l.) a constant pressure boundary was observable on the late time pressure reaction. These constant pressure boundaries were interpreted as the gravel aquifer of the Gastere Valley, which
on the other side means, that the radius of evaluation of a hydrotect is large, probably more than 1000 m. This interpretation is supported by observed reversible hydraulic head reactions in deep boreholes discussed in this study. This is an indication that the limestones of the Doldenhorn Nappe are not an isolated or tight unit as probably the Valanginian Marls are.

e) As discussed under Paragraph 4.4.4.5, a secret military excavation of unknown shape and expansion exists above the axis of the LBT, on the level of the LCT/LAT. Unfortunately only marginal information about the shape and location of this underground gallery is available. As the level of this excavation is surely not below the level of the LCT/LAT, a lowering of the hydraulic head below the level of the LCT/LAT can be excluded.

The explanations listed above cannot explain satisfactorily the observed low static formation pressure heads determined in the base tunnel. All of them seem to be unlikely with respect to the hydrogeologic setting of the region, or, because of technical reasons (e.g. cementation of stand pipes). As no other, realistic scenario is available to explain these low formation pressures, no general valid explanation can be given here.

4.7 Summary and Conclusions

To monitor the environmental impact of the excavation of the double tube Lötschberg Base Tunnel, hydraulic heads in the Quinter Limestone aquifer were continuously monitored in deep vertical boreholes. Small, reversible pore pressure changes could be related to an exploration program performed in the base tunnel with horizontal boreholes drilled through the tunnel face. It could be demonstrated that pressure pulses induced by the exploration boreholes travel with high velocities through the fractured and karstified rock mass. Large scale storativity values were determined based on the determined pressure pulse travel velocities. The hydraulic head in the Quintner Limestone was lowered irreversible on a regional scale by about 26 m after a brittle fault zone was crossed by the tunnel. Significantly bigger flow rates into the horizontal exploration boreholes than to the tunnel tubes could not only be attributed
to time, closure of initially conductive fractures around the tunnel excavation might be an explanation.

To quantify the regional impact on the limestone aquifers of two major tunnel excavations – the Lötschberg Crest Tunnel (LCT) and the Lötschberg Base Tunnel (LBT), separated in a vertical distance of approx. 400 m, a 3D steady state hydrodynamic numerical continuum model was built. Comparing determined discharge rates of the two tunnels with simulations of the discharge rates at the tunnel portal (LCT) and of a defined section of the LBT could only be performed successfully if depth dependent hydraulic conductivities were implemented into the model domain. Highly variable discharge rates at the LCT tunnel portal indicate a phreatic karst aquifer with highly variable hydraulic heads related to regional recharge. These high discharge variations were strongly underestimated by the model. The determined discharge of the LBT showed no annual variation. Simulations of the LBT discharge rates confirmed the observations. Active karst systems on the level of the base tunnel are rather unlikely and are mostly filled with clay, silt, sand or gravel.

The impact of the shallow LCT on the ground water flow system is massive and hydraulic heads within the limestone aquifers are lowered up to –180 m. The additional impact caused by the excavation of the deep LBT is less strong, hydraulic heads are lowered up to -50 m in the limestones. Simulation of flow paths showed, that major inflow into the LBT is controlled by the gravel aquifer of the Gastere Valley. As flow through the valley is large compared to the inflow into the LBT and controlled by melt water of a glacier, the environmental impact of the excavation of the LBT is small.

Low static hydraulic heads determined in horizontal exploration boreholes within the limestone formations could not be simulated by the model. It could be shown that drainage effects of the tunnel excavation, leaky stand pipes, far located receiving streams and under pressure zones cannot explain the low static hydraulic heads satisfactorily.
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4.8 Figures

Figure 4.1 Location including simplified geological surface map with main lithostratigraphical units (after Kellerhals and Isler, 1998) of the Lötschberg Base Tunnel with indicated study area.
Figure 4.2  Detailed geological cross section of the study area including lithostratigraphical sub-units, tunnel axis and start as well as end point of the exploration program. Selected deep drill boreholes with indicated open filter section and a major karst spring are also shown on the cross section.
Figure 4.3  Enlarged plan view of the area Gastere Valley and Kander Valley including the outline of the hydrodynamic model. Summits with elevation, major springs, rivers, subsurface galleries (incl. access locations to supposed military excavations), glaciers and the outline of a detailed view (Figure 4.4) are shown.
Figure 4.4  Detailed view of the area around the deep boreholes incl. a piezometer, with subsurface galleries of the Lötschberg Base Tunnel (LBT), the Lötschberg Crest Tunnel (LCT) and the Lötschberg Accident Tunnel (LAT). Start and End point of horizontal boreholes (to be projected onto the tunnel axis) drilled through the tunnel face of the LBT incl. identification are indicated with arrows on the map.
Figure 4.5 Flow rate comparison of the Doldenhorn – Springs (a), discharge of the LCT (b) and summed discharge from brittle faults within the section of the Doldenhorn Nappe in the base tunnel (c) between January 1995 and December 2006. As the Doldenhorn Nappe section on the level of the base tunnel was in excavation process until 02.04.2003, the discharge rate is continuously increasing as the amount of monitored brittle faults is increasing (1). After 02.04.2003 the flow rate stabilizes on a steady state level (2). The decreasing discharge rate from September 2004 on is due to manipulations on the monitoring system and the shut down of monitoring several brittle faults.
Figure 4.6  Discharge rate of the LCT divided into hydrological units (a). Cryst Crystalline rocks; Aut Autochthonous Sediments; Q Quintner Limestone; Öm Öhrli – Marl; Ök Öhrli – Limestone. Boundary indicates the measured flow rate at a lithological boundary. The percentage of inflow of the hydrological units is shown in (b).
Figure 4.7  a) and b): Discrete inflows in intervals of 330 m (distance between cross cuts of the base tunnel) determined in the West – and the East – Tunnel. A major inflow in the West – Tunnel at TM 26970 (Sum: 11.2 l/s) represents all inflows to the Öhrli – Marl (ÖM), while all other inflows (Sum: 41.8 l/s) are related to inflows within the Quintner Limestones. c): Summed water inflows into the West – Tunnel of the LBT from brittle fault zones within the model domain (TM 27000 – TM 28500). Strong fluctuations from September 2004 on are due to manipulations on the monitoring system and the shut down of monitoring several brittle faults.
Figure 4.8  a): Long term hydraulic head monitoring of borehole 92/7 (solid line – spline fit) and Piezometer GA20 (dashed line – daily average). b): Difference [m] between hydraulic head in piezometer GA20 and hydraulic head in borehole 92/7, including arithmetic mean (dashed lines) and the summed tunnel inflows [l/s] into the Lötschberg Base Tunnel.
Figure 4.9  

a) Comparison of the hydraulic head determined with piezoelectric pressure transmitter in borehole 92/7  
b) and c) Tunnel inflows and determined borehole outflows during blast hole and horizontal exploration drilling in the West – Tunnel (b) and East – Tunnel (c).
**Figure 4.10** Schematic horizontal view of the model domain with indicated size of the grid cells.
Figure 4.11  a) Simplified geological surface map of the model domain. For better orientation, locations (legend see Figure 4.3) are shown. Assumed impermeable boundaries, not parallel to the model outline are indicated with a dash – dot – dot line.
Figure 4.11  b) Simplified geological map of the model domain on the level of the LCT / LAT including subsurface gallery locations. c) Simplified geological map of the model domain on the level of the LBT including subsurface gallery locations. Legend see Page 193.
Figure 4.11  

**d)** Simplified cross section A – A’. The axes of the LCT and LBT are projected onto the section  

**e)** Simplified cross section B – B’. The axes of the LCT and LBT are projected into the section. Legend see Page 193.
Figure 4.12  Location of the three nested basins, within the river system of the Kander (Switzerland)
Figure 4.13  Observed and simulated hourly discharge hydrograph for three years in the verification period. The Gastere Valley is not plotted, since no hourly observations exist
Figure 4.14  Ratio (left y-axis, black symbols) and difference (right y-axis, grey symbols) between modelled (Model) and observed (Salt) runoff as a function of the observed runoff for the ungauged Gastere Valley (location “Chluse”, see Figure 4.3). 116 runoff measurements by salt dilution are available between January 1991 and August 2005. See Table 4.5 for statistical measures.
Figure 4.15  Map view of the different spatially distributed groundwater recharge rates applied to the hydrodynamic model. a) yearly mean recharge; b) maximum recharge (arithmetic mean of the months May, June, July and August); c) minimum recharge (arithmetic mean of the months November, December, January and February)
Figure 4.16  Scheme of the hydrodynamic modelling process with 3 steps
Figure 4.17  Topographical map of the model domain (contour interval: 100 m) with isohypses of the free water table (contour interval: 20 m) for a simulation with yearly mean recharge rate applied and depth dependent K – values. The section A – A’ is discussed in Figure 4.18 a) Natural conditions; b) after application of the LCT/LAT
Figure 4.17  

e) after including the LBT; d) Difference between e) and b), Contour Interval 10 m; Description see Page 201
Figure 4.18 Cross section A – A’ (see Figure 5.1) with topography (bold continuous line), water table (dashed line) and isopotential lines (thin continuous lines) for three different model steps. a) natural conditions, contouring distance: 5 m; b) after including the LCT/LAT, contouring distance 10 m; c) after including the LBT, contouring distance 25 m
Figure 4.19  Map view and cross section of pathlines of model step 1 including indicated drainage areas for natural conditions
Figure 4.20  Map view and cross section of pathlines of model steps 2 including indicated drainage areas with the LCT/LAT included in the model.
Figure 4.21  Map view and cross section of pathlines of model steps 3 including indicated drainage areas with the LBT included in the model.
Figure 4.22  Cross section along the LBT – Axis with projected axis of the LCT (dashed line), hydraulic heads determined in horizontal boreholes from the LBT (filled rotated squares) with interval length and simulated hydraulic heads (filled circles).
## 4.9 Tables

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*Table 4.1*  Horizontal boreholes drilled during the exploration program in the Lötschberg Base Tunnel with name, start and end point, borehole length and borehole diameter (NQ = 76 mm; HQ = 96 mm) discussed within this article.
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<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>Top of Layer [m a.s.l.]</td>
<td>800</td>
<td>775</td>
<td>750</td>
<td>725</td>
<td>700</td>
</tr>
<tr>
<td>Comment</td>
<td>Elevation LBT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Identification</th>
<th>Layer 36</th>
<th>Layer 37</th>
<th>Layer 38</th>
<th>Layer 39</th>
<th>Layer 40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heigth of Cell</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Top of Layer [m a.s.l.]</td>
<td>600</td>
<td>500</td>
<td>400</td>
<td>300</td>
<td>200</td>
</tr>
<tr>
<td>Comment</td>
<td>Elevation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Identification</th>
<th>Layer 41</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Heigth of Cell</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Top of Layer [m a.s.l.]</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Comment</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.2**  Heigth, elevation (top of Layer) and comments of the 41 Layers used within the model domain.
<table>
<thead>
<tr>
<th>Catchment characteristics</th>
<th>Kander Hondrich</th>
<th>Allenbach Adelboden</th>
<th>Gastere Valley</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment area (km²)</td>
<td>520</td>
<td>28.8</td>
<td>104</td>
</tr>
<tr>
<td>Mean altitude (m a.s.l.)</td>
<td>1900</td>
<td>1856</td>
<td>2517</td>
</tr>
<tr>
<td>Gauge altitude (m a.s.l.)</td>
<td>650</td>
<td>1297</td>
<td>1359</td>
</tr>
<tr>
<td>Highest point (m a.s.l.)</td>
<td>3808</td>
<td>2737</td>
<td>3808</td>
</tr>
</tbody>
</table>

Dominant land use:
- Forests: 17.0, 13.9, 3.9
- Pastures: 9.3, 5.1, 0.0
- Rocks: 32, 23.5, 53.8
- Glaciers: 7.9, 0.0, 24.4
- Alpine vegetation: 29.8, 49.7, 13.7

*Table 4.3* Main characteristics of the investigated basins
Table 4.4  Model calibration and verification. NSE (Nash – Sutcliffe Efficiency) is the agreement after *Nash and Sutcliffe (1970)*. LOG(NSE) is the logarithmic formulation of NSE (*Zappa et al., 2003*). VOL [%] is error in discharge volumes between simulation and observation.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Run</th>
<th>Period</th>
<th>NSE</th>
<th>LOG(NSE)</th>
<th>VOL [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kander</td>
<td>Calibration</td>
<td>1991-1995</td>
<td>0.890</td>
<td>0.924</td>
<td>0.82</td>
</tr>
<tr>
<td>Kander</td>
<td>Verification</td>
<td>1996-2004</td>
<td>0.857</td>
<td>0.926</td>
<td>-6.93</td>
</tr>
<tr>
<td>Allenbach</td>
<td>Calibration</td>
<td>1991-1995</td>
<td>0.743</td>
<td>0.803</td>
<td>-1.23</td>
</tr>
<tr>
<td>Allenbach</td>
<td>Verification</td>
<td>1996-2004</td>
<td>0.703</td>
<td>0.762</td>
<td>-10.2</td>
</tr>
</tbody>
</table>

Table 4.5  Analysis of the estimated discharge for the ungauged Gastere Valley basin on the basis of 116 observations of the runoff by salt dilution techniques. CORR is the correlation, AVG is the average, STDEV is the standard deviation. The values given in percent refer on the ratio observation divided by the modelled value. The values in m$^3$/s refer on the difference observed minus modelled value, as plotted on *Figure 4.14*.

