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REPORT

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COMPARISON OF DIRECT AND INDIRECT DIAGNOSIS TOOLS AND METHODS TO DETERMINE AND DISTINGUISH CLOGGING

Project acronym: WellMa1

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for
Kompetenzzentrum Wasser Berlin gGmbH

Preparation of this report was financed through funds provided by

VEOLIA WATER   Berliner Wasserbetriebe

Berlin, Germany

2009

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Title

Comparison of direct and indirect diagnosis tools and methods to determine and distinguish clogging [WellMa1: Nov. 07 - Dec. 08]

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Abstract

The assessment of methods for the diagnosis and distinction of well ageing types and processes with the aim to recommend methods and tools for further fieldwork was part of work package 1 of the preparatory phase WellMa1.

Therefore, field tests were carried out at selected well sites with a variety of methods covering standard monitoring methods to assess the constructive state of a well (TV inspections, borehole geophysical methods) and its performance (pump tests) as well as methods aiming at a better process understanding such as the hydrochemical and microbiological analysis of the raw water and clogging deposits.

Altogether ten methods were applied at 21 different wells of the Berliner Wasserbetriebe (BWB) covering

- Exposure of object slides during operation and rest periods for microbiological investigations
- BART with test kits for iron-related bacteria (IRB) and slime-forming bacteria (SLYM)
- Water sampling for the investigation of pristine groundwater organisms
- Online measurements of chemical parameters O_2, Eh, pH and T and water sampling for chemical analyses (main cations and anions)
- TV inspections
- Three-step pumping tests
- Borehole geophysics with Gamma-Gamma-Density scan (GG.D), Neutron-Neutron log (NN), Flowmeter (Flow) and Packer-Flowmeter (P.Flow) measurement
- Particle countings

The assessment and comparison should originally be completed by a horizontally directed core sampling from different depths from the screen sections of three of the chosen wells. Due to technical difficulties, this was not achieved during this phase of the project.

The investigations led to a development and refinement of the methods and approaches. Because of their limited accessibility to the different parts of a well, a combination of methods is always necessary. Especially for the indirect methods like borehole geophysics, an initial assessment of the well condition directly subsequent to construction is essential to provide a basis for the assessment of the well performance development.

Generally, the applied standard monitoring methods and diagnosis tools provided the expected identification of a performance deterioration and evidence for the presence of starting materials for clogging processes such as iron, oxygen, iron-related bacteria and particles. Room for improvement could be identified with regard to the reliability, information value and comparability of the tested methods, e.g. by a stepwise combination and extension of the methods to determine the interacting processes from the composition of the deposits.

Further investigations should aim at method validation, especially for well monitoring during routine operation (e.g. use of Δh, development of standards for Qs-measurements and TV inspections), and further method development for the ongoing project with scientific investigations to obtain deeper process understanding, e.g. investigating shares of deposits resulting from the different processes (chemical, biological, physical) and relations between the rate of clogging or the location of deposits to well characteristics and site conditions to separate the different well ageing processes. This will then lead to the identification of key parameters that may be influenced to slow down well ageing and keep the well performance and water quality at an optimum.

Kurzfassung

Der Vergleich und die Bewertung von Methoden zur Diagnose und Unterscheidung von Brunnenalterungsarten und -prozessen war Teil des Arbeitspaketes 1 der vorbereitenden Projektphase WellMa1. Ziel war die Ableitung von Empfehlungen für die Methodenauswahl und den Arbeitsumfang der Felduntersuchungen in der nachfolgenden Projektphase WellMa2.

Dafür wurde eine Vielzahl von Methoden an ausgewählten Brunnenstandorten getestet, unter anderem Standardüberwachungsmethoden zur Einschätzung des Bauzustands (Kamera-Inspektionen, geophysikalische Bohrlochverfahren) und der Brunnenleistung (Pumptests), aber auch auf ein besseres Prozessverständnis gerichtete Methoden, wie z.B. die hydrochemische und mikrobiologische Analyse von Rohwasser- und Ablagerungsproben.

Insgesamt wurden zehn Methoden an 21 verschiedenen Brunnen der Berliner Wasserbetriebe (BWB) getestet. Sie umfassten:

(1) die Exposition von Objektträgern für mikrobiologische Untersuchungen während Betriebs- und Ruhezeiträumen

(2) BART-Tests auf Eisenbakterien (IRB) und schleimbildende Bakterien (SLYM)

(3) Untersuchung des Auftretens von Grundwasserorganismen in Wasserproben

(4) Online-Messungen der chemischen Parameter O_2, Eh, pH und T sowie Wasserprobennahme für chemische Analysen (Hauptkationen und -anionen)

(5) Kamera-Inspektionen

(6) Dreistufige Pumptests

(7) Bohrlochgeophysik mit Gamma-Gamma-Dichtescan (GG.D) und Neutron-Neutron Log (NN), (8) Durchflussmessung (Flow) und (9) Packer-Flowmeter-Messung (P.Flow)

(10) Partikelzählungen

Der Vergleich und die Bewertung der Methoden sollten durch die Entnahme horizontaler Kernproben aus verschiedenen Tiefen des Filterbereichs von drei ausgewählten Brunnen ergänzt werden. Dieses Ziel wurde aufgrund technischer Schwierigkeiten in WellMa1 nicht erreicht.

Mithilfe der durchgeführten Felduntersuchungen konnten die Methoden und Verfahren zur Diagnose und Unterscheidung von Brunnenalterungsarten und -prozessen weiterentwickelt und verfeinert werden. Wegen der eingeschränkten Zugangsmöglichkeiten zu den verschiedenen Teilen eines Brunnens wird jedoch immer eine Kombination mehrerer Verfahren benötigt. Besonders für indirekte Methoden wie die Bohrlochgeophysik ist eine Ersteinschätzung des Brunnenzustands direkt nach dem Bau erforderlich, um eine Grundlage für die Einschätzung der Leistungsentwicklung des Brunnens zu erhalten.

Grundsätzlich konnte mit den angewendeten Standardüberwachungsmethoden und Diagnoseinstrumente eine Leistungsverschlechterung und Hinweise auf das Vorhandensein von Brunnenalterungsvorgängen, z.B. Eisen, Sauerstoff, Eisenbakterien und Partikeln festgestellt werden. Im Hinblick auf die Zuverlässigkeit, den Informationsgehalt und die Vergleichbarkeit der geprüften Methoden wurde Verbesserungspotential gefunden, beispielsweise für eine stufenweise Untersuchung der Zusammensetzung der Ablagerungen zur Ermittlung der Interaktionsprozesse.

Weitere Untersuchungen sollten auf die Validierung der Methoden gerichtet sein. Dazu zählen die Brunnenüberwachung im Routinebetrieb (z.B. Nutzen der Δh-Messung, Entwicklung von Standards für Qs-Messungen und Kamerainspektionen) und die Weiterentwicklung der wissenschaftlichen Untersuchungen des Prozessverständnisses, z.B. die Unterscheidung der aus den verschiedenen (chemischen, biologischen und physikalischen) Prozessen resultierenden Anteile von Ablagerungen und die Beziehungen zwischen der Verockerungsgeschwindigkeit und dem Ort der Ablagerungen zu den Brunnenparametern und den Standortbedingungen. Damit können die Schlüsselparameter ermittelt werden, auf die Einfluss genommen werden kann, um die Brunnenalterung zu verlangsamen und Brunnenleistung und Wasserqualität auf einem Optimum zu halten.

Résume

L'évaluation des méthodes de diagnostic et de distinction des catégories de vieillissement de puits et leurs processus associés dans le but de recommander méthodes et outils pour des essais sur le terrain ultérieurs a fait partie du premier paquet de travail de la phase préparatoire de WellMa1.

Par conséquent, des essais sur le terrain furent réalisés sur des puits présélectionnés suivant une variété de méthodes de surveillance standard visant à évaluer l'état de construction de puits (inspections télévisuelles, méthodes géophysiques par forage) et sa performance (essais de pompe), ainsi que des méthodes permettant de mieux comprendre les processus telles que l'analyse hydrochimique ou microbiologique de l'eau brute et des dépôts colmatants.

Au total, dix méthodes furent appliquées à 21 puits différents de la Berliner Wasserbetriebe (BWB) portant sur :

- L'exposition de lames minces en phase d'exploitation et de temps morts pour mener des recherches microbiologiques
- BART avec kits d'analyse pour déceler la présence de bactéries ferrugineuses (IRB) et bactéries visqueuses (SLYM), et
- Echantillonnage de l'eau pour étudier les organismes des nappes phréatiques intactes
- Mesures en ligne de paramètres O_2, Eh, pH et T ainsi que prélèvement d'eau pour analyse chimique (principaux cations et anions)
- Inspections télévisuelles
- Essais de pompage triphasiques
- Géophysique de forage par diagraphie gamma-gamma (GG.D), diagraphie neutron-neutron (NN), débitmètre (Flow) et débitmètre à packer (P.Flow)
- Comptage particulaire

A l'origine, l'évaluation et la comparaison devaient s'achever sur des carottages horizontaux à diverses profondeurs dans la section de la crépine de trois puits sélectionnées. En raison de problèmes techniques, ceci n'a pas pu se faire pendant cette phase du projet.

Les travaux de recherche ont abouti au développement et perfectionnement de méthodes et techniques. Etant donné l'accessibilité limitée des différentes sections d'un puits, une combinaison de méthodes s'avère incontournable. Ceci vaut particulièrement pour les méthodes indirectes comme la géophysique de puits. Une évaluation préalable de l'état du puits immédiatement après sa construction est essentielle afin de disposer d'une base d'évaluation de l'évolution de performance du puits.

Dans l'ensemble, les méthodes de surveillance et outils de diagnosic standard appliqués ont permis l'identification attendue d'une détérioration de performance et prouvé la présence de matières premières des processus de colmatage comme le fer, l'oxygène, les bactéries et particules ferrugineuses. L'on a identifié des pistes d'amélioration possibles relatives à la fiabilité, la valeur informative et la comparabilité des méthodes testées. Par exemple, une combinaison et extension successives des méthodes pour distinguer les processus d'interaction à partir de la composition des sédiments.

Des travaux scientifiques ultérieurs devraient examiner la validation des méthodes, particulièrement pour les contrôles de routine des puits en service (par ex. utilisation de Δh, élaboration de normes pour les mesures Qs, inspections télévisuelles etc.), et le

perfectionnement des méthodes du projet en cours. Il s'agira de mieux comprendre les processus, par exemple, par l'étude des dépôts provenant des divers processus (chimiques, biologiques, physiques) et de la relation entre le degré de colmatage ou l'emplacement des dépôts et les caractéristiques du puits et conditions du site, afin d'élucider les divers processus de vieillissement du puits. A terme, ceci permettra de déterminer les paramètres clés pouvant intervenir pour ralentir le vieillissement et maintenir à un niveau optimal la performance du puits et la qualité de l'eau.

Acknowledgements

The project team is grateful to *BWB* and *Veolia* for sponsoring the *WELLMA-project*.

We thank all involved persons at the technical divisions and research and development departments as well as the technical committee for the valuable discussions and provided information.

Thank you!

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Chapter 1
Introduction

All field investigations in this extended preparatory phase of the WellMa project were planned to assess methodological approaches for further use from the comparison of different microbiological, chemical, physical and visual inspections to diagnose well ageing processes.

Biggest issue for all diagnosis approaches is the accessibility of the fundamental parts of a well, which are at the same time the most vulnerable ones with regard to ageing: the submersible pump, the screen and its openings and the gravel pack.

Methodological approaches include comparatively simple technologies, like water sampling or video inspection and a number of more sophisticated, indirect inspection technologies, like borehole geophysics, developed to a big part from the oil exploitation industry, where physical responses are used to deduce certain characteristics. However, all methods are restricted in the access they provide. Visual inspection by a down-hole camera for example reaches only the well interior, but allows no view at the filter gravel, whereas sampling allows concluding present chemical equilibrium conditions, but as a mixture of water is drawn from the well, it does not represent redox layers and mixing processes itself.

Basis for any interpretation is a good understanding of the geochemical and hydrogeological context. As also concluded in the state-of-the-art report, no single method provides full understanding of ageing processes. They all show only single effects or impacts. The highest benefits can be expected from overlapping several, carefully selected methods. Generally, the simpler a method is, the more regularly it is expected to be used in daily operation and maintenance procedure. The best applicable and most promising methods have to be chosen depending on previous approaches, investigations and practical experience. Such standard protocols for regular monitoring need to be developed individually for groups of wells or wellfields with similar background conditions (*Please do also refer to the state-of-the-art-report*). According to HOWSAM, MISSTEAR et al. 1995 the following four questions need to be considered:

1. Which parameters need to be monitored?
2. How can these parameters be monitored?
3. Where does monitoring apply? Priority is at the point of activity!
4. When or rather how often do these parameters need to be measured?

During WellMa1, eleven indirect diagnosis methods (Table 1-1) were tested at selected wells. Aim was to specify sets of parameters, points of activity and needs for the frequency of any measurements.

The overlapping of the results should be compared to direct access to the filter gravel by core sampling in order to choose the most reliable diagnosis and monitoring methods to be applied in the further course of the project.

Table 1-1: Methodologically approaches included and assessed in WellMa1

Method	Advantages	Limitations
Water sampling for chemical analysis	Quick and simple.	Access to mixed water only. No layering. No depth profiles. Set of parameters needs to be defined. To assess ageing, regular sampling and follow-up needed.
Microbiological sampling [WellMa DNA]	Detailed composition of bacteria communities. Depth profiles possible.	Laboratory processing necessary (microscopic assessment, cultivation, DNA extraction etc.).
BART	Quick and simple assessment of bacteria activity. Distinction in main groups of bacteria (9 specified test-kits available) and aerobic and anaerobic bacteria.	No standardized procedure publicised. Cultivation-based (only cultivable bacteria are detectable). Costs for test-kits.
Sampling of clogging deposits for mineralogical analysis	Detailed composition of deposits, Also to assess rehabilitation approach. Depth-oriented sampling possible.	Access limited to a certain depth. Differences between original site conditions and surface/ laboratory condition. Limited analysis methods (chemical composition yes, mineralogical structure no etc.)
Particle counting	Simple detection of the abundance of particles	Necessity for sampling and analysis to identify their origin
Δh-calculation	Quick and simple.	Only useful, if on regular basis.
Short pumping test	One-step test can be done during operation.	Basic knowledge about hydrogeological context needed (confined/ unconfined aquifer, development of static water levels etc.). Comparability only for constant discharge rate. Only useful to follow-up ageing, if on regular basis.
TV camera inspection	Quick and simple. Direct assessment of type and extension of clogging deposits.	Only well interior. No assessment of gravel pack condition.
GG	Assessment of packing density in the gravel pack (e.g. bridging, gravel relocation etc.).	Costs. Significance to assess ageing (what is natural, what from ageing?)
NN	Assessment of clay sealing and water content in the gravel pack (indirect for packing density).	Costs. Significance to assess ageing.
Flow	Quantification of inflow about the total length of the filter section(s).	Significance (what is from hydrogeology, what from ageing?)
Packer-Flow	Assessment of the permeability of filter and gravel pack (near the filter).	Limited range of intrusion into the gravel pack.

Chapter 2
General characteristics of the Berlin wells

2.1 Hydrogeological situation and resulting chemical characteristics Regional Overview: Geomorphology, Geology and Hydrogeology [A. Pekdeger, G. Massmann, U.Maiwald, C. Menz, T. Taute]

The area of Berlin is a part of the central northern german lowland. The surface area covers about 884 km². The highest spots are the Müggelberge in the southeast part of the city with an altitude of 115 m above sea level (NN) and the Schäfersberg in the southwest with 103,20 m above sea level.

The climate of Berlin is dominated by the transition of marine and continental influences. The average precipitation is below 600 mm, which means it is the driest part of Germany. The average temperature is about 9,1° Celsius.

The recent geomorphological structures of Berlin are dominated by the advance of the glaciers in the Weichsel ice age, which is the last of the three main ice stages in the Quaternary (Weichsel, Saale, Elster). Therefore, Berlin is part of the younger moraine landscape of the Brandenburger stadium. As figure 1 shows, the area of Berlin is composed up of three ground moraine blocks (Teltow, Barnim & Nauener Platte) which are crossed by the Warschau Berliner glacial valley (Assmann 1957)

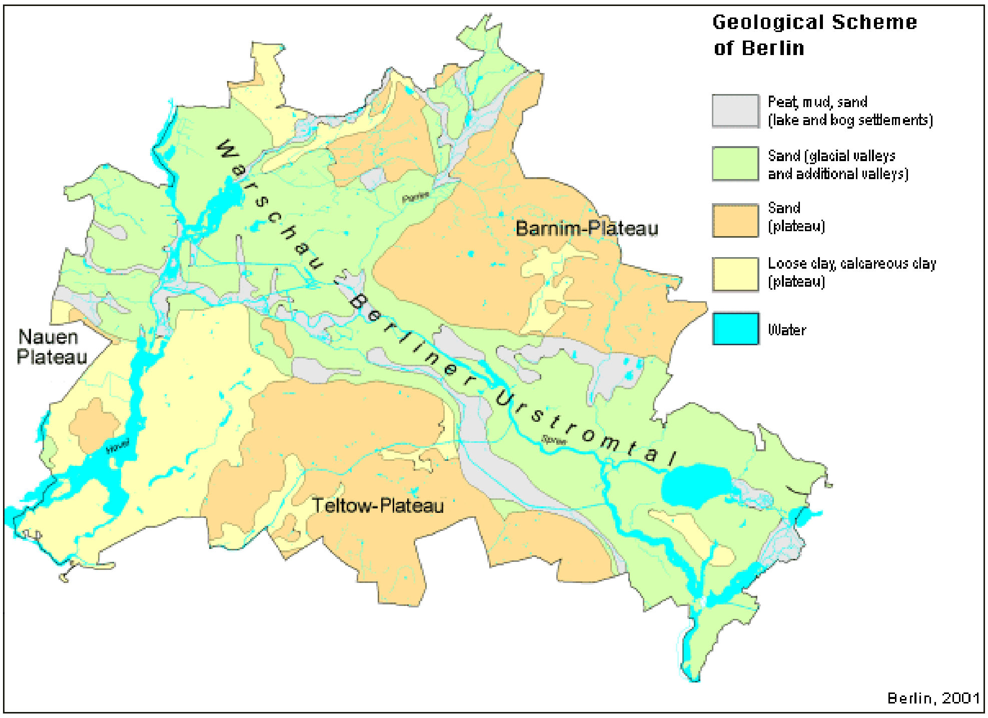

Figure 2-1: Schematic Map of the Occuring Kaenozoic Formations at the Berlin Surface [after Kloos (1986)].

The subsurface of Berlin is formed by two multiaquifer formations. The lower one is not suitable for the abstraction of drinking water, because it contains brines (highly saline ground water). The saline multiaquifer formation is separated from the overlying fresh water multiaquifer formation by the Rupelian marl (lower Oligocene) which has a thickness of about 100 m. The latter is divided into the 4 main aquifer complexes:

1. Holocene-Weichsel (upper Pleistocene), 2. Saale, 3. Holstein-Elster (lower Pleistocene), 4. Miocene-Cottbusser Schichten (LIMBERG & THIERBACH 1997). These are sub-divided by locally occurring confining units (e.g. 1.0, 1.1, 1.2 ...see table 1 and figure 2). The aquifer complex 2 (Saale) is called the “main aquifer” due to its continuously occurrence and importance to economic aspects. As a whole, all the aquifers of the fresh water multiaquifer formation in Berlin are working as a single hydraulic unit, due to leakages (hydraulic connections) between all of them. There are several spots where the rupelian marl is completely eroded by quaternary glacial channels. At these places the saline and the fresh water multiaquifer formations are connected (e.g. below the Zitadelle Spandau, the Stölpchensee and the Schmöckwitzer Werder) and lead to saline impacts into the fresh water aquifers. The thickness of the fresh water multiaquifer formation is in the southern parts of Berlin bigger than in the north. In the south, its basis is located below NN-100 m in the north above NN-100 m.

Differing from the systematic of the state geological survey, the Berliner Wasserbetriebe divide the fresh water multiaquifer formation into 3 main aquifer complexes. In the system of the Berliner Wasserbetriebe, the first and the second main aquifer complexes are identical to those of the Berliner Landesgeologie, but the third sums up the fourth due to the lack of clearly confining units between the lower Pleistocene and the Tertiary aquifers.

Table 2-1: Stratigraphy of the Area of Berlin [modified after Kallenbach 1980, Frey 1975 and Wurl 1995; Hydrogeological Stratification Limberg & Thierbach 1997]

<table>
<tr><th>Era</th><th>Period</th><th>Epoch</th><th></th><th>Sediments</th><th>Thickness</th><th>Aquifer</th></tr>
<tr><td rowspan="12">Cenozoic</td><td rowspan="6">Quaternary</td><td colspan="2">Holocene</td><td>Sand, Drifting Sand, Sapropel, Peat</td><td>max. 25 m</td><td rowspan="2">1. Aquifer</td></tr>
<tr><td rowspan="5">Pleistocene</td><td>Weichsel</td><td rowspan="5">Glacial Till, Grit, Gravel, Sand, Varved Clay, Sapropel, Peat, Silt, Clay</td><td rowspan="5">max. 250 m</td></tr>
<tr><td>Eem</td><td>Aquitard</td></tr>
<tr><td>Saale</td><td>2.Aquifer
(main aquifer)</td></tr>
<tr><td>Holstein</td><td rowspan="2">3. Aquifer</td></tr>
<tr><td>Elster</td></tr>
<tr><td rowspan="6">Tertiary</td><td colspan="2">Pliocene</td><td>-----------------------</td><td></td><td></td></tr>
<tr><td colspan="2">Miocene</td><td>Sand, Gravel, Silt, Lignite</td><td>max. 280 m</td><td rowspan="2">4.Aquifer
(occasionally aquitard)</td></tr>
<tr><td colspan="2" rowspan="2">Oligocene</td><td>Cottbusser Schichten, Sand</td><td>40 – 60 m</td></tr>
<tr><td>Rupelian Marl, Clay</td><td>80 – 100 m</td><td>Aquitard</td></tr>
<tr><td colspan="2">Eocene</td><td>-----------------------</td><td></td><td rowspan="3">Saltwater-aquifer-complex</td></tr>
<tr><td colspan="2">Paleocene</td><td>-----------------------</td><td></td></tr>
<tr><td colspan="2">Pretertiary</td><td></td><td></td><td>Hard rocks</td><td>>1000m</td></tr>
</table>

The groundwater of the freshwater multiaquifer formation in Berlin typically is a Ca-HCO_3-SO_4-water with electrical conductivities between 500 and 2500, and an average of 800 µS/cm.

Due to the similarity of the general lithological composition and the lack of continuously occurring confining units (see figure 2), it is hardly possible to divide the different aquifer complexes just by the chemical main components. The shallow aquifers often tend towards a dominance of SO_4 and sometimes an influence of Cl. The deep aquifers sometimes are of Na-Cl-type.

The redox potential varies between oxic and sulphate reducing. There is a trend of lower redox conditions in deeper aquifers but the average is in the range of iron reduction. Due to the content of iron and manganese as grain coatings on all sandy sediments and the occurring redox conditions, iron is the most common trace substance in the ground water in Berlin. The average content of iron is about 2 mg/l and of manganese 0,4 mg/l.

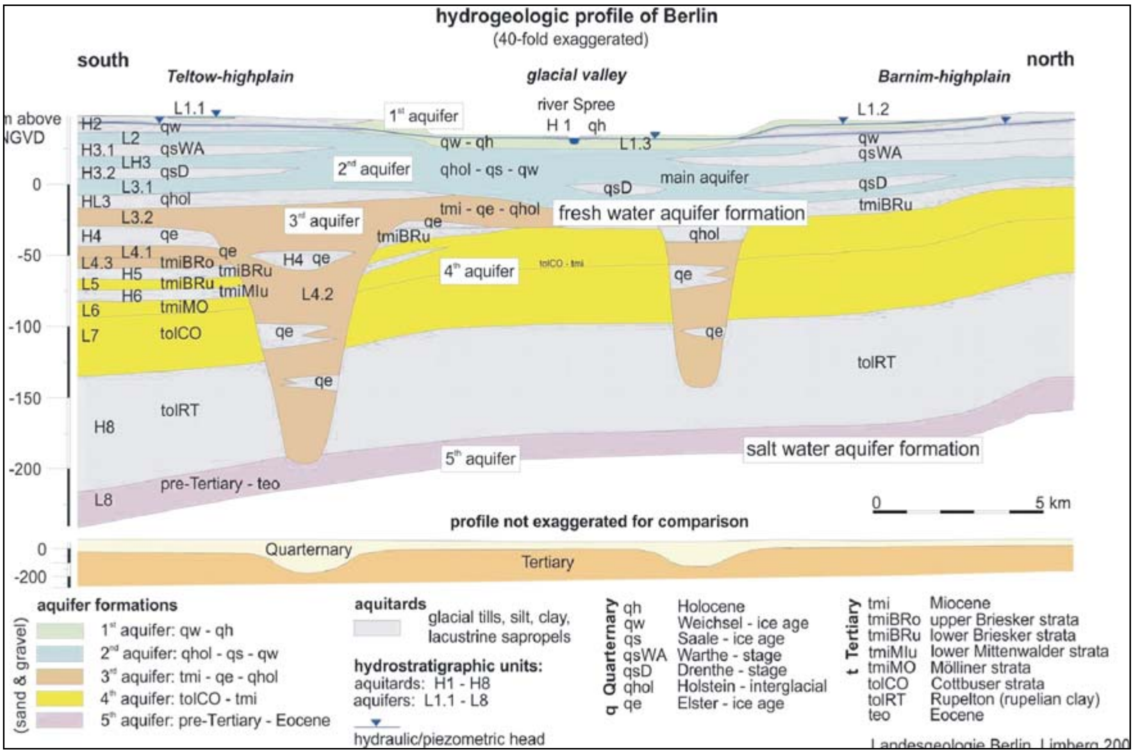

Figure 2-2: Schematic hydrogeological cross-section from the north to the south of Berlin (SenS 2005)

In places where Quaternary glaciofluviatile channels has eroded the Tertiary sediments down to the saline aquifer formation (see figure 2), the deep aquifers of the fresh water multiaquifer formation (upper Oligocene -Elster, SenGUV 3-4 = BWB 3) are contaminated with brines. The ground water in these areas also tend to have increased contents of DOC, dominated by humic acids dissolved from the distributed lignite in the Miocenian lignite sands.

The ground water in the uppermost aquifers are generally influenced by anthropogenic contaminants, especially sulphate, chloride, nutrients (Phosphate, Ammonia and DOC), traces of metals and artificial substances (e.g. hydrocarbons) and their metabolites.

Most of the wells used for the abstraction of potable water by the Berliner Wasserbertiebe, are located close to the wide spread surface water system in the glacial valley (see figure 1). That leads to a portion of about 70% of bank filtrate in the wells. Most of the wells have their filter screens in the second (Saale) aquifer complex. Apart from some single exceptions, there are only two major exceptions: the wells in the south-western part of the city (WW Beelitzhof) have their filter screens in the second or third or in both aquifers. The most northern wells (northern galleries of WW Stolpe) only have filter screens in the first aquifer complex. Due to the lack of a confining unit between the first and second aquifer complex in the glacial valley the anthropogenic contaminants of the surface water and the first aquifer complex are also present in the second aquifer complex.

2.2 Selected wells [D. Orlikowski, H. Wiacek]

2.2.1 Abandoned wells for assessment of standard monitoring methods

At BWB, about 20 wells per year are reconstructed. Hence, the “old” wells are abandoned and new ones are drilled. This implies pulling of the well interior (casing, screen, gravel) and filling of the borehole with different layers and materials to restore the original aquifer conditions (confining layers etc.). This anyway planned destruction of the well afforded an opportunity to get access to samples from the annular space. Three wells were selected to compare standard monitoring methods like TV inspection, pumping test and borehole geophysics, which all do give an indirect assessment of the conditions in the gravel pack with direct access from horizontal core sampling.

Reconstruction planning is integrated in mid-term budgeting for the well management division of BWB. The wells are selected according to:

- technical needs: remaining well capacity/ performance development etc.
- economic factors: coordination of reconstruction per waterworks, per gallery etc.

For WellMa 1, task 1.4 we could choose from a total of 28 wells, preselected by BWB on the basis of investment planning for 2008 and 2009.

Restrictions came from the technical implementation of core sampling and included the needs of a minimum diameter of casing and screen of 400 mm (DN 400) and the absence of heavy structural damages of the well construction (not too bad corrosion, intact sockets etc.) or previous restoration work (installation of inliners, filling of deep parts etc.). This left nine wells to choose from. Based on their geology, the capacity development, rehabilitation history and the material of casing and screen, the following wells (Table 2-2) were selected:

Table 2-2: Main technical characteristics of the selected wells for comparison of standard monitoring and following core sampling [KWB, 2008]

	Well 1	Well 2	Well 3
Well ID	**TEGhzk-13-/73V**	**TEGhzk-22-/71V**	**STOborg19-/90V**
Year of construction	1973	1971	1990
Geology/ water source	unconfined, middle sand, artificial recharge	confined, middle sand, artificial recharge	unconfined, middle sand, river bank filtrate
Casing	DN 400 Steel (Rilsan)	DN 400 Steel (Rilsan)	DN 400 PE
Gravel pack	twofold	twofold	twofold
Depth	40,4	33,6	19,3
Initial capacity	Q: 200 m³/h Qs: 76,9 m³/h*m	Q: 120 m³/h Qs: 49,2 m³/h*m	Q: 80 m³/h Qs: 76,9 m³/h*m
Actual pump capacity	60 m³/h	50 m³/h	50 m³/h
Last rehabilitation	2003	2003	2007
Method	Shock blasting	Shock blasting	Hydropuls
Capacity improvement	Qs before: 56,1 Qs after: 57,7	Qs before: 15,5 Qs after: 22,3	Qs before: ? Qs after: 19,4
remaining well performance	66% of initial capacity	45% of initial capacity	25% of initial capacity

Site maps and cross sections can be found within the appendix.

Applied methods were:

- Online measurements of chemical parameters O_2, Eh, pH and T and water sampling for chemical analyses
- Exposure of object slides during operation and rest periods for microbiological investigations
- BART with test kits for iron-related bacteria (IRB) and slime-forming bacteria (SLYM)
- Water sampling and investigation of pristine groundwater organisms
- Sampling of clogging deposits from the submersible pump for chemical, mineralogica and microbiological investigation
- Particle counting
- TV inspection
- Three-step pumping test
- Borehole geophysics with Gamma-Gamma-Density scan (GG.D), Neutron-Neutron log (NN), Flowmeter (Flow) and Packer-Flowmeter (P.Flow) measurement

2.2.2 Wells with different backgrounds and capacity development

For the assessment of mineralogical, bio- and geochemical methods for determination and analysis of the nature of clogging and the associated environmental parameters (task 1.3) additional ten wells should be investigated to be able to assess the methodologically approaches. These wells were selected after their hydrogeological context and the capacity development in comparison to adjacent wells. A pre-selection was presented by BWB by naming 14 wells with similar design and geology, but different behaviour during normal operation and maintenance procedure. Additionally, discussion led to the inclusion of direct neighbours for two wells. A total of 17 wells provides different data sets for comparison, e.g.:

- single and twofold gravel pack (SPANDAU Nord)
- steel, copper and PVC casing (different sites)
- wells with and without H_2O_2 treatment (KAULSDORF Nord/ STOLPE Borgsdorf)
- wells with irregular hydrochemistry (BEELITZHOF)
- water from natural river bank filtration and artificial recharge (different sites)

The advantages of using adjacent wells lies in the fact, that they have the same design, year of construction and in most cases also the same date of last rehabilitation, but different remaining capacities. The basic data are summarized in Table 2-3:

Table 2-3: Basic data of the selected wells for task 1.3

Water works	Wellfield	Well no.	Year of cons	Gravel pack	Screen material	Actual discharge [m³/h]	remaining capacity	H2O2-treatment	last/ planned rehab	Irregularities
Spandau	Nord	1	2004	1	Stainless steel	150	no PV	ja	2008	
Spandau	Nord	2	1982	2	Steel	100	47%	ja	2008	
Spandau	Nord	3	1999	2	Stainless steel	200	74%	ja	2008	
Tegel	West	12	1984	2	Steel	50	63%	ja	Sep 03	
Tegel	West	13	1985	2	Steel	100	46%	nein	July 07	
Tegel	West	14	1985	2	Steel	120	74%	ja	Oct. 03	
Tegel	Saatwinkel	19	1971	2	Steel	60	92%	ja	Feb 07	
Tegel	Saatwinkel	20	1971	2	Steel	60	64%	ja	Feb. 07	Carbamazepin
Stolpe	Borgsdorf	14	1994	2	PVC	50	65%	nein	Feb. 07	
Stolpe	Borgsdorf	20	1994	2	PVC	50	26%	nein	Sep. 07	
Kaulsdorf	Nord	5	1995	2	Steel	80	82%	ja	2008	
Kaulsdorf	Nord	6	1995	2	Steel	60	44%	nein	2008	
Kaulsdorf	Nord	7	1995	2	Steel	60	39%	ja	2008	
Beelitzhof	Lindwerder	1	1995	2	Steel	50	90%	nein	2008	Bacteria
Beelitzhof	Lindwerder	23	2002	2	Stainless steel	150	57%	nein	2007	
Beelitzhof	Großes Fenster	5	1993	2	Steel	100	73%	ja	2006	Carbamazepin
Tiefwerder	Süd	19	1960	2	Copper	45	47%	nein	2008	

2.3 Construction of a transect [T. Taute, U. Maiwald, C. Menz, A. Pekdeger]

Aim of the transect is to provide a high-resolution observation network to investigate the well clogging mechanisms in and close to the well.

Because instruments for monitoring all ageing aspects are not standard equipment at all BWB's wells, we installed a close-meshed observation network at one well.

We chose well STOborg15-/90V as test site, because it provides a set of significant characteristics of our interest. The well gallery STOborg includes 20 production wells. All filter screens of the wells are situated in the first aquifer. They provide the identical geological and constructional settings. The Aquifer is unconfined and mainly composed of medium and coarse-grained sands. Filter screens are situated in low depths (9 to 15m), compared to other locations (up to 80m). We assume a mixing of groundwater and bank filtrate in the wells of STOborg gallery due to the nearby Oder-Havel-Channel. Furthermore, all wells are of the same age, but differ significantly in their capacity and their degree of deterioration. Among the four STOborg-wells, participating at the short-termed monitoring, well STOborg15-/90V holds the highest capacity compared to its initial state. The treatment of the well STOborg15-/90V with H_2O_2 since 2003 fulfils another significant condition for the test site selection.

We assume that the treatment with H_2O_2 has an impact on the aquifer in the range of centimetres to a maximum of a few meters. To achieve a high-resolution of well surroundings, it was necessary to install the observation network as close as possible to the production well. Due to the well chamber, the closest position for observation well construction is 1.25m from the centre of the production well. We estimate a maximum range, affected by the H_2O_2-treatment, of 5m. Based on this assumption, we chose distances of 1.25m, 2.25m and 5m to the production well.

Because of an asymmetric well chamber, the transect is composed of five multi-level observation wells instead of six. Their position compared to the production well is shown in Figure 2-3. Their orientation allows a bi-directional monitoring and recording of the groundwater and bank filtrate, flowing towards the well.

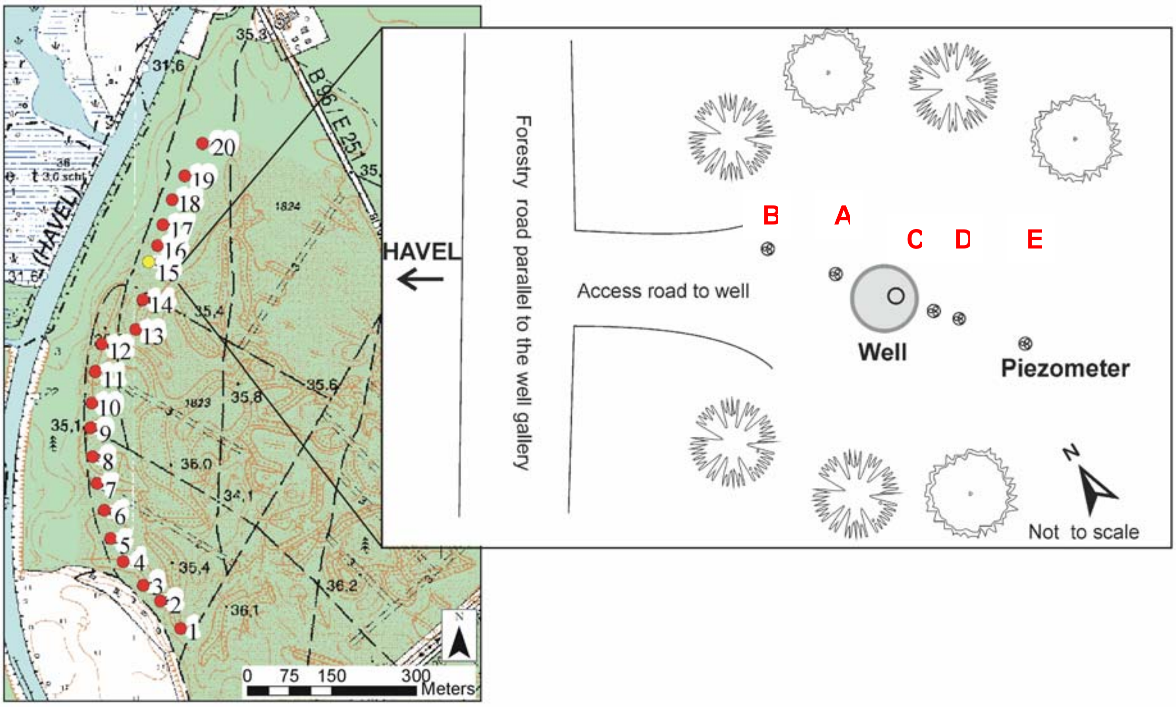

Figure 2-3: Location of well STOborg15-/90V and associated transect.

Each multi-level observation well is composed of three 2-inch piezometers, with filter screens from 5-7m, 11-13m and 14-16m below surface. In addition, we installed O_2-optodes parallel to the five multi-level observation wells. The optodes are fixed at the casing of the piezometer in depths of 3, 4, 5, 6, 9 and 14m (see Figure 2-4). The aim is to quantify the oxygen entry due to H_2O_2 treatment of the well and to prove how long its presence remains traceable in the vicinity of the well. Furthermore, we try to quantify the oxygen input from the unsaturated zone (atmosphere via soil air) generated by oscillation of the groundwater surface.

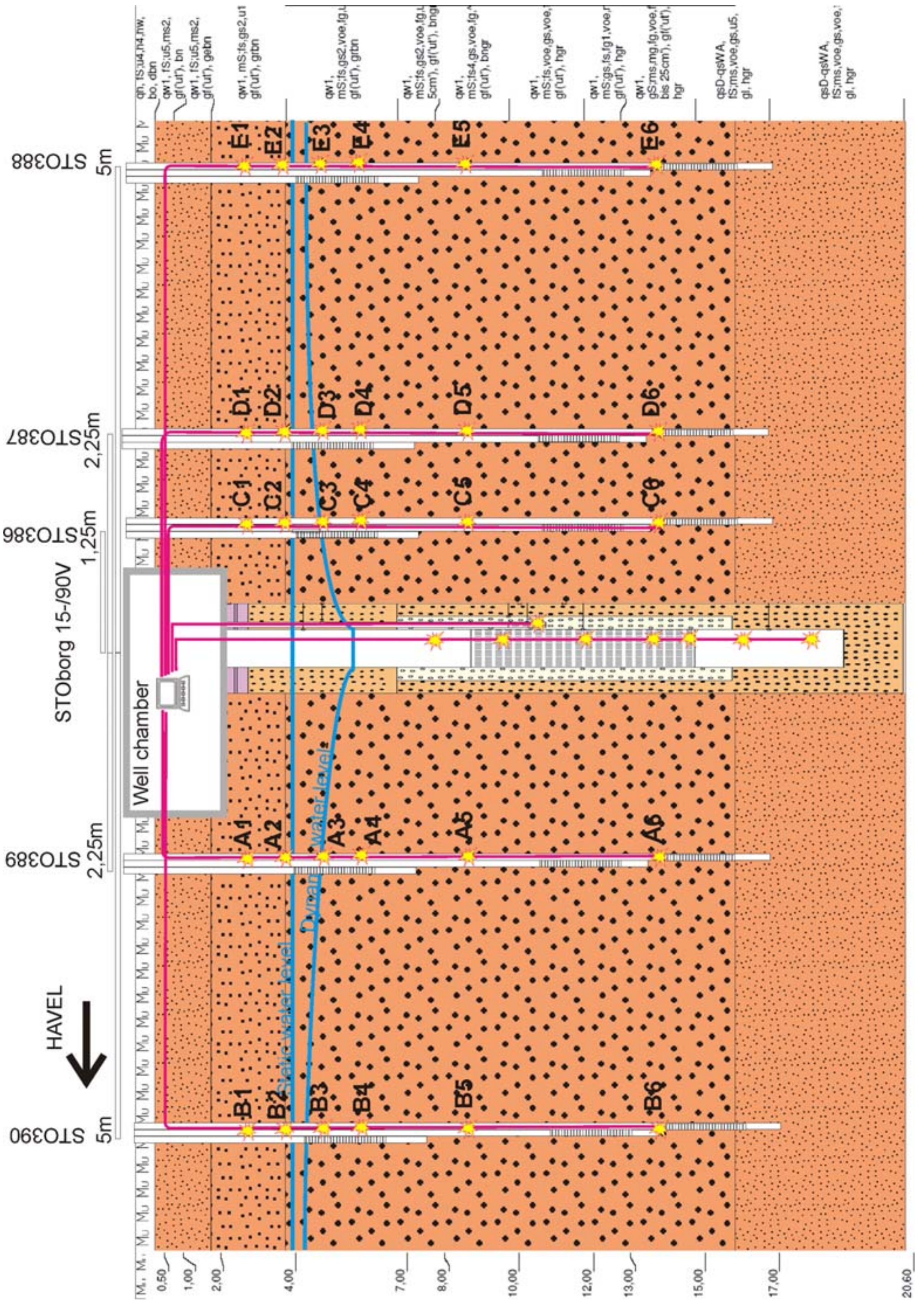

Figure 2-4: Construction scheme and geological cross-section of well STOborg15-/90V and associated transect. Yellow stars mark O_2-optodes

Chapter 3
Field investigations

The methods tested, can be divided into three different monitoring and diagnosis approaches:

A) Monitoring of the well performance (standard monitoring)
   (1) Step discharge test

B) Monitoring of the well condition (standard monitoring)
   (1) TV inspection
   (2) Gamma-Gamma density scan (GG:D) and Neutron-Neutron-Logging (NN)
   (3) Flowmeter (Flow)
   (4) Packer-Flowmeter (Packer-Flow)

C) Diagnosis of ageing types and their extension
   (1) Water sampling and hydrochemical analyses
   (2) Microbiological sampling and subsequent molecular investigations
   (3) BART (biological activity reaction test)
   (4) Particle counting

As all of these methods are only indirect measures in terms of assessing the gravel pack condition, it was originally planned to have horizontal cores taken from the selected wells providing direct access to the expected deposits and thus providing the opportunity to evaluate the significance of the tested methods.

While the monitoring of well performance and conditions can be regarded being standard methods, the methodology of geochemical and microbiological investigations needed to be developed first. Based on the hypothesis that clogging at the Berlin wells is mainly caused by the deposition of iron hydroxides induced by iron-related bacteria, focus of the hydrochemical and microbiological investigations lay on the assessment of redox conditions, the living environment and the composition of bacteria communities in biofilms.

Table 3-1 summarizes the scope of investigations at the selected wells:

Table 3-1: Selected well sites and field methods

METHOD	3 abandoned wells	1 well with transect	17 additional wells in operation
Hydrochemical analyses	x	x	x
Object slides	x	x	x
BART	x	x	
Particle counting	x		
Standard monitoring of well performance and condition	x	x	
H_2O_2 treatment		x	

3.1 Microbiological and molecular characterisation of well clogging [O. Thronicker, U. Szewzyk]

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3.1.1 Purpose of the investigations

WELLMA 1 was undertaken, to evaluate and document the involvement of microorganisms in the process of well clogging. Particularly the diversity of bacteria involved in the oxidation of iron and manganese was to be resolved. It was assumed, that different groups of bacteria occur in different parts of a well, depending on the local physico-chemical conditions, and that these different bacteria are responsible for different types of iron depositions.

From microscopic examinations it was known for long time, that some species of iron bacteria cause very soft depositions, which easily can be removed from any surface. On the other hand, species like Siderocapsa are known to cause hard, rock-like depositions, which can be removed from a surface only by application of strong mechanical forces.

The intention of the microbiological part project of WELLMA1 was to develop methods for reproducible and reliable sampling of biological materials from the wells, to carry out a first microscopic examination which should be accompanied by extraction of DNA and first molecular analysis.

3.1.2 Microbiology and well biofouling

Although iron bacteria are a group of bacteria known since the first half of the 19th century, their features nevertheless still remain controversial. Iron, constitutes approximately 4.7% by weight in the earth crust an is one of the most common metals on earth, beside aluminum. In anaerobic ground waters, it is continuously transformed from it's trivalent oxidized, to the water soluble, bivalent form. This happens chemically (e.g. FeOOH (Goethite) + e^- + $3H^+$ → Fe^{2+} +H_2O), but also through iron reducing bacteria, which use trivalent iron species as an electron acceptor, to oxidize organic substances (Teutsch et al. 1997).

When exposed to small amounts of oxygen, through construction and operation of drinking water abstraction wells, the iron in the anaerobic groundwater of Berlin, can be chemically and biologically reoxidized again. Iron bacteria are able to oxidize iron and are found especially in the border zone between anaerobic and aerobic groundwater. In the presence of ample nutrients provided by strong flow rates, a development of appreciable biomass is very possible. Therefore especially the upper filter area and the suction grid of the pump are impacted (Cullimore, R.1999).

Other factors are: temperature, pH-value and redox-potential of the respective water.

Some of the best known representatives of this group of organisms are: *Leptothrix ochracea, Gallionella ferruginea, Thiobacillus ferrooxidans* and *Siderocapsa sp*.

Some of these species are able to utilize the energy, provided by the oxidation of bivalent iron ($4Fe^{2+} + 4H^+ + O_2 = 4Fe^{3+} + 2H_2O$) for their metabolism. In this case reduced iron takes the role of electron donor and oxygen functions as the electron acceptor. Since the energy provided by this reaction is very small (29 kj per mol iron) (Neubauer et al. 2002), large amounts of iron have to be converted. This taken into account, it is not unusual for Berlin water wells to contain vast amounts of ferric hydroxides. The iron bacteria in the well biofilms use the bivalent, reduced iron or manganese provided by the raw water as electron donor and oxidize these soluble metals to a corresponding metal hydroxide, which is deposited in the biofilms. This observation, attributed to Winogradsky (Winogradsky 1888), was subject of debate for a long time.

Molish even went as far as to postulate that iron was absolutely unnecessary for the growth of the iron bacteria. Lieske was able to refute this, by showing that some iron bacteria are very well able to utilize other sources of energy, but, especially in media with reduced organic content, iron has a strong influence on bacterial growth (Lieske 1919). In this context it is interesting to note that iron oxidation seems to happen in close correlation to organically bound iron and that it happens in the cell envelope or even regions far from the cell (Zopf 1879). Certain outer membrane proteins and extracellular polymeric substances secreted by the cell are thought to be responsible for this observation (Adams, L. & Ghiorse, W. 1986). These different types of iron oxidation and precipitation are the core reason, why iron bacteria are such an important subject of research. Structure and composition of the ochre deposits are dependant on the prevalent species of iron bacteria and strongly influence the regeneration results of the wells. While *Gallionella* and *Leptothrix* can form long filaments and soft coatings, other iron bacteria (e.g. Siderocapsa spec.) form very compact and thick deposits (Figure 3-1).

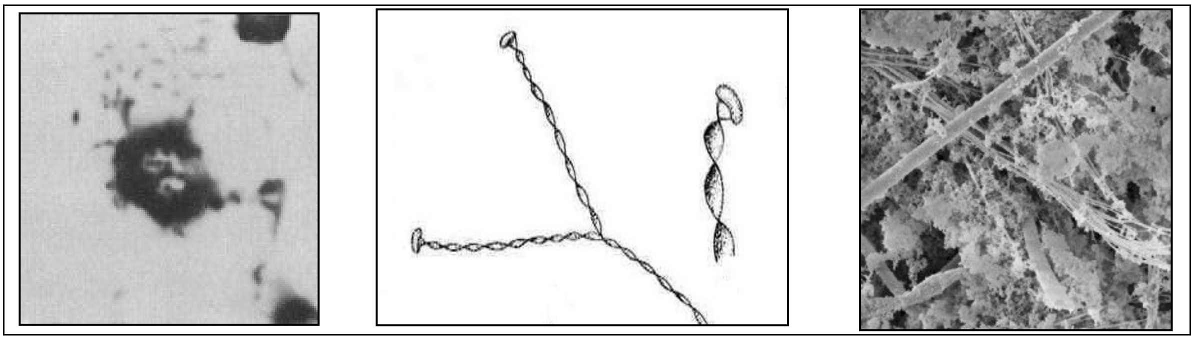


Figure 3-1: a) Siderocapsa sp. b) Gallionella sp. c) iron bacteria in a biofilm

Sources:: (a) Yvette Hardman et al. 1938, (b) J.Häusler 1982 (c) Thronicker 2005

Since the composition of the bacterial population of the wells strongly depends on the respective physical and chemical conditions, a molecular and microbiological characterization of the bacterial populations is to be performed. The received data are to be compared with data of the project partners and shall serve as basis for the development of an indicator system, to detect and prevent biological well clogging. The first phase of the project was focused on the development and testing of the materials and methods needed in the progression of the project. A sampling device had to be designed and the methods of the molecular and microscopic methods had to be optimized.

3.1.3 Field investigations for microbiological and molecular characterisation of well clogging

Sampling methods

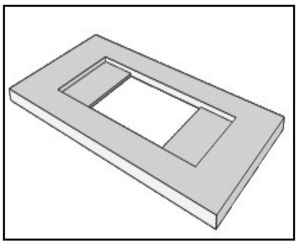


Figure3-2: Microscope adapter

Because of their construction characteristics, wells are a unique research environment, which makes sampling a delicate process. In order to ensure the undisturbed growth of biofilms, a suitable sampling device had to be designed. One of the requirements was the ability to take samples, without interrupting well operations beyond a reasonable level, so existing standpipes (interior and exterior) were utilized.

The designed sampling device made it possible that neither additional construction work was necessary, nor was it necessary to open the wellhead, which was a great advantage.

For safety reasons though, the pump had to be shut down briefly during introduction of the sampling device, but it could be restarted subsequently. The sampling device was redesigned and optimized several times during the project. Although we first used a nylon cord, this was later replaced by steel wire, because steel was easier to handle, in case the device got slightly jammed.

Alongside the steel wire, several perforated containers (15 ml falcon tubes) were attached with Simplex clamps. These autoclavable polypropylene containers were equipped with glass beads or microscope slides. Since normal slides wouldn't always fit into the standpipes, an instrument was developed to cut object slides in half. Simultaneously an adapter had to be designed, to allow microscopic analysis of the smaller object slides (Figure3-2)

While the slides were used for microscopic analysis, the glass beads in the containers were used as carrier material for bacteria, from which DNA was to be extracted. The terminal container was filled with a steel weight to keep the device straight (Figure 3-3)

During the sampling trial additional carrier materials, like silicium carriers were tested. This material enables a much easier elemental analysis of the biofilms, with the help of EDX (energy dispersive X-ray spectroscopy), since there are no interfering background signals.

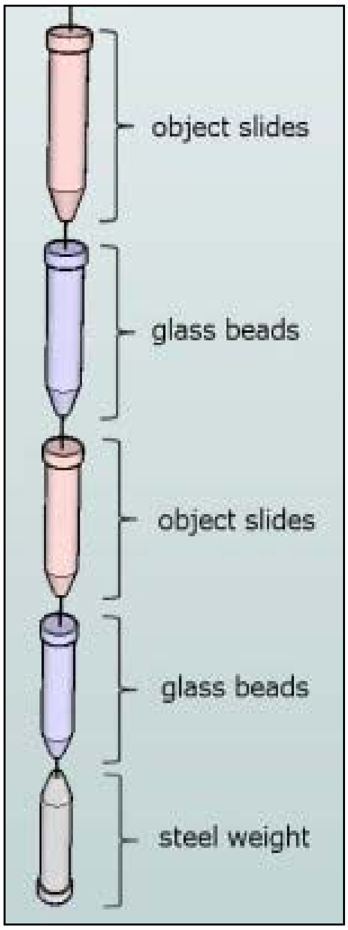


Figure 3-3: Sampling device

Microscope slides

The slides were used for a initial microscopic characterization of the biofilms. The fluorescent dyes that were used attach to DNA and greatly enhance the visualization of bacterial cells. In addition, gene probes, specific for the Beta- and Gamma-proteobacteria were tested. Because of the ability of the iron bacteria to create encrusting iron deposits, they are especially hard to stain with gene probes. Therefore, several methods for dissolving the encrustations without damaging the cell structure have been tested.

Cultivation and isolation

Efforts for isolation of iron bacteria have been started with different samples from the wells (water, pump coating and biofilms on glass beads). Decimal dilutions (up to $10^{-4,}$ depending on Inoculum) of biofilm suspensions were prepared with PBS (phosphate buffered saline). The last two dilution steps were spread on agar plates (media: modifed *Lepthothrix* medium and groundwater), two replicates per medium. The dilution was used for isolation and not for quantification. The primary plate (PP) was sealed with parafilm and incubated at room temperature for up to 2 months. The growth of colonies was checked regularly. Depending on the respective media and sample, several weeks were necessary for development of colonies.

Brown or black colonies were assumed results of iron or manganese oxidation. Such colonies were partly collected with sterile toothpicks and streaked on new agar plates for subcultivation.

Attempts were made to pick as many different morphologically different colonies as possible. The PP was incubated and slower growing colonies that developed were subsequently subcultivated for an additional period of time.

Depending on the dilution, it was not always possible to isolate dark colonies without touching other non-iron oxidizing colonies, resulting in contamination. It was not always possible to solve this problem through further dilution of the samples, since the undesired bacteria grew faster than the target organisms. Therefore, the non-iron oxidizing bacteria were gradually eliminated through repeated dilution streaking. The time required for isolation of a pure culture varied, but 3-10 transfers, each after 2-6 weeks, were generally needed. These cultures were morphologically consistent and stayed consistent after repeated streaking. The process of isolation through repeated streaking successfully resulted in a monoculture around 50% of the time.

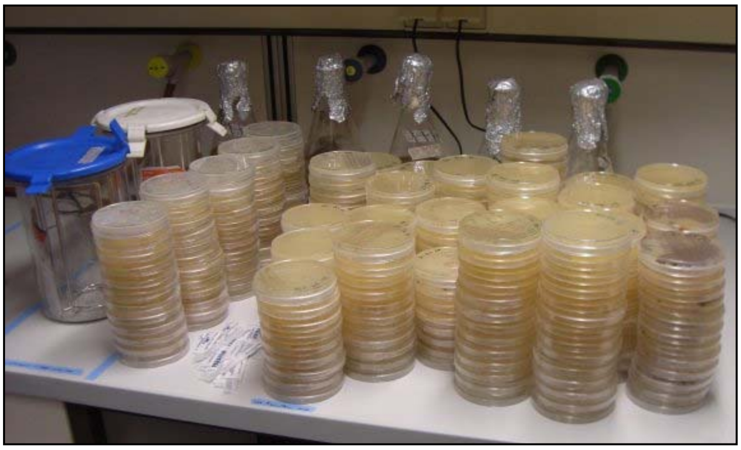


Figure 3-4: Cultivation and isolation

DNA-Probes

Many iron bacteria are part of the group of the Beta-proteobacteria, a class in the bacterial phylogenetic system, that groups bacteria according to base sequences of ribosomal 16S-ribonucleic acid (16S-rRNA). Important representatives of the Beta-proteobacteria can be found in the genera *Sphaerotilus, Nitrosomonas, Spirillum,Thibacillus* and *Gallionella*.

Using the FISH (Fluoresence In Situ Hybridization) method it is possible to specifically visualize target organisms on a slide. The method utilizes the fact that bacterial cells contain a multitude of ribosomes, partly composed of ribonucleic acid (RNA). Since ribosomal RNA contains very specific regions, genetic probes labeled with fluorescent dyes can bind selectively to bacteria that contain the target sequence. With the help of suitable light sources, these signals can be visualized (Figure 3-5):

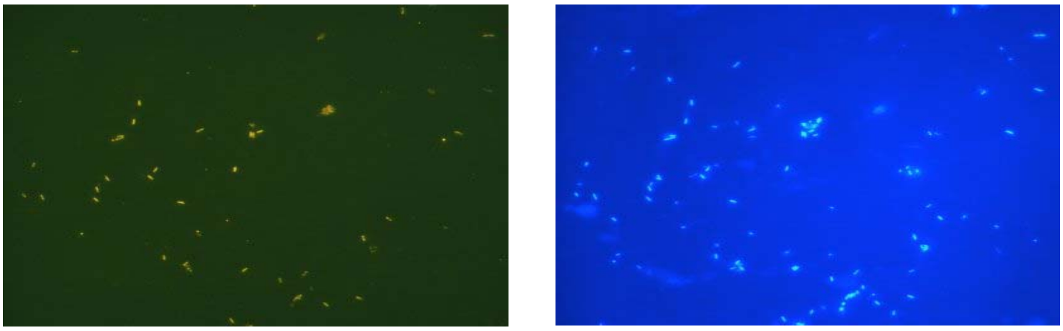


Figure 3-5 a) Epifluorescence signal total cell count b) Epifluorescence signal: probe

In order to extract bacterial DNA from the biofilms, glass beads (Ø 3 mm) were exposed in the wells in addition to the object slides. These glass beads were stored at – 20°C and the attached biofilm was detached with the help of vortexing and washing steps.

During test trials, it was first determined which extraction matrix was the most suitable for our samples. Collected DNA was amplified with PCR (polymerase chain reaction), following optimization of PCR parameters. To gain an initial overview of the population structure of the wells, we analysed selected samples using the DGGE (Denaturing Gradient Gel Elecrophoresis) method. With this method one can separate DNA fragments of the same length in a denaturing gradient based on base pair differences. In this fashion a specific fingerprint of the habitat can be created. In addition, cloning of selected samples was carried out, in order to collect initial data for further analysis (comparison of habitats and design of genetic probes).

3.1.4 Results

Sampling campaign

An important result of the research was the development of a sampling system that suited the needs of the project. After initial tests in the water body above the pump and further development, it was possible to retrieve biofilm samples at any desired depth. With few easy handholds, the exposition depth can now even be re-adjusted during the sampling campaign. In future investigations it is therefore possible to insert slides into the wells without major interference with normal well operations (removal of pump, opening of well head) and to cultivate undisturbed, well-specific biofilms in operating wells. The steel wire (2 mm 7x7) emerged as the optimal solution, because it was tearproof and autoclavable. In addition, the use of Simplex clamps poses a very flexible method for mounting the sampling containers.

Cultivations

Twenty iron oxidizing isolates have been obtained. An additional 160 isolation trials are still in progress. It remains to be clarified, how many separate strains are represented by this collection of isolates. The coatings of the pumps proved to be a very suitable inoculum, because of the very dense biofilms. Efforts to isolate iron bacteria from the free water, were less successful. A newer method, used the glass beads exposed for DNA extraction as inoculums. This method was very promising since it provided a very gentle way to transfer the bacteria to agar plates.

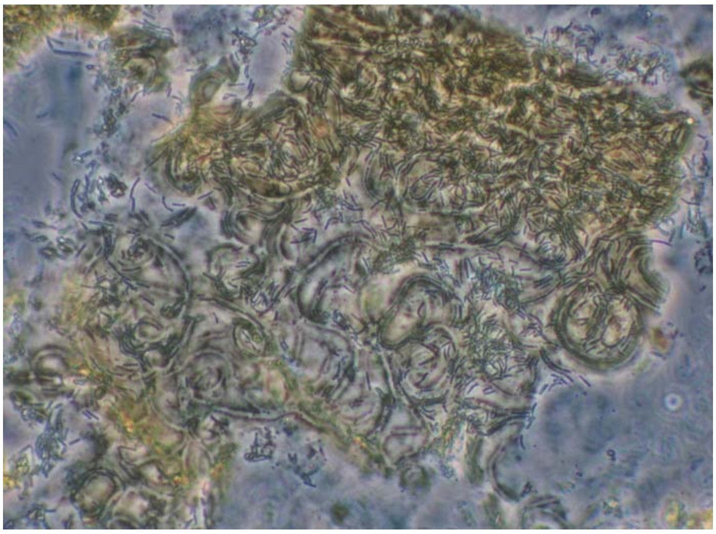


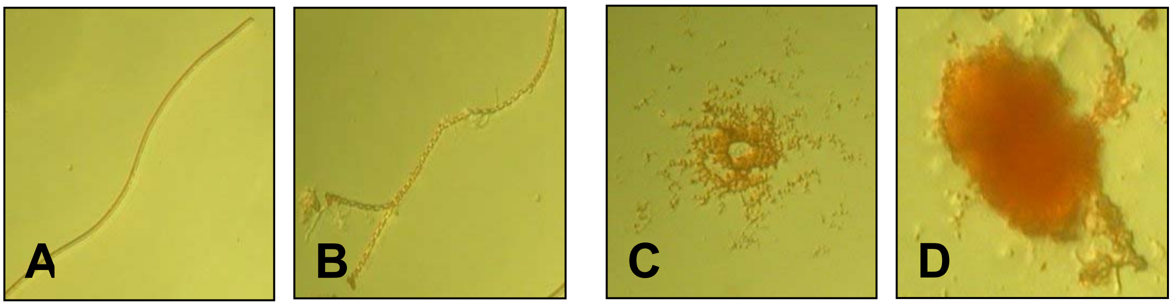
Figure 3-6: Isolat 152, sheath forming rod

Microscopic analysis

In order to allow a first microscopic evaluation of the chosen sampling sites and to see first differences in the dominant species of iron bacteria, object slides were exposed in 19 different Berlin wells, for several weeks.

Four major morphotypes of iron bacteria could be identified. Type A: sheath forming (e.g. *Leptothrix spec., Sphaerotilus spec*.), type B: Stalk forming (Gallionella spec., Toxothrix spec.), type C: corona forming (Siderocapsa spec.) and type D: cell agglomerates (e.g. Actinomycetes) (Figure 3-7).

The results of this microscopic characterization are summarized in the chart below.



A)sheath forming bacterium; B) stalk forming bacterium (Gallionella spec) C) corona forming bacterium (Siderocapsa spec.) D) cell agglomerates with ferric hydroxide;

Figure 3-7: Morphotypes

Table 3-2: Morphotypes

Well	Morphotype
TEGhzk-13-/73V	A,B
TEGhzk-22-/71V	D
SPAnord01-/04V	B (many),D (many)
SPAnord02-/82V	C (some)
SPAnord03-/99V	A,B,D
TEGsaat19-/71V	C (many)
TEGsaat20-/71V	D
TEGwest12-/84V	D
TEGwest13-/85V	A,B,C,D
TEGwest14-/85V	B,C,D
KAUnord05-/95V	A (some),C,D
KAUnord06-/95V	A, C (many)
KAUnord07-/95V	A,C,D(many)
STOborg14-/90V	-
STOborg15-/90V	A (many),B,D (many)
STOborg19-/90V	-
STOborg20-/90V	A,B,D
BEEgrfe05-/93V	C (some)
BEElind01-/95V	C
BEElind23-/02V	A, B
TIEsued19-/60V	-

Results of the hybridizations

Initial experiments were also done to evaluate hybridization of gene probes to native biofilms on exposed glass slides. Since encrustation of bacteria by iron hydroxides could interfere with hybridization, selected slides were pretreated with oxalic acid to dissolve precipitates. Probes for the group of Gamma- and Beta-proteobacteria were used. It turned out that with glass slides that have been exposed for one or two weeks, hybridization was possible without problems. Glass slides that were exposed for more than seven weeks had to be pretreated, to improve hybridization results.

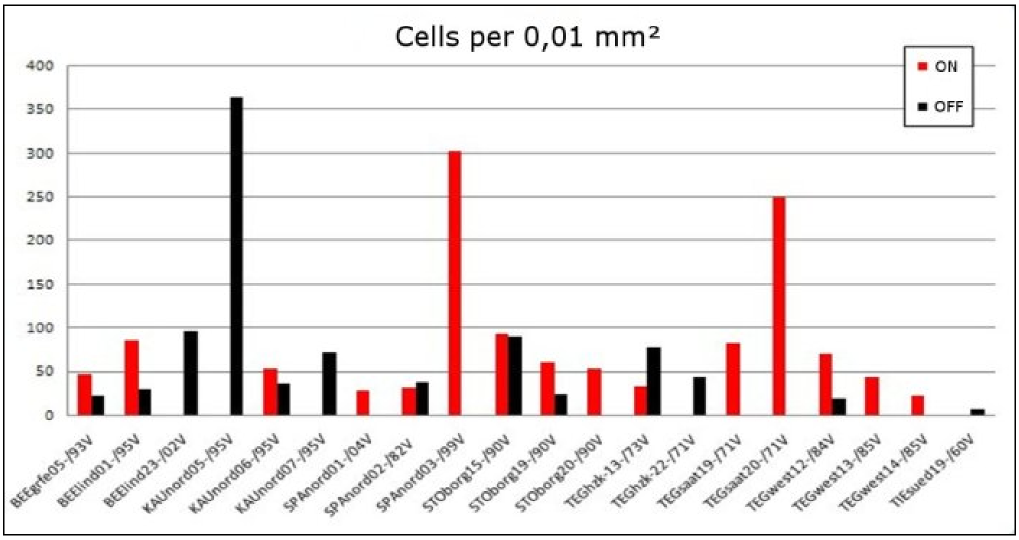


Figure 3-8: Total cell count on glass sildes

With some slides, it was noted that the ratio of Beta-proteobacteria to the total cell count appeared to be lower. They were exposed in not operating (OFF) wells. Compared to those exposed in operating (ON) wells. In addition, differences in total cell count and ratio of Beta-proteobacteria could be observed in the respective wells (Figure 3-8+3-9).

Detailed results of the hybridization trials, can be found in Appendix C.

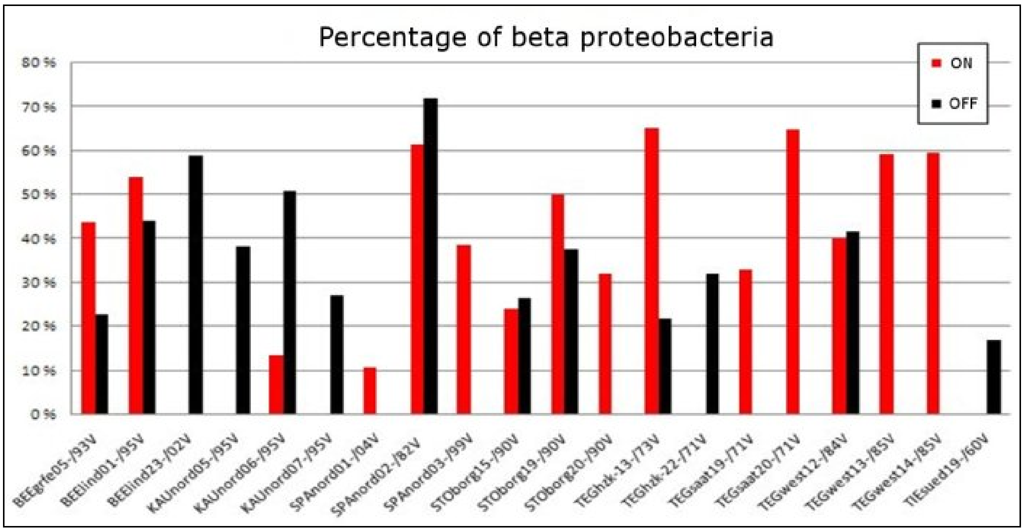


Figure 3-9: Percentage of beta-proteobacteria to total cell count

State of the molecular biological trials

During the progress of the project more than hundred fifty samples from different sampling locations have been collected, including water- as well as biofilm samples. The samples have been processed and the bacterial DNA has been extracted, generating enough material for follow up analyses. DNA amplification, cloning and DGGE trials have begun. It was observed that many of the biofilm samples yielded only low amounts of DNA, compared to the water samples. In addition certain substances accumulated in the Biofilms and appeared to interfere with the PCR.

PCR- conditions could be optimized to a sufficient degree to resolve these problems, but during the progress of the project further optimization will be necessary.

The results of the first DGGE trials show similarities but also differences between populations of different wells (Figure 3-10). This means that each well has to be analyzed individually and a differential diagnosis of the populations of the different sampling sites is necessary.

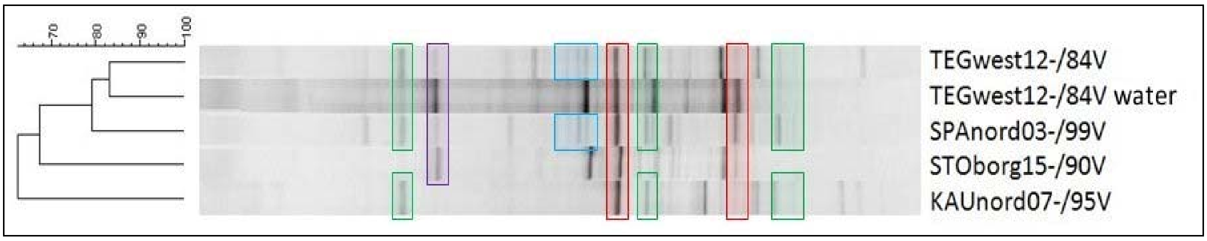


Figure 3-10: DGGE bonds of different sampling sites. Some similarities have been marked.

3.1.5 Discussion of results

The examinations carried out during WellMa1 revealed that the problems faced during operation of drinking water wells are caused by a complex community of microorganisms. In contrast to former (primarily microscopic) examinations, the diversity of bacteria being involved in the oxidation and deposition of iron and manganese minerals is very high.

Many of these bacteria cannot be discovered and identified by microscopic examinations alone. Only the combined application of classical microbiological methods (microscopy, cultivation) and modern molecular methods revealed the presence of so far undiscovered bacteria. These new bacteria have been identified by molecular signatures, which in return allow developing specific detection methods.

The various methods developed and optimized during WellMa1 will allow detecting and quantifying the different bacteria involved in the process of well clogging. Since bacteria, which are involved in deposition of soft and hard ochrous deposits, respectively, have been identified, it will be possible to detect these bacteria in biofilm and probably even water samples from different wells. An in detail analysis of selected wells will reveal the correlation between occurrence of specific bacteria and physico-chemical conditions.

The further correlation of the measurements in the wells and associated soil compartments with operation conditions of the wells will allow to deduct the influence of the mode of operation on the development of specific bacterial populations (respectively of different types of clogging). In reverse, it should be possible to optimize the operating conditions such to largely avoid ochrous depositions in the wells.

3.1.6 Conclusions and recommendations

Conclusions:

- Biological clogging in different wells is caused by different bacterial populations.
- Based on initial tests the bacterial populations in the free water zone and the biofilms show similarities.
- Microscopic analysis revealed that different morphotypes of ochre forming bacteria occurred in the wells (soft and hard ochre)

Working hypotheses for WellMa2:

- The different iron bacteria in the biofilms cause different forms of clogging.
- To predict the biological clogging potential, a differential diagnosis is necessary.
- Certain types of iron bacteria can be assigned an indicator function
- Special detection methods for the indicator bacteria will be developed
- The type of complexation of iron- and manganese, the type of organic compounds and the oxidation potential are critical factors for well clogging.

3.1.7 Summary

During WellMa1, the emphasis has been on the development of methods. These developments included the methodology of collecting microbiological samples from wells and especially the retrieval of undisturbed biofilm samples. For this purpose a device has been developed that can be exposed in the well and simultaneously generates both biofilm on exposed materials and bacterial biomass.

The experimental approach and the design of the device proved suitable in the phase WellMa1 and can be used for a multitude of different systems as well (wells and water processing steps) In the progress of WellMa1, microbiological and molecular methods were modified for sampling materials with high percentages of inorganic compounds, e.g. ferric and manganese oxides.

The microscopic analyses revealed distinct differences in composition and structure between the different wells. Especially the appearance of organisms, which develop soft coatings and such, that develop hard incrustations, was of special interest. The respective group of organisms, were found separate (soft type, hard type) as well as in collectives with other forms.

Comparative analyses of the bacteria in free water and the biofilms, hinted to similarities between the populations. These findings indicate exchange processes between biofilm and the free water zone. This has always been postulated for biofilms, but, based on cultivation trials, it has been challenged as well. For WellMa it is important that population similarities enable a detection of critical ochre forming bacteria in the water body. Since these species are present in the free water only in small numbers during the start of a blocking event, specific, sensitive and fast detection methods are necessary.

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3.2 Microbiological Testing: BART™ and Groundwater organisms [A. Bartetzko]

The environment contains a myriad of different bacteria that are all capable of causing problems. These problems can range from slimes, plugging, discoloration and cloudiness to corrosion and infections. Such a wide variety of bacteria is not easy to detect and identify using a single test and yet their impact can make the water unsafe, unacceptable or unavailable due to losses in flow through plugging or equipment failure due to corrosion. The biological activity reaction test (BART™) is a water testing system for nuisance bacteria and can involve several different tests. These tests detect the activity (aggressivity) of these nuisance bacteria by the time lag (TL, measured in the number of days from the start of the test to when a reaction is observed). The longer the TL before the observation of activity, the less aggressive the bacteria are in that particular sample.

Seven different tests are recognizable by coloured cap coding and the initial letters preceding the word BARTTM. These include selective tests for:

Iron Related Bacteria	IRB-BART™
Sulphate Reducing Bacteria	SRB-BART™
Heterotrophic Aerobic Bacteria	HAB-BART™
Slime Forming Bacteria	SLYM-BART™
Denitrifying Bacteria	DN-BART™
Nitrifying Bacteria	N-BART™
Fluorescing Pseudomonades	FLOR-BART™
Acid Producing Bacteria	APB-BART™

Each of these bacterial groups cause different problems and often a combination of these tests should be used to determine which bacteria are present and causing problems. In the event that further information beyond presence/absence is needed, information on these reactions can be accessed using the Internet: www.DBI.ca. To read all of the reactions, lift the inner test vial carefully out of the outer BARTTM test vial and view through the inner vial against an indirect light.

3.2.1 BART™

Each of the reactions in the test has been produced in a unique manner by the various species and consortia of bacteria becoming active in test. There is, therefore, no specific form of any reaction pattern because these are controlled by the form of bacterial growths.

A common list of the methodologies and applications would be:

IRB-BART™

Test becomes positive when there foam is produced and/or a brown colour develops as a ring or dirty solution. The TL (time lag) to that event is the delay. A negative has no brown colour developing, no foaming or clouding. This test is commonly used to detect plugging, corrosion, cloudiness and colour. The bacteria that may be detected by this test include iron oxidizing and reducing bacteria, the sheathed iron bacteria, Gallionella, pseudomonad and enteric bacteria.