<table>
<thead>
<tr>
<th>Threshold</th>
<th>CASES</th>
<th>CORR</th>
<th>AVG [%]</th>
<th>STDEV [%]</th>
<th>AVG [m$^3$/s]</th>
<th>STDEV [m$^3$/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>116</td>
<td>0.881</td>
<td>0.612</td>
<td>0.258</td>
<td>-1.59</td>
<td>2.25</td>
</tr>
<tr>
<td>Observation $&gt; 5$ m$^3$/s$^{-1}$</td>
<td>39</td>
<td>0.442</td>
<td>0.836</td>
<td>0.282</td>
<td>-2.49</td>
<td>3.54</td>
</tr>
<tr>
<td>Observation $&lt; 5$ m$^3$/s$^{-1}$</td>
<td>77</td>
<td>0.888</td>
<td>0.513</td>
<td>0.161</td>
<td>-1.14</td>
<td>0.89</td>
</tr>
</tbody>
</table>
Table 4.6  Simulation results with uniform K – values for a limestone formation (Öhrli – Marl, Quintner Limestone) within the model domain. The Table shows calibrated K – values (bold) and corresponding discharge rates (bold) with calibration targets. As the model was performed once with LCT/LAT and then with LBT the discharge rates are divided into two columns. For a sensitivity analysis, the calibrated K – values were changed ± 20 % (left and right value of bold value, in brackets) and resulting discharge rates are shown left and right of bold value in brackets. For a model run, all listed K – values were changed ± 20 %. Following K – values are kept constant throughout all models: Gravel aquifer Gastere Valley (2E-4 m/s); Öhrli – Limestone (1.4E-6 m/s). *: Only West - Tunnel
<table>
<thead>
<tr>
<th>Recharge</th>
<th>Tunnel / Formation Section</th>
<th>Geo mean K - value from Hydrotests</th>
<th>Calibrated K - Value [m/s] (± 20%)</th>
<th>Calibration Target without LBT [l/s] (± 20%)</th>
<th>Calibration Target with LBT [l/s] (± 20%)*</th>
<th>Simulated Discharge without LBT [l/s]</th>
<th>Simulated Discharge with LBT [l/s]*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly Mean</td>
<td>LCT Öhrli - Marl</td>
<td>-</td>
<td>2.5E-7 (3.0E-7)</td>
<td>15.0</td>
<td>15.0</td>
<td>(14.5) 17.0 (19.5)</td>
<td>(4.7) 4.8 (5.1)</td>
</tr>
<tr>
<td></td>
<td>LAT Quintner Limestone</td>
<td>-</td>
<td>2.7E-7 (3.2E-7)</td>
<td>35.0</td>
<td>35.0</td>
<td>(25.9) 31.9 (37.8)</td>
<td>(18.3) 22.4 (26.4)</td>
</tr>
<tr>
<td></td>
<td>LCT Quintner Limestone</td>
<td>-</td>
<td>2.7E-7 (3.2E-7)</td>
<td>40.0</td>
<td>40.0</td>
<td>(34.6) 40.6 (46.4)</td>
<td>(25.6) 29.5 (33.3)</td>
</tr>
<tr>
<td></td>
<td>LBT Öhrli - Marl</td>
<td>1.60E-07</td>
<td>4.7E-8 (5.7E-8)</td>
<td>-</td>
<td>11.0</td>
<td>-</td>
<td>(9.5) 11.8 (14.0)</td>
</tr>
<tr>
<td></td>
<td>LBT Quintner Limestone</td>
<td>1.20E-07</td>
<td>9.9E-8 (1.2E-7)</td>
<td>-</td>
<td>42.0</td>
<td>-</td>
<td>(33.6) 41.8 (49.8)</td>
</tr>
<tr>
<td>Maximum</td>
<td>LCT Öhrli - Marl</td>
<td>-</td>
<td>2.5E-7</td>
<td>15.0</td>
<td>15.0</td>
<td>19.7</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>LAT Quintner Limestone</td>
<td>-</td>
<td>2.7E-7</td>
<td>35.0</td>
<td>35.0</td>
<td>32.8</td>
<td>23.4</td>
</tr>
<tr>
<td></td>
<td>LCT Quintner Limestone</td>
<td>-</td>
<td>2.7E-7</td>
<td>40.0</td>
<td>40.0</td>
<td>48.8</td>
<td>37.2</td>
</tr>
<tr>
<td></td>
<td>LBT Öhrli - Marl</td>
<td>1.60E-07</td>
<td>4.7E-8</td>
<td>-</td>
<td>11.0</td>
<td>-</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>LBT Quintner Limestone</td>
<td>1.20E-07</td>
<td>9.9E-8</td>
<td>-</td>
<td>42.0</td>
<td>-</td>
<td>42.3</td>
</tr>
<tr>
<td>Minimum</td>
<td>LCT Öhrli - Marl</td>
<td>-</td>
<td>2.5E-7</td>
<td>15.0</td>
<td>15.0</td>
<td>14.2</td>
<td>2.6</td>
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<td>LAT Quintner Limestone</td>
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<td>35.0</td>
<td>35.0</td>
<td>30.7</td>
<td>21.1</td>
</tr>
<tr>
<td></td>
<td>LCT Quintner Limestone</td>
<td>-</td>
<td>2.7E-7</td>
<td>40.0</td>
<td>40.0</td>
<td>30.9</td>
<td>20.3</td>
</tr>
<tr>
<td></td>
<td>LBT Öhrli - Marl</td>
<td>1.60E-07</td>
<td>4.7E-8</td>
<td>-</td>
<td>11.0</td>
<td>-</td>
<td>11.4</td>
</tr>
<tr>
<td></td>
<td>LBT Quintner Limestone</td>
<td>1.20E-07</td>
<td>9.9E-8</td>
<td>-</td>
<td>42.0</td>
<td>-</td>
<td>41.3</td>
</tr>
</tbody>
</table>

*Table 4.7* Simulation results with depth dependent K – values for a limestone formation (Öhrli – Marl, Quintner Limestone) within the model domain. Results from a yearly mean recharge are compared to results of a maximum – and minimum recharge applied to the model. Description of the results as *Table 4.6*: Only West - Tunnel
Table 4.8 Water balances of three recharge scenarios – yearly mean, maximum and minimum. The water balance is divided into “IN” – flow into the model and “OUT” – flow out of the model. A water balance is separated into the three stages of a simulation – “Natural Conditions”, “LCT/LAT applied to model” and “LBT applied to model”. The error of the total flow through the model is generally less than 0.05% for all simulations.
A.

Tunnel Face Position vs. Time
In this attachment we present the absolute and relative position of the tunnel faces of the East – and the West – tunnel during the excavation of the Doldenhorn Nappe.

*Figure A.1* shows the position of the tunnel face of the West – tunnel (normalized to the East – tunnel) vs. the date, while *Figure A.2* shows the position of the tunnel face of the East – tunnel vs. the date. Subtracting the position of the tunnel face of the East – tunnel from the position of the West – tunnel for a given date results in the relative position of the tunnel faces shown in *Figure A.3*. A positive value represents a leading West – tunnel face, a negative value a lagging West – tunnel face. The West tunnel was leading between TM 25000 and TM 25978, between TM 27456 and TM 27519, between TM 27640 and TM 28495, between TM 28519 and 28657 and between TM 28763 and TM 30000, in the other intervals the East tunnel was leading.
Figure A.1  Position of the tunnel face West (normalized to East – tunnel) vs. date

Figure A.2  Position of the tunnel face East vs. date

Figure A.3  Distance in m between the West – tunnel face and the East – tunnel face from 2001 to 2003 in 24 h increments. Positive value: West – tunnel ahead of East – tunnel. Cross - hatched area: West – tunnel behind East – tunnel
B.

Comparison of Tunnel and Borehole Inflows from TM 25’000 to TM 29’000
In this attachment we present a comparison of the flow rate and the location of initial inflows determined in horizontal boreholes during the drilling process by the drilling crew and flow rate and the location of initial inflows determined in the excavation zone during tunnel excavation for both tunnels, the East – and the West – Tunnel, respectively. An initial inflow rate into the horizontal borehole could be determined after one drilling cycle, i.e. after reaching an additional depth of 3 m. The flow rates are always determined with the rods in the borehole but without core catcher. The flow rate was determined at the borehole head with a normalized barrel and a stop watch. The error of this method was determined empirically and is on a flow rate of 5 l/s ± 0.1 /s.

An initial inflow rate into the excavation zone (tunnel face minus 12 m) was determined 1 - 10 h after the excavation of a water conductive structure by the tunnel geologists. If the water conductive structure was accessible, the flow rate was determined with a normalized barrel and a stop watch, equal to the flow rate on the head of the horizontal borehole, if the structure was not accessible, the flow rate was estimated (error ± 100 %). Unfortunately, it is not known on which water conductive structure the flow rate was estimated and on which one it was determined with a normalized barrel.

In *Figure B.1 – Figure B.8* the results of the comparison between borehole inflows and tunnel inflows are shown for the East – and the West – Tunnel. Tunnel inflows not related to borehole inflows within a distance of ± 20 m are encircled with a continuous line. These inflows represent not detected inflows during the exploration program and are therefore critical for the tunnel excavation. Encircled inflows with a dashed line represent inflows from karst zone or due to solution voids enlarged fractures. Bold continuous lines on the X – Axis represent locations where an expanded exploration program was performed with three or more horizontal boreholes per tunnel.
Figure B.1  Comparison of tunnel inflows and borehole inflows for the West – and East – Tunnel between TM 25000 and TM 25500.

Figure B.2  Comparison of tunnel inflows and borehole inflows for the West – and East – Tunnel between TM 25500 and TM 26000.
Figure B.3 Comparison of tunnel inflows and borehole inflows for the West – and East – Tunnel between TM 26000 and TM 26500.

Figure B.4 Comparison of tunnel inflows and borehole inflows for the West – and East – Tunnel between TM 26500 and TM 27000.
Figure B.5  Comparison of tunnel inflows and borehole inflows for the West – and East – Tunnel between TM 27000 and TM 27500.

Figure B.6  Comparison of tunnel inflows and borehole inflows for the West – and East – Tunnel between TM 27500 and TM 28000.
Figure B.7 Comparison of tunnel inflows and borehole inflows for the West – and East – Tunnel between TM 28000 and TM 28500.

Figure B.8 Comparison of tunnel inflows and borehole inflows for the West – and East – Tunnel between TM 28500 and TM 29000
C.

Compilation and Description of all Performed Hydrotests Measured with Piezoelectric Pressure Transmitters during the Exploration of the Doldenhorn Nappe
During the exploration of the Doldenhorn Nappe many hydraulic crosshole tests were performed in horizontal boreholes and pressure reactions were recorded with piezoelectric pressure transmitters. Subsequently we present all these performed hydraulic tests including a standardized test report. The test report includes borehole parameters as length and diameter, end of drilling phase and the time the gate valve has been closed. Additional it includes information about the equipment to determine the flow rate during the hydrotest. The hydrotest description is usually separated into two phases, a drawdown and a build up phase. The test report describes all relevant events during the phases with the exact time. If more than one drawdown or build up phase was performed during the hydrotest, the number of described phases is increased in the test report. In most cases, the gate valve of one borehole was opened after a phase of pressure stabilization (active borehole) and one borehole remained closed, but was also equipped with a piezoelectric pressure transmitter to record the pressure reaction in that borehole (observation borehole). The boreholes are indicated as “active” and “observation” borehole in the test report. If more than one observation boreholes were equipped with pressure transmitters, the test report is expanded by these boreholes.

Subsequently, always the test report is followed by a graphical representation of the pressure reaction in the active as well as in all recorded observation boreholes (Figure C.1 to Figure C.53). The flow rate of the active borehole is always represented by a filled circle (●) while the pressure reaction (in the active as well as in the observation borehole) is represented by a rotated square (◇).
## Summary of the Test “K8WC – K8WA”

<table>
<thead>
<tr>
<th>Boreholes:</th>
<th>Open hole Test</th>
<th>Date: 30.07.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>K8WC – K8WA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### General Information

<table>
<thead>
<tr>
<th>Borehole: K8WC</th>
<th></th>
<th>Borehole: K8WA</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length: 130 m</td>
<td>Diameter: 76 mm</td>
<td>Length: 300 m</td>
<td>Diameter: 76 mm</td>
</tr>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>End of drilling: 29.07.2002 20:00</td>
<td>End of drilling: 27.07.2002 23:00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closing of Gate Valve: 30.07.2002 08:40 AM</td>
<td>Closing of Gate Valve: latest on 30.07.2002 08:40 AM (no information on drilling Protocol)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

### Test Performance

#### Phase 1 Drawdown:

<table>
<thead>
<tr>
<th>K8WC (active):</th>
<th>K8WA (observation):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 30.07.2002 10:30 AM</td>
<td>Start: 30.07.2002 10:30 AM</td>
</tr>
<tr>
<td>Mean Flow Rate: 2.9 l/s</td>
<td></td>
</tr>
</tbody>
</table>

Remarks Phase 1: Due to false manipulation on the pressure transmitter, some data have been overwritten of the data of the observation borehole.

#### Phase 2 Build Up:

<table>
<thead>
<tr>
<th>K8WC:</th>
<th>K8WA:</th>
</tr>
</thead>
</table>

Remarks Phase 2: At 13:04 AM borehole K8WD hit the major water conductive zone resulting in a pressure reaction in borehole K8WA and K8WC

---

**Figure C.1** active borehole K8WC  
**Figure C.2** observation borehole K8WA
Summary of the Test “K8WC – K8WD”

<table>
<thead>
<tr>
<th>Boreholes</th>
<th>Open hole Test</th>
<th>Date: 30.07.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>K8WC – K8WD</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**General Information**

Borehole: K8WC  
Length: 130 m  
Diameter: 76 mm  
Pressure Transmitter: KELLER, ± 0.001 bar  
End of drilling: 29.07.2002 20:00  
Closing of Gate Valve: latest on 30.07.2002 19:40 PM (no information on drilling Protocol)

Borehole: K8WD  
Length: 99 m  
Diameter: 76 mm  
Pressure Transmitter: KELLER, ± 0.001 bar  
End of drilling: 30.07.2002 17:40  
Closing of Gate Valve: 30.07.2002 19:40 PM

Flow rate: Determined during the hydrottest with a normalized (200 l) barrel and a stop watch

**Test Performance**

**Phase 1 Drawdown:**

K8WC (active):
Start: 30.07.2002 20:55 PM  
End: 30.07.2002 21:30 PM  
Mean Flow Rate: 3.64 l/s

K8WD (observation):
Start: 30.07.2002 20:55 PM  
End: 30.07.2002 21:30 PM

Remarks Phase 1: -

**Phase 2 Build Up:**

K8WC:
Start: 30.07.2002 21:30 PM  
End: 30.07.2002 22:07 PM

K8WA:
Start: 30.07.2002 21:30 PM  
End: 30.07.2002 22:13 PM

Remarks Phase 2: -

*Figure C.3 active borehole K8WC  
Figure C.4 observation borehole K8WD*
Summary of the Test “K8WD – K8WA”

<table>
<thead>
<tr>
<th>Boreholes:</th>
<th>Open hole Test</th>
<th>Date: 30.07.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>K8WD – K8WA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### General Information

<table>
<thead>
<tr>
<th>Borehole:</th>
<th>Length: 99 m</th>
<th>Diameter: 76 mm</th>
<th>Pressure Transmitter: KELLER, ± 0.001 bar</th>
<th>End of drilling: 30.07.2002 17:40 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>K8WD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K8WA</td>
<td>300 m</td>
<td>76 mm</td>
<td>KELLER, ± 0.001 bar</td>
<td>27.07.2002 23:00 PM</td>
</tr>
</tbody>
</table>

Remark: The Gate Valve of the previous test was closed on 30.07.2002 21:30 PM

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

### Test Performance

**Phase 1 Drawdown:**

<table>
<thead>
<tr>
<th>K8WD (active):</th>
<th>K8WA (observation):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Flow Rate: 2.94 l/s</td>
<td></td>
</tr>
</tbody>
</table>

Remarks Phase 1: -

**Phase 2 Build Up:**

<table>
<thead>
<tr>
<th>K8WD:</th>
<th>K8WA:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 30.07.2002 23:10 PM</td>
<td>Start: 30.07.2002 23:10 PM</td>
</tr>
<tr>
<td>End: 31.07.2002 00:03 AM</td>
<td>End: 30.07.2002 23:51 PM</td>
</tr>
</tbody>
</table>

Remarks Phase 2: -

---

*Figure C.5* active borehole K8WD

*Figure C.6* observation borehole K8WA
Summary of the Test “K8WD – K8WB”

Boreholes: K8WD – K8WB

Open hole Test

Date: 31.07.2002

General Information

Borehole: K8WD
Length: 99 m
Diameter: 76 mm
Pressure Transmitter: KELLER, ± 0.001 bar
End of drilling: 30.07.2002 17:40 PM

Borehole: K8WB
Length: 301.5 m
Diameter: 96 mm
Pressure Transmitter: KELLER, ± 0.001 bar
End of drilling: 28.07.2002 21:00 PM

Remark: The Gate Valve of the previous test was closed on 30.07.2002 23:10 PM

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

Test Performance

Phase 1 Drawdown:
K8WD (active):
Start: 31.07.2002 00:10 AM
End: 31.07.2002 00:43 AM
Mean Flow Rate: 3.7 l/s
Remarks Phase 1: -

K8WB (observation):
Start: 31.07.2002 00:10 AM
End: 31.07.2002 00:43 AM

Phase 2 Build Up:

K8WD:
Start: 31.07.2002 00:43 AM
End: 31.07.2002 01:17 AM
Remarks Phase 2: -

K8WA:
Start: 31.07.2002 00:43 AM
End: 30.07.2002 01:13 AM

Figure C.7 active borehole K8WD

Figure C.8 observation borehole K8WB
Summary of the Test “K8WC – K8WA”

**Boreholes:**

| **K8WC** – **K8WA** – **K8WD** | **Open hole Test** | **Date:** 31.07.2002 |

<table>
<thead>
<tr>
<th><strong>General Information</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole: K8WC</td>
</tr>
<tr>
<td>Length: 130 m</td>
</tr>
<tr>
<td>Diameter: 76 mm</td>
</tr>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
</tr>
<tr>
<td>End of drilling: 29.07.2002 20:00 PM</td>
</tr>
<tr>
<td><strong>End of drilling:</strong> 31.07.2002 00:43 AM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Borehole: K8WA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length: 300 m</td>
</tr>
<tr>
<td>Diameter: 76 mm</td>
</tr>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
</tr>
<tr>
<td>End of drilling: 27.07.2002 23:00 PM</td>
</tr>
<tr>
<td><strong>End of drilling:</strong> 31.07.2002 01:41 AM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Borehole: K8WD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length: 99 m</td>
</tr>
<tr>
<td>Diameter: 76 mm</td>
</tr>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
</tr>
<tr>
<td>End of drilling: 30.07.2002 17:40 PM</td>
</tr>
<tr>
<td><strong>End of drilling:</strong> 31.07.2002 02:00 AM</td>
</tr>
</tbody>
</table>

Remark: The Gate Valve of the previous test was closed on 31.07.2002 00:43 AM.

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch.

**Test Performance**

**Phase 1 Drawdown:**

<table>
<thead>
<tr>
<th><strong>K8WC (active):</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 31.07.2002 01:41 AM</td>
</tr>
<tr>
<td>End: 31.07.2002 01:57 AM</td>
</tr>
<tr>
<td>Mean Flow Rate: 5.53 l/s</td>
</tr>
</tbody>
</table>

Remarks Phase 1: -

<table>
<thead>
<tr>
<th><strong>K8WA (observation):</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 31.07.2002 01:41 AM</td>
</tr>
<tr>
<td>End: 31.07.2002 01:57 AM</td>
</tr>
</tbody>
</table>

**Phase 2 Build Up:**

<table>
<thead>
<tr>
<th><strong>K8WC:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 31.07.2002 01:57 AM</td>
</tr>
<tr>
<td>End: 31.07.2002 02:00 AM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>K8WA:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 31.07.2002 01:57 AM</td>
</tr>
<tr>
<td>End: 30.07.2002 02:00 AM</td>
</tr>
</tbody>
</table>

Remarks Phase 2: -

**Phase 3 Drawdown:**

<table>
<thead>
<tr>
<th><strong>K8WD (active, but not logging):</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 31.07.2002 02:00 AM</td>
</tr>
<tr>
<td>End: 31.07.2002 02:09 AM</td>
</tr>
<tr>
<td>Mean Flow Rate: ~12.0 l/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>K8WC (observation):</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 31.07.2002 02:00 AM</td>
</tr>
<tr>
<td>End: 31.07.2002 02:09 AM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>K8WA (observation):</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 31.07.2002 02:00 AM</td>
</tr>
<tr>
<td>End: 31.07.2002 02:09 AM</td>
</tr>
</tbody>
</table>

Remarks Phase 3: No logger was installed on the active borehole.

**Phase 4 Build Up:**

<table>
<thead>
<tr>
<th><strong>K8WC:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 31.07.2002 02:09 AM</td>
</tr>
<tr>
<td>End: 31.07.2002 02:16 AM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>K8WA:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 31.07.2002 02:09 AM</td>
</tr>
<tr>
<td>End: 31.07.2002 02:16 AM</td>
</tr>
</tbody>
</table>

Remarks Phase 4: -

Figure C.9 active borehole K8WC, flow rate of K8WD, respectively

Figure C.10 observation borehole K8WA
Summary of the Test “K8WC – K8WA”

<table>
<thead>
<tr>
<th>Boreholes:</th>
<th>Open hole Test</th>
<th>Date: 31.07.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>K8WC – K8WA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Borehole: K8WC
- Length: 130 m
- Diameter: 76 mm
- Pressure Transmitter: KELLER, ± 0.001 bar
- End of drilling: 29.07.2002 20:00
- Closing of Gate Valve: unknown

Borehole: K8WA
- Length: 300 m
- Diameter: 76 mm
- Pressure Transmitter: KELLER, ± 0.001 bar
- End of drilling: 27.07.2002 23:00
- Closing of Gate Valve: unknown

Flow rate: Determined during the hydrotst with a normalized (200 l) barrel and a stop watch

Test Performance

Phase 1 Drawdown:

<table>
<thead>
<tr>
<th>K8WC (active):</th>
<th>K8WA (observation):</th>
</tr>
</thead>
<tbody>
<tr>
<td>End: 01.08.2002 20:43 PM</td>
<td>End: 01.08.2002 20:43 PM</td>
</tr>
<tr>
<td>Mean Flow Rate: ~6.0 l/s</td>
<td></td>
</tr>
</tbody>
</table>

Remarks Phase 1: The test was performed as a constant head test, i.e. the gate valve was completely opened. The pressure at start of Phase 1 wasn’t completely stabilized.