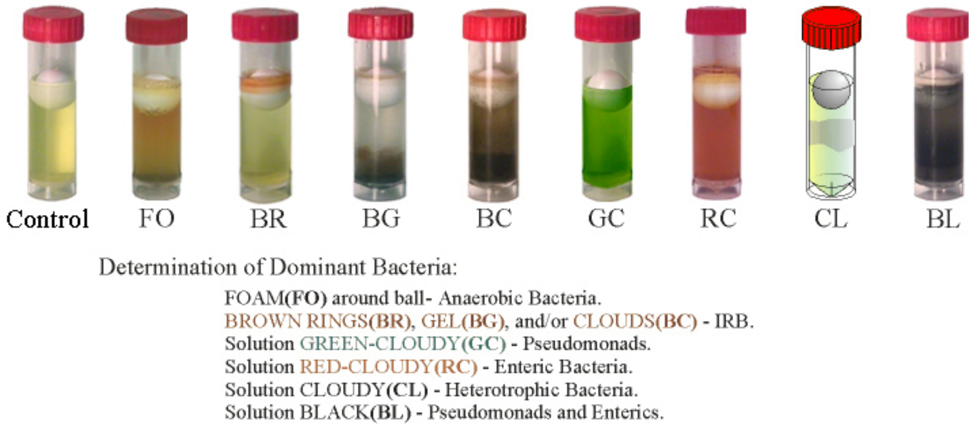


Figure 3-11: Reaction Patterns IRB-BART™.

SLYM-BART™,

Some bacteria can produce copious amounts of slime that can contribute to plugging, loss in efficiency of heat exchangers, clouding, taste and odour problems. This is one of the most sensitive BART™ tests. A positive involves a cloudy reaction in the inner test vial often with thick gel-like rings around the ball. A negative test remains clear.

3.2.2 Groundwater organisms

Aquifer Organisms living underground within the aquifer are subject to extremely uniform conditions compared with surface life. There is very little diversity of habitat type, conditions such as temperature vary only slightly, and darkness is permanent.

Species living in groundwater need special adaptations to survive. Many have elongate body forms to facilitate movement through small openings. The lack of eyes and body pigment is common, as is the increased development of other sensory organs such as antennae.

Groundwater species are Amphipoda, Syncardia, Polychaeta, Copepoda and Nematoda.

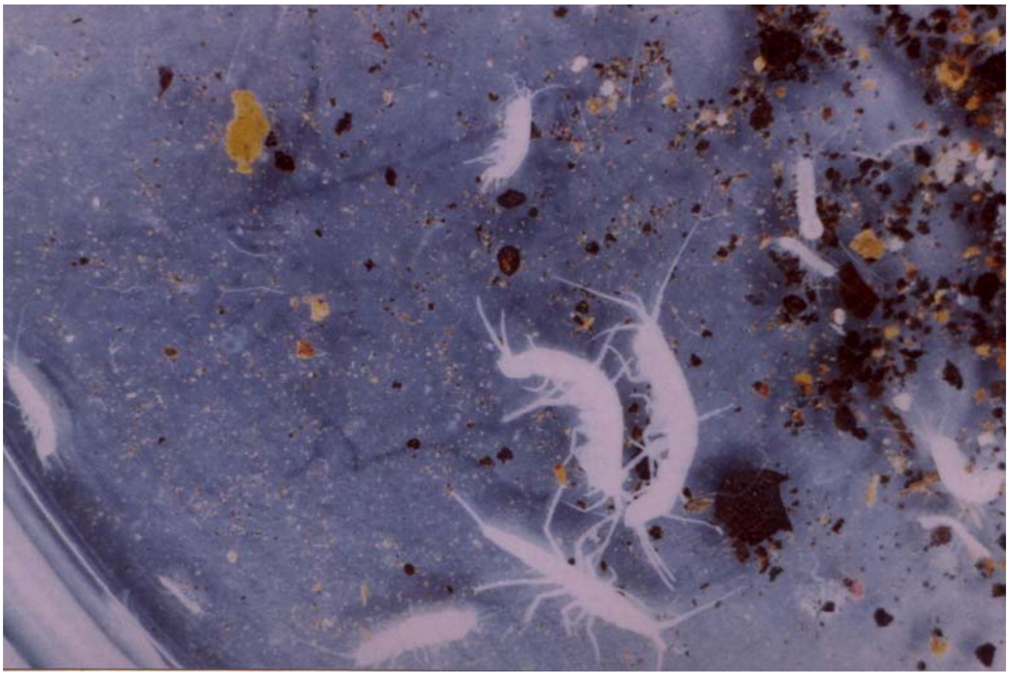


Figure 3-12: Groundwater organisms.

Groundwater organisms are more commonly found near the surface, where oxygen and food are more abundant. This is especially true in the hyporheic zone, the area under and to the sides of rivers.

3.2.3 Research and Results

Four different wells were tested for bacterial concentration with the dilution method on R2A-Agar, for the bacterial species with the BART™ and for groundwater organisms.

In the case of the H_2O_2 treatment, the bacteria concentration and the species were examined before and after treatment.

The results are presented in the table:

Table 3-3: Results of microbiology testing

microbiology investigations: total bacteria, BART and groundwater organisms						
		total bacteria		BART		bacteria population
		aerob	anaerob	IRB	SLYM	
Tegel Hohenzollernkanal Well 13						
watersample	CFU / ml	4,0E+05	6,0E+05	1,0E+04	< 100	anaerobic bacteria, iron and slime-forming bacteria
encrustation	CFU / g	6,0E+05	1,0E+05	very high	few	anaerobic bacteria, iron and slime-forming bacteria, Pseudomonads
groundwater organisms						none
Tegel Hohenzollernkanal Well 22						
watersample	CFU / ml	3,0E+05	4,0E+05	2,0E+03	< 100	anaerobic bacteria, iron and slime-forming bacteria
encrustation	CFU / g	1,0E+06	4,0E+05	high	few	anaerobic bacteria, iron and slime-forming bacteria, Pseudomonads
groundwater organisms						Nematoden (4)
Stolpe Borg. Well 19						
watersample	CFU / ml	5,0E+02	6,0E+01	1,0E+04	2,0E+02	Pseudomonads, Enterococci, slime-forming bacteria
encrustation	CFU / g	1,2E+04	1,0E+04	high	medium	Pseudomonads, Enterococci, slime-forming bacteria
groundwater organisms						none
Stolpe Borg. Well 15 before H2O2						
watersample	CFU / ml	1,0E+05	3,1E+04	1,0E+03	5,0E+02	anaerobic bacteria, iron and slime-forming bacteria
encrustation	CFU / g	1,0E+07	9,0E+05	very high	high	anaerobic bacteria, iron and slime-forming bacteria
groundwater organisms						Oligochaeta (4)
Stolpe Borg. Well 15 after H2O2						
watersample	CFU / ml	5,3E+04	5,0E+04	3,0E+02	5,0E+02	iron and slime-forming bacteria
encrustation	CFU / g	-	-	-	-	-
groundwater organisms						Oligochaeta (2)

3.2.4 Discussion

Groundwater organisms were not found. In two wells were hints for the presence of these organisms.

In the wells, the bacteria concentrations vary. By using R2A-Agar, the concentration of bacteria is higher than using standard agar.

In the wells, the corresponding water and encrustation probes showed the same microorganisms population.

In the case of H_2O_2 treatment, a reduction of the bacterial concentration was detected after the treatment.

The minimal research produced only a hint of the biological groundwater system in counting the bacterial concentrations and determining the bacteria species with the BART™.

3.3 Hydrochemical investigations [T. Taute; U. Maiwald; C. Menz; A. Pekdeger]

The short-term monitoring aims on recognizing variations in hydrochemical parameters during the initial phase of pumping, which possibly influence the formation of iron ocres within the well. For this purpose, the Berliner Wasserbetriebe (BWB) selected 21 representatives from 686 possible wells (Table 3-4). Different conditions were taken into account like the development in productivity, frequency of H_2O_2-treatment or the construction material of the well. Due to technical problems within the gallery no STM could be carried out at the wells from Tegel Saatwinkel so far.

Table 3-4: Selected wells for the short-term monitoring. Terms for "Origin of ground water" are: gw for ground water; rbf for river bank filtrate; arp for artificial recharge pond

Name of Well	Water Works	Gallery	Well No.	Material	Origin of GW	Capacity
BEEgrfe05-/93V	Beelitzhof	Gr. Fenster	5	steel	gw, rbf	72,9
BEElind01-/95V	Beelitzhof	Lindwerder	1	steel	gw, rbf	90,4
BEElind23-/02V	Beelitzhof	Lindwerder	23	stainless steel	gw, rbf	57,0
KAUnord05-/95V	Kaulsdorf	Nord	5	steel	gw	82,8
KAUnord06-/95V	Kaulsdorf	Nord	6	steel	gw	44,0
KAUnord07-/95V	Kaulsdorf	Nord	7	steel	gw	39,3
SPAnord01-/04V	Spandau	Nord	1	stainless steel	arp	
SPAnord02-/82V	Spandau	Nord	2	Steel	arp	45,0
SPAnord03-/99V	Spandau	Nord	3	stainless steel	arp	74,0
STOborg14-/90V	Stolpe	Borgsdorf	14	plastics	rbf	65,0
STOborg15-/90V	Stolpe	Borgsdorf	15	plastics	rbf	91,0
STOborg19-/90V	Stolpe	Borgsdorf	19	plastics	rbf	25,0
STOborg20-/90V	Stolpe	Borgsdorf	20	plastics	rbf	26,0
TEGhzk-13-/73V	Tegel	Hohenzollernkanal	13	steel		57,7
TEGhzk-22-/71V	Tegel	Hohenzollernkanal	22	steel		22,3
TEGsaat19-/71V	Tegel	Saatwinkel	19			
TEGsaat20-/71V	Tegel	Saatwinkel	20	steel/stainless steel	arp	64,0
TEGwest12-/84V	Tegel	West	12			
TEGwest13-/85V	Tegel	West	13	steel	rbf	46,0
TEGwest14-/85V	Tegel	West	14			
TIEsued19-/60V	Tiefwerder	Süd	19	copper	gw, rbf	47,6

3.3.1 Sampling and analytics

The sampling campaign for the STM-wells was conducted from February to March 2008 following a detailed timetable, which was predetermined together with the technical divisions of BWB.

For comparability of the results for the different wells, we designed a fixed sampling procedure. Prior to the STM sampling, the sampled well and the two neighbour-wells were shut down for a minimum period of one week. Before switching on the pump, the sampling device was installed. To provide an uncontaminated microbiological sampling, we used an autoclaved sampling device, which was installed before switching on the well.

Figure 3-13: Sampling devices for the short term monitoring for microbiological and hydrochemical water sampling. Measuring system with flow-through cell for hydrochemical field parameters.

Hydrochemical field parameters like pH, redox-potential, O_2-content, conductivity and temperature were measured quasi continuously in a flow-through chamber (Figure 3-13).

Measuring and sampling intervals were set to one minute during the first ten minutes after switching on the pump, subsequently with increasing intervals. Duration of the monitoring for each well was depended on the stability of the field parameters, whereas values had to be stable for one hour.

To reduce the number of analyses to a practicable quantity, representative sample times were selected, considering the development of the field parameters. The first sample was directly taken after switching on the pump, to characterize the condition in the well during shutdown; the second sample after 1 minute represents the starting phase; the sample after nine minutes was taken, when the first quick changes finished; the last sample represents steady flow system with stable field parameters.

Critical parameters like HS^-, NH_4, NO_2^-, colour, clouding and HCO_3^- were determined in situ. The drawdown within the well was measured with an electric contact meter at sampling times. Samples for anion- and cation-analyses were filtered with cellulose acetate filters with a pore size of 0.45 µm. Cation samples were acidified with concentrated HNO_3 to avoid precipitation of oxides or hydroxides. Besides the filtered cation sample, an unstrained, acidified sample was taken for the investigation of particulate Iron and Manganese in the water.

Anion and cation analyses were carried out in the laboratory of the FU Berlin. The measuring range for the different parameters and the detection limits are listed in Table 3-5.

Table 3-5: Measuring range and detection limit of ion analyses. Measuring devices are: ICP for Inductively Coupled Plasma Spectroscopy: IC for Ion Chromatography, AA for Auto Analyzer

Parameter	Measuring Device	Measuring Range [mg/l]	Detection Limit [mg/l]
Ca	ICP	0,02-100	0,02
Mg	ICP	0,02-20	0,02
Na	ICP	0,1-100	0,1
K	ICP	0,1-100	0,1
Sr	ICP	0,01-10	0,01
Ba	ICP	0,01-10	0,01
Fe	ICP	0,02-100	0,02
Mn	ICP	0,01-100	0,01
Cl	IC	0,1-20	0,1
SO4	IC	0,1-20	0,1
NO3	IC	0,1-20	0,1
Br	IC	0,1-20	0,1
PO4	IC	0,1-20	0,1
F	IC	0,1-20	0,1
DOC	AA	0,5-15	0,5

3.3.2 Results

The detailed documentation of field parameters and the results of chemical analyses were included in a results-database, which collects data from all investigations for a common interpretation. Graphical documentation of the development of field parameters during the test phases can be found in Appendix D.

Measurement period for the different wells varied between 90 min and 270 min depending on the development and stability of field parameters.

The conductivity ranged between 520 µS/cm (Stolpe) and >800 µS/cm (Kaulsdorf). With few exceptions, stable values were usually reached within the period of the first 10 minutes after switching on the pump (Figure 3-14).

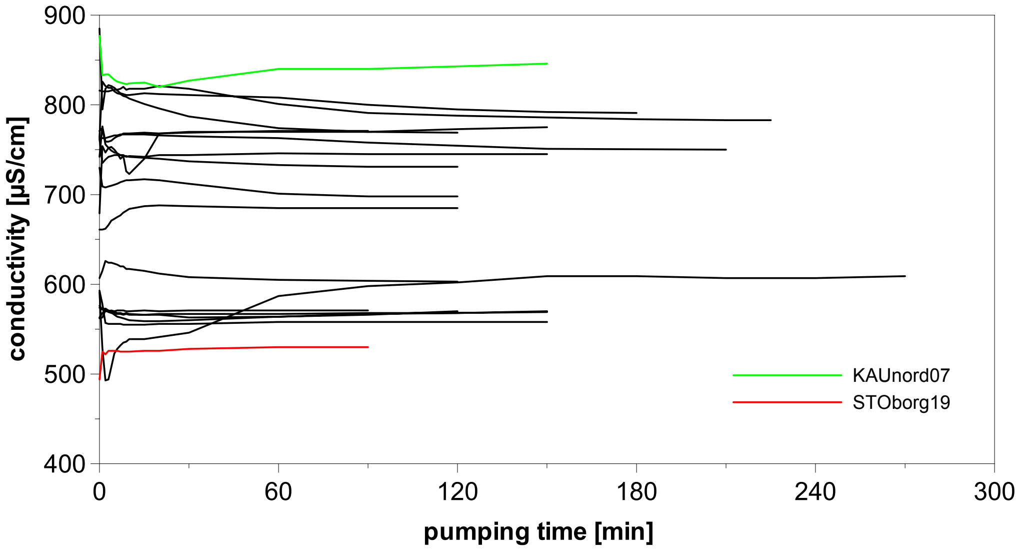


Figure 3-14: Development of conductivity in all wells during the sampling periods in the framework of the short-term monitoring.

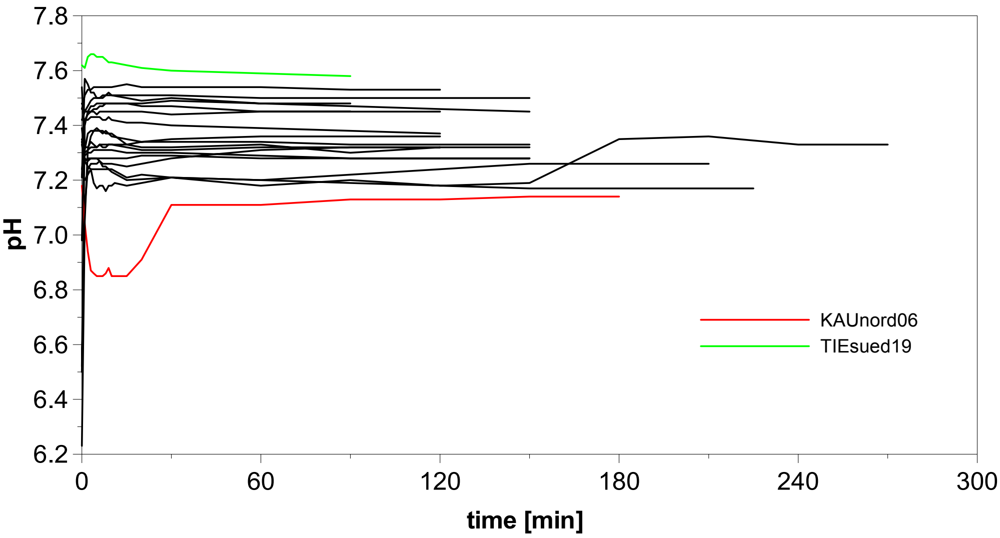


Figure 3-15: Development of pH values in all wells during the sampling periods in the framework of the short-term monitoring.

The pH values of the investigated wells are neutral within a range of 7.1 and 7.6. Stable values were reached after some minutes (Figure 3-15). Only well KAUnord06 showed a noticeable curve progression within the first 30 minutes after the test start, where the pH value first decreased below pH 7 and then rose steeply and immediately reached relatively constant level after 30 minutes. This might lead back to leaky tubing or to the influence of very limited shallow aquifer.

With regard to ochre accumulation, the oxygen content as well as the redox potential during the starting phase of the well's operation phase is of primary interest. Their development over the test periods are shown in Figure 3-16 and Figure 3-17.

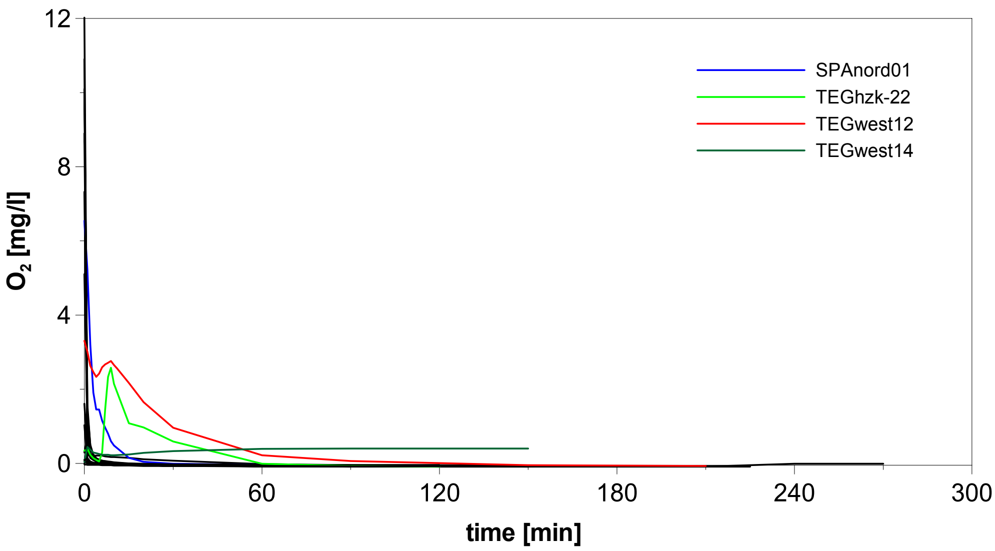


Figure 3-16: Development of oxygen content in all wells during the sampling periods in the framework of the short-term monitoring.

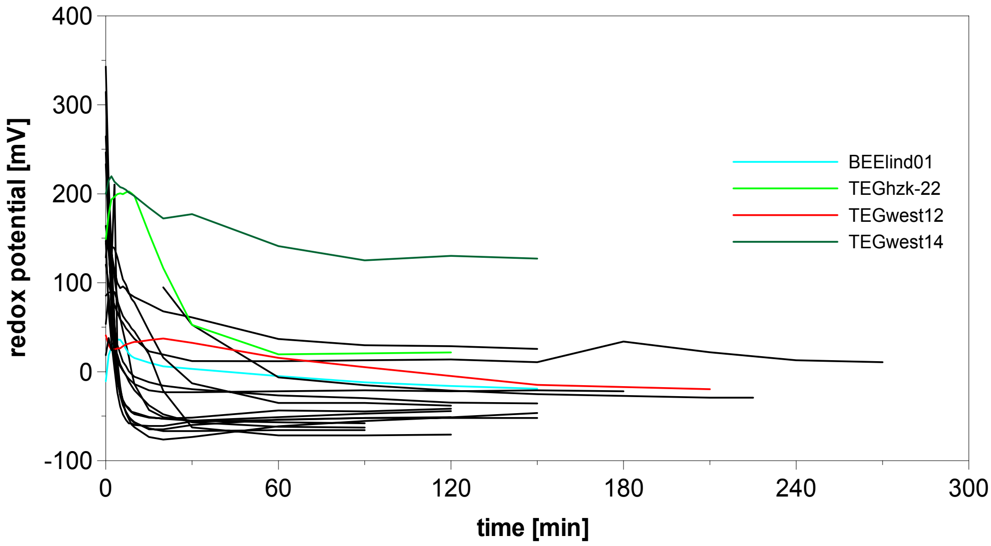


Figure 3-17: Development of redox potential in all wells during the sampling periods in the framework of the short-term monitoring.

With few exceptions, the oxygen content within the wells declined rapidly during the first minutes and remained stable at 0 mg/l until the end of the test. Exceptions are some wells within the galleries of Spandau and Tegel, which showed oxygen peaks or lower decline during the first hour of pumping procedure. After two hours, all wells except TEGwest14 were free of oxygen. This well also showed an extraordinary high redox potential during the whole test phase. These conditions might lead to precipitation of dissolved iron.

Within their total dissolved solids the investigated wells show variations between 0.43 g/l and 0.69 g/l with Ca^{2+} and Mg^{2+} as main cations and HCO3- as dominating anion. SO_4^{2-} concentrations varied from 40 mg/l to 140 mg/l, whereas Cl- concentrations ranged from 20 mg/l to 83 mg/l. NO_3^- concentrations are in mean at about 4,5 mg/l with a range of 0,06-57 mg/l. The composition of main constituents of the investigated ground water is displayed in Figure 3-18.

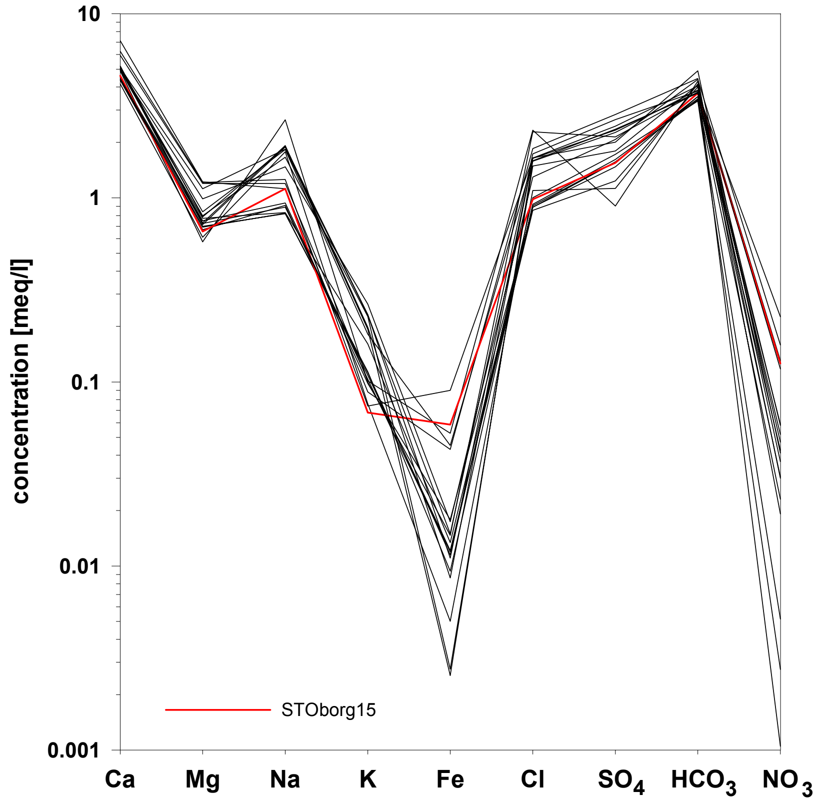


Figure 3-18: Schöller-diagram of the investigated wells. Displayed are the last water samples, taken under stable condition of the field parameters

Iron concentrations up to 4 mg/l were analysed, often with high particulate iron content (Figure 3-19). This leads to a high availability of iron for ochre formation in presence of oxygen. Considering the iron analyses of all investigated wells, at the galleries of the water works Tegel, the wells generally show the lowest iron concentrations

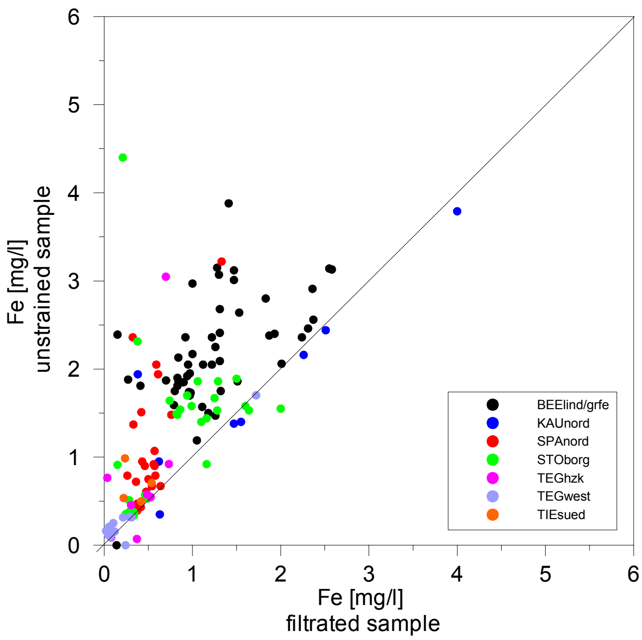


Figure 3-19: Comparison of dissolved and particulate iron in the water samples during the short-term monitoring at the different wells of the short-term monitoring. Iron content in acidified, filtrated and unstrained samples was analysed.

Investigations on dissolved Fe^{2+}/Fe^{3+} composition of the waters by BWB have shown that Fe^{2+} is the predominant oxidation state for the investigated wells (Figure 3-20).

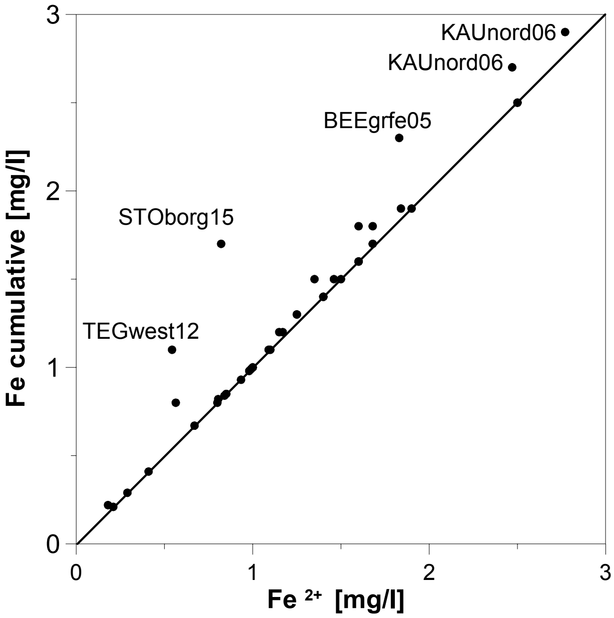


Figure 3-20: Comparison of cumulative Iron concentration and Fe2+ within the wells, investigated during the short-term monitoring.

For some selected wells, the whole sample series of the STM were analysed for Fe^{2+} and Mn^{2+}, to get information on sequential development of these parameters during the test phase.

Generally, the iron concentrations show the highest variations directly after switching on the well, especially in particulate iron. To exemplify this, the development of dissolved and particulate iron in well BEEgrfe05 is shown in Figure 3-21. With increasing time, the particulate iron decreased whereas the dissolved iron reached a constant level.

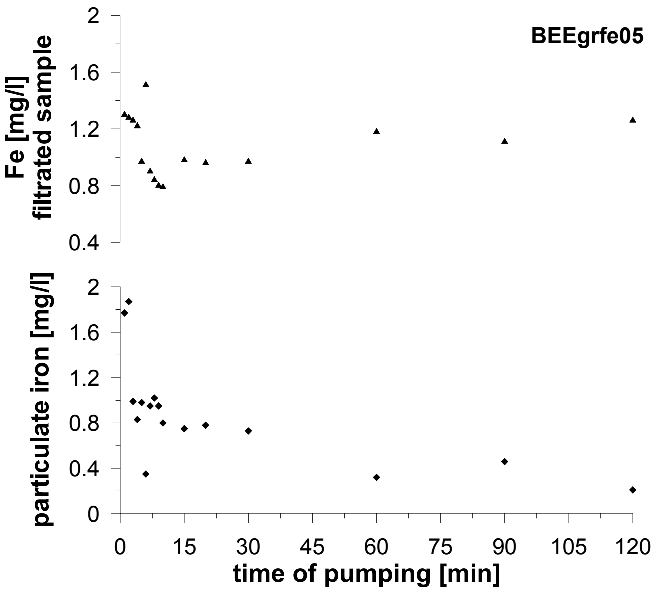


Figure 3-21: Development of dissolved and particulate iron concentrations through pumping time within well BEEgrfe05 during the short-term monitoring.

Comparison of Mn concentrations in filtrated and unstrained samples shows no significant differences (Figure 3-22). Exceptions are indicated for the wells of the gallery SPAnord, which are known to be significantly influenced by artificial recharge.

The analyses of samples from the STM at well SPAnor02 show an increasing particulate Mn content during the first 30 minutes after test start and subsequently decreasing values (Figure 3-23). Parallel curve characteristics can be observed within the pH value, which seem to control the precipitation/dissolution of manganese in this well, although the range in pH between 7.45 and 7.52 in marginal.

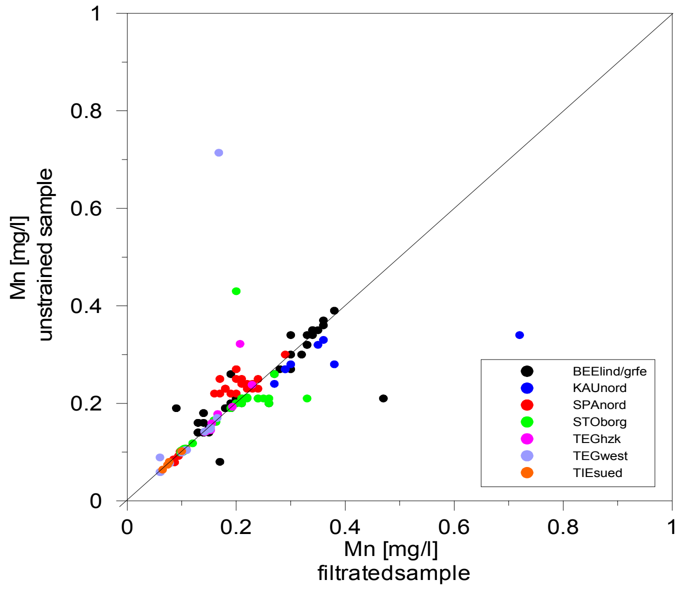


Figure 3-22: Comparison of dissolved and particulate manganese in the water samples during the short-term monitoring in all wells. Investigated was the iron content in acidified, filtrated and unstrained samples.

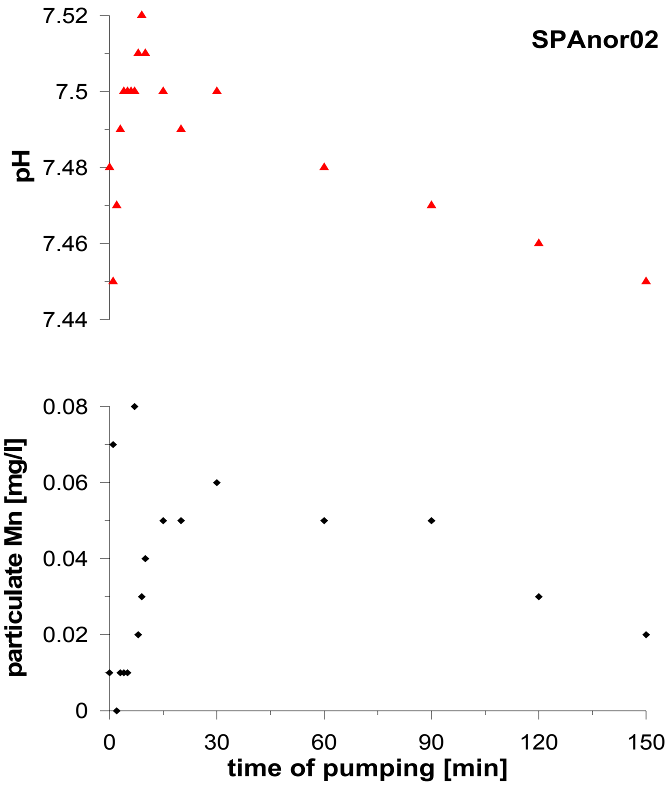


Figure 3-23: Development of particulate manganese content and pH value during short-term monitoring at well SPAnord.

Summarizing the results of the short-term monitoring, almost all wells showed high variations in several parameters directly after switching on the well. Especially the particulate and dissolved iron content, as well as the field parameters, seem to be significantly influenced by the switching operation. Nearly every well becomes free of measurable oxygen after a short pumping period. The influence of the water level recovery after switching off the pump has to be investigated in detail.

3.4 Well condition analyses

To compare the reliability of monitoring and diagnosis methods, three wells planned for abandonment and reconstruction were available. For these three wells and the operation well of the transect the following methods were applied:

Table 3-6: Procedure of well condition analysis

	Well 1	Well 2	Well 3	Well 4
	TEGhzk-13-/73V	**TEGhzk-22-/71V**	**STOborg19-/90V**	**STOborg15-/90V**
3-steps pumping test	15.04.2008	17.04.2008	21.04.2008	22.04.2008 22.05.2008
Dismantling of submersible pump	17.04.2008	17.04.2008	23.04.2008	23.04.2008
TV inspection	23.04.2008	23.04.2008	24.04.2008	24.04.2008
Borehole geophysics	06.05.2008	06.05.2008	05.05.2008	05.05.2008 23.05.2008
H_2O_2 treatment	-	-	-	06.05.2008

3.4.1 Step-drawdown test [T. Taute, U. Maiwald, C. Menz, A. Pekdeger]

For the WellMa investigations we decided to perform a three-steps pumping test with stationary conditions for each step instead of a short pumping test.

Thus, we can determine the aquifer loss component and the well loss component of the drawdown.

Method

One-time three-steps-pumping tests were performed at the wells TEGhzk13, TEGhzk22 and STOborg19 and at STOborg15. Generally, discharge was controlled by a water meter and water levels were taken in the well and his annulus automatically using pressure probes.

For basic data and construction schemes for each well, please refer to chapter 2.

For well performance tests, we used submersible pumps from normal operation. The adjustment of pumping rates was made by manual operation of the valve of the discharge tube.

General procedure of well performance tests are shown in Table 3-7:

Table 3-7: General procedure of well performance tests.

Well	Date	max. capacity of installed pump [m³/h]	No. of step	Rate of discharge [m³/h]	Duration of pumping [min]	Observed piezometers
TEGhzk-13-/73V	15.04.2008	75	1	35	90	production well + annulus
			2	55	90	
			3	78	72	
TEGhzk-22-/71V	17.04.2008	50	1	35	68	production well + annulus
			2	55	72	
			3	20	58	
STOborg19-/90V	21.04.2008	50	1	35	65	production well + annulus
			2	55	61	
			3	72	66	
STOborg15-/90V	22.04.2008	50	1	30	92	production well + annulus, 5 multilevel wells
			2	60	89	
			3	90	103	
	30.05.2008		1	30	90	production well + annulus, 5 multilevel wells
			2	60	90	
			3	85	102	

For estimation of well capacities, we compared the recent well performance tests with the initial performance test of the wells at the date they were built. Additionally, we consulted previous capacities taken from the database to compare the results and to evaluate the development of well ageing.

Results

The results of investigated wells are discussed individually below. Δh and specific capacities for the investigated wells are abstracted in Table 3-8.

Table 3-8: Δh and specific capacities for investigated wells.

Well	Year	Water table below casing [m]	Rate of discharge [m³/h]	Drawdown well [m]	Drawdown annulus [m]	Δh [m]	Specific capacity [m³/h/m]
TEGhzk-13-/73V	1973	8.10	40	0.43	0.42	0.01	92.9
			80	0.90	0.98	-0.08	88.9
			120	1.42	1.41	0.01	84.6
			150	1.73	1.72	0.01	86.8
	2008	6.33	35	0.56	0.58	-0.02	62.3
			55	0.89	0.91	-0.02	61.6
			78	1.31	1.33	-0.02	57.2
TEGhzk-22-/71V	1971	5.48	40	0.86	0.86	0.00	46.4
			80	1.57	1.57	0.00	51.1
			120	2.44	2.42	0.02	49.3
	2008	7.15	20	1.67	n. s.	n. s.	12.2
			35	2.87	n. s.	n. s.	12.2
			55	4.37	n. s.	n. s.	12.6
STOborg15-/90V	1990	n. s.	32	0.70	0.69	0.01	44.6
			65	0.93	0.89	0.04	68.7
			83	1.02	0.95	0.07	81.0
	2008	4.10	29	0.68	0.68	0.00	43.9
			61	1.14	1.13	0.01	52.6
			90	1.55	1.54	0.01	58.0
STOborg19-/90V	1990	n. s.	32	0.67	0.65	0.02	46.8
			65	1.06	1.03	0.03	60.1
			83	1.60	1.58	0.02	51.5
	2008	3.03	36	1.78	1.66	0.08	19.8
			54	2.71	2.59	0.12	20.2
			72	3.47	3.35	0.12	20.9

Well TEGhzk-13-/73V

We performed a three-step-drawdown test at well TEGhzk-13-/73V with pumping rates [m^3/h]: (1) 35, (2) 55 and (3) 78. Time-drawdown and discharge curves are shown in Figure 3-24.