Figure C.11 active borehole K8WC  
Figure C.12 observation borehole K8WA
Summary of the Test “K9WA – K9WB”

<table>
<thead>
<tr>
<th>Boreholes: K9WA – K9WB</th>
<th>Open hole Test</th>
<th>Date: 27.08.2002</th>
</tr>
</thead>
</table>

**General Information**

Borehole: K9WA  
Length: 104 m  
Diameter: 96 mm  
Pressure Transmitter: KELLER, ± 0.001 bar  
End of drilling: 26.08.2002 11:00 AM  
Closing of Gate valve: approx. 27.08.2002 21:40 PM (not known exactly)

Borehole: K9WB  
Length: 207 m  
Diameter: 76 mm  
Pressure Transmitter: KELLER, ± 0.001 bar  
End of drilling: approx. 27.08.2002 20:00 PM (not known exactly)  
Closing of Gate valve: approx. 27.08.2002 21:40 PM (not known exactly)

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch  
Remark: Drilling was continued in borehole K9WB after this hydrotest was performed

**Test Performance**

### Phase 1 Drawdown:

<table>
<thead>
<tr>
<th>K9WA (active)</th>
<th>K9WB (observation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 27.08.2002 22:43 PM</td>
<td>Start: 27.08.2002 22:43 PM</td>
</tr>
<tr>
<td>End: 27.08.2002 23:03 PM</td>
<td>End: 27.08.2002 23:03 PM</td>
</tr>
</tbody>
</table>

Remarks Phase 1: strong disturbance of pressure due to wash out from material (gravel)

### Phase 2 Build Up:

<table>
<thead>
<tr>
<th>K9WA:</th>
<th>K9WB:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 27.08.2002 23:03 PM</td>
<td>Start: 27.08.2002 23:03 PM</td>
</tr>
<tr>
<td>End: 27.08.2002 23:26 PM</td>
<td>End: 27.08.2002 23:26 PM</td>
</tr>
</tbody>
</table>

Remarks Phase 2: -

### Phase 3 Drawdown:

<table>
<thead>
<tr>
<th>K9WA (active)</th>
<th>K9WB (observation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 27.08.2002 23:26 PM</td>
<td>Start: 27.08.2002 23:26 PM</td>
</tr>
<tr>
<td>End: 27.08.2002 23:54 PM</td>
<td>End: 27.08.2002 23:54 PM</td>
</tr>
</tbody>
</table>

Remarks Phase 3: -

### Phase 4 Build Up:

<table>
<thead>
<tr>
<th>K9WA:</th>
<th>K9WB:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 27.08.2002 23:54 PM</td>
<td>Start: 27.08.2002 23:54 PM</td>
</tr>
<tr>
<td>End: 28.08.2002 00:20 AM</td>
<td>End: 28.08.2002 00:20 AM</td>
</tr>
</tbody>
</table>

Remarks Phase 4: -

### Phase 5 several short Drawdown and Build Up:

<table>
<thead>
<tr>
<th>K9WA (active)</th>
<th>K9WB (observation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 28.08.2002 00:20 AM</td>
<td>Start: 28.08.2002 00:20 AM</td>
</tr>
<tr>
<td>End: 28.08.2002 00:39 AM</td>
<td>End: 28.08.2002 00:39 AM</td>
</tr>
</tbody>
</table>

Remarks Phase 5: -
Figure C.13 active borehole K9WA

Figure C.14 observation borehole K9WB
Summary of the Test “K9WB – K9WA”

<table>
<thead>
<tr>
<th>Boreholes:</th>
<th>Open hole Test</th>
<th>Date: 28.08.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>K9WB – K9WA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**General Information**

<table>
<thead>
<tr>
<th>Borehole: K9WB</th>
<th>Length: 207 m</th>
<th>Diameter: 76 mm</th>
<th>Pressure Transmitter: KELLER, ± 0.001 bar</th>
<th>End of drilling: 28.08.2002 10:40 AM</th>
<th>Closing of Gate Valve: 28.06.2002 12:54 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole: K9WA</td>
<td>Length: 104 m</td>
<td>Diameter: 96 mm</td>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>End of drilling: 26.08.2002 11:00 AM</td>
<td>Closing of Gate Valve: 28.06.2002 12:54 PM</td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

**Test Performance**

**Phase 1 Drawdown:**

<table>
<thead>
<tr>
<th>K9WB (active):</th>
<th>Start: 28.08.2002 14:51 PM</th>
<th>End: 28.08.2002 15:55 PM</th>
<th>Mean Flow Rate: ~4.0 l/s</th>
</tr>
</thead>
</table>

Remarks Phase 1: strong disturbance of pressure due to wash out from material (gravel). At 28.08.2002 15:15 PM a blasting event in the other tunnel (EAST – Tunnel) disturbed the drawdown pressure reaction.

**Phase 2 Build Up:**

|-------|---------------------------|-------------------------|

Remarks Phase 2: -

![Figure C.15 active borehole K9WB](image1)

![Figure C.16 observation borehole K9WA](image2)
Summary of the Test “K9WC – K11EA – K11EB”

<table>
<thead>
<tr>
<th>Boreholes: K9WC – K11EA – K11EB</th>
<th>Open hole Test</th>
<th>Date: 03.09.2002</th>
</tr>
</thead>
</table>

**Borehole: K9WC**
- Length: 160 m
- Ø: 76 mm
- Pressure Transmitter: KELLER, ± 0.001 bar
- End of drilling: 02.09.2002 02:32 AM
- Closing of Gate Valve: 3.09.2002 13:00 PM

**Borehole: K11EA**
- Length: 220 m
- Ø: 76 mm
- Pressure Transmitter: KELLER, ± 0.001 bar
- End of drilling: 02.09.2002 22:00 PM
- Closing of Gate Valve: 3.09.2002 13:00 PM

**Borehole: K11EB**
- Length: 140 m
- Ø: 76 mm
- Pressure Transmitter: KELLER, ± 0.001 bar
- End of drilling: 01.09.2002 02:40 AM
- Closing of Gate Valve: 3.09.2002 13:00 PM

Flow rate: Determined during the hydrotest with a normalized (68 l) barrel and a stop watch.

**Test Performance**

**Phase 1 Drawdown:**
- **K9WC (active):**
  - Start: 03.09.2002 14:12 PM
  - End: 03.09.2002 15:23 PM
  - Mean Flow Rate: 1.4 l/s (not constant during the drawdown phase)

- **K11EA (observation):**
  - Start: 03.09.2002 14:12 PM
  - End: 03.09.2002 15:23 PM

- **K11EB (observation):**
  - Start: 03.09.2002 14:12 PM
  - End: 03.09.2002 15:23 PM

Remarks Phase 1: Manipulation on gate valve resulting in a “stepwise” drawdown

**Phase 2 Build Up:**
- **K9WC:**
  - Start: 03.09.2002 15:23 PM
  - End: 03.09.2002 17:22 PM

- **K11EA:**
  - Start: 03.09.2002 15:23 PM
  - End: 03.09.2002 17:37 PM

- **K11EB:**
  - Start: 03.09.2002 15:23 PM
  - End: 03.09.2002 17:29 PM

Remarks Phase 2: -
Figure C.17 active borehole K9WC

Figure C.18 observation borehole K11EA

Figure C.19 observation borehole K11EB
### Summary of the Test “K9WD - K9WC – K11EA – K11EB”

<table>
<thead>
<tr>
<th>Boreholes: K9WD - K9WC – K11EA – K11EB</th>
<th>Open hole Test</th>
<th>Date: 03.09.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General Information</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borehole: K9WD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length: 61 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter: 76 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>End of drilling: 03.09.2002 19:00 PM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closing of Gate Valve: 03.09.2002 19:30 PM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borehole: K9WC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length: 160 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter: 76 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>End of drilling: 02.09.2002 02:32 AM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closing of Gate Valve: 03.09.2002 19:30 PM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borehole: K11EA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length: 220 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter: 76 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>End of drilling: 02.09.2002 22:00 PM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closing of Gate Valve: 03.09.2002 19:30 PM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borehole: K11EB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length: 140 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter: 76 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>End of drilling: 01.09.2002 02:40 AM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closing of Gate Valve: 03.09.2002 19:30 PM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

### Test Performance

**Phase 1 Drawdown:**

- **K9WD (active):**
  - Start: 03.09.2002 21:56 PM
  - End: 03.09.2002 22:21 PM
  - Mean Flow Rate: 0.82 l/s (not constant during the drawdown phase)

- **K9WC (observation):**
  - Start: 03.09.2002 21:56 PM
  - End: 03.09.2002 22:21 PM

- **K11EA (observation):**
  - Start: 03.09.2002 21:56 PM
  - End: 03.09.2002 22:21 PM

- **K11EB (observation):**
  - Start: 03.09.2002 21:56 PM
  - End: 03.09.2002 22:21 PM

Remarks Phase 1: Manipulation on gate valve resulting in a “stepwise” drawdown

**Phase 2 Build Up:**

- **K9WD (active):**
  - Start: 03.09.2002 22:21 PM
  - End: 04.09.2002 00:11 AM

- **K9WC (observation):**
  - Start: 03.09.2002 22:21 PM
  - End: 04.09.2002 00:11 AM

- **K11EA (observation):**
  - Start: 03.09.2002 22:21 PM
  - End: 04.09.2002 00:11 AM

- **K11EB (observation):**
  - Start: 03.09.2002 22:21 PM
  - End: 04.09.2002 00:11 AM

Remarks Phase 2: Several pressure disturbances. Origin unknown.
Figure C.20 active borehole K9WD

Figure C.21 observation borehole K9WC

Figure C.22 observation borehole K11EA

Figure C.23 observation borehole K11EB
Summary of the Test “K11EA - K9WC – K9WD – K11EB”

<table>
<thead>
<tr>
<th>Boreholes:</th>
<th>Open hole Test</th>
<th>Date: 04.09.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>K11EA - K9WC – K9WD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>– K11EB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**General Information**

<table>
<thead>
<tr>
<th>Borehole: K11EA</th>
<th>Length: 220 m</th>
<th>Diameter: 76 mm</th>
<th>Pressure Transmitter: KELLER, ± 0.001 bar</th>
<th>End of drilling: 02.09.2002 22:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole: K9WC</td>
<td>Length: 160 m</td>
<td>Diameter: 76 mm</td>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>End of drilling: 02.09.2002 02:32 AM</td>
</tr>
<tr>
<td>Borehole: K9WD</td>
<td>Length: 61 m</td>
<td>Diameter: 76 mm</td>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>End of drilling: 03.09.2002 19:00 PM</td>
</tr>
<tr>
<td>Borehole: K11EB</td>
<td>Length: 140 m</td>
<td>Diameter: 76 mm</td>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>End of drilling: 01.09.2002 02:40 AM</td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

**Test Performance**

**Phase 1 Drawdown:**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Flow Rate: 3.93 l/s (not constant during the drawdown phase)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Remarks Phase 1: Pressure signal disturbed due to material (gravel) flushed through the drill string

**Phase 2 Build Up:**

<table>
<thead>
<tr>
<th>K11EA:</th>
<th>K9WC:</th>
<th>K9WD:</th>
<th>K11EB:</th>
</tr>
</thead>
</table>

Remarks Phase 2: -
Figure C.24 active borehole K11EA

Figure C.25 observation borehole K9WC

Figure C.26 observation borehole K9WD

Figure C.27 observation borehole K11EB
Summary of the Test “K9WA”

<table>
<thead>
<tr>
<th>Boreholes:</th>
<th>Open hole Test</th>
<th>Date: 27.08.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>K9WA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

General Information

Borehole: K9WA
Length: 104 m
Diameter: 96 mm
Pressure Transmitter: KELLER, ± 0.001 bar
End of drilling: 26.08.2002 11:00 AM
Closing of Gate Valve: approx. 26.08.2002 23:40 PM (not known exactly)

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

Test Performance

**Phase 1 Drawdown:**
K9WA (active):
Start: 27.08.2002 00:40 AM
End: 27.08.2002 00:52 AM
Mean Flow Rate: 5.46 l/s (not constant during the drawdown phase)
Remarks Phase 1: Strong disturbance of pressure signal due to shaking of logger (flow rate too big)

**Phase 2 Build Up:**
K9WA:
Start: 27.08.2002 00:52 AM
End: 27.08.2002 01:12 AM
Remarks Phase 2: -

Figure C.28 active borehole K9WA
Summary of the Test “K9WA”

Boreholes: K9WA

Open hole Test

Date: 27.08.2002

General Information

Borehole: K9WA
Length: 104 m
Diameter: 96 mm
Pressure Transmitter: KELLER, ± 0.001 bar
End of drilling: 26.08.2002 11:00 AM
Closing of Gate Valve: 27.08.2002 00:52 AM
Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

Test Performance

Phase 1 Drawdown:

K9WA (active):
Start: 27.08.2002 01:17 AM
End: 27.08.2002 01:26 AM
Mean Flow Rate: 6.39 l/s (not constant)
Remarks Phase 1: Strong disturbance of pressure signal due to flushing material through the drill string

Phase 2 Build Up:

K9WA:
Start: 27.08.2002 01:26 AM
End: 27.08.2002 01:36 AM
Remarks Phase 2: -

Phase 3 multiple Drawdown / Build Up:

K9WA:
Start: 27.08.2002 01:36 AM
End: 27.08.2002 01:50 AM
Remarks: several short Drawdown / Build Up

Figure C.29 active borehole K9WA
Summary of the Test “K10WA - K10WB”

<table>
<thead>
<tr>
<th>Boreholes: K10WA – K10WB</th>
<th>Open hole Test</th>
<th>Date: 27.08.2002</th>
</tr>
</thead>
</table>

**General Information**

Borehole: K10WA  
Length: 294 m  
Diameter: 96 mm  
Pressure Transmitter: KELLER, ± 0.001 bar  
End of drilling: 26.09.2002 11:00 AM  
Closing of Gate Valve: approx. 26.09.2002 20:17 PM (not known exactly)

Borehole: K10WA  
Length: 200 m  
Diameter: 76 mm  
Pressure Transmitter: KELLER, ± 0.001 bar  
End of drilling: 26.09.2002 09:00 AM  
Closing of Gate Valve: approx. 26.09.2002 20:17 PM (not known exactly)

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

**Test Performance**

**Phase 1 Drawdown:**

K10WA (active):  
Start: 26.09.2002 22:17 PM  
Mean Flow Rate: 4.0 l/s

K10WB (observation):  
Start: 26.09.2002 22:17 PM  

Remarks Phase 1: -

**Phase 2 Build Up:**

K10WA:  

K10WB:  

Remarks Phase 2: -

*Figure C.30* active borehole K10WA  
*Figure C.31* observation borehole K10WB
**Summary of the Test “K11WA - K11WB”**

<table>
<thead>
<tr>
<th>Boreholes</th>
<th>Open hole Test</th>
<th>Date: 28.10.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>K11WA – K11WB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**General Information**

<table>
<thead>
<tr>
<th>Borehole: K11WA</th>
<th></th>
<th>Borehole: K11WB</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length: 233.5 m</td>
<td>Diameter: 76 mm</td>
<td>Length: 300 m</td>
<td>Diameter: 76 mm</td>
</tr>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>End of drilling: 27.10.2002 23:00 PM</td>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>End of drilling: 27.10.2002 11:30 AM</td>
</tr>
<tr>
<td>End of drilling: 27.10.2002 05:25 AM (not exactly known)</td>
<td></td>
<td>Closing of Gate Valve: approx. 27.10.2002 05:25 AM (not exactly known)</td>
<td></td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (68 l) barrel and a stop watch

**Test Performance**

**Phase 1 Drawdown:**

<table>
<thead>
<tr>
<th>K11WA (active):</th>
<th></th>
<th>K11WB (observation):</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Flow Rate: 1.15 l/s</td>
<td>Remarks Phase 1: -</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Phase 2 Build Up:**

<table>
<thead>
<tr>
<th>K11WA:</th>
<th>K11WB:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remarks Phase 2: -</td>
<td></td>
</tr>
</tbody>
</table>

---

Figure C.32 active borehole K11WA  
Figure C.33 observation borehole K11WB
Summary of the Test “K12WA - K12WB”

<table>
<thead>
<tr>
<th>Boreholes:</th>
<th>Open hole Test</th>
<th>Date: 28.10.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>K12WA – K12WB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**General Information**

<table>
<thead>
<tr>
<th>Borehole: K12WA</th>
<th>Length: 300 m</th>
<th>Diameter: 96 mm</th>
<th>Pressure Transmitter: KELLER, ± 0.001 bar</th>
<th>End of drilling: 25.11.2002 02:00 AM</th>
<th>Closing of Gate Valve: approx. 25.11.2002 17:55 PM (not known exactly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole: K12WB</td>
<td>Length: 300 m</td>
<td>Diameter: 76 mm</td>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>End of drilling: 24.11.2002 11:00 AM</td>
<td>Closing of Gate Valve: approx. 25.11.2002 17:55 PM (not known exactly)</td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (68 l) barrel and a stop watch

**Test Performance**

**Phase 1 Drawdown:**

<table>
<thead>
<tr>
<th>K12WA (active):</th>
<th>Start: 25.11.2002 19:35 PM</th>
<th>End: 25.11.2002 21:35 PM</th>
<th>Mean Flow Rate: 3.3 l/s</th>
</tr>
</thead>
</table>

Remarks Phase 1: -

**Phase 2 Build Up:**

|--------|-----------------------------|---------------------------|

Remarks Phase 2: -

---

**Figure C.34** active borehole K12WA

**Figure C.35** observation borehole K12WB
**Summary of the Test “K13WB - K13WA”**

<table>
<thead>
<tr>
<th>Boreholes:</th>
<th>Open hole Test</th>
<th>Date: 11.01.2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>K13WB – K13WA</td>
<td>Open hole Test</td>
<td>Date: 11.01.2003</td>
</tr>
</tbody>
</table>

**General Information**

<table>
<thead>
<tr>
<th>Borehole: K13WB</th>
<th>Length: 283.5 m</th>
<th>Diameter: 96 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>End of drilling: 11.01.2003 08:50 AM</td>
<td>Closing of Gate Valve: 11.01.2002 14:04 PM</td>
</tr>
<tr>
<td>Borehole: K13WA</td>
<td>Length: 300 m</td>
<td>Diameter: 76 mm</td>
</tr>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>End of drilling: 11.01.2003 08:50 AM</td>
<td>Closing of Gate Valve: 11.01.2002 14:04 PM</td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

**Test Performance**

**Phase 1 Drawdown:**

<table>
<thead>
<tr>
<th>K13WB (active):</th>
<th>Start: 11.01.2003 15:04 PM</th>
<th>End: 11.01.2003 17:06 PM</th>
<th>Mean Flow Rate: 1.62 l/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remarks Phase 1: -</td>
<td>K13WA (observation):</td>
<td>Start: 11.01.2003 15:04 PM</td>
<td>End: 11.01.2003 17:06 PM</td>
</tr>
</tbody>
</table>

**Phase 2 Build Up:**

| K13WB: | Start: 11.01.2003 17:06 PM | End: 11.01.2003 17:30 PM |
| K13WA: | Start: 11.01.2003 17:06 PM | End: 11.01.2003 17:30 PM |
| Remarks Phase 2: - | K13WA: | Start: 11.01.2003 17:06 PM | End: 11.01.2003 17:30 PM |

![Figure C.36 active borehole K13WB](image1)

![Figure C.37 observation borehole K13WA](image2)
Summary of the Test “K14WA - K14WB”

<table>
<thead>
<tr>
<th>Boreholes:</th>
<th>Open hole Test</th>
<th>Date: 11.01.2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>K14WA – K14WB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

General Information

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Length: 321 m</th>
<th>Diameter: 96 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>K14WA</td>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>End of drilling: 14.02.2003 09:00 AM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Closing of Gate Valve: approx. 14.02.2002 09:30 AM (not known exactly)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Length: 288 m</th>
<th>Diameter: 96 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>K14WB</td>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>End of drilling: 13.02.2003 16:00 PM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Closing of Gate Valve: approx. 14.02.2002 09:30 AM (not known exactly)</td>
<td></td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

Test Performance

**Phase 1 Drawdown:**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>K14WA</td>
<td>Mean Flow Rate: 6.25 l/s</td>
<td></td>
</tr>
</tbody>
</table>

Remarks Phase 1: -

**Phase 2 Build Up:**

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Start: 14.02.2003 13:30 PM</th>
<th>End: 14.02.2003 14:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>K14WA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Remarks Phase 2: -

---

Figure C.38 active borehole K14WA

Figure C.39 observation borehole K14WB
### Summary of the Test “K12EC – K12EA – K12EB”

<table>
<thead>
<tr>
<th>Boreholes:</th>
<th>Open hole Test</th>
<th>Date: 22.09.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>K12EC – K12EA – K12EB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### General Information

<table>
<thead>
<tr>
<th>Borehole:</th>
<th>Length:</th>
<th>Diameter:</th>
<th>Pressure Transmitter:</th>
<th>End of drilling:</th>
<th>Closing of Gate Valve:</th>
</tr>
</thead>
<tbody>
<tr>
<td>K12EC</td>
<td>246 m</td>
<td>76 mm</td>
<td>KELLER, ± 0.001 bar</td>
<td>22.09.2002 11:00 AM</td>
<td>22.09.2002 18:38 PM</td>
</tr>
<tr>
<td>K12EA</td>
<td>89 m</td>
<td>96 mm</td>
<td>KELLER, ± 0.001 bar</td>
<td>18.09.2002 16:00 PM</td>
<td>22.09.2002 16:23 PM</td>
</tr>
<tr>
<td>K12EB</td>
<td>242 m</td>
<td>76 mm</td>
<td>KELLER, ± 0.001 bar</td>
<td>latest on 22.09.2002 18:38 PM (no information on drilling protocol)</td>
<td></td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch.

### Test Performance

**Phase 1 Drawdown:**
- **K12EC (active):**
  - Start: 22.09.2002 20:51 PM
  - End: 22.09.2002 21:31 PM
  - Mean Flow Rate: 5.0 l/s
- **K12EA (observation):**
  - Start: 22.09.2002 20:51 PM
  - End: 22.09.2002 21:31 PM
- **K12EB (observation):**
  - Start: 22.09.2002 20:51 PM
  - End: 22.09.2002 21:31 PM

Remarks Phase 1: -

**Phase 2 Build Up:**
- **K12EC:**
  - Start: 22.09.2002 21:31 PM
  - End: 22.09.2002 22:25 PM
- **K12EA:**
  - Start: 22.09.2002 21:31 PM
  - End: 22.09.2002 22:25 PM
- **K12EB:**
  - Start: 22.09.2002 21:31 PM
  - End: 22.09.2002 22:25 PM

Remarks Phase 2: -
**Figure C.40** active borehole K12EC

**Figure C.41** observation borehole K12EA

**Figure C.42** observation borehole K12EB
## Summary of the Test “K12EB – K12EA – K12EC”

<table>
<thead>
<tr>
<th>Boreholes: K12EB – K12EA – K12EC</th>
<th>Open hole Test</th>
<th>Date: 22.09.2002</th>
</tr>
</thead>
</table>

### General Information

| Borehole: K12EB | Length: 242 m | Diameter: 76 mm | Pressure Transmitter: KELLER, ± 0.001 bar | End of drilling: 20.09.2002 17:00 PM |
| Borehole: K12EA | Length: 89 m  | Diameter: 96 mm | Pressure Transmitter: KELLER, ± 0.001 bar | End of drilling: 18.09.2002 16:00 PM |
| Borehole: K12EC | Length: 246 m | Diameter: 76 mm | Pressure Transmitter: KELLER, ± 0.001 bar | End of drilling: 22.09.2002 11:00 AM |


Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

### Test Performance

#### Phase 1 Drawdown:


Remarks Phase 1: -

#### Phase 2 Build Up:


Remarks Phase 2: -
Figure C.43 active borehole K12EB

Figure C.44 observation borehole K12EA

Figure C.45 observation borehole K12EC
## Summary of the Test “K13EA – K13EB”

**Boreholes:**

<table>
<thead>
<tr>
<th>K13EA – K13EB</th>
<th>Open hole Test</th>
<th>Date: 20.10.2002</th>
</tr>
</thead>
</table>

### General Information

<table>
<thead>
<tr>
<th>Borehole: K13EA</th>
<th>Length: 201 m</th>
<th>Diameter: 96 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>End of drilling: 20.10.2002 01:30 AM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closing of Gate Valve: latest on 20.10.2002 12:24 PM (no information on drilling protocol)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow rate: Determined during the hydrotest with a normalized (68 l) barrel and a stop watch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Borehole: K13EB</td>
<td>Length: 199 m</td>
<td>Diameter: 76 mm</td>
</tr>
<tr>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>End of drilling: 20.10.2002 07:30 AM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closing of Gate Valve: 20.10.2002 12:24 PM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Test Performance

**Phase 1 Drawdown:**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Remarks Phase 1:</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Phase 2 Build Up:**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Remarks Phase 2:</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

---

**Figure C.46** active borehole K13EA  
**Figure C.47** observation borehole K13EB
Summary of the Test “K14EA – K14EB”

<table>
<thead>
<tr>
<th>Boreholes:</th>
<th>Open hole Test</th>
<th>Date: 11.11.2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>K14EA – K14EB</td>
<td>Open hole Test</td>
<td>Date: 11.11.2002</td>
</tr>
</tbody>
</table>

**General Information**

<table>
<thead>
<tr>
<th>Borehole: K14EA</th>
<th>Length: 300 m</th>
<th>Diameter: 96 mm</th>
<th>Pressure Transmitter: KELLER, ± 0.001 bar</th>
<th>End of drilling: 11.11.2002 03:45 AM</th>
<th>Closing of Gate Valve: 11.11.2002 07:49 AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole: K14EB</td>
<td>Length: 300 m</td>
<td>Diameter: 76 mm</td>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>End of drilling: 10.11.2002 19:50 PM</td>
<td>Closing of Gate Valve: 11.11.2002 03:00 AM</td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch.