The aquifer is unconfined and filter screens are set in two different depths from 20 m to 28 m and 31 m to 39 m below surface.

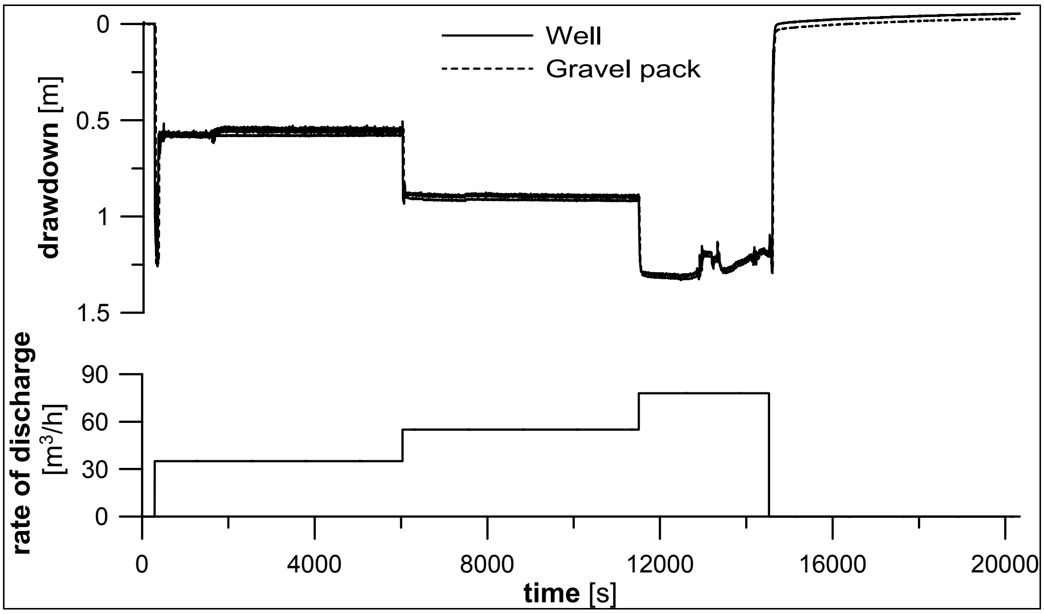


Figure 3-24: Drawdown and discharge of step-drawdown test at well TEGhzk-13-/73V

The first peak of the drawdown is due to the adjustment of the valve and represents a higher discharge than intended for step (1). Drawdown fluctuations at step (3) are probably due to a short-circuit between groundwater and discharged water.

We observed a very quick drawdown for all three steps as well as for the recovery and achieve quasi-stationary conditions after seconds. This is characteristic for good permeable sediments. We also observe an almost identical drawdown in the well and in his annulus, which indicates no significant deterioration.

Figure 3-25 shows a comparison of well capacity and losses between the initial and recent state:

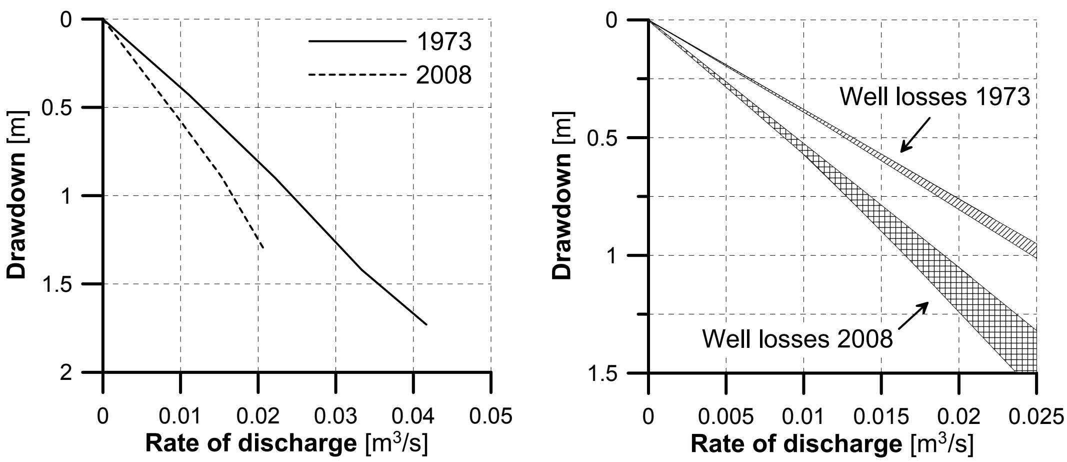
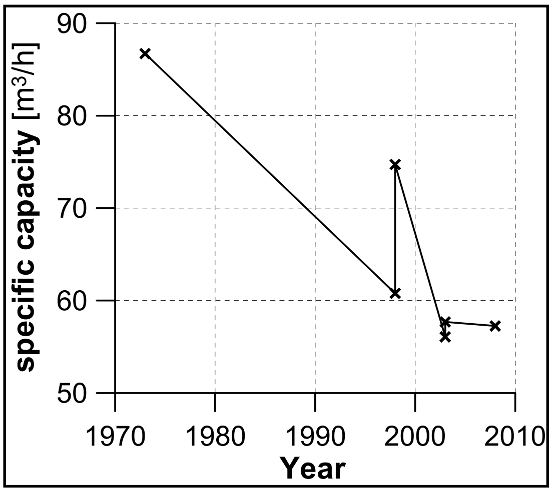


Figure 3-25: Comparison of capacity (left) and well losses (right) of well TEGhzk-13-/73V for 1973 and 2008

TEGhzk-13-/73V currently possesses still 65 % of his initial capacity. The specific capacity for a discharge rate of around 80 m^3/h, decreases from 87 m^3/h per m drawdown in 1971 to only 57m^3/h per m drawdown today.



Well loss coefficients for the initial state 1973 (110 s^2/m^5) and the current state (417 s^2/m^5) are still representing a good developed well with no significant deterioration. Nevertheless, well losses increased significantly from 1973 to 2008, as shown in Figure 3-25 (right).

Comparison of previous capacities, show only a minor decrease since the last rehabilitation in 2003 (see Figure 3-26).

Figure 3-26: Development of well capacity

Well TEGhzk-22-/71V

We performed a three-step-drawdown test at well TEGhzk-22-/71V with the following pumping rates [m^3/h]: (1) 35, (2) 55 and (3) 20. Time-drawdown and discharge curves are shown in Figure 3-27.

The aquifer is confined and the filter screen is set from 20 m to 32 m depth below surface.

In this case, we only provide drawdown data for the well, because of a defective data logger in the annulus. The operation pump was started with a maximum pumping rate of 75m^3/h, but discharged only about 60 m^3/h and was down-regulated for step (1). The lowest pumping rate is at step (3).

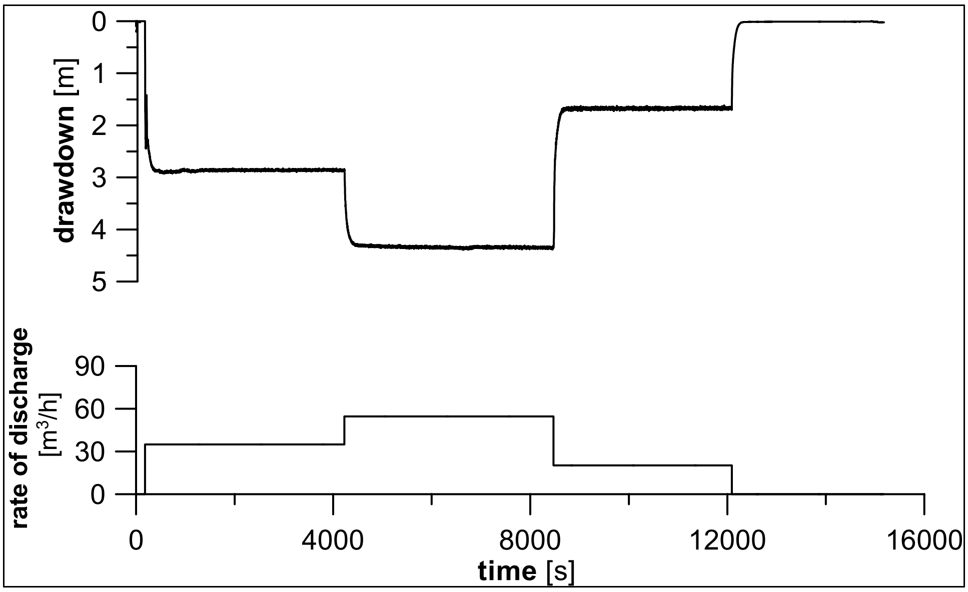


Figure 3-27: Drawdown and discharge for step-drawdown test at well TEGhzk-22-/71V.

We observed a drawdown and recovery, and reach quasi-stationary conditions after a few minutes.

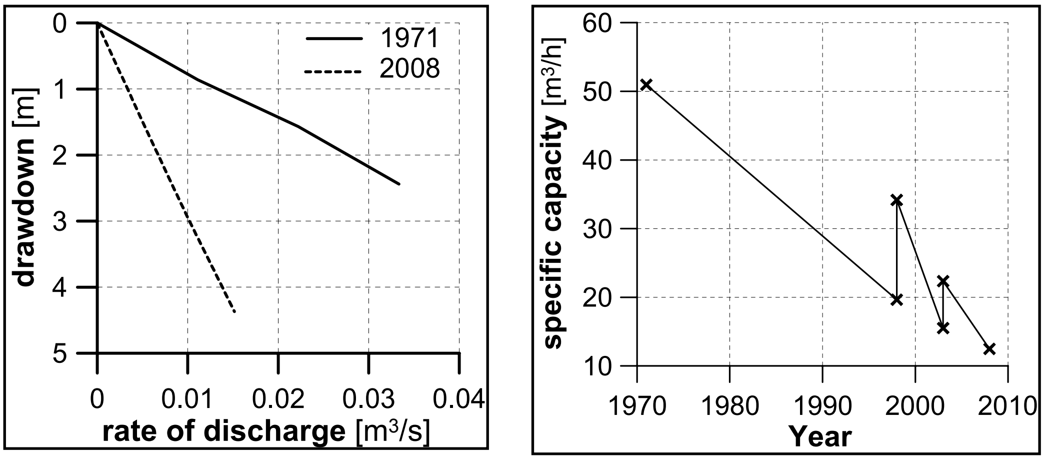


Figure 3-28: Q/s-Diagram of step-drawdown test (left) and development of well capacity (right) of TEGhzk-22-/71V in 1971 and 2008

Well TEGhzk-22-/71V possesses only 25% of his initial capacity (Figure 3-28). The specific capacity decreased from 51m3/h per m drawdown in 1971 to only 13m3/h per m drawdown today.

The time-dependent development of capacity shows a considerable decrease for the last ten years. Calculations of well loss coefficients result in negative values for the initial state 1971 as well as for the recent state. Nevertheless, a significant increase in drawdown from 1971 to 2008 indicates a distinct well deterioration.

Well STOborg19-/90V

We performed a three-step-drawdown test at well STOborg19-/90V with pumping rates [m^3/h]: (1) 35, (2) 55 and (3) 73. Time-drawdown and discharge curves are shown in Figure 3-29.

The aquifer is unconfined and the filter screen is set from 9 to 15m depth below surface.

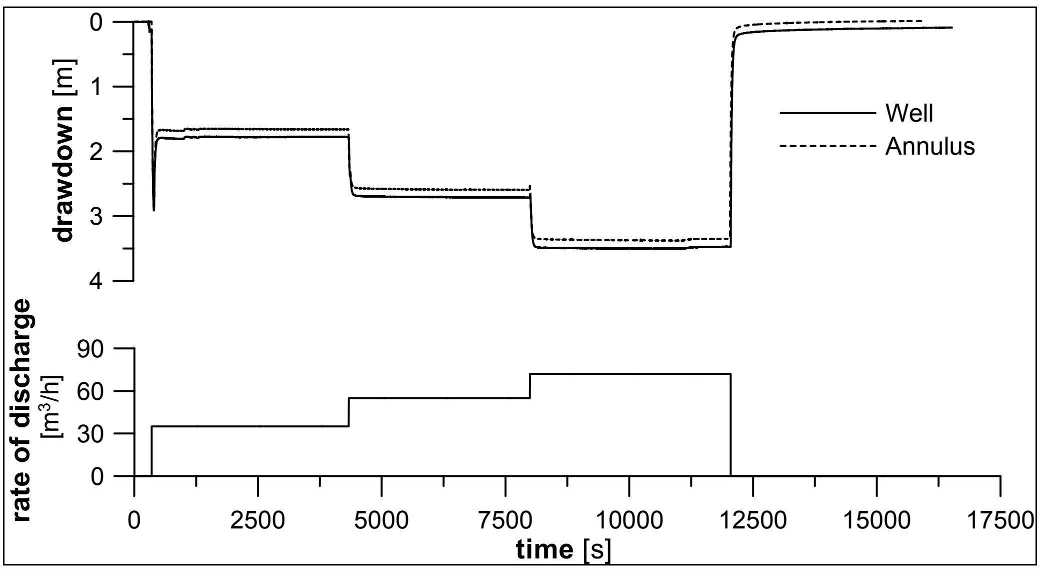


Figure 3-29: Drawdown and discharge for step-drawdown test at well STOborg19-/90V.

The first peak of the drawdown is due to the adjustment of the valve and represents a higher discharge than intended for step (1). We already discussed this occurrence above. Similarly to TEGhzk-wells a quick drawdown and recovery occurs. Nevertheless, drawdown in well and his annulus differ quite clearly. This difference still exists after recovery and is possibly caused by a defective pressure probe. Otherwise greater drawdown in the well compared to his annulus points to an advanced degree of well clogging located somewhere between the two points of measurement. Drawdown and recovery take a few minutes.

STOborg19 actually possesses only 35% of his initial capacity (Figure 3-30). The specific capacity decreases from 60m^3/h per m drawdown in 1990 to currently 20m^3/h per m drawdown. Increasing Δh-values also represent this decrease.

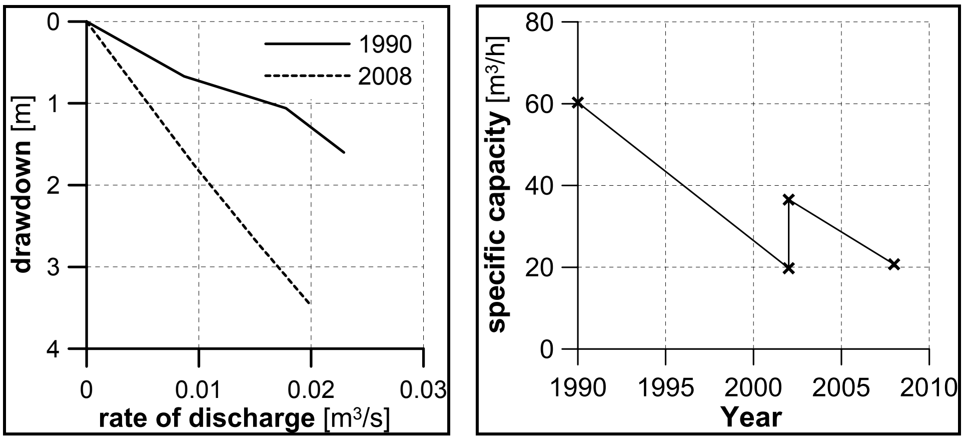


Figure 3-30: Q/s-Diagram of step-drawdown test (left) and development of well capacity (right) of STOborg19-/90V in 1990 and 2008

As shown in Figure 3-30 (left), actual capacity decreases intensely with increasing discharge rate and diverge considerably from initial conditions. Furthermore, it can be noted that the decrease in capacity is slower since the last rehabilitation compared to the development since 1990.

Calculations of well loss coefficients result in negative values for the initial state 1990 as well as for the recent state.

STOborg15-/90V

We performed a three-step-drawdown test at well STOborg15-/90V with pumping rates [m^3/h]: (1) 30, (2) 60 and (3) 90. Time-drawdown and discharge curves are shown in Figure 3-31.

The aquifer is unconfined and the filter screen is set from 9 m and 15 m depth below surface.

The first part of the drawdown represents a higher discharge than intended for step (1) due to the adjustment of the valve. We already discussed this occurrence above. Further on, we observed a very quick drawdown for each step and the recovery. This normally indicates high aquifer permeabilities.

The drawdown curve shows an unsteady behaviour in the onward course of the single steps. This may be due to minor changes of the pumping rate.

Drawdown in well and his annulus is quite similar and indicates no significant deterioration.

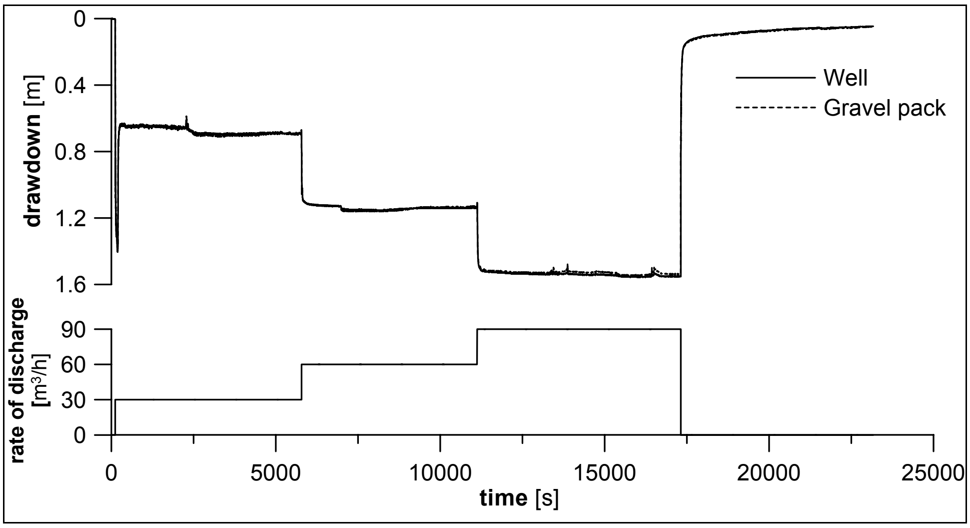
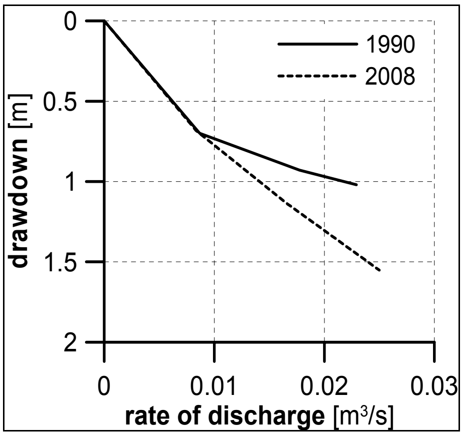


Figure 3-31: Drawdown and discharge for step-drawdown test at well STOborg15-/90V.

Figure 3-32 show the comparison of initial and recent capacity depended on the rate of discharge. Compared to the initial state the actual capacity decreases not until pumping rates higher than 30 m^3/h.



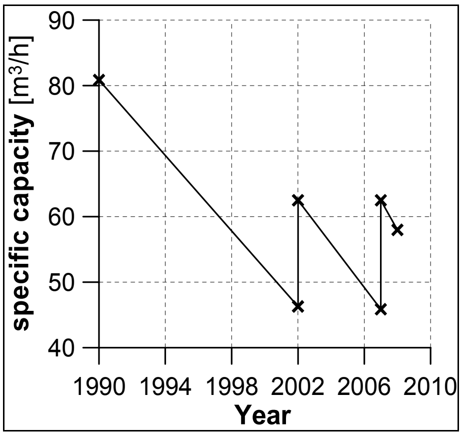


Figure 3-32: Q/s-Diagram of step-drawdown test (left) and development of well capacity (right) of STOborg15-/90V in 1990 and 2008

Time-dependent development of capacity shows a light, but obvious increase of well deterioration. STOborg15-/90V actually possesses 72 % of his initial capacity. The specific capacity decreases from 81 m^3/h/m drawdown in 1990 to currently 58 m^3/h/m drawdown. Δh-values for 1990 increase with increasing pumping rate, but actual Δh-values do not show this dependency. So the decrease in capacity is not represented by Δh-values.

For the wells STOborg15-/90V and STOborg19-/90V, the actual capacities (70-90 m^3/h) of the installed pumps diverge significant from the declared values in the database (50 m^3/h). Different pipe resistances for normal operation and in-situ discharge could cause this deviation.

3.4.2 TV inspection [H. Wiacek]

Method

TV inspections are carried out at the Berlin wells prior to every maintenance procedure. On the one hand side it aims on the assessment of the need for rehabilitation or reconstruction. On the other hand, it protects the maintenance company against potential loss or damage to their equipment by failures in the well construction itself.

On all four wells, TV inspections were carried out by BWS/ Pigadi using their standard equipment. The TV camera system consists of a rotatable lense (0 to 70°, from vertical to nearly horizontal view) and a light source.

The inspections were recorded on DVD. Additionally, main results were described in a short report with a few pictures.

Reference point for all depth information is the top of the well chamber.

Results

As expected, in all four inspected wells the most clogging deposits are located between dynamic water level and depth of pump intake. Thickness of encrustations is highest immediately at the pump intake and decreasing towards the top.

Although the Stolpe-wells were rehabilitated in 2007, encrustations are more distinct than in the Tegel-wells, which were rehabilitated in 2003.

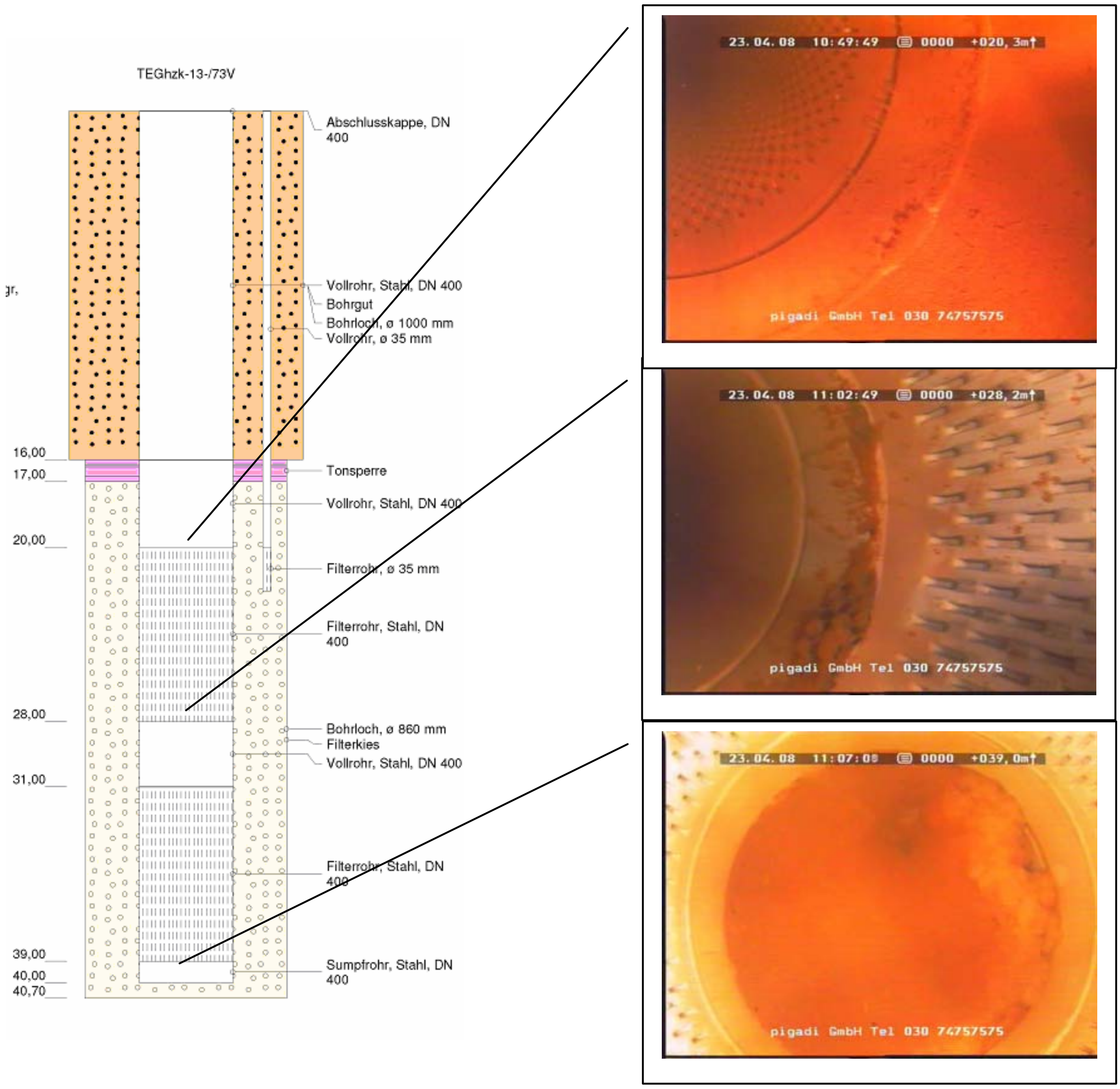
Generally, the two PVC wells (Stolpe) are more affected by clogging than the steel wells (Tegel). The latter are affected by corrosion due to damages to the protective coating.

Noticeable is the sharp boundary between the casing with clogging deposits and the filter screen, which is in all four wells free of deposits. This sharp contrast applies especially to the PVC wells.

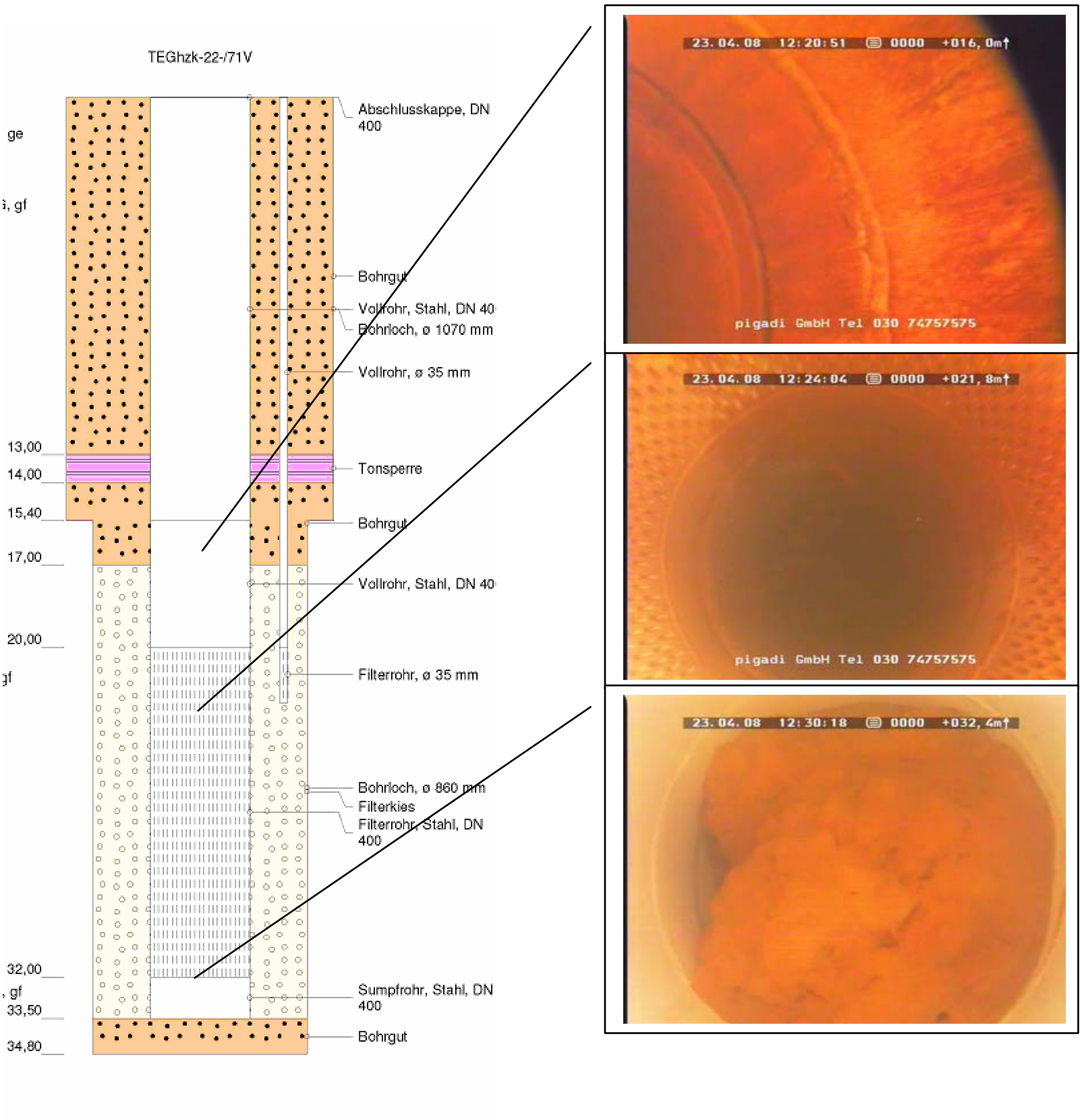
All deposits can be characterised as reddish brown and unconsolidated.

A summary of the TV inspections for each well follows on the next pages:

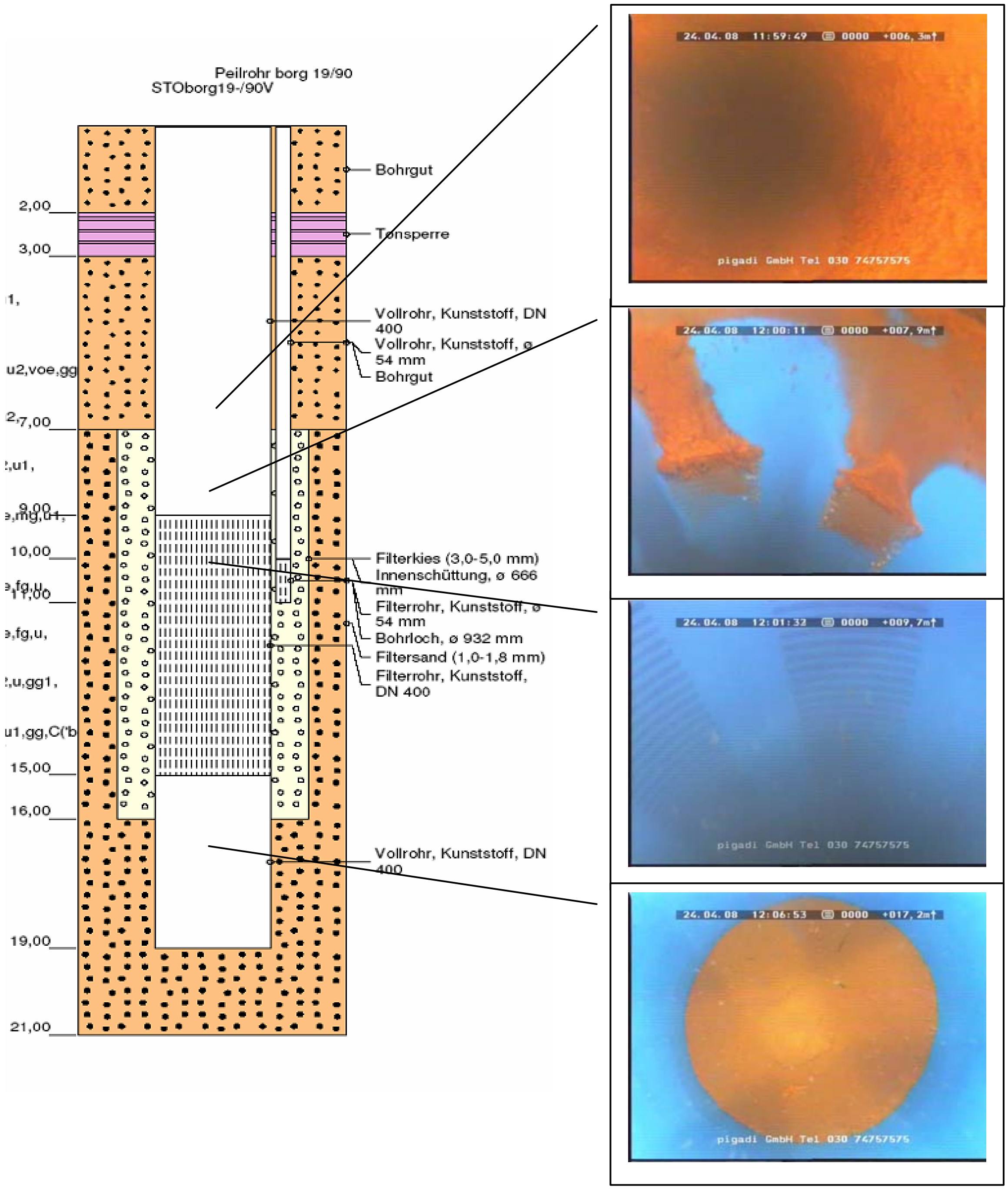
RESULTS	Well 1 TEGhzk-13-/73V
General remarks	Static water level is at 6 m below reference. Dynamic water level is usually at about 8.5 m below reference. Pump intake of the submersible is at 18.7 m below reference.
Deviation from drilling log	No. Upper filter section with higher open area.
General condition	Rilsan-coating partly damaged, leading to corrosion of the underlying steel.
Signs of ageing	Casing: between 9 and 19 m thin layer of red coloured, unconsolidated deposits (iron encrustation), most prevalent between 18 and 19 m. Top of filter section: clean, partially red coloured spots (old iron crusts, not removable). First filter section: clean. Second filter section: partially clean, partially with old deposits. Bottom: aggradations of fine sand material.



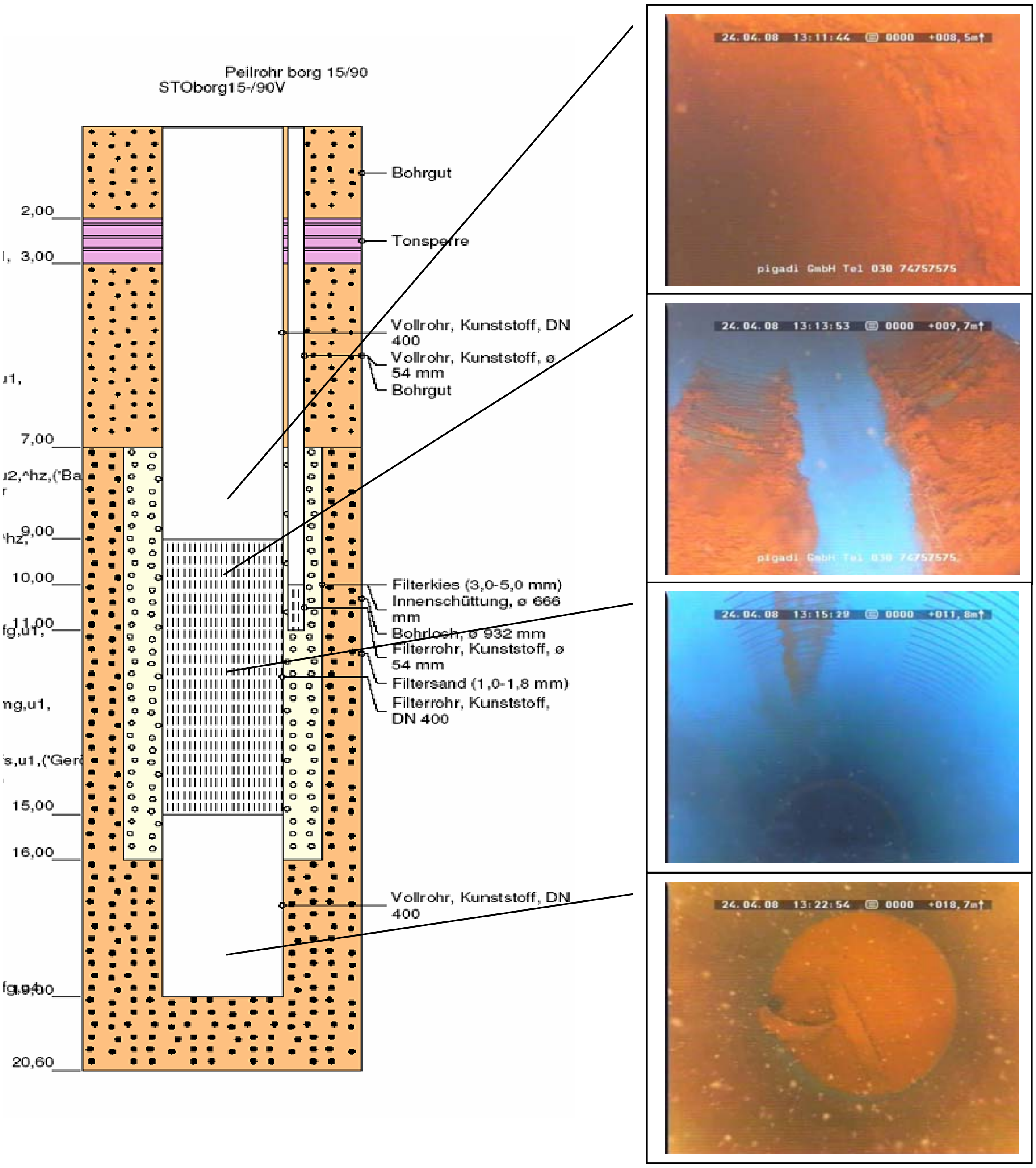
RESULTS	Well 2 TEGhzk-22-/71V
General remarks	Static water level is at 6.2 m below reference. Dynamic water level is usually at about 13.6 m below reference. Pump intake is at 18.9 m.
Deviation from drilling log	No.
General condition	Rilsan coating partly damaged. Corrosion.
Signs of ageing	Casing: red coloured deposits start at 15 m. Increase in thickness between 18 and 20 m. Filter section: top red coloured, from 21 m onwards clean. Bottom: aggradations of fine sand and reddish soft material.



RESULTS	Well 3 STOborg19-/90V
General remarks	Static water level at 3 m below reference. Dynamic water level usually at about 8 m below reference. Pump intake is in operation at 8.4 m below reference.
Deviation from drilling log	No. Please note: Reference point for drilling log is ground surface.
General condition	PVC casing and screen. No damages.
Signs of ageing	Casing: from 5 m onwards distinct, red coloured deposits (iron encrustation). Filter section: sharp boundary between clogging/ non clogging at the top of the screen. Bottom: fine sand aggradations.



RESULTS	Transect STOborg15-/90V
General remarks	Static water level is at 4,2 m below reference. Dynamic water level is usually at about 5.6 m below reference. Pump intake is at 8.4 m below reference.
Deviation from drilling log	No.
General condition	PVC casing and screen. No damages. Two foreign objects in the tailpipe.
Signs of ageing	Casing: Deposits start at 7,5 m. Quickly growing thickness. Filter section: sharp boundary between clogging/ no clogging at the top of the screen, between 10 and 14 m red coloured spots along one screen slot section. Bottom: fine sand aggradations.



3.4.3 Borehole geophysical methods [H. Wiacek after K. Baumann]

Methods

All measurements were carried out by BLM Bohrlochmessungen Storkow GmbH, subcontracted by Pigadi GmbH. BWB provided a drillers log and a cross section for each of the four wells.

The investigation program included the following measurements:

- Caliper logs to record the diameter of casings and screens. Changes in borehole diameter are related to well construction. Because the diameter commonly affects log response, the caliper log is useful in the analysis of other geophysical logs, including interpretation of flowmeter logs.
- Gamma logs to record the amount of natural gamma radiation emitted by the rocks or sediments surrounding the borehole. Because of the natural potassium-40 occurring in clay, they are used to detect the clay sealing.
- Neutron porosity (dual detector) logs to record scattered neutron rays. The rate of reflection changes with the water content and reflects the porosity of the gravel pack.
- Gamma-Gamma density-logs to record scattered reflection of emitted gamma rays. The rate of reflection is dependant on the density of the surrounding rock or sediment. Such density logs reflect the condition of clay sealing and gravel pack.
- Flowmeter logs (Figure 3-33A) to record the direction and rate of vertical flow in the borehole. Flow rates can be calculated from downhole-velocity measurements and diameter recorded by the caliper log. Flowmeter logs can be collected under non-pumping and(or) pumping conditions. They reflect the distribution of inflow along the filter sections.
- Packer flowmeter logs (Figure 3-33B) to record the flow through a filter section, limited by packers on top and bottom so that the water can only pass through the filter or along the impeller. From the impeller speed, the filter porosity can be calculated.

The results were summarized in a short report for each well, containing the reference depths, static water level, data on pump rates for flowmeter measurements and a short assessment of the well condition. Attached are the logs and calculations of inflow distribution.

Reference point for all depth information is the top of the well chamber.

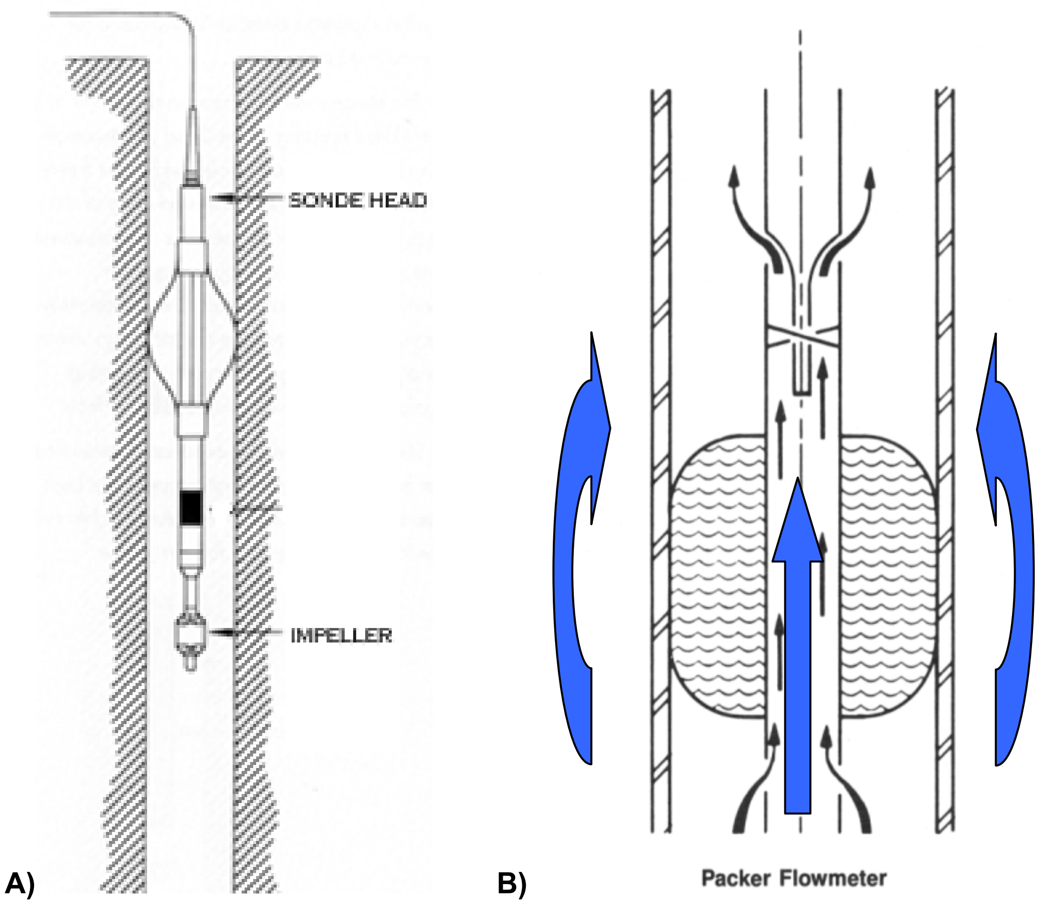


Figure 3-33: Scheme of a flowmeter measurement; (A) Impeller flowmeter for measurement of distribution of inflow [www.geologging.com, 10/2008]; (B) packer flowmeter for measurement of the permeability of screen and gravel pack [www.spwla.org, 10/2008]

Results

Due to the fact, that all borehole geophysical measurements present only indirect access to the well parts behind the filter section, some results cannot be finally assessed.

Generally, the distribution of permeability and water intake reflects the geological situation. Coarse sand layers provide good permeability and water inflow while fine sand layers show a decreased inflow.

All wells showed an accumulation of fine material near or at the top of the filter screen sections. This corresponds to the TV inspection results, where the most deposits were located near the pump intake between the top of the screen and the dynamic water level. However, it could not be determined if this is due to improper well construction or to secondary well ageing processes. Here, core sampling should provide great benefit.

The capacity calculations are consistent with pumping test data from the database and the step tests described before.

RESULTS	Well 1 TEGhzk-13-/73V
Comparison with drilling log	No deviation regarding the depths of casing and screen sections. Presence of the clay sealing could not be proofed. Upper filter screen has wider slots and lower material thickness than lower filter section and thus a higher open area for water intake.
Assessment of gravel pack condition	Varying porosity of the backing of the casing (filled with drilling material). Accumulation of fine material within the upper 2 metres of the gravel pack (18.2 to 20.2 m) shown by a higher gamma activity. Low permeability from 28.0 m to the bottom.
Distribution of water intake	90% in the upper, 10% in the lower filter section. 49% between 25.6 and 27.5 m. In idle state vertical flow from top to bottom. Evenly distributed inflow in both filter sections. In operation state no water intake below 35.2 m.
Well capacity	Q = 49 m^3/h, drawdown from 5.55 m to 6.43 m -> Qs = 55.7 $m^3/h*m$
General remarks	Sections of highest and low intake correspond to geological situation (drillers log states coarse sand layer at 24.3 to 28.8 m and fine sand between 32.5 and 38.8 m).

RESULTS	Well 2 TEGhzk-22-/71V
Comparison with drilling log	No deviation regarding the depths of casing and screen sections. Presence of the clay sealing could not be proofed. Decreased diameter between 22.4 and 32.4 m (could not be related to deposits with the TV inspection results)
Assessment of gravel pack condition	Considerably varying porosity of the backing of the casing (filled with drilling material). Low porosity between 6.4 to 8.9 m and 10.4 to 15.7 m. Accumulation of fine material within the upper 2 metres of the gravel pack (19.5 to 21.3. m) shown by a higher gamma activity. Low permeability from 28.0 m to the bottom.
Distribution of water intake	Uneven distribution. Highest intake in a very short interval, between 21.6 and 21.9 m (17 % or 16.7 m^3/h per 1 m filter - that is 3 to 4 times higher than in the other sections) and at the bottom of the well at 31.9 to 32.4 m (10 % or 9.8 m^3/h per 1 m filter).
Well capacity	Q = 49 m^3/h, drawdown from 5.76 m to 9.64 m -> Qs = 12.6 $m^3/h*m$
General remarks	As the packer flowmeter measurement shows an evenly distributed permeability along the gravel pack, the distribution of water intake must be caused by the geological setting. As the drillers log states only “middle sand” for the whole filter section this cannot be further assessed.

RESULTS	Well 3 STOborg19-/90V
Comparison with drilling log	No deviation regarding the depths of casing and screen sections. Clay sealing at 2.6 to 3.4 m depth. Upper filter section (10 to 13 m) thinner PVC and smoother surface.
Assessment of gravel pack condition	Accumulation of fine material between 9.2 and 10.2 m at the top of the filter screen. Decreased permeability between 10.2 and 11.3 m at the top of the screen in the packer flowmeter measurement.
Distribution of water intake	In idle state vertical flow from top to bottom. In operation mode uneven distribution of intake. Highest intake in short sections at 10.0 to 10.9 m , 13.7 to 14.2 m and 15.6 to 16.0 m.
Well capacity	Q = 46 m^3/h, drawdown from 3.05 m to 5.60 m -> Qs = 18.0 $m^3/h*m$
General remarks	No correlation between distribution of intake and permeability measurement from packer flowmeter. As the drillers log states only “middle sand” this cannot be further assessed.

RESULTS	Well 4 STOborg15-/90V
Comparison with drilling log	No deviation regarding the depths of casing and screen sections. Clay sealing at 3.4 to 4.4 m depth, one meter deeper as stated in the well cross section. Upper filter section (9.7 to 12.7 m) thinner PVC and smoother surface.
Assessment of gravel pack condition	Accumulation of fine material between 8.3 and 9.6 m at the top of the filter screen, displayed by an increased gamma ray activity. Decreased permeability in the packer flowmeter measurement from top of the screen (9.7 m) up to 12 m depth. Homogeneous distribution of porosity and permeability along the gravel pack.
Distribution of water intake	In idle state homogeneous vertical flow from top to bottom. In operation mode uneven distribution of intake. Low intake in the upper filter part (9.7 to 12.3 m). Inflow from the annular space from above at the top of the screen.
Well capacity	Q = 46 m^3/h, drawdown from 4,20 m to 5.01 m -> Qs = 56.8 $m^3/h*m$
General remarks	Good correlation between gamma ray activity (fine material), distribution of intake and permeability measurement from packer flowmeter.
Impact of H_2O_2	No changes in porositites, permeability and inflow distribution.

3.4.4 Summary of well condition analyses

Pumping tests, TV inspections and borehole geophysical investigations vary in their correlation for the four wells.

Generally, the TV inspections gave no hints on clogging deposits along the filter screens. All deposits were located between dynamic water level and top of the filter with highest accumulation near the pump intakes. This corresponded to gamma measurements indicating the accumulation of fine materials within the upper two metres of the gravel pack for all four wells.

The two wells with good remaining specific capacity compared to initial pumping tests (these are TEGhzk13 and STOborg15) do also require the shortest time to reach final drawdown and recovery.

Altogether, the further applied borehole geophysical methods to assess porosities and permeabilities of the gravel pack and the distribution of water intake (mainly flowmeter and packer flowmeter) were not sufficient to indicate well ageing processes. The additional assessment of pumping tests and TV did also not contribute clearly to a final assessment of well condition.

TEGhzk13 preserved 66% of its initial capacity and shows only minor decrease in specific capacity since its last rehabilitation in 2003. However, flowmeter measurement shows that the water comes mainly from the second half of the upper filter section. This can be explained by coarser aquifer sediment in this section.

TEGhzk22 was at 45% of initial capacity at the time of the last rehabilitation in 2003. Since then, performance decreased further and more rapid to only 25% of initial Qs. Although packer flowmeter measurement reflects an even permeability of the gravel pack, water intake comes mainly from a very short filter section. Because the drillers log did not provide high resolution of sand layers for the aquifer sediments, further investigations, e.g. by subsequent planned core sampling, is needed.

STOborg19 has only about 25% of its initial specific capacity. Since the last rehabilitation in 2007, the capacity remained nearly constant. Comparing the TV records, this well is not conspicuous. However, it has the highest Δh of all four wells. This correlates with the low remaining Qs. Remarkably, the well shows a low permeability of the gravel pack (packer flowmeter) between 10 and 11 m below well head, but at the same time the highest share of water intake (flowmeter) in that section. Again, this might be due to the geological setting, but this cannot be read from the driller’s log. Additional investigations are needed.

At **STOborg15,** about 70% of its initial capacity could be preserved. The decrease in Qs since the last rehabilitation in 2007 runs parallel to previous performance development. TV inspections and borehole geophysical measurements correlate and reveal that the upper part of the filter section seems to be blocked.

(Please note for the assessment of drawings and pictures: Due to well head construction work in 2007, the reference depths for the Stolpe-wells are not consistent. For the above-described tables they were corrected.)

3.5 Particle measurements [K. Raat]

Summary

This report presents the first attempts to better understand the role of particles in abstracted water from biologically / chemically clogged wells. Results are presented from experiments with three chemically clogged wells of the Berliner Wasserbetriebe (BWB). For 3 days, these wells were operated following a schedule of 24h operation followed by 3h rest. Particle concentrations and size distributions in the abstracted water were recorded, as well as hydraulic head and discharge of the well and operation of neighbouring wells.

The most important conclusions of these experiments are:

- Particle concentrations in chemically clogged wells respond instantly and strongly to switching on water wells (pump). An hour after switching, concentrations have stabilized at low levels;
- For one well, particle concentrations also respond to switching off the pump. A similar response is possible in the other two wells, but this was not recorded as the particle counter was switched off;
- Peak concentrations recorded after switching are much higher than concentrations in Dutch, mechanically clogged wells. Peak concentrations vary between 2,400 and 4,000 mL^{-1} for the Tegel wells and between 16,000 and 36,000 for STOborg19-/90V (Dutch wells between 200 and 2000 mL^{-1});
- Switching of neighbouring wells has no or a negligible effect on particle concentrations in the well of interest;
- The origin of the particles is unknown. Most likely, recorded ‘particles’ are bacteria and/or iron precipitates, that are released from pump and/or well screen

One of the goals of this experiment was to test, whether repetitive on and off switching can be used to prevent biological and/or chemical clogging. Clearly, material is removed during switching thereby somewhat cleaning pump and filter screen and preventing the build-up of the bacterial population and/or iron precipitates. Yet, for a good evaluation, better information is required on particle origin, the quantity removed and formation rate of bacteria and/or iron precipitates.

Contents

3.5.1 Introduction

In the Netherlands, about one-third of the water abstraction wells suffer from clogging at or near the borehole wall. This type of clogging is characterized by spotless clean well screens and a high entrance resistance between aquifer and gravel pack (Figure 3-34A). Contrary, wells that suffer from chemical and / or biological clogging (another one-third of Dutch wells) are characterized by an entrance resistance between gravel pack and fouled filter screens (Figure 3-34B). Research has shown that mechanical filtration of particles is the dominant process causing clogging near the borehole wall and this clogging type is thus often referred to as mechanical clogging (De Zwart, 2007). Particle countings in the abstracted water have shown that when a well is switched on, part of the filtrated particles are released again and pulled through the gravel pack and filter. Moreover, regularly switching off and on water wells may seriously reduce or even prevent mechanical clogging. This 'switching' is now a common means of operation in many well fields in the Netherlands (e.g. Van Beek et al., 2007).

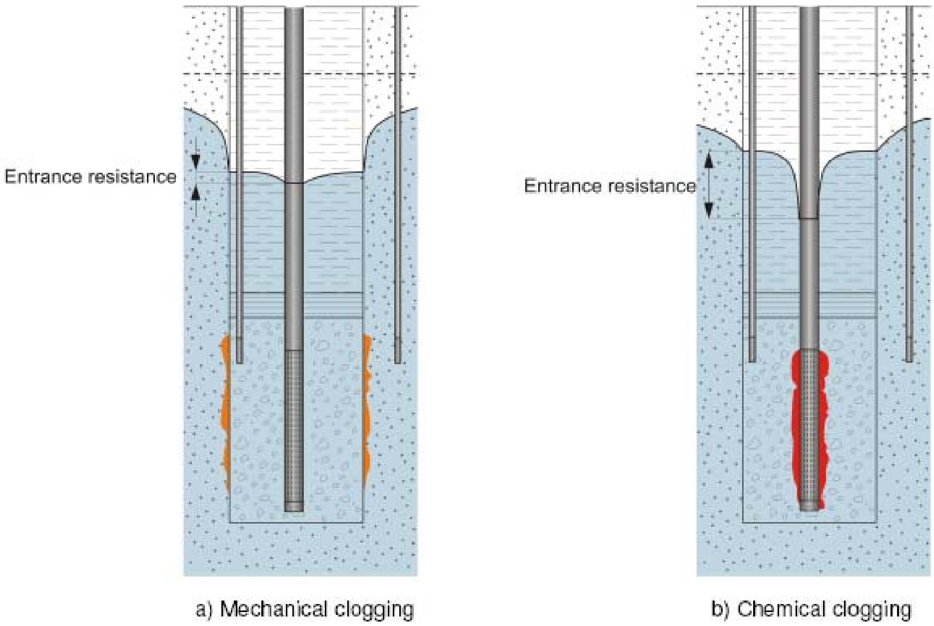


Figure 3-34 Clogging types. A. Mechanical clogging; B. Chemical clogging

For wells suffering from chemical clogging, it is common practice to run the well as constant (continuous) as possible (Makkink et al., 2000; Van den Berg et al., 2007). The idea is that the redox cline is most stable under continuous operation, thereby lowering the risk of mixing of oxic and anoxic water types. Also, it is often thought that clogging by particles does not play an important role in these types of wells. Likewise, it has never been tested fully whether continuous operation is indeed the most efficient way of preventing chemical clogging or that regular switching may offer an interesting alternative way of operation.

The current report presents some first attempts to better understand the role of particles in abstracted water of chemically clogged wells. Results are presented from experiments with three chemically clogged wells of the Berliner Wasser Betriebe (BWB). For 3-and-a-half days, these wells were operated following a schedule of 24h operation followed by 3h rest. Particle concentrations and size distributions in the abstracted water were recorded, as well as hydraulic head and discharge of the well and operation of neighboring wells. The results from these experiments were analyzed and compared to results from similar studies on (Dutch) mechanically clogged wells.

3.5.2 Materials and methods

Well and site description

Experiments were conducted at three BWB wells, which were planned for later abandonment. Two wells (TEGhzk-13-/73V and TEGhzk-22-/70V) are in the northwestern part of Berlin near Lake Tegel. These are old wells (constructed in 1973 and 1971), which were initially planned for reconstruction for 2008. The third well (STOborg19-/90V; constructed in 1990) is north of Berlin at the river Havel (location Stolpe). This well was investigated because of its very poor capacity and to have another well type to compare with the others (river bank filtrate versus artificial recharge).

Table 3-9 lists the main characteristics of the three wells. Clearly, all three wells suffer from severe clogging, with a decrease in performance between 34 and 75% percent compared to the initial capacity. All three wells are located in middle sand geology. TEGhzk-13-/73V and STOborg19-/90V abstract water from unconfined aquifers; TEGhzk-22-/70V extracts from a confined aquifer. The Tegel-wells have steel casings, the Stolpe-well has a polyethylene casing. Soil profiles of the three wells are given in the Appendix B. These profiles also include information on the filter screens (depth, length, diameter) and the gravel pack.

Table 3-9: Main characteristics of water wells

	Well 1	**Well 2**	**Well 3**
Well ID	**TEGhzk-13-/73V**	**TEGhzk-22-/71V**	**STOborg19-/90V**
Year of construction	1973	1971	1990
Geology/ water source	unconfined, middle sand, artificial recharge	confined, middle sand, artificial recharge	unconfined, middle sand, river bank filtrate
Casing	DN 400 Steel (Rilsan)	DN 400 Steel (Rilsan)	DN 400 PE
Depth	40,4	33,6	19,3
Initial capacity	Q: 200 m^3/h Qs: 76,9 $m^3/h*m$	Q: 120 m^3/h Qs: 49,2 $m^3/h*m$	Q: 80 m^3/h Qs: 76,9 $m^3/h*m$
Installed pump now	60 m^3/h	50 m^3/h	50 m^3/h
Last rehabilitation	2003	2003	2007
Method	Shock blasting	Shock blasting	Hydropuls
Capacity improvement	Qs before: 56,1 Qs after: 57,7	Qs before: 15,5 Qs after: 22,3	Qs before: ? Qs after: 19,4
Well performance (actual vs. new)	66% of initial capacity	45% of initial capacity	25% of initial capacity

Last rehabilitations of the wells were performed in 2003 (Tegel; shock blasting) and August 2007 (STOborg19-/90V; hydropuls), respectively. This is reflected in the amount and type of coating observed on the pumps around the time of the experiments. Biomass (bacteria) was present at pumps of all three wells, but was less abundant at STOborg19-/90V than at the Tegel wells (observations by Oliver Thronicker, Technical University Berlin).

This is reflected in bacterial countings in water samples taken from these wells (under continuous operation of the wells; field campaign by Technical University). Cell counts were 230,000 (TEGhzk-13), 700,000 (TEGhzk-22) and 12,000 cells mL^{-1} (STOborg19-/90V), respectively (data by Oliver Thronicker, Technical University Berlin). Photographs of the pumps of the three wells are given in Appendix E

Experimental setup

Two different types of tests are often conducted in particle concentration experiments. The first is the relation between abstraction (discharge) rate and particle concentrations, which for mechanically clogged wells provides insight into the maximum acceptable discharge rate. For the current experiment, this test is of minor importance. The second test is the response of the particle concentrations to switching of the water wells. These experiments provide insight into the amount of particles removed after switching. For mechanically clogged wells, factors that may affect the particle concentrations recorded after switching include the degree of clogging, length of rest period before switching and the length of the preceding period of operation. In addition, switching of neighbouring wells is sometimes noticeable by a release of particles in the well of interest.

In the current experiment, we tested the response of particle concentrations to switching of the water wells. In principle, the wells were operated following a repetitive schedule of 24h of operation followed by 3h of rest. Two repetitive schedules were studied for all three wells. The rest period preceding the experiment (i.e. before the first ‘on switching’) was 52h for the Tegel-wells (TEGhzk-13-/73V and TEGhzk-22-/70V) and just 4.5h for well STOborg19-/90V.

The experiment ran from Monday April 7 (Stolpe) or Tuesday April 8 (Tegel) until Friday April 11. In principal, the neighbouring wells were either operated continuously or out of operation. However, some occurrences of switching of neighbour wells did occur, of which one switching was originally planned in the experiment.

For well TEGhzk-13, next-door neighbour TEGhzk-14 ran continuously during the whole course of the experiment; the other next-door neighbour (TEGhzk-12) was out of operation during the first part of the experiment, but switched on at 14:00h, April 10. For well TEGhzk-22, neighbour TEGhzk-23 was out of operation all the time. Neighbour TEGhzk-21 was out of operation at the start of the experiment, was turned on at 00:00h, April 9, and was turned off again at 10:00h, April 11. For well STOborg19-/90V, neighbour STOborg18 was in operation most of the time, but deliberately turned off between 09:35h and 15:00h, April 10, to investigate the response of particle concentrations in well STOborg19-/90V. The complete operation schedule of wells at Tegel and Stolpe is given in the appendix.

Particle concentrations were recorded using a Pamas WaterViewer with sensor HCB-LD-50/50 (PAMAS Partikelmess- und Analysesysteme GmbH). Particle concentrations were recorded in a by-pass flow from the raw water. Eight different size classes were recorded, namely >1µm, >2µm, >3µm, >4µm, >5µm, >7µm, >10µm and >15µm. Measurements of the smallest size class are often somewhat inaccurate and this is why in text and figures of this report the cumulative concentration of particles >2µm is presented, unless stated otherwise. Particle measurements were conducted once every minute. For the Tegel wells, particle concentrations were recorded only during time of abstraction, i.e. when the pump was turned on. At Stolpe, measurements continued after turning off the pump. In addition to the particle countings, the hydraulic head in the wells were recorded automatically (pressure logger, Ackermann), with a measurement frequency of 1 per minute.

3.5.3 Results and discussion

Peak response to on and off switchings

Figure 2 shows the particle concentrations in all three wells, recorded over the course of the experiment. All three wells show a clear response to switching on the well pump, as noticed by the high peaks in particle concentrations. The Tegel wells show 3 peaks, corresponding to the three ‘on switchings’. STOborg19-/90V shows five clear peaks. Peaks number 1, 3 and 5 correspond to the on switchings; peaks number 2 and 4 correspond to the off switchings. As such, particle concentrations in STOborg19-/90V do not just respond to on switchings, but also to off switchings. At Tegel, particle countings stopped directly after switching off the pump. As such, a similar response of particle concentrations to off switchings may also be present at the Tegel wells, but was not recorded as the counting device was turned off.

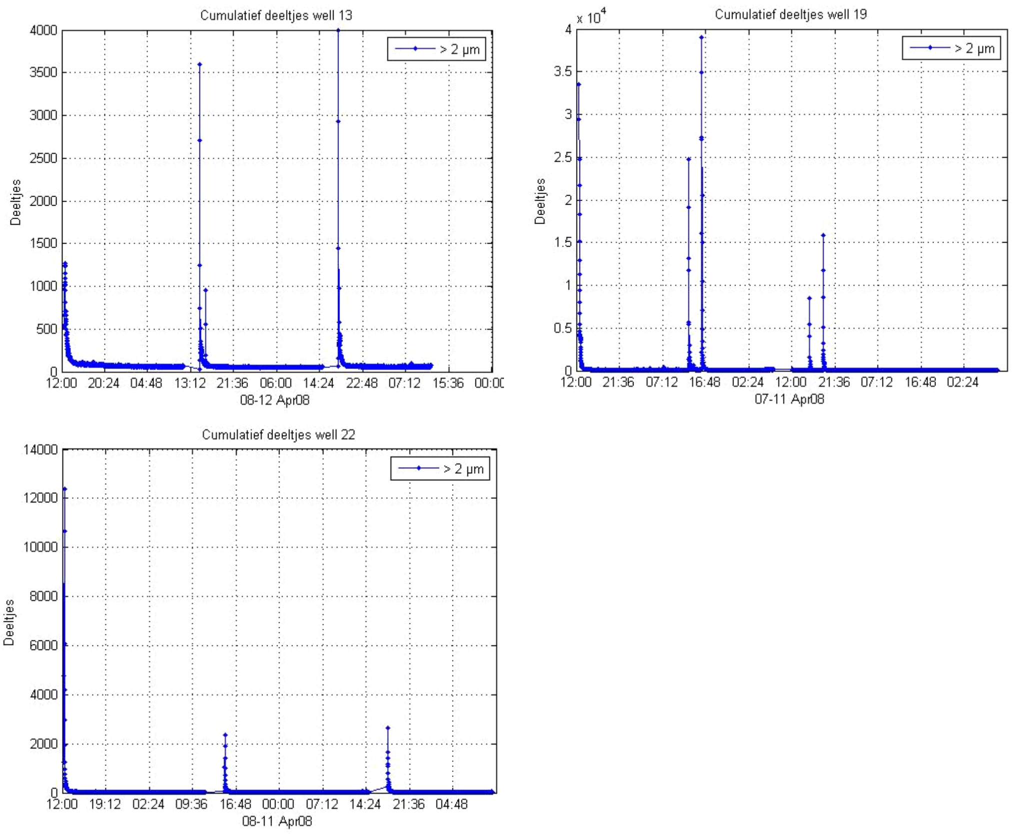


Figure 3-35 Particle concentrations for Tegel and Stolpe wells, during 3 days experiment: (A) TEGhzk-13; (B) TEGhzk-22; (C) STOborg19. Concentrations are cumulative concentrations of all particles >2µm.

The high particle concentrations following the off switchings in Stolpe (and possibly Tegel) may have resulted from the shock effect from turning off the pump. It seems this shock is large enough to release particles from filter screen, pump and/or gravel pack. In Dutch mechanically clogged wells, a response of particle concentrations to off switchings has never been observed. This could be because most countings in mechanically clogged wells were performed in deep wells, meaning that particles released during off switchings do not reach the particle counter as the flow of water fades out rapidly after the pump is turned off. Also, it could be that a response is absent in mechanical clogged wells as, contrary to chemically / biological fouled wells, the clogging is at distance form the filter screen, behind the gravel pack.

Peaks recorded after the 2nd and 3rd on switchings (Tegel wells peaks 2 and 3; STOborg19-/90V peaks 3 and 5) are best suited for comparing wells, as these peaks were all preceded by the same operation scheme of 24h operation and 3h rest. Recorded peaks of the Tegel-wells are in the same order of magnitude, i.e. between 3500 and 4000 mL^{-1} (TEGhzk-13) and between 2300 and 2700 mL-1 (TEGhzk-22). Note that these concentrations are higher than those generally observed in Dutch mechanically clogged wells (200 – 2000 mL^{-1}). The number of particles released by the Stolpe well was almost 1 order of magnitude larger than the Tegel wells, namely around 39,000 mL^{-1} (peak 3) and 16,000 mL^{-1} (peak 5). Likewise, the peaks recorded after switching off this well were high, with particle concentrations of 25,000 and 8,500 mL^{-1}.

It was not possible to infer the exact reason why the number of particles is that much higher for STOborg19-/90V. A reason could be that the STOborg19-/90V is more severely clogged than the Tegel wells (specific capacity at 45-66% of initial capacity for Tegel wells and 25% for STOborg19-/90V), thereby offering a larger source of removable particles. However, the Stolpe well was rehabilitated less than 1 year (August 2007) before the experiments took place (April 2008), which could imply that particles (iron oxides, bacteria, clay, other) are less abundantly present at this well. Indeed, visual inspection of the pump showed less abundant biomass growth at the pump of STOborg19-/90V than at the Tegel wells. Also, bacterial countings in water samples from STOborg19-/90V were much lower than the Tegel wells (12,000 cells mL^{-1} for STOborg19-/90V versus 230,000 and 700,000 for TEGhzk-13 and TEGhzk-22; data by Oliver Thronicker, Technical University Berlin). Another explanation for the high concentrations could be the geology at STOborg19-/90V. Downstream of the well, the sands are finer than upstream and possibly also finer than the sands at Tegel (Hella Wiacek, personal communication). This would mean that the high concentrations are caused by particles present in the native groundwater, similar to Dutch mechanically clogged wells. However, judging from the very high concentrations at Stolpe compared to Dutch wells (concentrations 20-fold higher) this explanation seems unlikely. A third possible reason could be the discharge per meter filter length (m3 h-1 m_{filter}^{-1}), which is 2 to 2.5 times higher for STOborg19-/90V (similar pump capacity, total filter length is 6m for STOborg19-/90V, 16m for TEGhzk-13 and 12m for TEGhzk-22).

Size distributions of particles are presented in Figure 3-36. This figure reflects some of the points already mentioned, like the high peak concentration recorded at Stolpe. As with mechanical clogged wells, the number of particles is most abundant in the smallest size class (1 – 2 µm) and decreases with increasing size class. It is interesting to compare particle concentrations during peaks (Figure 3-36B) and stable conditions (Figure 3-36C). Obviously, concentrations are much higher for all size classes during the peaks, however, judging from these figures it seems that relative size distributions do not seriously change during peaks, for all three wells. For example, consider particle size distributions of STOborg19-/90V. Going from stable to peak conditions, concentrations of all size classes increase with a factor of approximately 10^2 and thus relative size distributions do not change.

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As mentioned earlier, the time of operation and rest period preceding the first peak differed between the wells. The rest period preceding the experiment (i.e. before the first ‘on switching’) was 52h for the Tegel-wells and just 4.5h for STOborg19-/90V. For TEGhzk-13, the peak recorded after the first on switching (1300 mL^{-1}) was smaller than the peaks recorded later on in the experiment (3500 – 4000 mL^{-1}). Contrary, for TEGhzk-22, this first peak was much higher (12,000 mL^{-1}) than later on in the experiment (2400 – 2600 mL^{-1}). As such, judging from these observations it seems there is no clear relation between the preceding rest period and the amount of particles released after switching on the well. For the Stolpe well, particle concentrations after the first switching were in the same order as concentrations recorded later on (note that rest period before first on switching was also in same order as the other rest periods, i.e. 4.5h rest and 3h rest).

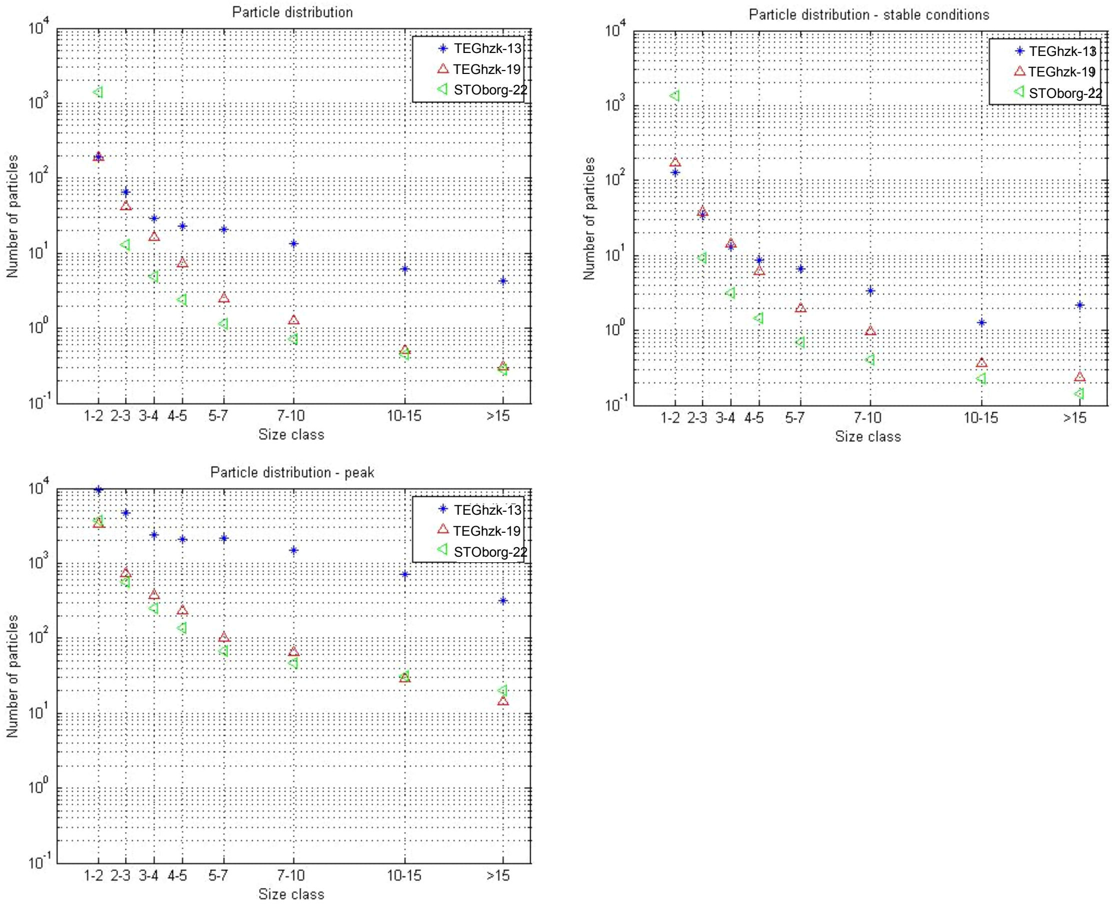

Figure 3-36 Particle size distributions of Tegel and Stolpe wells. (A) whole experiment; (B) peaks; (C) stable concentrations

Water level response to switching

The water levels recorded in the wells are presented in Figure 3-37. All three wells respond instantly to both on and off switchings. Recorded drawdown was approximately 1.3m for TEGhzk-13, 4.0m for TEGhzk-22, and 2.6m for STOborg19-/90V. In both the Tegel wells, water levels do not stabilize within the 24h of operation, meaning that the drawdown still increases after 24h. Similar, for TEGhzk-13, a 3h rest period seems too short for the water level to recover from pumping. At Stolpe, water levels do stabilize within 24h of operation, but here also 3h rest is not enough to recover from pumping.