**Test Performance**

**Phase 1 Drawdown:**

<table>
<thead>
<tr>
<th>K14EA (active):</th>
<th>Start: 11.11.2002 09:12 AM</th>
<th>End: 11.11.2002 09:15 AM</th>
<th>Mean Flow Rate: undefined</th>
<th>Remarks Phase 1: After the start of the drawdown phase it was recognized that the gate valve has been opened too much. The gate valve was therefore closed to stabilize the pressure and to restart the test.</th>
</tr>
</thead>
<tbody>
<tr>
<td>K14EB (observation):</td>
<td>Start: 11.11.2002 09:12 AM</td>
<td>End: 11.11.2002 09:15 AM</td>
<td>Mean Flow Rate: undefined</td>
<td></td>
</tr>
</tbody>
</table>

**Phase 2 Build Up:**

| K14EA: | Start: 11.11.2002 09:15 AM | End: 11.11.2002 09:21 AM | Remarks Phase 2: - |
| K14EB: | Start: 11.11.2002 09:15 AM | End: 11.11.2002 09:21 AM |                                                                                     |

**Phase 3 Drawdown:**

<table>
<thead>
<tr>
<th>K14EA (active):</th>
<th>Start: 11.11.2002 09:21 AM</th>
<th>End: 11.11.2002 09:46 AM</th>
<th>Mean Flow Rate: 1.0 l/s</th>
<th>Remarks Phase 3: -</th>
</tr>
</thead>
</table>

**Phase 4 Build Up:**

| K14EA: | Start: 11.11.2002 09:46 AM | End: 11.11.2002 10:00 AM | Remarks Phase 4: - |
| K14EB: | Start: 11.11.2002 09:46 AM | End: 11.11.2002 10:00 AM |                                                                                     |

**Phase 5 Drawdown:**

<table>
<thead>
<tr>
<th>K14EA (active):</th>
<th>Start: 11.11.2002 10:00 AM</th>
<th>End: 11.11.2002 10:34 AM</th>
<th>Mean Flow Rate: 2.0 l/s</th>
<th>Remarks Phase 4: -</th>
</tr>
</thead>
<tbody>
<tr>
<td>K14EB (observation):</td>
<td>Start: 11.11.2002 10:00 AM</td>
<td>End: 11.11.2002 10:34 AM</td>
<td>Mean Flow Rate: undefined</td>
<td></td>
</tr>
</tbody>
</table>

**Phase 6 Build Up:**

Figure C.48 active borehole K14EA

Figure C.49 observation borehole K14EB
Summary of the Test “K15EA – K15EB”

Boreholes: K15EA – K15EB
Date: 17.12.2002

General Information

<table>
<thead>
<tr>
<th>Borehole:</th>
<th>K15EA</th>
<th>K15EB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>300 m</td>
<td>300 m</td>
</tr>
<tr>
<td>Diameter</td>
<td>96 mm</td>
<td>76 mm</td>
</tr>
<tr>
<td>Pressure Transmitter</td>
<td>KELLER, ± 0.001 bar</td>
<td>KELLER, ± 0.001 bar</td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (200 l) barrel and a stop watch

Test Performance

Phase 1 Drawdown:

<table>
<thead>
<tr>
<th>K15EA (active):</th>
<th>Start: 17.12.2005 00:59 AM</th>
<th>End: 17.12.2002 03:00 AM</th>
<th>Mean Flow Rate: 2.1 l/s</th>
</tr>
</thead>
</table>

Remarks Phase 1: At 17.12.2002 02:40 AM a blasting event in the other tunnel (WEST – Tunnel) disturbed the drawdown pressure reaction

Phase 2 Build Up:

|--------|-----------------------------|--------------------------|

Remarks Phase 2: -

Figure C.50 active borehole K15EA

Figure C.51 observation borehole K15EB
## Summary of the Test “K16EB – K16EA”

**Boreholes:**  
K16EB – K16EA  
**Open hole Test**  
**Date:** 06.02.2003

### General Information

<table>
<thead>
<tr>
<th>Borehole: K16EB</th>
<th>Length: 229 m</th>
<th>Diameter: 96 mm</th>
<th>Pressure Transmitter: KELLER, ± 0.001 bar</th>
<th>End of drilling: 05.02.2003 05:00 AM</th>
<th>Closing of Gate Valve: latest on 06.02.2003 02:07 AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole: K16EA</td>
<td>Length: 249 m</td>
<td>Diameter: 96 mm</td>
<td>Pressure Transmitter: KELLER, ± 0.001 bar</td>
<td>End of drilling: 05.02.2003 20:00 AM</td>
<td>Closing of Gate Valve: 06.02.2003 02:07 AM</td>
</tr>
</tbody>
</table>

Flow rate: Determined during the hydrotest with a normalized (68 l) barrel and a stop watch

### Test Performance

#### Phase 1 Drawdown:

<table>
<thead>
<tr>
<th>K16EB (active):</th>
<th>Start: 06.02.2003 03:07 AM</th>
<th>End: 06.02.2003 05:10 AM</th>
<th>Mean Flow Rate: 1.1 l/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>K16EA (observation):</td>
<td>Start: 06.02.2003 03:07 AM</td>
<td>End: 06.02.2003 05:10 AM</td>
<td></td>
</tr>
</tbody>
</table>

Remarks Phase 1: At 06.02.2003 03:50 AM a blasting event in the other tunnel (WEST – Tunnel) disturbed the drawdown pressure reaction

#### Phase 2 Build Up:

<table>
<thead>
<tr>
<th>K16EB:</th>
<th>Start: 06.02.20023 05:10 AM</th>
<th>End: 06.02.20023 05:50 AM</th>
</tr>
</thead>
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<tr>
<td>K16EA:</td>
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<td>End: 06.02.20023 05:50 AM</td>
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Remarks Phase 2: -

---

*Figure C.52 active borehole K16EB  
Figure C.53 observation borehole K16EA*
D.

Selected Hydrotests from Active Boreholes for Log – Log Diagnostic Analysis
We present 18 selected hydrotests for an advanced non-linear analysis with the software code SAPHIR. The test description and the selected models are described in detail in Chapter 3 of this thesis. Here, only the graphical representations of the hydrotests including the selected models of the active boreholes are presented in Figure D.1 to Figure D.22. Usually it was possible to produce a log–log diagnostic plot the drawdown and the build–up phase but, as in certain cases – where the pressure data of the drawdown phase were heavily disturbed – only the build up phase was selected to produce a diagnostic plot. The drawdown phase of the standardized graphical representation of the diagnostic plot is left blank in such a case.

As described in Chapter 3, some pressure reactions could not be modeled under the assumption of a wellbore storage coefficient $C = 0$. These tests, including the related analysis with $C \neq 0$ are also presented here. Those tests are indicated with $C \neq 0$ in the figure description.

For two pressure reactions (K13EA and K16EB) no accurate model was found to represent the pressure reaction accurately.
Figure D.1  Pressure reaction including models of borehole K8WC. C = 0.

Figure D.2  Pressure reaction including models of borehole K8WC. C = 0.
Figure D.3  Pressure reaction including models of borehole K8WD. C = 0.

Figure D.4  Pressure reaction including models of borehole K8WD. C = 0.
Figure D.5  Pressure reaction including models of borehole K9WB. C = 0.

Figure D.6  Pressure reaction including models of borehole K9WA. C = 0.
Figure D.7  Pressure reaction including models of borehole K10WA. C = 0.

Figure D.8  Pressure reaction including models of borehole K11WA. C = 0.
Figure D.9  Pressure reaction including models of borehole K11WA. C ≠ 0.

Figure D.10  Pressure reaction including models of borehole K12WA. C = 0.
Figure D.11  Pressure reaction including models of borehole K13WB. C = 0.

Figure D.12  Pressure reaction including models of borehole K13WB. C ≠ 0.
Figure D.13  Pressure reaction including models of borehole K14WB. C = 0.

Figure D.14  Pressure reaction including models of borehole K11EA. C = 0.
Figure D.15  Pressure reaction including models of borehole K12EC. C = 0.

Figure D.16  Pressure reaction including models of borehole K12EC. C ≠ 0.
Figure D.17  Pressure reaction including models of borehole K12EB. C = 0.

Figure D.18  Pressure reaction including models of borehole K13EA. No accurate model for representing the pressure reaction found.
Figure D.19  Pressure reaction including models of borehole K14EA. C = 0.

Figure D.20  Pressure reaction including models of borehole K15EA. C = 0.
Figure D.21  Pressure reaction including models of borehole K15EA. C ≠ 0.

Figure D.22  Pressure reaction including models of borehole K16EB. No accurate model for representing the pressure reaction found.
E.

Selected Hydrotests from Observation Boreholes for Log – Log Diagnostic Analysis
As described in Chapter 3 of this thesis the pressure reaction of observation boreholes was used to determine aquifer parameters with straight line fitting methods such as transmissivity, storativity and the initial formation pressure. Equal to the active boreholes, log–log diagnostic plots were used to determine the “correct” straight line. As the flow field around an observation borehole is highly complex and standardized log–log diagnostic plots are not commonly available, first synthetically generated log–log diagnostic plots were used to compare them to the determined pressure reactions in horizontal boreholes and to decide subsequently if the pressure reactions match the simple model assumptions. All synthetic models were generated with the same assumptions (reasonable parameters for the LBT - Aquifer). Figure E.1 to Figure E.4 show the synthetic models created with the code SAPHIR. Crosses represent the pressure reaction, open circles the derivative. Table E.1 to Table E.4 present the model parameters to create the synthetic pressure reactions. After comparing the pressure reactions from horizontal boreholes with the synthetically generated models, 5 pressure reactions from observation holes were selected and analyzed. The selected pressure reactions are presented in Figure E.5 to Figure E.9. Rotated squares represent the pressure reaction, open circles the derivative.

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<tr>
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<tr>
<td>Porosity ( \Phi ) [%]</td>
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<td>Total Compressibility ( c_t ) [Pa(^{-1})]</td>
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<tr>
<td>Distance to active Well [m]</td>
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<tr>
<td>Wellbore Storage Coefficient ( C ) [m(^3)/Pa]</td>
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<tr>
<td>Skin Factor ( s )</td>
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<tr>
<td>Initial Pressure ( P_i ) [bar]</td>
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<tr>
<td>Hydraulic Conductivity ( K ) [m/s]</td>
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*Table E.1* Parameters for synthetically generated model shown in *Figure E.1*
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*Table E.2*  Parameters for synthetically generated model shown in *Figure E.2*

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<tr>
<td>Distance to active Well [m]</td>
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<tr>
<td>Wellbore Storage Coefficient $C$ [m$^3$/Pa]</td>
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*Table E.3*  Parameters for synthetically generated model shown in *Figure E.3*

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<td>Initial Pressure $P_i$ [bar]</td>
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<tr>
<td>Distance to linear constant pressure boundary $L$ [m]</td>
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*Table E.4*  Parameters for synthetically generated model shown in *Figure E.4*
**Figure E.1** Synthetic Log – Log plot for an observation borehole with no skin factor, no wellbore storage coefficient and no late time boundary effect

**Figure E.2** Synthetic Log – Log plot for an observation borehole with no skin factor, with wellbore storage coefficient and no late time boundary effect

**Figure E.3** Synthetic Log – Log plot for an observation borehole with no skin factor, no wellbore storage coefficient but late time no flow boundary effect

**Figure E.4** Synthetic Log – Log plot for an observation borehole with no skin factor, no wellbore storage coefficient and late time constant pressure boundary effect
Figure E.5  Pressure reaction from observation borehole K8WB (K8WD active borehole) with log – log diagnostic plots of the drawdown and the build up phase

Figure E.6  Pressure reaction from observation borehole K9WA (K9WB active borehole) with log – log diagnostic plots of two build up phases
Figure E.7  Pressure reaction from observation borehole K10WB (K10WA active borehole) with log – log diagnostic plots of the drawdown and the build up phase

Figure E.8  Pressure reaction from observation borehole K13WA (K13WB active borehole) with log – log diagnostic plots of the drawdown and the build up phase
Figure E.9   Pressure reaction from observation borehole K14WB (K14WA active borehole) with log – log diagnostic plots of the drawdown and the build up phase
F.