Over the course of the experiments, water levels at STOborg19-/90V show some irregularities. At April 10, these are related to switching of a neighbour well; the cause for sudden decrease in water levels on April 7, 23:30h is unknown.

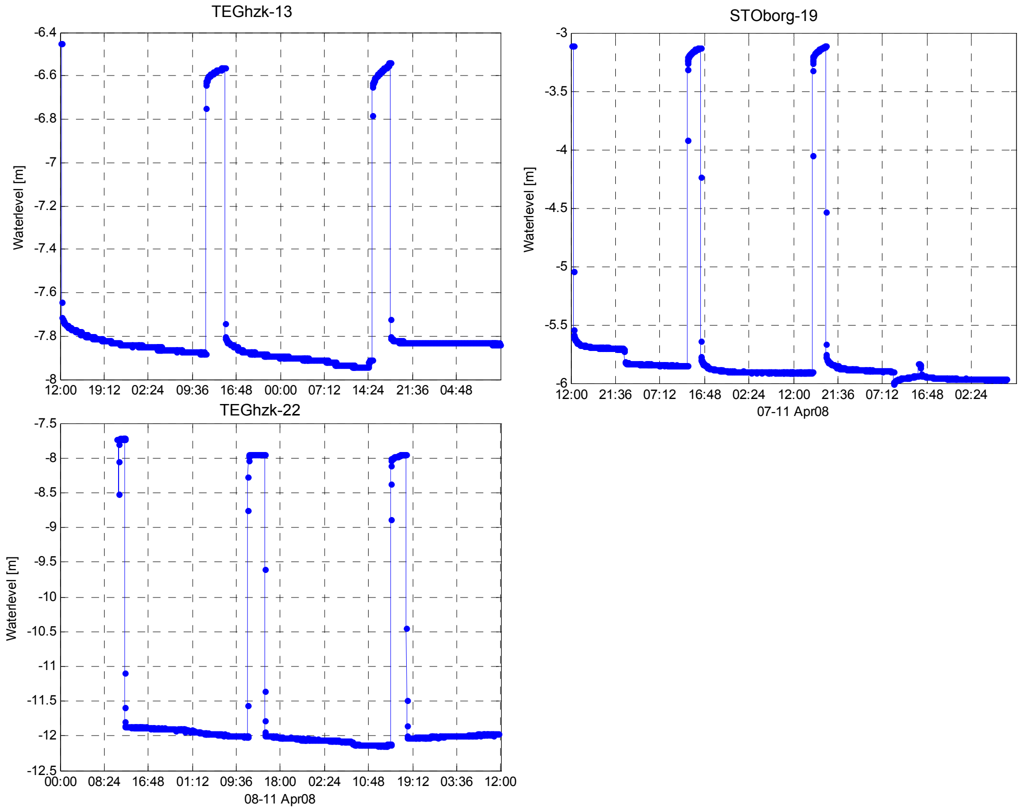

Figure 3-37 Water levels in Tegel and Stolpe wells, during 3 days experiment: (A) TEGhzk-13; (B) TEGhzk-22; (C) STOborg19-/90V

Responses to on switchings: detailed look

Figure 3-38 shows the particle concentrations after switching #2 for TEGhzk-22. Concentrations show an abrupt increase directly after on switching, followed by a gradual decrease to a stable concentration. Stable concentrations are reached after 6 – 9h for the Tegel wells and after 1 – 3.5h for the Stolpe well. For TEGhzk-13, this stable concentration was 50 – 60 mL^{-1}; it was around 10 for TEGhzk-22, and 50 – 100 for STOborg19-/90V. Note that this sequence in particle concentrations mimics the sequence in peak concentrations, i.e. concentrations increase following STOborg19-/90V > TEGhzk-13 > TEGhzk-22. In broad lines, this figure mimics the reaction to on switching in Dutch mechanically clogged wells, i.e. steep rise in concentrations when the underwater pomp is turned on, followed by a steady decrease. However, during this decrease, mechanically clogged wells often show minor, secondary peaks in particle concentrations, which are related to the design and construction of the water well. Compared to stable concentrations observed in Dutch, mechanically clogged wells, concentrations in these chemically clogged wells are in the same order of magnitude. On average particle concentrations in Dutch wells (under stable conditions) are between 1 and 120 mL^{-1} (Van Beek et al., 2008).

Other peaks observed at TEGhzk-22 and all peaks observed at STOborg19-/90V (including peaks following off switching) are in line with the text book example of Figure 3-38.

When zooming in on peaks of TEGhzk-13, it appears that this well has a more complicated response to switching on. Figure 3-39A and B present switchings #2 and #3 of this well. In both figures, the initial high peak is followed by a small peak (bulb), some 13 minutes later. Such a response is typical for wells with two filter screen sections, like TEGhzk-13 (filter screens between 20 and 28 m depth and between 31 and 39m). An hour after switching #2 (Figure 3-39A), a third concentration peak was observed. It is difficult to explain this peak, which, for instance, was not reflected in observed water levels in the well and was not related to switching of other wells. Rehabilitation work was done at nearby wells; a possible explanation for the peak in particles is the heavy traffic (trucks) passing by at the end of the work day, that may have influences the particle counter.

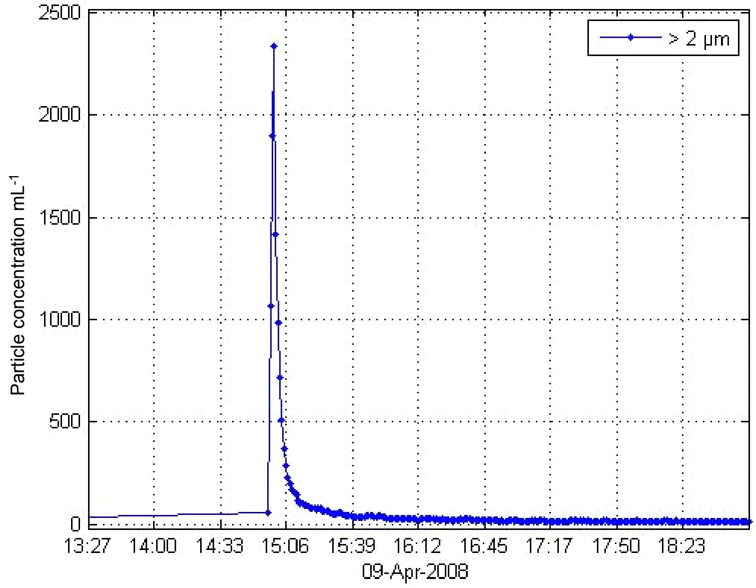

Figure 3-38 Particle concentrations after switching #2, TEGhzk-22.

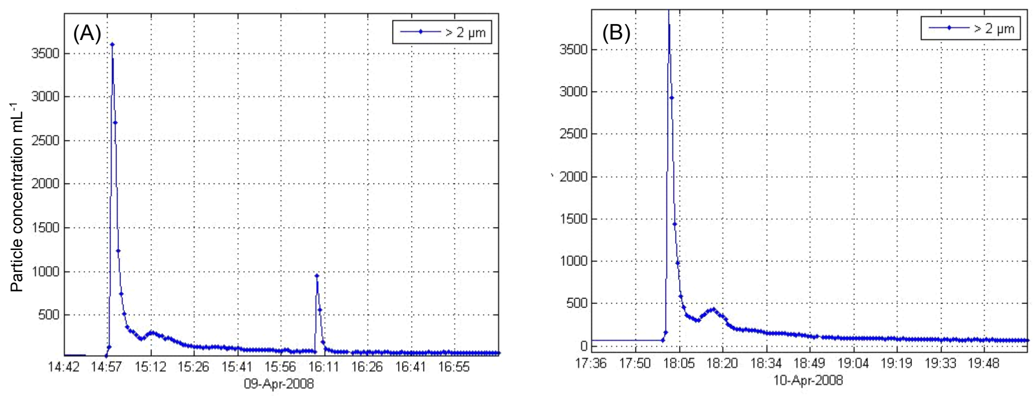

Figure 3-39 Particle concentrations after switching #2 (A) and #3 (B), TEGhzk-13.

The total amount of particles removed after switching can be estimated from the surface under the above graphs and the discharge. Moreover, using the data on particle size distributions in combination with assumptions on the particle shape (sphere) and bulk

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density, estimates on the total mass of material removed can be made. Total number of particles removed after switching were in the order of 10^{10} for the Tegel wells and around 10^{11} for STOborg19-/90V. The total mass removed was in the order of 1 (Tegel) to 10 grams (Stolpe).

This seems like a small amount of mass removed after switching, yet a good understanding of these numbers requires them to be related to the total, daily amount of biomass and/or precipitate formed. When done accordingly, it can be checked whether regular switching is effective in removing the formed precipitates and/ or in obstructing the build-up of a bacterial population.

Effects of neighbouring wells on particle concentrations

A number of next-door neighbouring wells switched on and off during the experiments. For TEGhzk-13, a neighbour was switched on at 14:00h, April 10. For TEGhzk-22 a neighbour well was turned on at 00:00h, April 9 and was turned off again at 10:00h, April 11. Thirdly, for well STOborg19-/90V a neighbour was turned off between 09:35h and 15:00h, April 10.

No changes in particle concentrations or water level were recorded for TEGhzk-13 and TEGhzk-22, after their respective neighbours were turned on. Likewise, TEGhzk-22 did not respond to switching off its neighbour. The only well that responded to its neighbour was STOborg19-/90V, as seen in Figure 7. Directly after switching off of its neighbour at 09:35h, particle concentrations in STOborg19-/90V increased from around 25 to about 45 mL^{-1} (note that this increase is very small compared to the high concentrations recorded after switching!). Levels stayed amplified until the neighbour was turned on again at 15:00h. This increase in particle concentrations may be explained by a mild increase in discharge of STOborg19-/90V when its neighbour was turned off. From experiments in the Netherlands, it is known that particle concentrations increase with increasing discharge.

Surprisingly, water levels in STOborg19-/90V show a reaction opposite to what may be expected when a nearby well is switched off. Water levels decreased in the well, whereas an increase is generally expected. An explanation could be that the nearby well suppresses STOborg19-/90V, for instance due to higher pressure in the transport pipe. As such, the discharge of STOborg19-/90V is somewhat lowered when the neighbour is running, and will increase when the neighbour is turned off. This increase in discharge is then reflected in a lower water level, as seen in Figure 3-40.

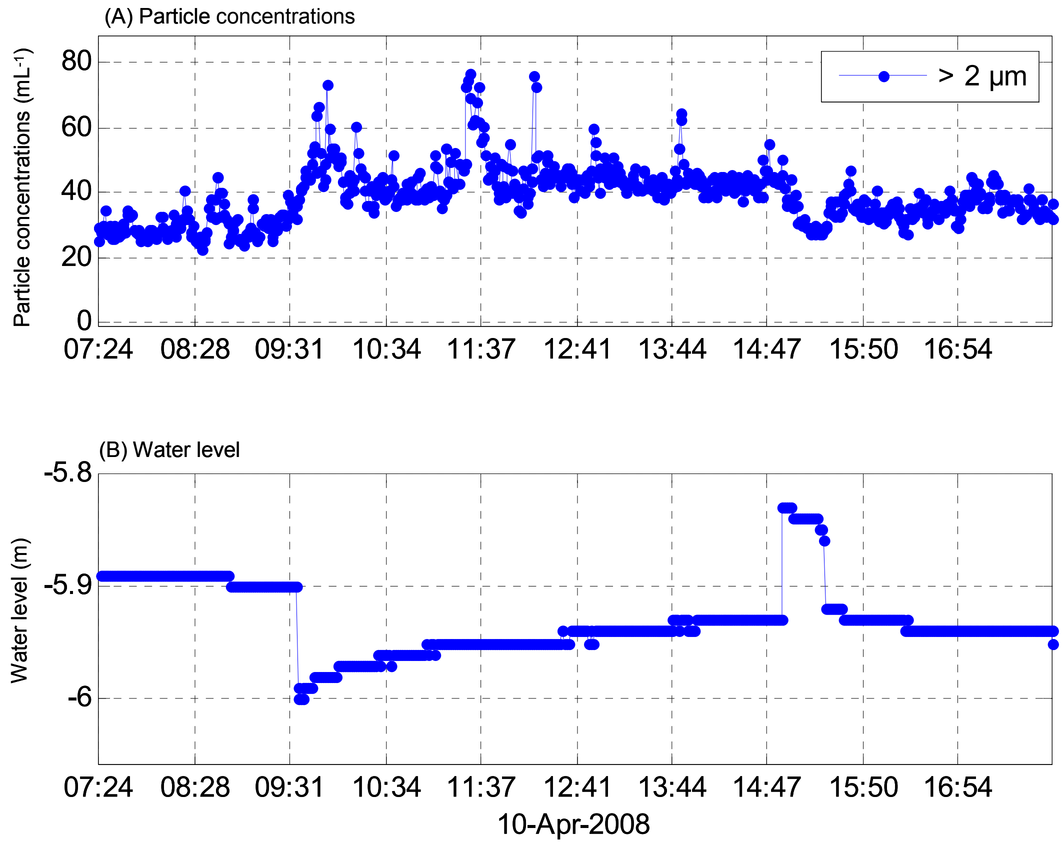

Figure 3-40 Effects of turning off and on neighbour well of STOborg19-/90V. (A) particle concentrations; (B) water level.

Type and origin of particles

At this point, it is important to note an important difference between particles measured in abstracted water from mechanically and biologically/chemically clogged wells. Particles observed in mechanically clogged wells include both particles that are released from the borehole wall (i.e. earlier filtrated particles) as well as particles that pass through gravel pack and well screen unhindered. Contrary, for particles measured in water abstracted from chemically clogged wells it is uncertain what type of particles are measured and what their origin is. In theory, three types of 'particles' may be distinguished: (1) bacteria, (2) (iron) precipitates and (3) inert particles in the native groundwater (clay, fines, calcite; from here on referred to as 'inert particles'). Bacteria and (iron) precipitates can be removed from the well screen and/or pump; inert particles may be removed from the borehole wall.

It was already noted that the particle concentrations after switching were larger than concentrations observed in Dutch, mechanically clogged wells. Concentrations in Dutch wells after switching are generally in the order of 200 – 2000 mL^{-1}, the Tegel wells recorded concentrations 3500 – 4000 mL^{-1} (TEGhzk-13) and 2400 – 2600 mL^{-1} (TEGhzk-22), and STOborg19-/90V even recorded peaks as high as 16,000 – 39,000 mL^{-1} (all data regarding the 2nd and 3rd on switching). Judging from these high concentrations it seems unlikely that inert particles (from groundwater) are the dominant source of particles recorded at Tegel and Stolpe.

Bacteria and precipitates released from pump and well screen following (on and off) switchings seem most likely to be the dominant source of particles. That bacteria may play an important role is supported by some observations. First, bacterial biomass was observed at the pumps of all three wells. Second, observed bacteria are in the right size class to be recorded by the particle counter with lengths between 0.5 and 2.5μm and widths of 0.5μm. In addition, bacteria may clog together, thereby generating 'particles' larger than 2μm.

Bacteria were indeed abundantly present in the abstracted water, with bacteria countings roughly between 10^5 and 10^7 mL^{-1} for the Tegel wells and around 10^4 for STOborg19-/90V (data by Oliver Thronicker, Technical University Berlin). However, note that these numbers are much larger than the amount of particles recorded during the 'stable' conditions, which were in the order of 50 – 100 mL^{-1} (section 3.3). Therefore, it is unclear whether bacteria are recorded (or fully recorded) by the particle counter. If not, it seems more likely that most particles counted reflect released iron hydroxide flocs.

One of the goals of this experiment was to test whether repetitive on and off switching can be used to prevent biological and/or chemical clogging. Clearly, material is removed during switching thereby somewhat cleaning pump and filter screen and preventing the build-up of the bacterial population and/or iron precipitates. Yet, for a good evaluation better information is required on particle origin, the quantity removed and formation rate of bacteria and/or iron precipitates.

3.5.4 Conclusions

Particle countings were performed in three biologically / chemically clogged wells in Berlin (Berliner Wasserbetriebe), following on and off switchings of the wells. The most important conclusions of these experiments are:

- Particle concentrations respond instantly and heavily to switching on water wells (pump). An hour after switching, concentrations have stabilized at low levels;
- Particle concentrations at STOborg19-/90V also respond to switching off the pump. A similar response is also possible at the other two wells (but not recorded as particle device was switched off);
- Peak concentrations recorded after switching are much higher than concentrations in Dutch, mechanically clogged wells. Peak concentrations vary between 2400 and 4000 mL-1 for the Tegel wells and between 16,000 and 36,000 for STOborg19-/90V (Dutch wells between 200 and 2000 mL-1);
- Switching of neighbouring wells has no (Tegel) or negligible effect on particle concentrations;
- The origin of the particles is unknown. Most likely, recorded 'particles' are bacteria and/or iron precipitates, that are released from well head, pump and/or well screen

It is unclear if switching can be used to prevent chemical clogging. For this, information is required on particle origin and formation rate of bacteria and/or iron precipitates.

3.5.5 References

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3.5.6 Appendix

Operation schedule Tegel-Hohenzollernkanal and Stolpe-Borgsdorf (from BWB)

	April				2008		
	Su	Mo	Tue	Wed	Thu	Fr	Sa
	6	7	8	9	10	11	12
TEGhzk							
Br. 1	out of operation						
Br. 2	out of operation						
Br. 3	out of operation						
Br. 4	continuous operation						
Br. 5	continuous operation						
Br. 6	out of operation						
Br. 7	out of operation						
Br. 8	out of operation						
Br. 9	out of operation						
Br. 10	out of operation						
Br. 11	out of operation						
Br. 12	ON	ON	ON	ON	ON 14:17 p.m. OFF	OFF	OFF
Br. 13	ON 8 a.m. OFF	OFF	OFF 12:16 ON	12:00 OF 15:00 ON	15:00 OFF 18:00 ON	ON	ON
Br. 14	continuous operation						
Br. 15	out of operation						
Br. 16	out of operation						
Br. 17	out of operation						
Br. 18	ON	ON	ON	OFF	OFF 2 p.m. ON	ON	ON
Br. 19	ON	ON	ON	ON	ON 2 p.m. OFF	OFF	OFF
Br. 20	continuous operation						
Br. 21	OFF	OFF	OFF	00:00 ON	ON	ON 10 a.m. OFF	OFF
Br. 22	ON 8 a.m. OFF	OFF	OFF 12:16 ON	12:00 OF 15:00 ON	15:00 OFF 18:00 ON	ON	ON
Br. 23	out of operation						
Br. 24	OFF	OFF	OFF	OFF	OFF 2 p.m. ON	ON	ON

		April			2008		
	Su	Mo	Tue	Wed	Thu	Fr	Sa
STOborg	6	7	8	9	10	11	12
Br. 1	out of operation						
Br. 2	out of operation						
Br. 3	out of operation						
Br. 4	out of operation						
Br. 5	out of operation						
Br. 6	out of operation						
Br. 7	OFF	8 a.m. ON	3 p.m. OFF	OFF	OFF	OFF	OFF
Br. 8	out of operation						
Br. 9	out of operation						
Br. 10	ON	ON	OFF	OFF	OFF	OFF	12:00 ON
Br. 11	ON	ON	OFF	OFF	OFF	OFF	12:00 ON
Br. 12	continuous operation						
Br. 13	ON	ON	ON	ON	3 p.m. OFF	OFF	OFF
Br. 14	out of operation						
Br. 15	out of operation						
Br. 16	out of operation						
Br. 17	continuous operation						
Br. 18	out of operation						
Br. 19	ON	07.32 OFF 12:30 ON	13:03 OFF 16:00 ON	16:00 OFF 19:00 ON	ON	ON	ON
Br. 20	ON	ON	ON	ON	ON 9:35 a.m. OFF 15:00 ON	ON	ON

3.6 Core sampling

At current date (December 2008), the prototype of the core sampler was tested under real well conditions, but the sampling failed. Pigadi is working on re-developing the device.

3.7 Preventive treatment with H2O2

3.7.1 General procedure of H2O2 application at BWB

The preventive treatment with chemicals started as early as in the late 1960s for the BWB wells in the western part of the City (KREMS 1972). Since then, procedure and treatment intervals have been changed several times. For example since 1997, H_2O_2 is used instead of HClO.

The decision, which well is included in the preventive treatment program bases mainly on:

- visual inspections of the well interior by downhole cameras
- practical experience - for the western part of Berlin, Krems (KREMS 1972) studied microbiological clogging and developed recommendations for treatment; for the eastern part of Berlin, affected wells were equipped with gamma-emitters. After reunion these wells were included in the preventive treatment program
- field tests in the waterworks Friedrichshagen (personal note Lutz Schmolke, BWB-WV, 19.06.08)

Standard procedure is

- use of 1% H_2O_2 solution
- target concentration within the well is 300 ppm (eqivalent to 300 mg/l)
- treatment once per month

The H_2O_2 solution is mixed by BWS-staff prior to daily operation routine at a dosing station by adding a defined amount of water to a 50% solution.

The application into the well is done with an injection nozzle with a working pressure of 20 litres per minute. The nozzle is moved through the filter screen section of the well from top to bottom to distribute the H_2O_2 solution evenly to the whole filter section.

For the application at the single wells, the well management department of BWB (BWB-WV) has provided a list containing for each well:

- treatment interval
- calculation of the water volume from well diameter and length of filter section
- calculation of volume of 1% H_2O_2 solution to reach the target concentration
- calculation of time of application via high-pressure injection nozzle

3.7.2 Application at the transect [T. Taute, U. Maiwald, C. Menz, A. Pekdeger]

In the well, the inserted hydrogen peroxide dissociates in a catalytic reaction to oxygen and water.

$$2\ H_2O_2 \rightarrow 2\ H_2O + O_2$$

Because of high threshold energy, hydrogen peroxide is stable under normal conditions. Due to the presence of catalysts Fe^{3+}, Mn^{4+} or Cu^{2+} in groundwater, the reaction rate increases sharply.

By means of oxygen optodes, we are able to determine the amount of released oxygen from H_2O_2 dissociation in the saturated zone. The measuring principle of the optodes is based on the effect of dynamic luminescence quenching by molecular oxygen.

The oxygen sensors (optodes) are composed of 2 mm polymer optical fibre with an oxygen-sensitive foil. The detection device is a Fibox 3 from the company PreSens. According to PreSens, the optimal measuring range of the oxygen sensors is from 0 to 50 % oxygen and the limit of detection (LOD) is 15 ppb.

For the calibration of optodes, we use a 100 % oxygen-saturated solution and a completely oxygen-free solution.

For characterization of the spatial spread of oxygen, we installed optodes in six different depths of the five multi-level observation wells (see chapter 2.4). Additionally we placed a string of 7 optodes in intervals of 2m in the production well. A single optode was placed in a piezometer in the annulus of the production well in a depth of 11 m.

Impact of operation on the oxygen distribution during normal operation

Prior to the H_2O_2-treatment, we investigated the input of oxygen into the groundwater due to well operation. Therefore, we performed a short pumping test and measured drawdown and oxygen concentration for the well STO386 in a depth of 5 m.

Under static hydraulic conditions optode C3 is situated in the groundwater-saturated zone. During well operation, the optode falls dry due to the development of cone of depression.

In Figure 3-41, drawdown and oxygen concentration are shown for a short pumping test at well STOborg15-/90V.

We observed oxygen concentration of around 70 % air saturation during drawdown phase. After end of operation, the oxygen initially decreased quickly to 30 %. However, after complete recovery oxygen concentration is still around 10 % air saturation, which corresponds to 1mg/l dissolved oxygen.

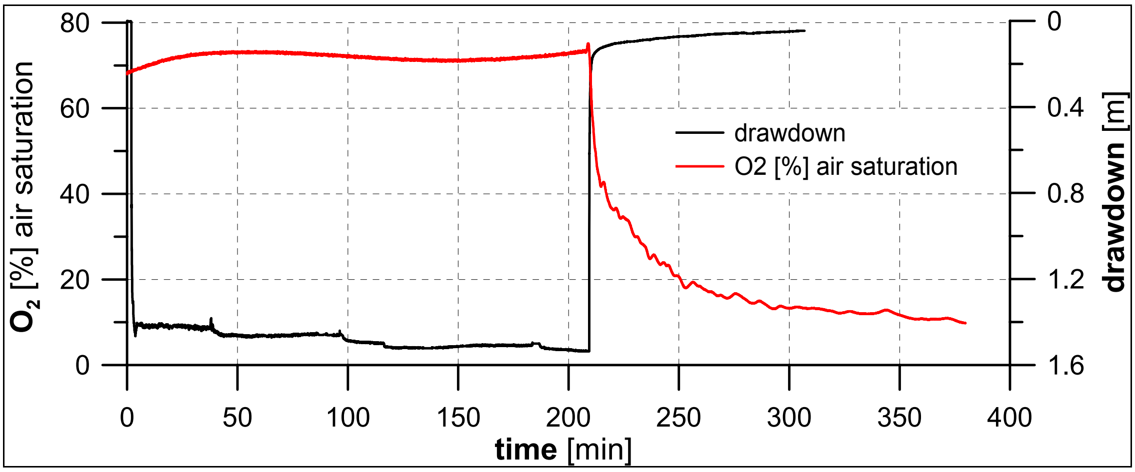


Figure 3-41: Recorded oxygen saturation and drawdown during a short-term pumping test at well STOborg15-/90V

During drawdown, air enters the unsaturated cone of depression. After shutdown of the operation pump, the cone of depression is filled up again and entrapping air bubbles, which are remaining in the pore space. Now the gases from these bubbles can be dissolved by the ground water and enter the well during the next drawdown.

Figure 3-42 shows the process of oxygen input due to air entrapment as a result of well operation.

This process recur every well operation interval. Thus, frequently operating wells abet under certain hydrochemical conditions the precipitation of dissolved iron and the clogging of wells.

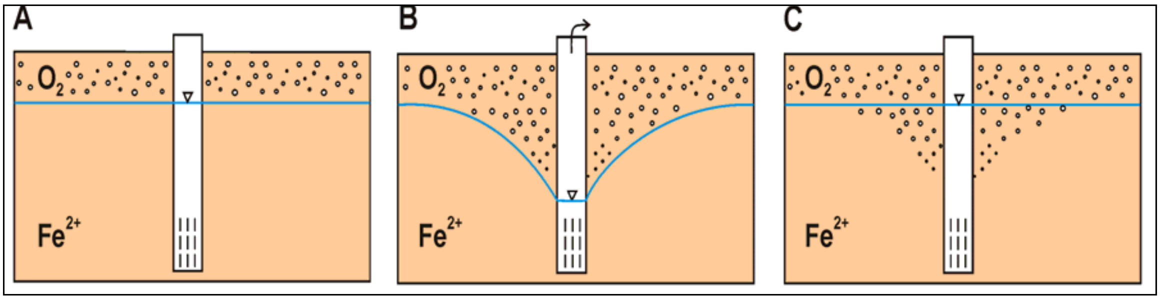


Figure 3-42: Schematic diagram of oxygen input due to air entrapment as a result of well operation: A: undisturbed hydraulic and hydrochemical conditions. B: Oxygen entry into the temporary unsaturated zone of cone of depression during well operation. C: Air entrapment due to recovery after shutdown of pump.

To specify the exact amount of input and degradation rates of oxygen, we have to perform a pumping test with 24h duration and recovery until initial state of oxygen before pumping.

Results

First experiments at the transect of well STOborg15-/90V show that the H_2O_2-treatment extensively affects the hydrochemical conditions around the well.

We observed the impact of H_2O_2 during und subsequent to the treatment in the operation well and the observation wells of the transect. The recorded oxygen measurements are shown as time series for every location.

The H_2O_2-treatment occurs at the time of 0. Deviating from the regular procedure described above, the contact time was 48 hours instead of 24 hours. After 30 hours contact time, we had to shutdown the pump again after 2 minutes of operation. A leaky sealing in the well chamber caused this extension of treatment. .

Oxygen measurement

Already a few minutes after the H_2O_2-input, we observed oxygen concentrations up to 100% in the production well. Within the first 24 hours of contact time concentrations decreased depth-depended to partially stable states (see Figure 3-43).

Therefore, oxygen concentrations noticeably reach their minimum after 24 to 30h contact time. During the pumping phase, (after 48 hours contact time) optodes reported elevated concentrations only for the well sump. Concentrations in the well decreased to zero within an hour after starting pump.

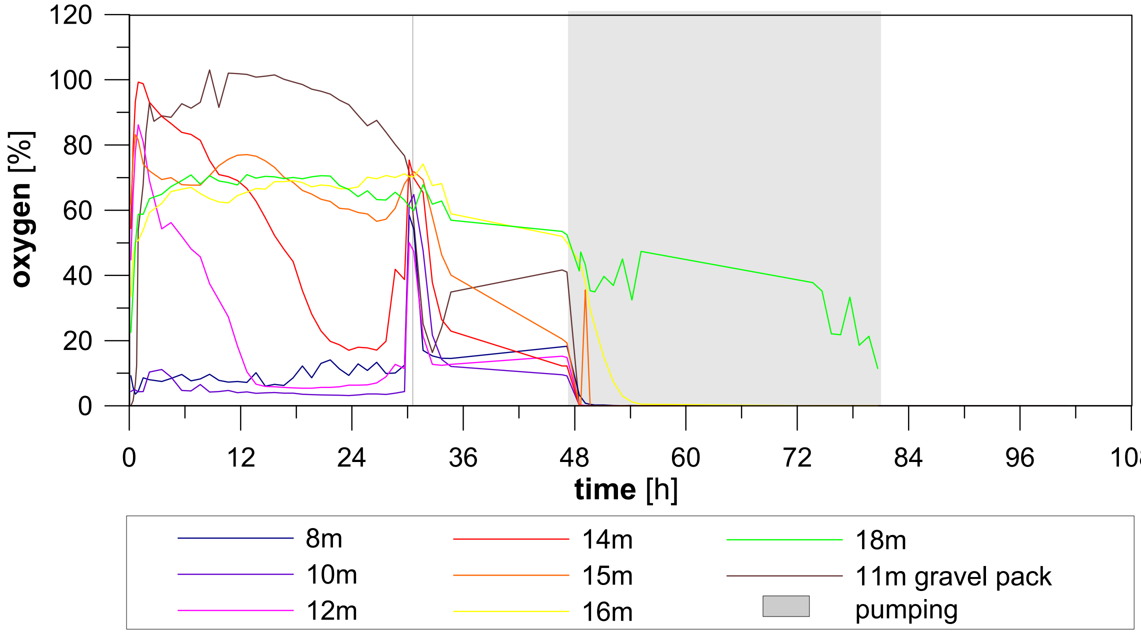


Figure 3-43: Time series of oxygen-measurements in the production well STOborg15-/90V during H2O2-treatment.

Measurements of oxygen concentrations in the transect show a different behaviour as expected (see Figure 3-44).

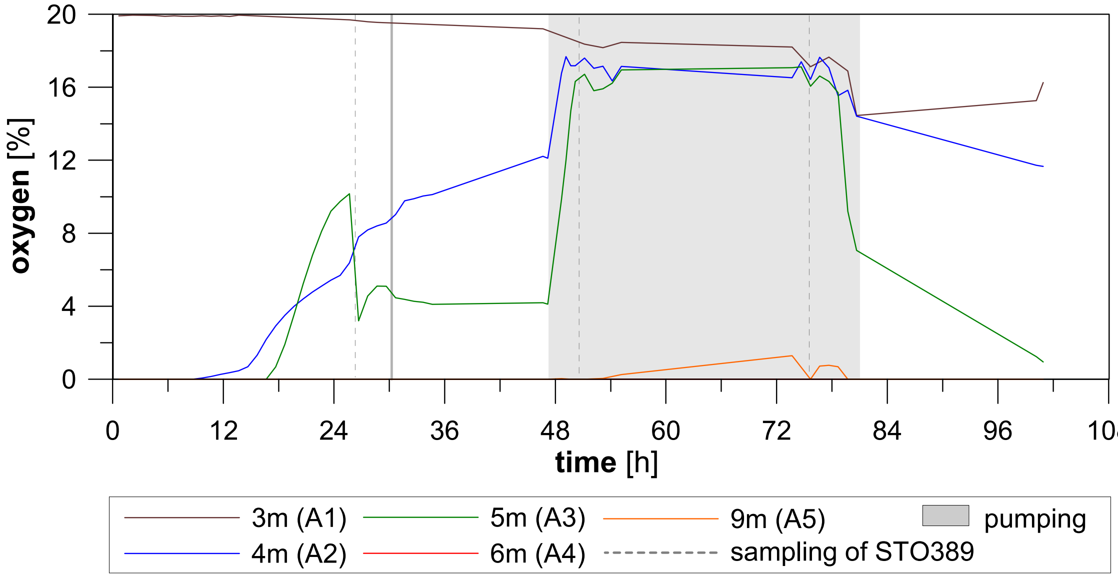
Oxygen concentrations in a depth of 3m represent the unsaturated zone with concentrations related to atmosphere.

Furthermore, measurements show increasing oxygen concentrations with increasing contact time in the upper 2m of the aquifer. Concentrations are about 4 to 12% at the end of contact time. Immediately after starting the pump, concentrations increase up to 18%. This is probably related to the development of the cone of depression and represents the transition from saturated to unsaturated conditions.

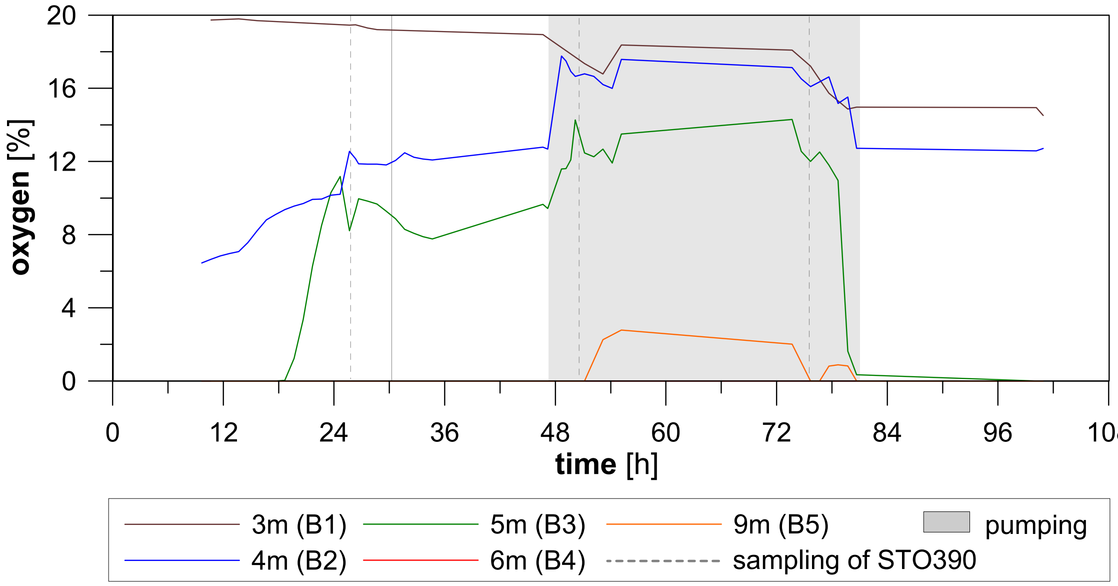
Furthermore, we observed an appearance of oxygen in a depth of 9m after 3h duration of pumping with concentrations up to 8%. After 6 hours duration of pumping similar oxygen concentrations appear in a depth of 6m.

Groundwater in a depth of 14m seems to be not influenced by the treatment and remained oxygen free.