Lithology and Hydraulic Heads in Deep Boreholes and Piezometers in the Gastere Valley
During the 1990’s several deep boreholes (up to 750 m deep) were drilled from various locations in the Gastere Valley. Additional to the deep boreholes several piezometers (approx. 30 m deep) were drilled into the gravel aquifer of the valley.

The location of 3 selected deep boreholes (94/19, 91/2, 92/7) and 1 piezometer (GA20) is shown in Chapter 4 of this thesis. Subsequently a description about the boreholes and the piezometer is presented. Additional to this description, the hydraulic head (m a.s.l.) determined manually from 1992 to 2002 with an electric light gauge is presented in Figure 4 for the boreholes 91/2, 92/7 and the piezometer GA 20. These manual measurements are not air – pressure corrected. The hydraulic heads shown in Figure F.4 are spline interpolated as the boreholes are usually not accessible for measurements in winter time from November to approx. April because of high avalanche danger. In Figure F.4 only the time interval between 1992 and 2002 is shown. In this interval the hydraulic head in the various aquifers is not influenced by the tunnel excavation process due to drainage. The influenced head is discussed in Chapter 4 of this thesis.

F.1 Piezometer GA 20

The piezometer (Ø 96 mm) was installed in 1992 to monitor the hydraulic head in the gravel aquifer in the Gastere Valley. The piezometer pipe was drilled approx. 30 m into the gravel of the Gastere Valley and has an open filter section on the lower end. The coordinates (Swiss – Grid) of the piezometer – pipe are W619’060; N145155 with a top edge of the pipe of 1392.2 m.a.Sl.

Figure F.4 shows a clearly annual variation in the hydraulic head of gravel aquifer of the Gastere Valley with a minimum in approx. January and a maximum in approx. July. The total head change during the yearly cycle is approx. 25 m.
F.2 Deep Borehole 91/2

Borehole 91/2 was performed in 1992. *Ingenieurgemeinschaft Lötschberg Basistunnel (1993a)* describe in detail all procedures to drill the borehole, all performed borehole tests and give a detailed geological profile along the borehole. *Figure F.1* shows a simplified profile including borehole lining. A piezometer pipe was cemented to a borehole depth of 290 m with an open filter interval in the Quintner Limestone. The hydraulic head determined in the piezometer pipe is therefore corresponding to the head in the Quintner Limestone. The variation in the head as presented in *Figure F.4* is parallel to the head change in the piezometer GA20 and is within one year approx. 16 m. Additional to the open piezometer pipe an electronic pressure transmitter was installed on approx. 900 m.a.Sl. to determine the hydraulic head on the base of the Quintner Limestone. Unfortunately the pressure transmitter was shut down in the late 1990’s and the data are not available to us.

F.3 Deep Borehole 92/7

Borehole 92/7 was performed in 1992. *Ingenieurgemeinschaft Lötschberg Basistunnel (1993b)* describe in a detailed drilling report all results from the borehole including a detailed geological profile. *Figure F.2* shows a simplified profile including borehole lining. A piezometer pipe was cemented down to the boundary Quintner – Limestone and Autochthonous Sediments. The open filter interval is located in the Quintner – Limestone. The hydraulic head in the piezometer pipe is therefore corresponding to the head in the Quintner Limestone. In August 2002 an electronic pressure transmitter was installed in the borehole to determine the hydraulic head. Results of these measurements are discussed in *Chapter 4* of this thesis.

As presented in *Figure F.4* the hydraulic head in the piezometer GA20 and in the deep borehole 92/7 show a parallel yearly variation. The head change in a yearly cycle in borehole 92/7 is approx. 17 m.
F.4 Deep Borehole 94/19

Borehole 94/19 was performed in 1994. *Ingenieurgemeinschaft Lötschberg Basistunnel (1995)* describes in a detailed drilling report all results from the borehole including a detailed geological profile. *Figure F.3* shows a simplified profile including borehole lining. A piezometer pipe was cemented down to the crystalline and the filter interval is open in the Autochthonous Sediments and in parts of the crystalline. After finishing the installation of the borehole, water was leaking out at the borehole head (artesian conditions). It was therefore decided to install an analogue pressure gauge at the piezometer pipe head to determine the overpressure. Manual pressure readings were performed in irregular intervals. In August 2002 the manual pressure gauge was replaced by an electronic pressure transmitter. *Figure F.4* shows the pressure development from the installation of the manual pressure gauge until its replacement. At installation the hydraulic head is approx. 1379 m a.s.l. (approx. 9 m above the borehole head – artesian conditions) and continuously slightly increasing until July 1996. At this point the gradient of the hydraulic head gradient is steep until October 1997 followed by a stabilization phase until April 2000. Hydraulic head increase to a maximum of 1447 m a.s.l. is observed until the end of the manual reading interval. A general valid explanation for this behavior – an alternating pressure increase followed by a stabilization phase is difficult. Compared to the other boreholes, where the open borehole interval is located in gravel or in the Quintner - Limestone, no yearly hydraulic head variation cycles can be observed on this borehole.

F.5 References


Figure F.1 Geologic profile along borehole 91/2; including schematic borehole equipment
**Legend (Borehole)**

- **Piezometer Pipe**
- **Sealing (Cement - Packer)**
- **Cementation**
- **Borehole Filling**
- **Filtersand**
- **Open Borehole**

**Figure F.2**  Geologic profile along borehole 92/7; including schematic borehole equipment
### 94/19 “Gasteretal III”

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<td>Terrain: 1370.00 m.a.Sl.</td>
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#### Figure F.3
Geologic profile along borehole 94/19; including schematic borehole equipment
Figure F.4  Hydraulic head of the Quintner Limestone determined in two vertical boreholes (91/2 and 92/7) and hydraulic head of the Triassic Sediments (borehole 94/19). The hydraulic head in the gravel aquifer is determined in piezometer GA20.
G.

Exploration Borehole related Pressure Reactions in the Deep Borehole 92/7
Discussed in Chapter 4 of this thesis the performance of the exploration boreholes K15E, K16E, K13W and K14W induced a significant reversible hydraulic head change in the borehole 92/7. Outflow from the borehole were continuously monitored by the drilling crew and were determined after one drilling cycle, i.e. after an additional depth of three meters was reached. Based on drilling protocols written by the drilling crew, the exact time crossing a conductive structure can be determined. The watches of the crew were synchronized every shift and given times on the protocols are reliable. Despite this precision it was assumed during the analysis that time shown on the protocols have an error of ± 5 min.

As presented in Chapter 4 of this thesis, the time difference between a first detection of a flow rate and the lowering of the hydraulic head in borehole 92/7 can be used to determine a large scale storativity value based on Jacob’s formula. For this determination the hydraulic head reaction induced by the exploration borehole K16EA and K16EB was chosen, respectively. Figure G.1 shows the flow rate of the boreholes K16EA and K16EB determined by the drilling crew together with the hydraulic head (airpressure corrected) reaction in borehole 92/7.

The lowering of the hydraulic head in borehole 92/7 follows a continuous curve. To determine the exact time of the lowering of the hydraulic head it was decided to plot the difference between two heads $h_1$ at $t_1 = 0$ and $h_2$ at $t_2 = t_1 + 10$ min versus the effective time (Figure G.2). Based on Figure G.2 it was empirically decided that the hydraulic head was lowered surely on the 03.02.2003 at 23:40 [UTM]. Comparing in a later performed study the internal clock of the piezoelectric pressure transmitter with an atomic clock we can assume that the internal transmitter clock was not more than ± 5 min shifted at this moment. The latest possible reaction of the hydraulic head in borehole 92/7 occurred therefore at 23:45 [UTM]. If flow out of a conductive formation at 23:05 [UTM] with a clock error of ± 5 min is assumed, the earliest possible flow took place at 23:00 [UTM]. The maximum time difference between earliest possible flow out of a water conductive formation, drained by borehole K16EA and a latest possible head reaction in borehole 92/7 is therefore 45 min. This
time difference was used in Jacob’s equation to estimate the large scale storativity in the Quintner Limestone.
Figure G.1  Hydraulic head reaction in borehole 92/7 caused by exploration drilling K16E

Figure G.2  Hydraulic head difference in 10 min intervals to determine the exact head reaction time in borehole 92/7
H.

**Tunnel Map, Horizontal Exploration Boreholes and Long Term Tunnel Inflows**
During the excavation of the Lötschberg Base Tunnel geological structures, lithology and tunnel inflows into the excavation zone were mapped and determined by the tunnel geologists. As described in Chapter 2 of this thesis, water inflows into the horizontal exploration boreholes were determined by the drilling crew. Figure H.1 shows a compilation of all information gained during the tunnel excavation and the exploration boreholes between TM 26’743 and TM 28’564. All information shown on Figure H.1 is discussed in detail subsequently.

- **Projection Method**: The two parallel tunnel tubes (West – and East – tunnel) are shown on a horizontal map view. The tunnel walls are unrolled; the tunnel floor is not displayed in this view.

- **Tunnel Meters**: On the view, only the section of the tunnel is shown on which piezoelectric pressure transmitters were used to determine the pressure reaction in the horizontal exploration boreholes. In contrast to the common description in this thesis, the tunnel meters of the West – tunnel are NOT normalized to East – Meters. Attention must be paid if events e.g. the location of a borehole inflow into the West – tunnel (normalized on East – Meters) shown in tables within this thesis is compared to the map where the West – tunnel is not normalized on East meters.

- **Lithology**: below the shown enrolled tunnel tubes, the lithology of the units – Öhrli – Limestone, Öhrli – Marl and Quintner Limestone is shown.

- **Geological Structures**: during tunnel excavation clearly visible geological structures are shown on the enrolled tunnel section such as bedding structures, foliation, karst pipes or fractures filled with calcite. Additional to the representation of the geological structures areas of strong disaggregation of rocks or rockfall areas are shown. Selected major brittle faults are indicated with a continuous numbering as BFExx for a brittle fault in the East – Tunnel and BFWxx in the West – Tunnel. A description of all selected brittle faults including Dip Direction and Dip Angle, location and initial flow rate is given in Table H.1.
• **Flow into the excavation zone:** all determined initial flow’s from conductive structures are shown above the tunnel profile for the East – and the West – Tunnel. The flow rate was usually determined between 1 and 10 hours after the excavation of a conductive structure. Usually, the flow rate was determined with a stop watch and a normalized barrel, or, if the zone was not accessible the flow rate was estimated. An exact description about the determination of the flow rates is given in Chapter 2 of this thesis. If the flow rate was smaller than 0.1 l/s it is represented by the expression “Dropwater” on the profile.

• **Long term inflow survey into tunnel:** Long term monitored inflows into the tunnel are indicated with a flag “Q,T,σ” which represents flow rate (Q), T (temperature) and σ (electrical conductivity). Usually the flow rate survey started 2 – 3 week after the excavation of a conductive structure, when hoses and pipes were installed to collect the water flow out of the structure and the flow could be determined easily. *Figure H.2 to Figure H.19* show the determined flow rates, temperature and electrical conductivity. The Figure description is directly related to indicated locations on the tunnel, i.g. *Figure 1* with description QWS 26935 refers a water survey point in the West – tunnel at tunnel meter 26935 (in West – Meters). For *Figure H.2 – Figure H.19* equal symbols are used:
  - Open squares (□) represent estimated flow rates; no normalized barrel was available to determine the flow rate (error: ± 100%).
  - Rotated open squares (◇) represent determined flow rates with a normalized barrel and a stop watch (error: ± 0.1 l/s at a flow rate of 5 l/s).
  - Open triangles (△) represent the determined water temperature (°C).
  - Open Circles (○) represent the determined electrical conductivity (µS/cm).