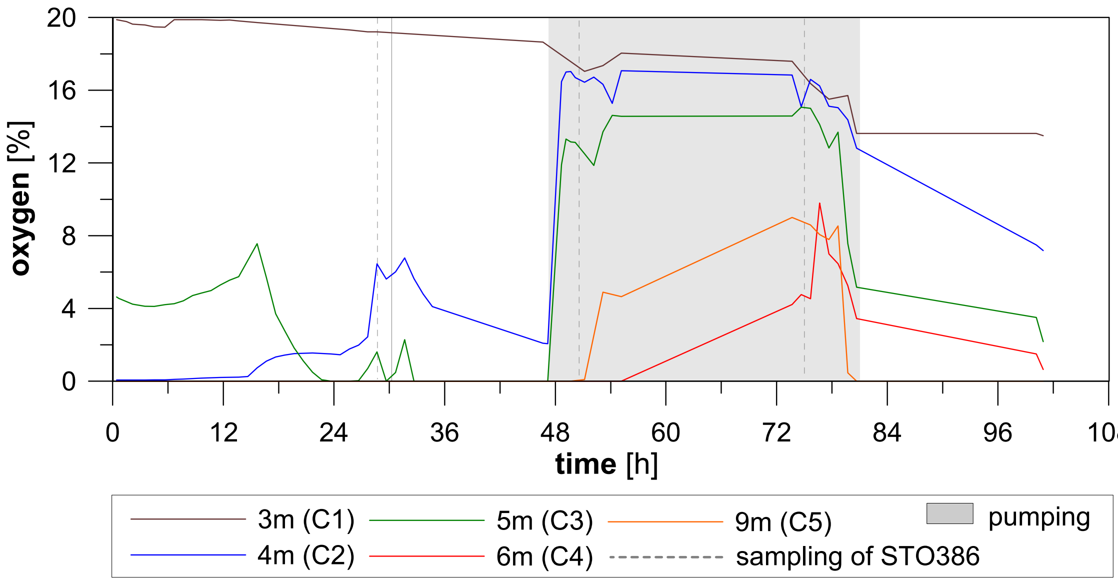
Additionally, the oxygen concentration and its appearance depend on the distance to the operating well. Near to the operating well, concentrations increase at first and in a distance of 5m delayed.



oxygen [%]
20
16
12
8
4
0
0
12
24
36
48
60
72
84
96
108
time [h]
3m (A1)
4m (A2)
5m (A3)
6m (A4)
9m (A5)
sampling of STO389
pumping



oxygen [%]
20
16
12
8
4
0
0
12
24
36
48
60
72
84
96
108
time [h]
3m (B1)
4m (B2)
5m (B3)
6m (B4)
9m (B5)
sampling of STO390
pumping



oxygen [%]
20
16
12
8
4
0
0
12
24
36
48
60
72
84
96
108
time [h]
3m (C1)
4m (C2)
5m (C3)
6m (C4)
9m (C5)
sampling of STO386
pumping

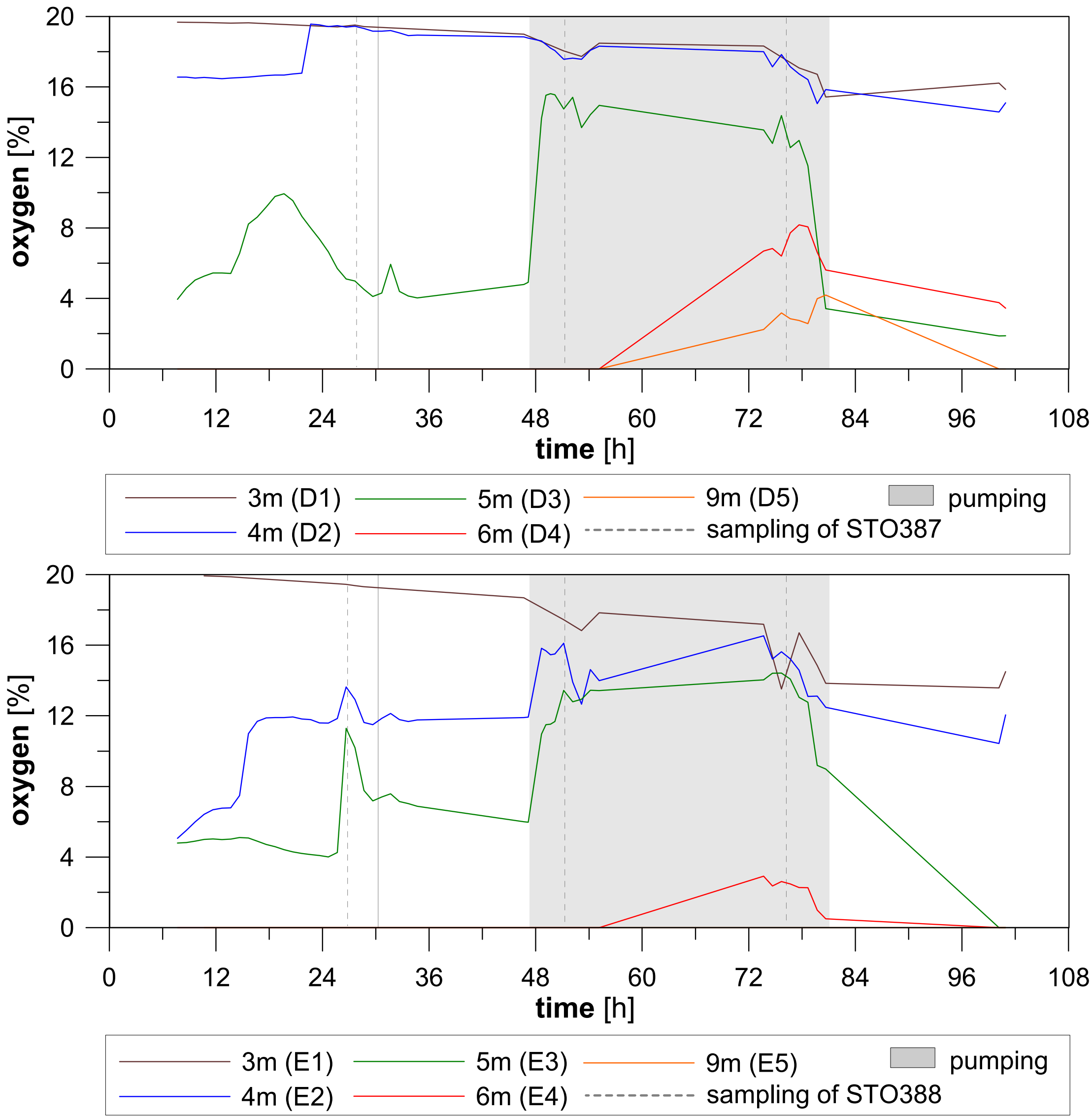


Figure 3-44: Time series of oxygen-measurements from the five observation wells of the transect.

Measurements indicate a disturbance of the hydraulic conditions by the hydrochemical sampling of the transect. This disturbance partially affects adversely the development of oxygen concentrations in the well vicinities.

First interpretations result in the assumption, that the H_2O_2-treatment affects extensively the physicochemical environment of the treated well. The measured oxygen concentrations indicate a lateral spread of oxygen beyond the 5m range in the upper zone of the aquifer during the contact time. Switching on the pump apparently results in a displacement of oxygen into deeper zones of the aquifer and a change of physicochemical conditions. The impact of H_2O_2-treatment is illustrated in Figure 3-45.

Measurements indicate a mushroom-shaped spread of oxygen dissociated from H_2O_2. We assume that the development of oxygen gas bubbles could be responsible for the rapid and widespread displacement of oxygen. Elevated permeabilities in the gravel pack could provide the rapid ascent of gas bubbles. Further investigations will be required proving this thesis.

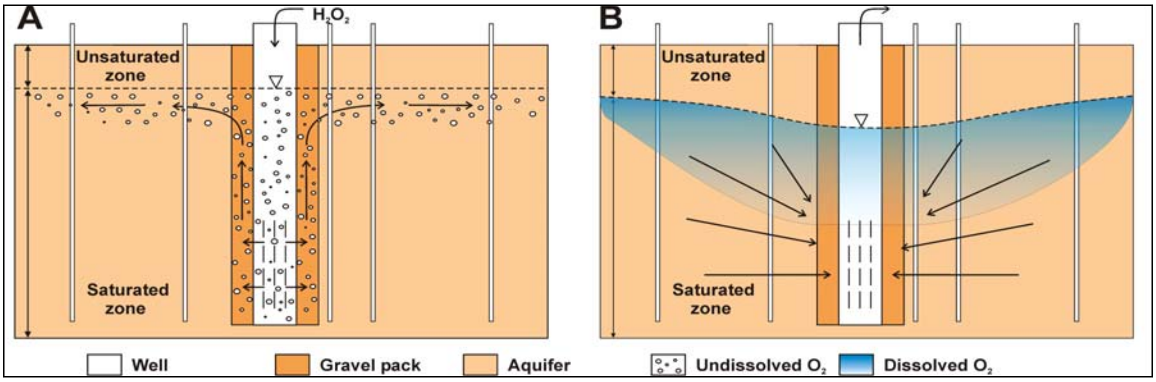


Figure 3-45: Schematic view at the spread and distribution of oxygen during (A) and after (B) H2O2-treatment

Iron mass balance calculations

For a first estimation of precipitation rates for iron(III)hydroxides, we compared iron(III) concentrations of abstracted water from the production well and from the observation transect.

We calculated Fe-concentrations for bank filtrate and groundwater entering the production well. For every sub zone of the aquifer profile, we determined discharge rates, based on hydraulic conductivities, and associated Fe-concentration (see Figure 3-46):

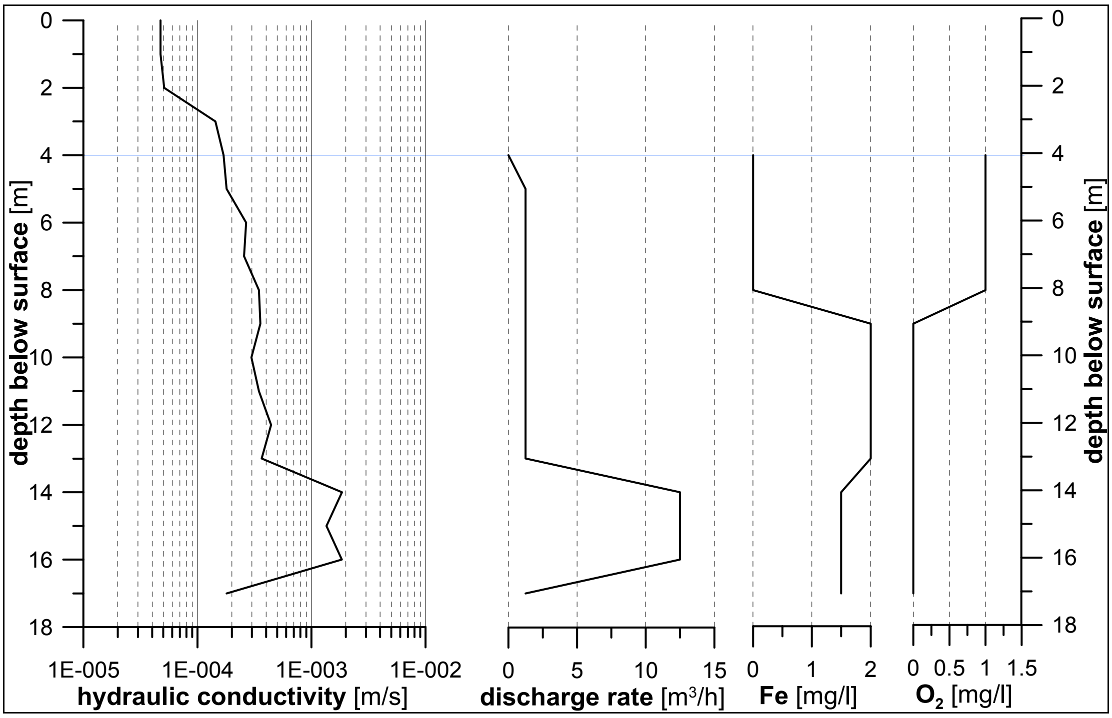
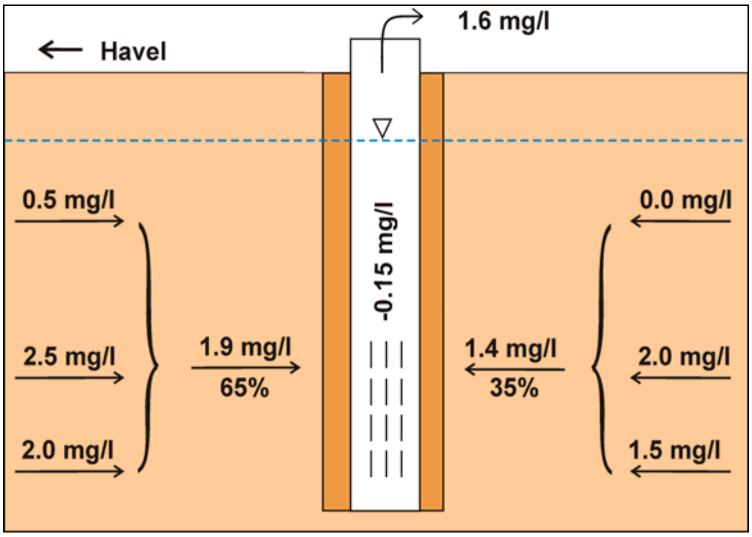


Figure 3-46: Vertical distribution of hydraulic conductivity, specific discharge rate, Fe and O2-concentrations of STO387.



We assume a mixing of bank filtrate and groundwater in a ratio of 2:1 in the production well. This assumption based on analysis of electric conductivities and stable isotope data. Characterisation of Fe-concentrations in the in the well vicinity are shown in Figure 3-47.

Measured Fe-concentrations of abstracted well water are about 1.6 mg/l, whereas calculated Fe-concentrations are about 1.75 mg/l.

Figure 3-47: Characterisation of Fe-concentrations of different groundwater layers mixing in well STOborg15-/90V.

This means a loss of around 10% Fe and corresponds approximately to 7g Fe per hour for an overall discharge rate of 50m^3/h. Hence, this loss is in all probability due to precipitation of Fe(III)hydroxides in the well and its vicinity.

Due to the estimation of parameters, calculated values are not considered as absolute values. However, results provide valuable indications to quantify the dimension of precipitation rates of Fe.

Impacts of H_2O_2 on the hydrochemical conditions

Hydrochemical analyses of samples taken from transect show significant changes during H_2O_2-treatment. These changes are obvious for concentrations of Fe, Mn, and DOC and show a spatial dependence (see Figure 3-48).

Concentrations of bank filtrate in STO389 show no significant variations during test duration. However landwards, Fe and DOC concentrations increased considerably during the contact time in deeper groundwater.

After initiation of well operation, Fe and DOC concentrations decreased extensively and remained low. Due to the presence of oxygen from H_2O_2-treatment Fe probably precipitated in the well near aquifer and depleted in the groundwater.

Depletion of DOC could be the result of chemical or/and microbiological processes also driven by the presence of oxygen.

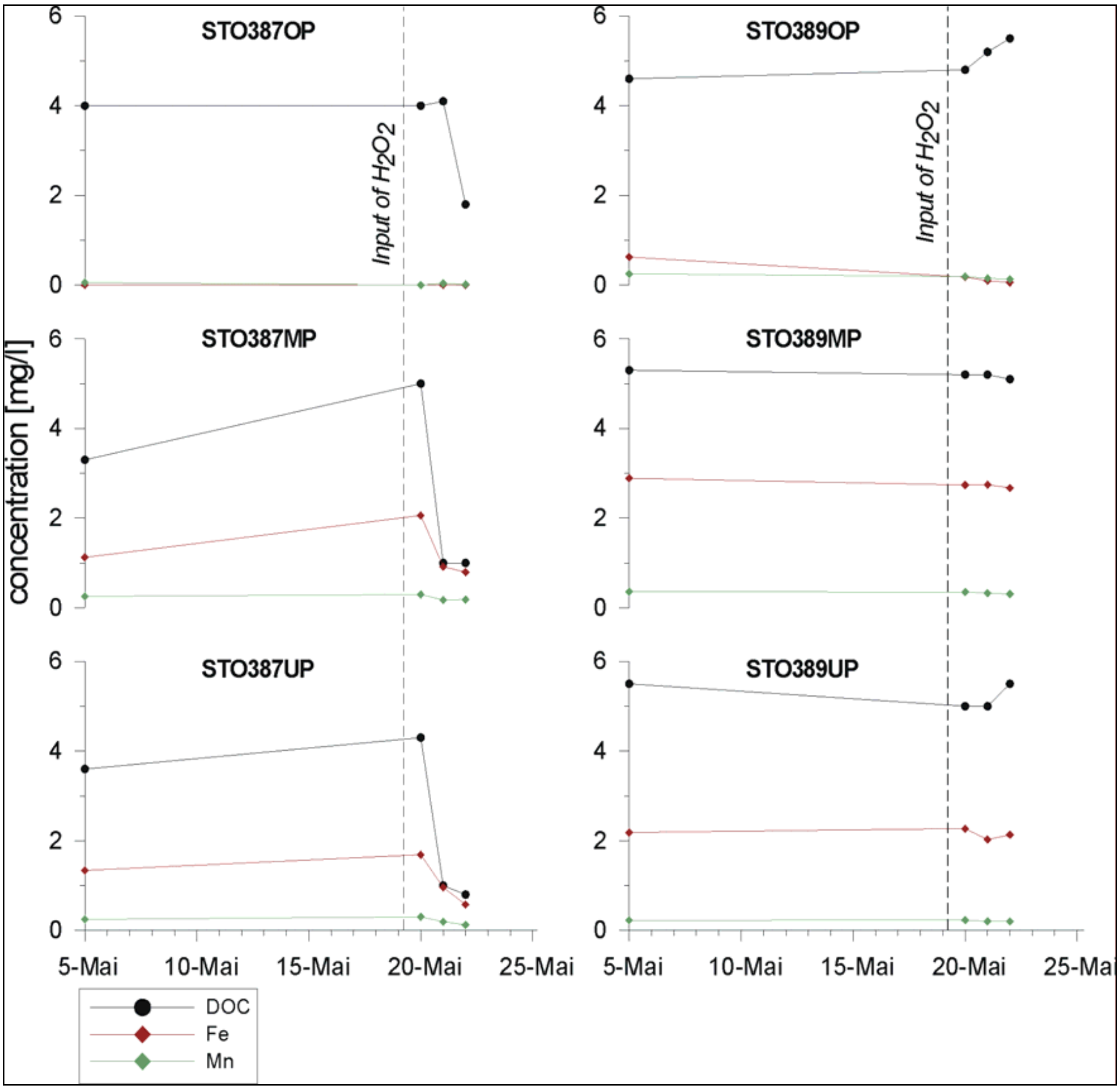


Figure 3-48: Development of Fe, Mn and DOC concentrations during investigation of H2O2 influence on hydrochemistry in two observation wells of the transect at well STOborg15. The observation wells are installed in a distance of 2,50 m from the well.

Impact on well capacity

To evaluate the immediate impact of the H_2O_2-treatment on the well clogging, we perform two step-drawdown tests at the well STOborg15-/90V.

The tests were carried out two weeks before and one week after the treatment. We try to provide equal conditions (pumping rates, duration of pumping, stable hydraulic environment) for both tests. Figure 3-49 shows drawdown and discharge before and after the treatment for the well and a nearby piezometer.

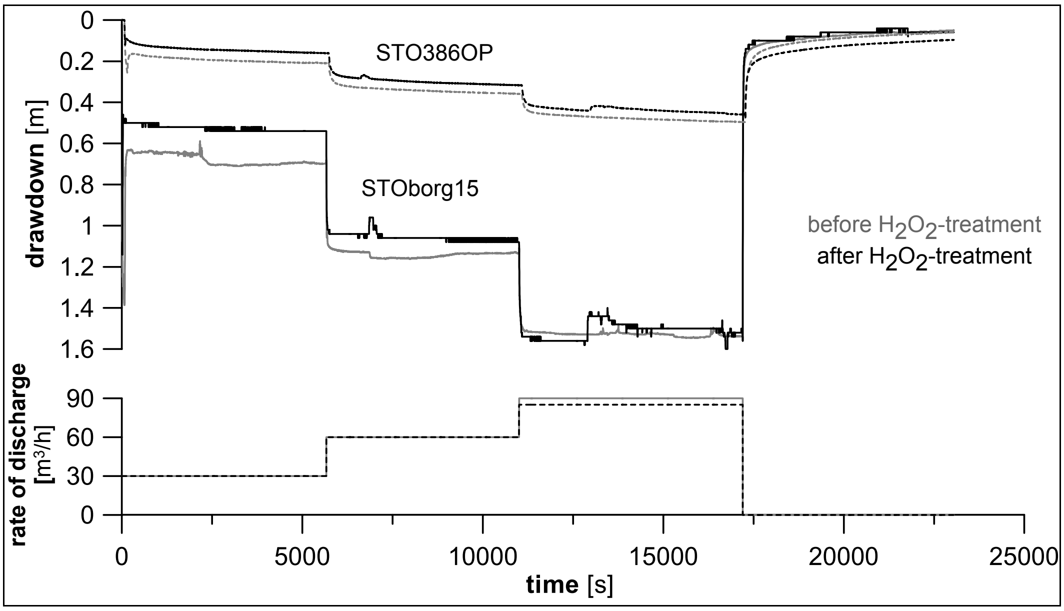
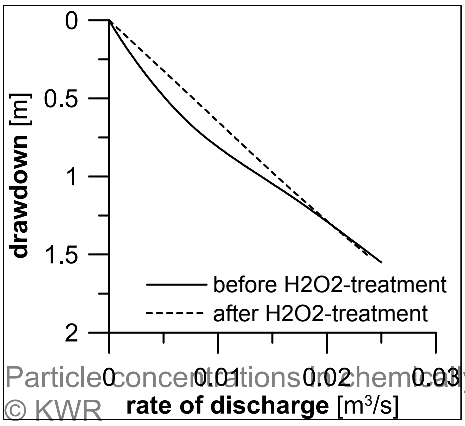


Figure 3-49: Recorded drawdown and pumping rates of well performance tests at well STOborg15-/90V.

We almost achieve similar conditions for the tests. We observe a significant difference in drawdown for the well as well as for the piezometer. The decreased drawdown for all steps in the piezometer after the treatment indicates a better hydraulic connection between aquifer and well. For the well, this difference decreases in second step. Comparison of step (3) is complicated due to variations of pumping rates. The recovery phases of the tests do not show significant differences.

Table 3-10: Specific capacities for every step of the performance tests

	Rate of discharge	drawdown	Specific capacity
	$[m^3/h]$	[m]	$[m^3/h/m]$
Before H_2O_2-treatment	30	0.7	41.1
	60	1.14	53.7
	90	1.55	58.1
After H_2O_2-treatment	30	0.54	55.6
	60	1.08	55.6
	85	1.52	56.8



We calculate specific capacities for every step of the performance tests (see Table 3-10 and

Figure 3-50). From this follows, that capacities for the step (1) and (2) are higher after the treatment than before. However, for step (3) capacity this is vice versa. Possibly fluctuating pumping rates affect this result.

Figure 3-50: Q/s-diagram for performance tests before and after H_2O_2-treatment.

From Table 3-11 it appears that water table was 11cm higher during the pre-treatment test. This also may cause differences in drawdown.

A first interpretation of the data, point to a minor impact of the H_2O_2-treatment on the well clogging. This impact appears more obvious for lower pumping rates and fades with increasing discharge.

For a definite evaluation of the direct impact of the H_2O_2-treatment on the well clogging, we have to compare these results with those of the TV-inspection and borehole geophysical tests.

Furthermore, we recommend to repeat this test to back up our thesis and to eliminate potential sources of error.

Comparison of borehole geophysical logging before and after H_2O_2 treatment

The measurement program was the same as for the three abandoned wells, described in chapter 3.4.3, page 47 and - to provide comparability - before (05.05.2008) and after (23.05.2008) H_2O_2 treatment.

In addition, the same persons did the logging and interpretation.

The borehole geophysical investigations showed no impacts of an H_2O_2 treatment on the permeability of the gravel pack or the distribution of water intake. The logs before and after H_2O_2 application show identical characteristics for all measurements.

Table 3-11: Basic data and initial water level of well STOborg15-/90V and associated transect for well performance tests.

Observation well	Casing top above s. l.	Surface above s. l.	Before H_2O_2-treatment 22.04.2008			After H_2O_2-treatment 30.05.2008			Reference point
			Water table below casing	Water table below surface	Water table above s. l.	Water table below casing	Water table below surface	Water table above s. l.	
STOborg15 well	35.200	34.740	4.100	3.640	31.100	4.215	3.755	30.985	well cover
STOborg15 annulus	35.200	34.740	4.100	3.640	31.100	4.210	3.750	30.990	well cover
STO386OP	35.715	34.817	4.610	3.712	31.105	4.720	3.822	30.995	casing
STO386MP	35.715	34.817	4.605	3.707	31.110	4.720	3.822	30.995	casing
STO386UP	35.715	34.817	4.605	3.707	31.110	4.720	3.822	30.995	casing
STO387OP	35.677	34.862	4.570	3.755	31.107	4.681	3.866	30.996	casing
STO387MP	35.677	34.862	4.565	3.750	31.112	4.681	3.866	30.996	casing
STO387UP	35.677	34.862	4.570	3.755	31.107	4.682	3.867	30.995	casing
STO388OP	35.736	34.897	4.620	3.781	31.116	4.742	3.903	30.994	casing
STO388MP	35.736	34.897	4.625	3.786	31.111	4.742	3.903	30.994	casing
STO388UP	35.736	34.897	4.620	3.781	31.116	4.742	3.903	30.994	casing
STO389OP	35.577	34.778	4.465	3.666	31.112	4.586	3.787	30.991	casing
STO389MP	35.577	34.778	4.465	3.666	31.112	4.586	3.787	30.991	casing
STO389UP	35.577	34.778	4.465	3.666	31.112	4.582	3.783	30.995	casing
STO390OP	35.670	34.895	4.555	3.780	31.115	4.672	3.897	30.998	casing
STO390MP	35.670	34.895	4.560	3.785	31.110	4.675	3.900	30.995	casing
STO390UP	35.670	34.895	4.555	3.780	31.115	4.672	3.897	30.998	casing

Chapter 4
Discussion of the field investigation results

Clogging of wells leads to different characteristics of the resulting deposits. Not only is the quantity varying, but also the composition, structure and location.

Based on the results of the microbiological and molecular biological examinations during WellMa1/ WellMaDNA, it can be concluded that bacteria with the potential to deposit iron and/or manganese occurred in all investigated wells.

First trials to correlate physico-chemical parameters of a well with the existing bacteria by a cluster analysis of the chemical data together with the band patterns of the DGGE trials yielded promising results as they indicate a correlation of the predominant morphotype of iron bacteria and the chemical conditions in the well (see Figure 4-1).

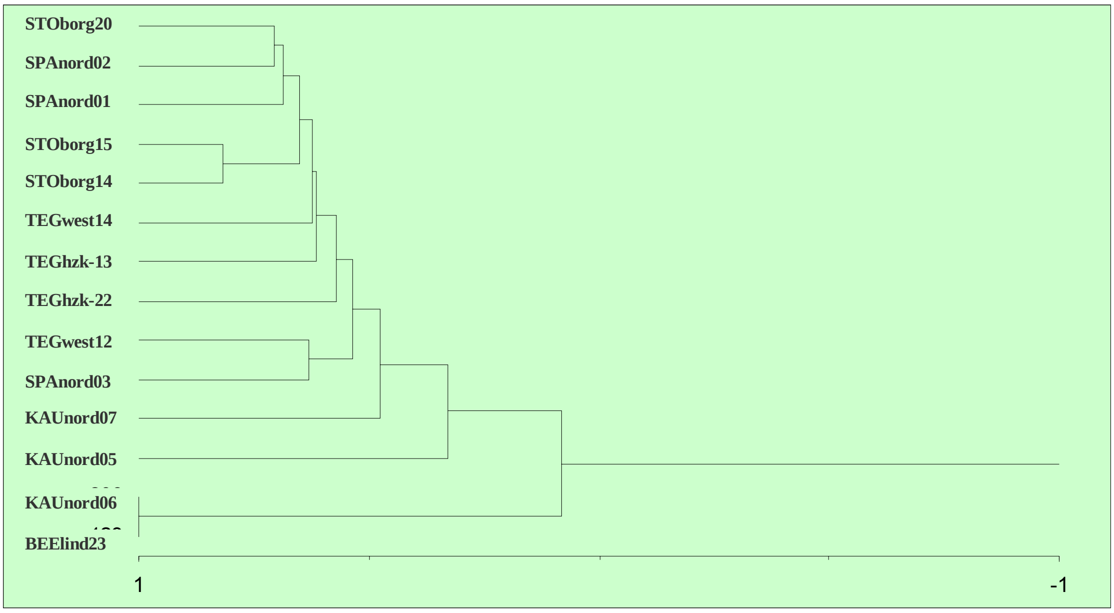


Figure 4-1: Cluster analysis for STM-wells based on hydrochemical parameters and DGGE bands.

In addition, the correlation of the ratio of beta-proteobacteria (iron-related bacteria) to the total cell count with the Iron-Manganese ratio showed that at low iron-manganese-ratios the ratio of beta-proteobacteria is high (see Figure 4-2).

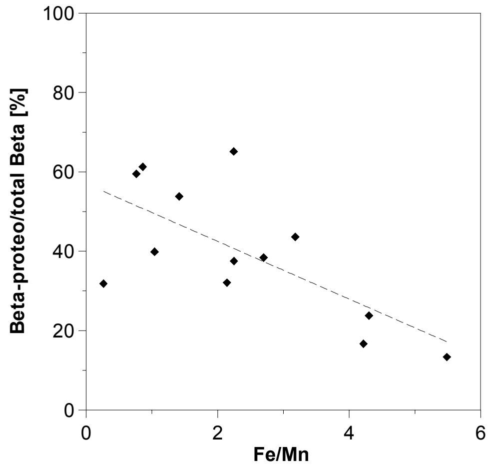


Figure 4-2: Correlation of the ratio of beta-proteobacteria to the total cell count with the Iron-Manganese ratio

This reinforces the working hypothesis that bacterial population of the respective wells correlate with the chemical condition and indicates the occurrence of biological clogging processes.

While the presence of iron-related bacteria in water, deposit and biofilm samples and their correlation to the geochemical site conditions could be proven, it remains unclear

(1) if biological clogging is really the dominant process with regard to the composition of the abundant deposits or to which share chemical precipitation and physical processes (colmation) contribute to clogging and

(2) to which extent the observed loss of well performance is due to the visible deposits (TV inspection) or caused by processes hidden within the gravel pack.

Therefore, future investigations at selected sites should include the detailed evaluation of clogging deposit samples from different locations within a well (pump, casing, screen), e.g. by

- the loss on ignition to determine the share of organic material in relation to the total mass
- X-ray fluorescence analyses to determine the abundance of clay minerals, silicates, carbonates etc.

To differentiate the impact on the well performance from the differently located deposits, a combination of pump tests and cleaning steps is recommended.

Chapter 5
Conclusions

5.1 Comparison of field methods

Generally, step discharge tests have the potential to provide an early identification of well deterioration. However, for the significance of pump tests to evaluate the well performance, the rate of discharge is the decisive factor as was also concluded from the statistical analyses. For a comparability of step-drawdown tests as well as for short pumping tests the discharge rates have to be equal.

Altogether, the further applied borehole geophysical methods to assess porosities and permeabilities of the gravel pack and the distribution of water intake (flowmeter and packer flowmeter) were not sufficient to clearly indicate well ageing processes as they remain to be indirect methods only. Statements can only be made by comparison to the initial status. For a final assessment of these standard methods, core sampling needs to be successfully implemented to compare the location and extent of deposits within the gravel pack to the indications from Δh-values, loss of specific capacity, TV inspection, borehole geophysical logging and particle counting.

Compared to routine analyses of the water quality, the hydrochemical investigations conducted at the 21 wells yielded no additional benefits for the diagnosis of ageing processes. Generally, the analysis of the physico-chemical water parameters (pH, redox-potential, O_2-content, conductivity and temperature), main cations (calcium, magnesium, potassium, sodium, iron, manganese), anions (chloride, brome, florid, sulphate, phosphate, nitrate) and nutrients (DOC) allows the assessment of

(1) the presence of starting materials for chemical clogging and
(2) the living conditions for bacteria responsible for biologically induced clogging.

But, as the sampling was done within the already mixed raw water, it does not allow the identification of redox processes and the potential to precipitate deposits. Here, a depth-oriented sampling would be necessary to allow the evaluation of

(1) Saturation indices (e.g. for iron or carbonates) and
(2) Redox clines

to conclude the preferred location of deposits (see chapter 2.2 of the full state of the art report).

The different molecular biological investigation methods applied have proven to be suitable and reliable identification and detection of bacteria causing ochreous depositions. However, the diversity of these bacteria is higher than expected from the work of other groups during the last centuries. Bacteria, which have been identified by microscopic features and classified only by morphology, can now be more precisely specified with the developed methods. These new methods will allow to correlate specific groups of ochreous-depositing bacteria with environmental conditions in the respective wells and operation procedures of the wells.

The assessment of the significance of the BART tests is subject of further molecular biological investigations, in which DGGE will be used to identify, if the bacteria cultivated within the BART test kits correspond to the IRB relevant for clogging. The continuation of BART is therefore not recommended at the moment.

The benefit and significance of particle measurements cannot be finally assessed yet, because horizontal cores have not been taken. However, particle counting was successfully applied to assess physically clogged wells in the Netherlands. The method might be used in France at wells known to be affected by physical clogging, but together with a sampling and characterization of the abstracted particles to determine their origin.

5.2 Recommendations for well monitoring and diagnosis

Generally, the field tests have shown that only a combination of methods leads to an early recognition and diagnosis of ageing processes. The application of the above-described methods has already now shown that there is the following room for improvement for the methodologically approaches for well monitoring:

- The initial evaluation of a well (at the start of operation) should include in addition to the step discharge test: a GG.D, FLOW and Packer-FLOW to record the initial condition of the gravel pack for the later assessment of the porosity and permeability to distinguish between geologically induced intake distributions and deterioration by well ageing processes (deposits within the gravel pack).
- Short pumping tests are suitable for routine monitoring of well performance, if they are carried out with constant discharge and duration (per well).
- For a control of rehabilitation methods, step-drawdown tests provide the required information. They should be performed with pumping rates and durations specified during the initial tests after building.

5.3 Recommendations for the design of field investigations for WellMa2

Further field investigations should aim at:

(1) Method validation

- The evaluation of the use of Δh and the combination of Qs measurement and TV inspection to assess the degree of ageing and location of the deposits
- Input-output-calculations for iron- and oxygen concentrations in the well and well surrounding to identify the amount of iron deposition rates

(2) Method development

- Depth-oriented sampling to assess the redox clines within the well before mixing
- Combined examination by microscopy and molecular methods (DGGE and PCR) of deposit and biofilm samples to develop an easy to apply molecular tool based on qPCR to quantify the presence of iron-related bacteria
- Mineralogical and microbiological characterization of deposit samples from different depths within the well (e.g. pump, casing, top of filter, end of filter)
- Qs assessment with a stepwise removal of deposits to determine their share on the total loss of performance (accompanying rehabilitation)

Step discharge tests, or at least short pumping tests with fixed discharge rates should be implemented in routine measurements for all wells, so that the data will be available from the well files.