• **Horizontal exploration boreholes:** additional to the tunnel profiles, all performed horizontal exploration boreholes are shown on the Figure. Borehole number, start and end point, detected flow rates during the drilling process (determined with rods in the borehole, but without core catcher), determined
flow rates after the borehole was finished (without rods) are shown. A continuous bold line represents cored boreholes, while dashed bold lines represent boreholes performed with an inhole hammer. Boreholes, not drilled along the tunnel axis e.g. borehole K9WD are indicated with the index “projected”.

*Figure H.1* Tunnel map including boreholes, water inflows and all mapped structures during excavation (see external sheet)
Figure H.2  QWS 26935

Figure H.3  QWS 26937

Figure H.4  QWS 26950 tot

Figure H.5  QWS 26955
Figure H.18    QWS28491    Figure H.19    QWS 28578
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<td>89</td>
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<td>Brittle Fault undulated with slickenside. Opening strongly variable, between 2 mm and 250 mm; Dip Direction and Dip of major fault between 042 / 89 and 048 / 62. Major Fault after ~20 m splitting up in fine, altered network of fractures; strike and dip of fracture network strongly variable (e.g. 257 / 74). Major Fault filled with fault gauge (Sand, Mud). Rock in network area strongly altered. Extension &gt; 50 m, probably visible in other tunnel; possible connection to BFW07</td>
</tr>
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<td>85</td>
<td>27725</td>
<td>-</td>
<td>Brittle Fault. No information about infill, cover, alteration etc.</td>
</tr>
<tr>
<td>BFE14</td>
<td>262</td>
<td>24</td>
<td>27894</td>
<td>2.0</td>
<td>Brittle Fault, not indicated on geologists log – sheet but identified during floor mapping campaign. Undulated brittle fault, with slickenside but no alteration of fault visible. No infill. Extension probably &gt; 50 m. Possible connection to brittle fault BFW 20 in other tunnel.</td>
</tr>
</tbody>
</table>

$^1$ All Tunnel – Meters (TM) are normalized on East – Meters. For linear structures the cross – point with the tunnel crown is given as a reference.

$^2$ Represents the flow rate determined between 1 and 10 hours after the excavation of a water conductive structure.
<table>
<thead>
<tr>
<th>Fault Id. No.</th>
<th>Dip Dir.</th>
<th>Dip Angle</th>
<th>TM East</th>
<th>Initial Flow [l/s]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFE15</td>
<td>55</td>
<td>82</td>
<td>27083</td>
<td>2.0</td>
<td>Brittle Fault, not indicated on geologists log – sheet but identified during floor mapping campaign. Undulated brittle fault, with slickenside. Fault partly rusty altered. No alteration of surrounding rock. Fault opening approx. 2 mm. No infill. Extension probably &gt; 50 m. Possible connection to brittle fault BFW 21 in other tunnel.</td>
</tr>
<tr>
<td>BFE16</td>
<td>~283</td>
<td>17</td>
<td>28350</td>
<td>0.3</td>
<td>Fracture (classification by tunnel geologist). Because of possible larger extension classified during this study as “Brittle Fault”. No information about infill, cover, alteration etc.</td>
</tr>
<tr>
<td>BFE17</td>
<td>~325</td>
<td>45</td>
<td>28387</td>
<td>3.0</td>
<td>Bedding Plane (classification by tunnel geologist). Because of possible extension and water inflow classified during this study as “Brittle Fault”. No information about infill, cover, alteration etc. Extension probably &gt; 50 m. Possible connection to brittle fault BFW23 in other tunnel.</td>
</tr>
<tr>
<td>BFW01</td>
<td>~055</td>
<td>80</td>
<td>26876</td>
<td>1.5 (total with BFW02, 05, 06)</td>
<td>Brittle Fault with calcite crystal cover; along fault several karst caves (Size: approx. 0.5 m wide, 1 m high) with infill of sand, mud and gravel. Limestone alteration around Fault only few mm. Possible extension of the Fault &gt; 50 m (Fault probably visible in other tunnel).</td>
</tr>
<tr>
<td>BFW02</td>
<td>~055</td>
<td>80</td>
<td>26889</td>
<td>1.5 (total with BFW01, 05, 06)</td>
<td>Brittle Fault with undulated surface. No crystals visible. No information about infill. Possible extension of the Fault &gt; 50 m (Fault probably visible in other tunnel)</td>
</tr>
<tr>
<td>BFW03</td>
<td>~055</td>
<td>80</td>
<td>26903</td>
<td>6.0</td>
<td>Brittle Fault with thick (35 mm) cover of calcite crystals. Crystals covered with rusty colored fine crystalline calcite. Fault infill of sand and mud. Possible extension of the Fault &gt; 50 m (Fault probably visible in other tunnel)</td>
</tr>
<tr>
<td>BFW04</td>
<td>~055</td>
<td>80</td>
<td>26912</td>
<td>8.0</td>
<td>Brittle Fault with thick (35 mm) cover of calcite crystals. Crystals covered with rusty colored fine crystalline calcite. Fault infill of sand and mud. Possible extension of the Fault &gt; 50 m (Fault probably visible in other tunnel)</td>
</tr>
<tr>
<td>BFW05</td>
<td>~303</td>
<td>10</td>
<td>26890</td>
<td>1.5 (total with BFW01, 02, 06)</td>
<td>Brittle Fault. No information about infill, cover, alteration etc.</td>
</tr>
<tr>
<td>BFW06</td>
<td>~303</td>
<td>10</td>
<td>26884</td>
<td>1.5 (total with BFW01, 02, 05)</td>
<td>Brittle Fault. No information about infill, cover, alteration etc.</td>
</tr>
<tr>
<td>BFW07</td>
<td>040</td>
<td>80</td>
<td>27172</td>
<td>13.5 (total with BFW08)</td>
<td>Brittle Fault, partly covered (~20mm) with calcite crystals. Crystals covered with rusty colored fine crystalline calcite. Fault walls undulated and altered due to fluid flow. Extension of Fault probably &gt; 50 m; possible connection to Fault BFE05 in other tunnel.</td>
</tr>
<tr>
<td>BFW08</td>
<td>~230</td>
<td>70</td>
<td>27195</td>
<td>13.5 (total with BFW07)</td>
<td>Brittle Fault. No information about infill, cover, alteration etc.; probably equal to BFW07. Extension of Fault probably &gt; 50 m; possible connection to Fault BFE04 in other tunnel.</td>
</tr>
<tr>
<td>BFW09</td>
<td>320</td>
<td>35</td>
<td>27216</td>
<td>8.0</td>
<td>Brittle Fault. No information about infill, cover, alteration etc.; probably equal to BFW07. Extension of Fault probably &gt; 50 m; possible connection to Fault BFE04 in other tunnel.</td>
</tr>
<tr>
<td>BFW10</td>
<td>~230</td>
<td>60</td>
<td>27220</td>
<td>-</td>
<td>Brittle Fault. No information about infill, cover, alteration etc; probably equal to BFW07. Extension of Fault probably &gt; 50 m; possible connection to Fault BFE04 in other tunnel.</td>
</tr>
<tr>
<td>Fault Id. No.</td>
<td>Dip Dir.</td>
<td>Dip Angle</td>
<td>TM East</td>
<td>Initial Flow [l/s]</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
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</tr>
<tr>
<td>BFW11</td>
<td>260</td>
<td>20</td>
<td>27257</td>
<td>1.0</td>
<td>Brittle Fault, thickness approx. 0.3 m. No information about infill, cover, alteration etc.; Extension of Fault probably &gt; 50 m; possible connection to Fault BFE05 in other tunnel.</td>
</tr>
<tr>
<td>BFW12</td>
<td>-050</td>
<td>80</td>
<td>27385</td>
<td>-</td>
<td>Brittle Fault. No information about infill, cover, alteration etc. Extension of Fault probably &gt; 50 m; possible connection to Fault BFE07 and / or BFE08 in other tunnel.</td>
</tr>
<tr>
<td>BFW13</td>
<td>046</td>
<td>80</td>
<td>27475</td>
<td>-</td>
<td>Brittle Fault. No information about infill, cover, alteration etc.</td>
</tr>
<tr>
<td>BFW14</td>
<td>-050</td>
<td>80</td>
<td>27511</td>
<td>-</td>
<td>Brittle Fault. No information about infill, cover, alteration etc.</td>
</tr>
<tr>
<td>BFW15</td>
<td>277</td>
<td>75</td>
<td>27525</td>
<td>-</td>
<td>Brittle Fault. No information about infill, cover, alteration etc.</td>
</tr>
<tr>
<td>BFW16</td>
<td>-260</td>
<td>40</td>
<td>27560</td>
<td>6.0</td>
<td>Bedding Plane (classification by tunnel geologist). Because of water inflow classified during this study as “Brittle Fault”. No information about infill, cover, alteration etc.</td>
</tr>
<tr>
<td>BFW17</td>
<td>-60</td>
<td>80</td>
<td>27600</td>
<td>0.5</td>
<td>Brittle Fault. No information about infill, cover, alteration etc.</td>
</tr>
<tr>
<td>BFW18</td>
<td>065</td>
<td>70</td>
<td>27647</td>
<td>-</td>
<td>Brittle Fault. No information about infill, cover, alteration etc. Same Fault as BFW17?</td>
</tr>
<tr>
<td>BFW19</td>
<td>065</td>
<td>70</td>
<td>27657</td>
<td>-</td>
<td>Brittle Fault. No information about infill, cover, alteration etc. Same Fault as BFW17?</td>
</tr>
<tr>
<td>BFW20</td>
<td>272</td>
<td>15</td>
<td>27925</td>
<td>1.8</td>
<td>Shear Plane (classification by tunnel geologist). Because of extension and water inflow classified during this study as “Brittle Fault” with partly filled calcite veins. Extension of Fault probably &gt; 50 m; possible connection to Fault BFE14 in other tunnel.</td>
</tr>
<tr>
<td>BFW21</td>
<td>300</td>
<td>30 - 45</td>
<td>28122</td>
<td>1.0</td>
<td>Shear Plane (classification by tunnel geologist). Because of extension and water inflow classified during this study as “Brittle Fault”. Several fractures, secondary filled with calcite. Extension of Fault probably &gt; 50 m; possible connection to Fault BFE15 in other tunnel.</td>
</tr>
<tr>
<td>BFW22</td>
<td>307</td>
<td>25</td>
<td>28295</td>
<td>18.0</td>
<td>Bedding Plane (classification by tunnel geologist). Because of possible extension and water inflow classified during this study as “Brittle Fault”. No information about infill, cover, alteration etc. No connection to a fault in other tunnel visible, but several water inflows in other tunnel at same location (out of steep fractures).</td>
</tr>
<tr>
<td>BFW23</td>
<td>294</td>
<td>30</td>
<td>28430</td>
<td>11.0</td>
<td>Bedding Plane (classification by tunnel geologist). Because of possible extension and water inflow classified during this study as “Brittle Fault”. No information about infill, cover, alteration etc. No connection to a fault in other tunnel visible, but several water inflows in other tunnel at same location (out of steep fractures).</td>
</tr>
<tr>
<td>BFW24</td>
<td>026</td>
<td>74</td>
<td>28495</td>
<td>3</td>
<td>Brittle Fault. No information about infill, cover, alteration etc.</td>
</tr>
<tr>
<td>BFW25</td>
<td>-060</td>
<td>80</td>
<td>28550</td>
<td>1</td>
<td>Brittle Fault. No information about infill, cover, alteration etc.</td>
</tr>
</tbody>
</table>

*Table H.1* Detailed description of all brittle faults
Curriculum Vitae
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Personal Details
Date of Birth          November 2nd 1971
Nationality            Swiss and Austria (Mandach, AG)

Education
2002 to 2006           Swiss Federal Institute of Technology (ETH); Engineering
                        Geology, ETH Hönggerberg; PhD - student
1997 to 2002           Swiss Federal Institute of Technology (ETH); Studies in Earth
                        Science
1996 to1997            Introductory studies of Mathematics at University Zürich
1993 to 1996           Night – School for access to University as mature student
1988 to 1992           Apprenticeship as Mechanic for Gas Turbines at Asea Brown
                        Boveri, Baden, Switzerland

Languages
German, English and French       Oral and written
Spanish                        Basic knowledge