(3) Knowledge transfer

- Correlations between bacteria communities and living conditions (geochemical characterization)
- Correlations between the appearance and rate of clogging to well construction materials and between well construction materials and different bacteria communities

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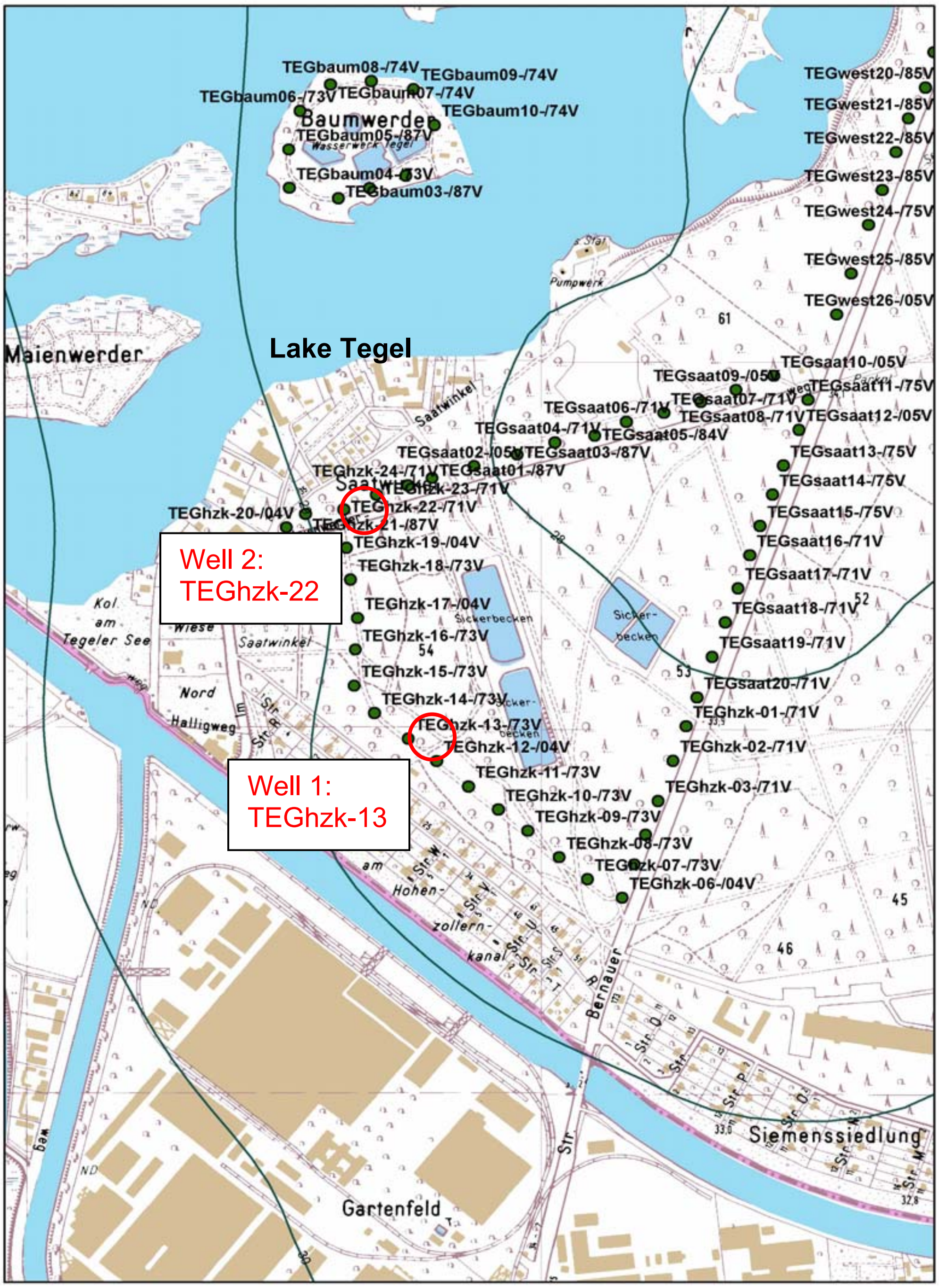
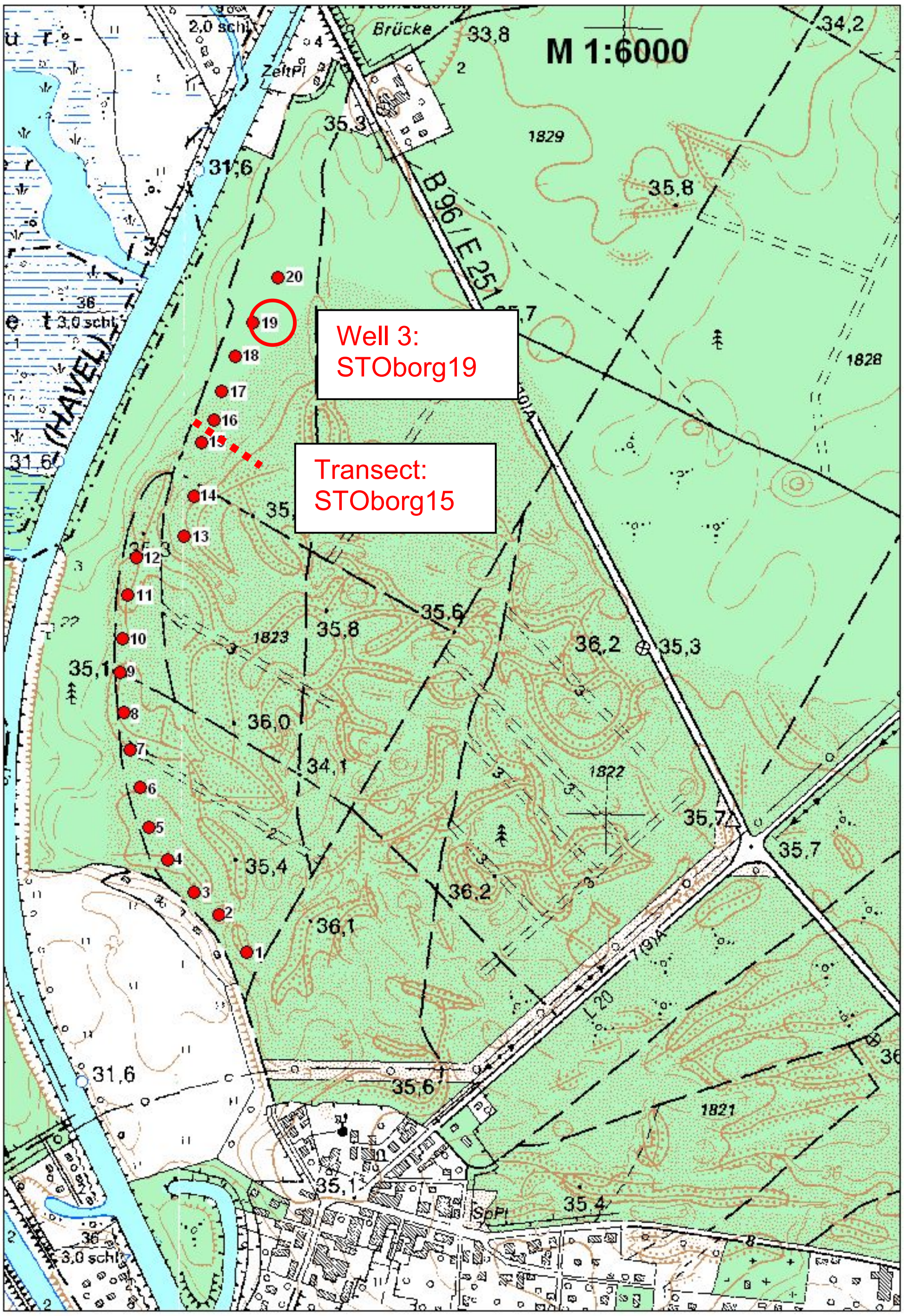
Appendix A

Well sites for task 1.4



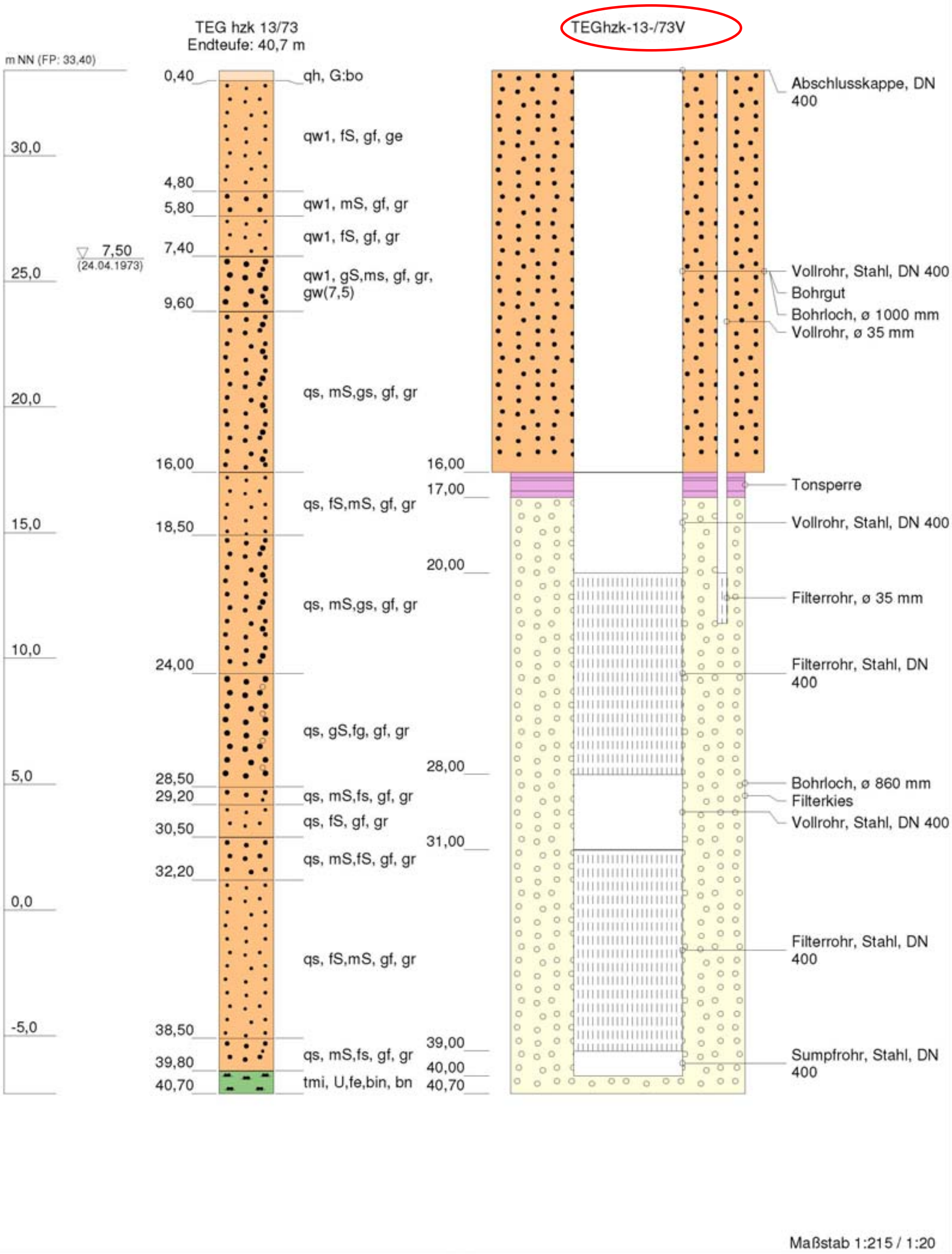
Map 1: Location of the wells at Tegel Hohenzollernkanal, D-13599 Berlin-Tegel



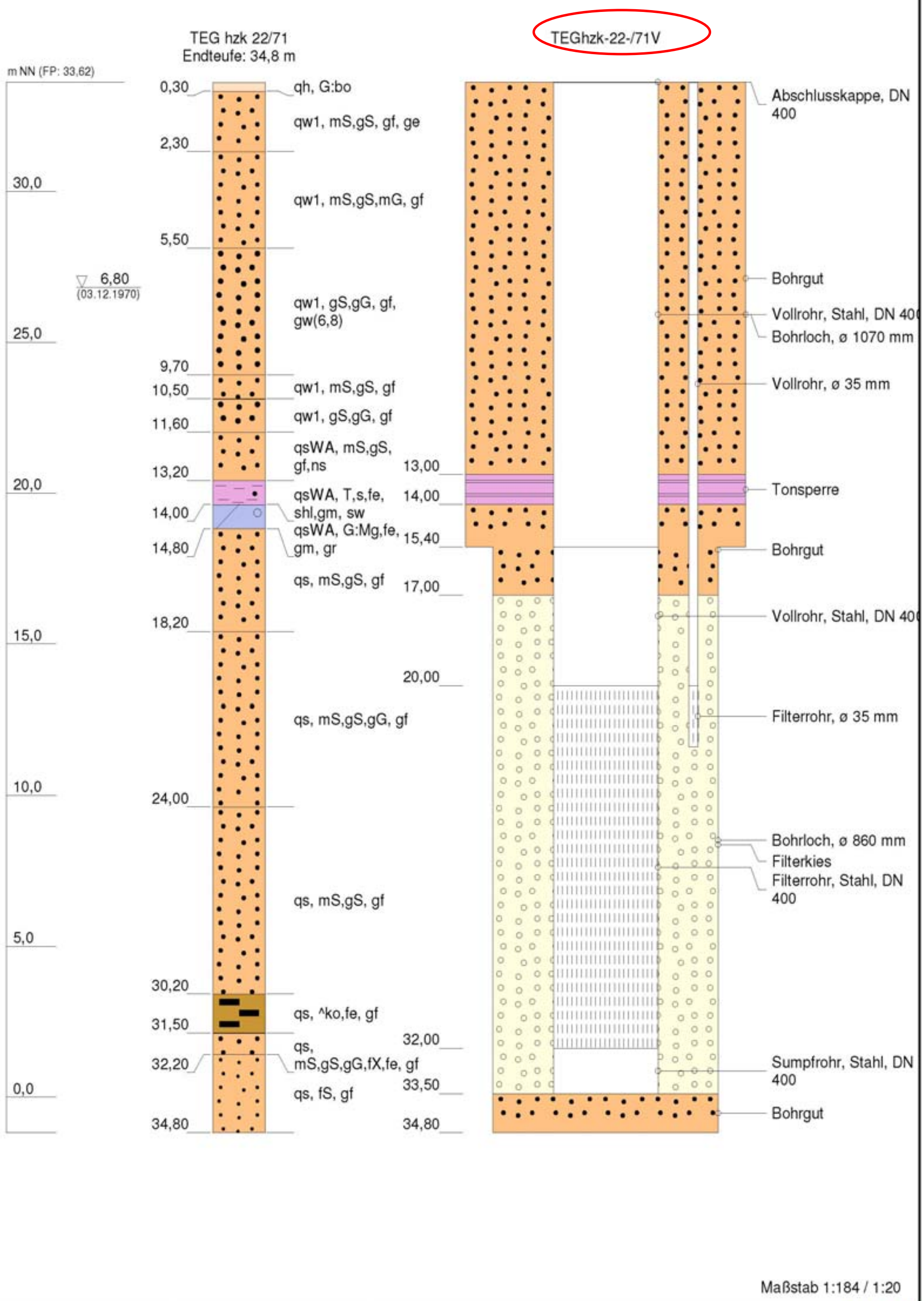
Map 2: Location of the well sites at Stolpe Borgsdorf, D-16556 Borgsdorf

Appendix B

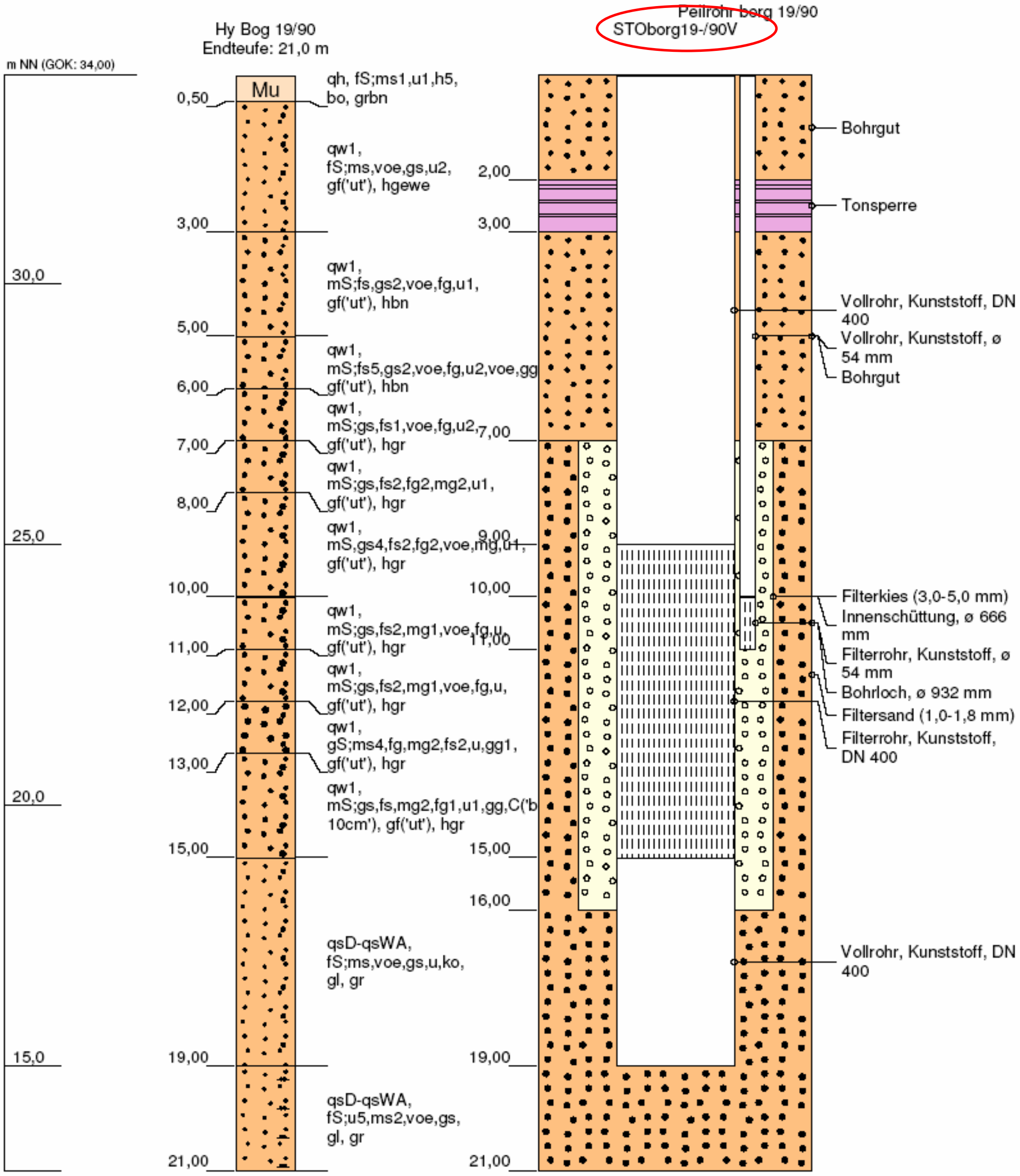
Cross sections of the four wells for task 1.4



Berliner Wasserbetriebe WV-S/W		WW Tegel	WRM
	Siebenthaler 31.03.2008	Gal. Hohenzollernkanal	

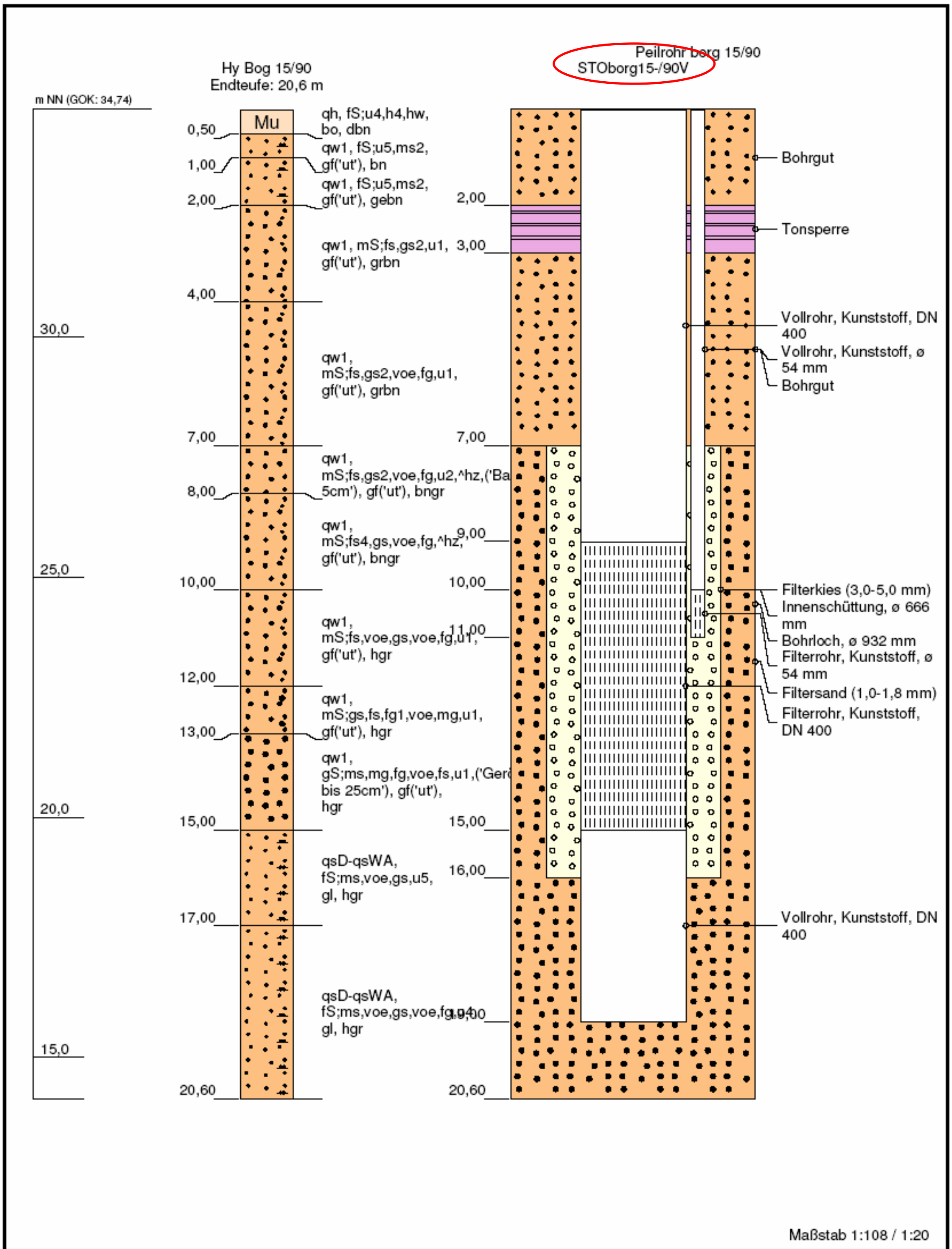


Berliner Wasserbetriebe WV-S/W		WW Tegel	WRM
	Siebenthaler 31.03.2008	**Gal. Hohenzollernkanal**	



Maßstab 1:111 / 1:20

Berliner Wasserbetriebe WV-S/W			WRM
	Siebenthaler 20.12.2007	**Ausbau- und Schichtenverzeichnis**	

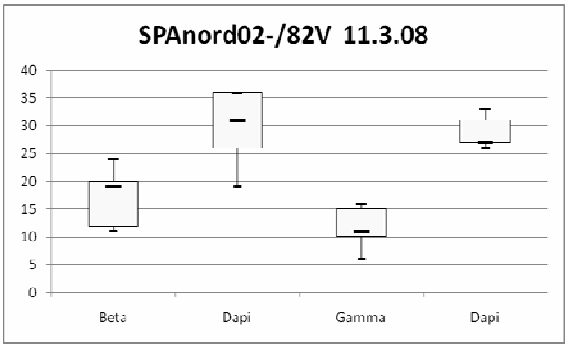


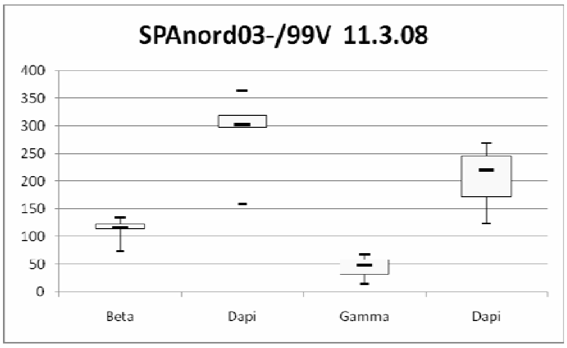
Berliner Wasserbetriebe WV-S/W			WRM
	Siebenthaler 20.12.2007	**Ausbau- und Schichtenverzeichnis**	

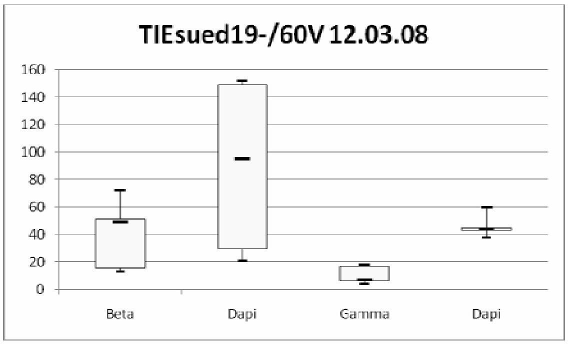
Appendix C

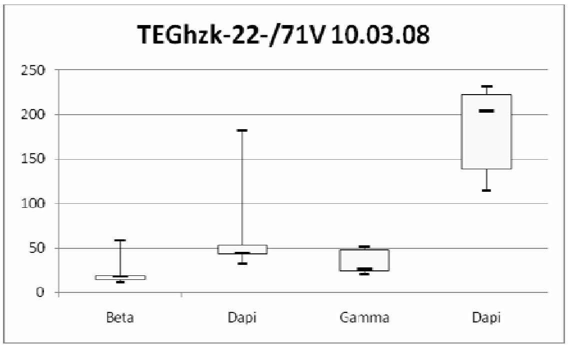
Results of hybridization trials

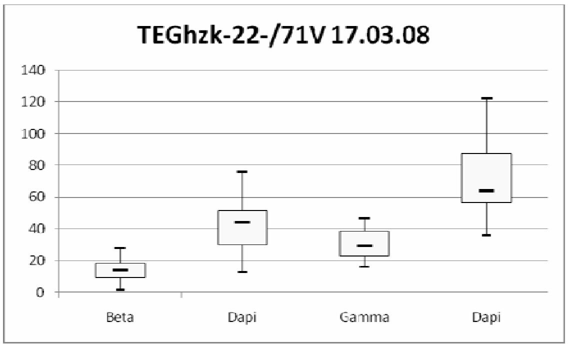
On the x-axis the respective probes (beta and gamma) , on the y-axis the cell count per counting array is depicted. “Dapi” labels the respective total cell count for each probe, with the unspecific DNA dye DAPI.

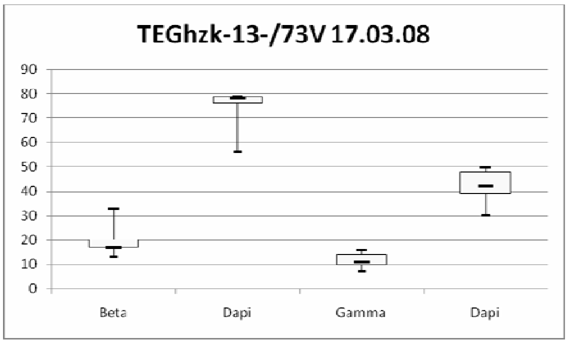


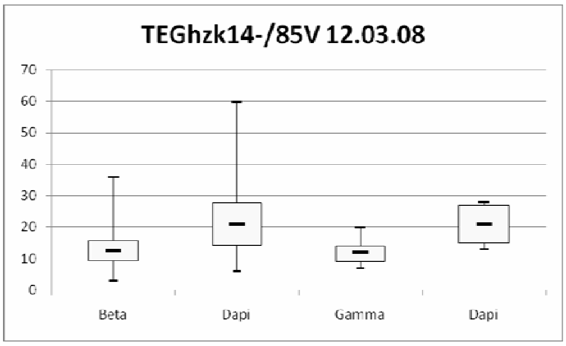


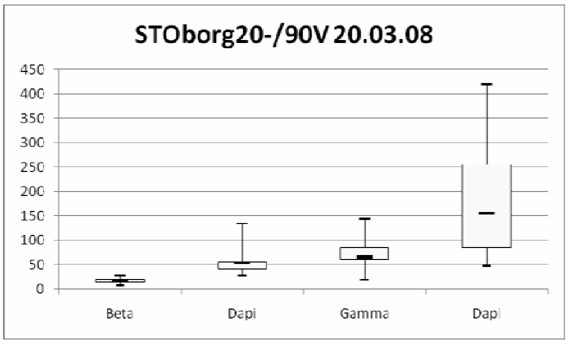


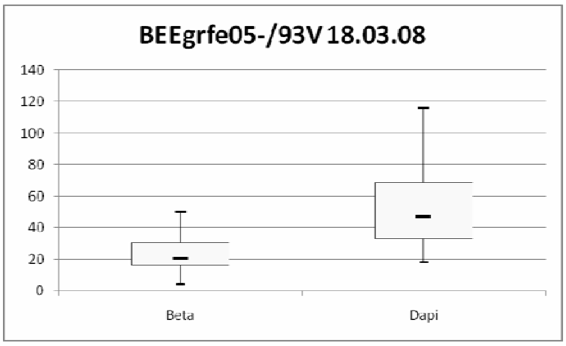








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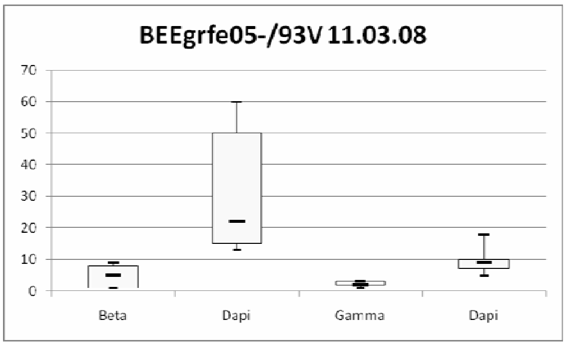
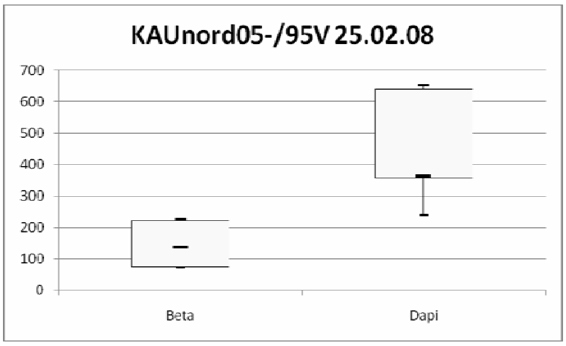
140
120
100
80
60
40
20
0
Beta
Dapi


BEEgrfe05-/93V 11.03.08
70
60
50
40
30
20
10
0
Beta
Dapi
Gamma
Dapi


KAUnord05-/95V 25.02.08
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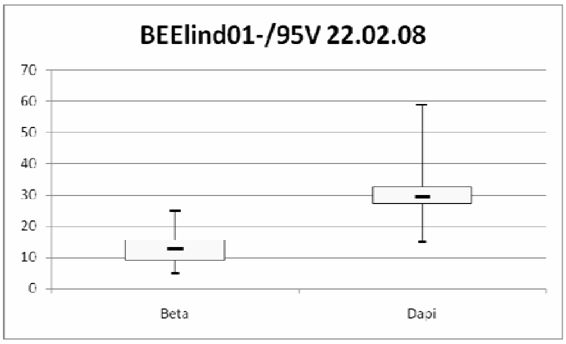
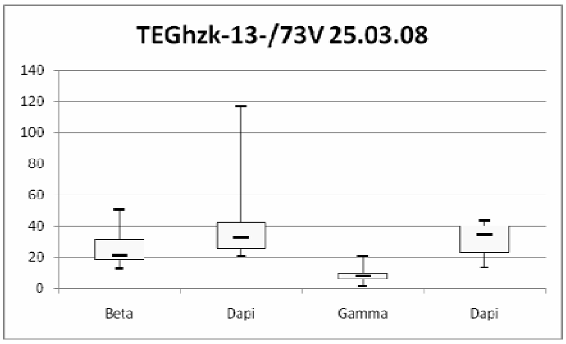
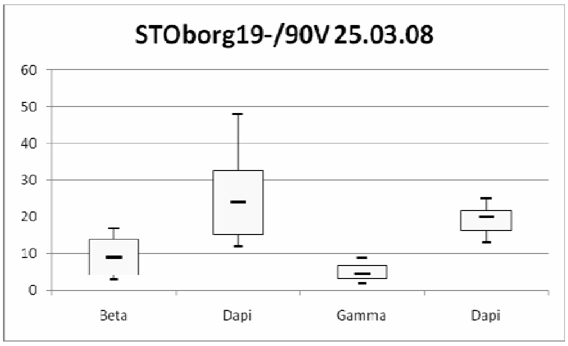
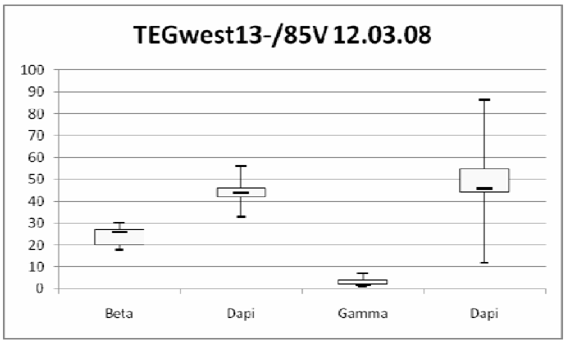
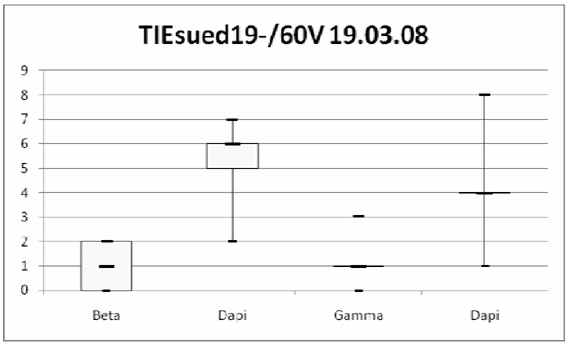
600
500
400
300
200
100
0
Beta
Dapi

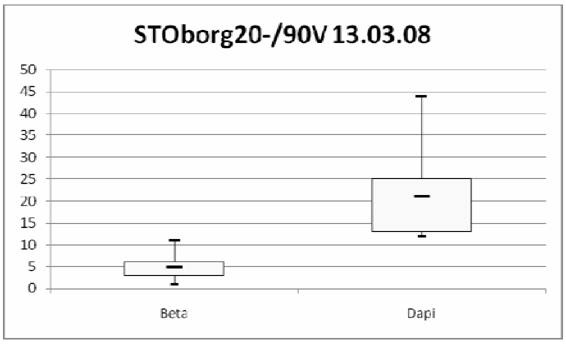

BEElind01-/95V 22.02.08
70
60
50
40
30
20
10
0
Beta
Dapi

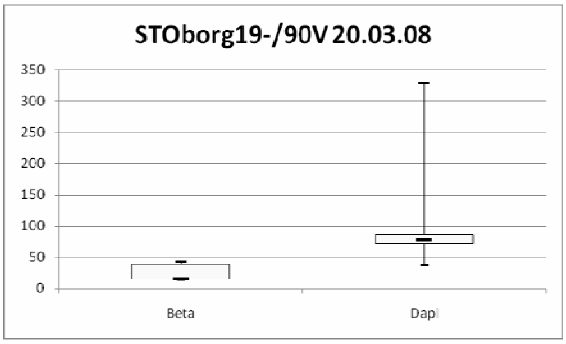

TEGhzk-13-/73V 25.03.08
140
120
100
80
60
40
20
0
Beta
Dapi
Gamma
Dapi


STOborg19-/90V 25.03.08
60
50
40
30
20
10
0
Beta
Dapi
Gamma
Dapi


TEGwest13-/85V 12.03.08
100
90
80
70
60
50
40
30
20
10
0
Beta
Dapi
Gamma
Dapi


TIEsued19-/60V 19.03.08
9
8
7
6
5
4
3
2
1
0
Beta
Dapi
Gamma
Dapi


STOborg20-/90V 13.03.08
50
45
40
35
30
25
20
15
10
5
0
Beta
Dapi


STOborg19-/90V 20.03.08
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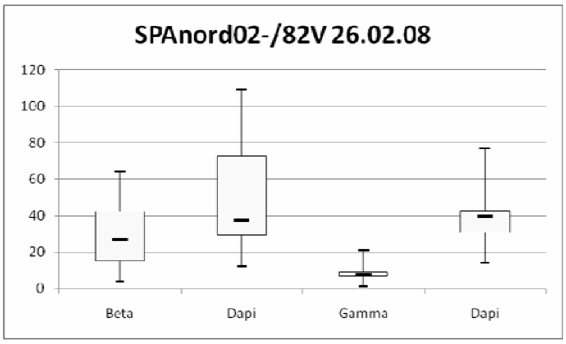
300
250
200
150
100
50
0
Beta
Dapi


SPAnord02-/82V 26.02.08
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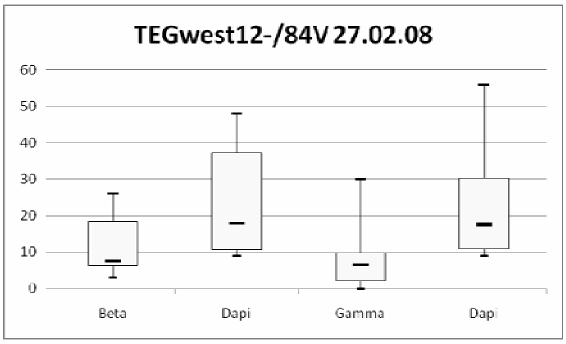
100
80
60
40
20
0
Beta
Dapi
Gamma
Dapi


TEGwest12-/84V 27.02.08
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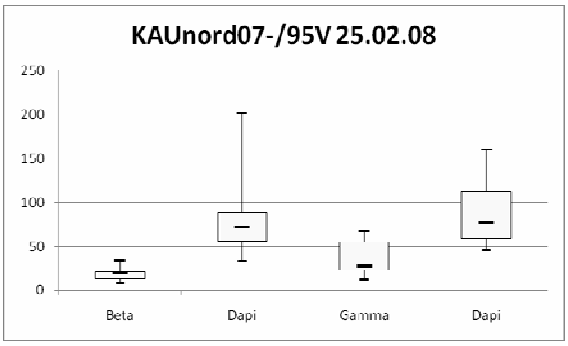
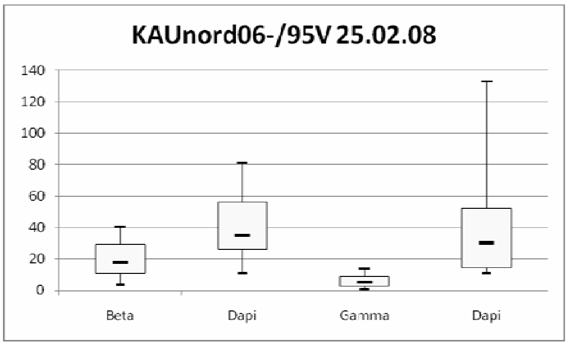
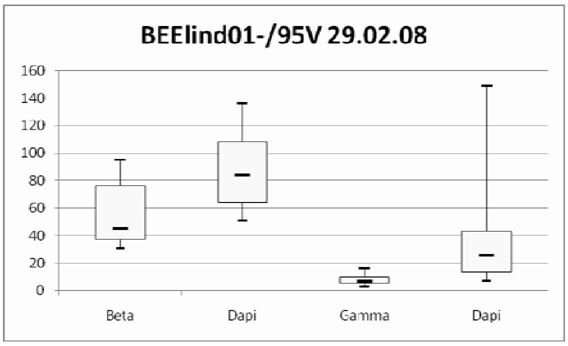
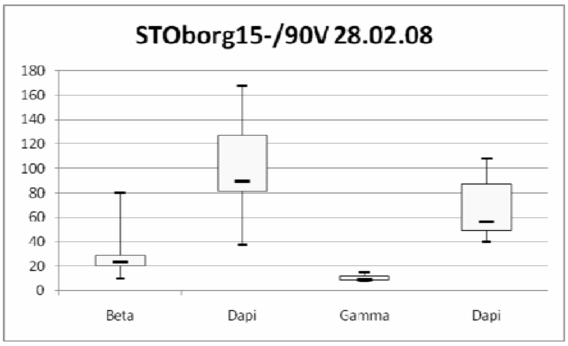
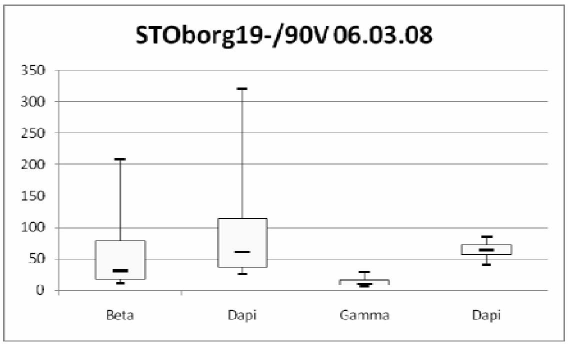
50
40
30
20
10
0
Beta
Dapi
Gamma
Dapi


KAUnord07-/95V 25.02.08
250
200
150
100
50
0
Beta
Dapi
Gamma
Dapi


KAUnord06-/95V 25.02.08
140
120
100
80
60
40
20
0
Beta
Dapi
Gamma
Dapi


BEElind01-/95V 29.02.08
160
140
120
100
80
60
40
20
0
Beta
Dapi
Gamma
Dapi


STOborg15-/90V 28.02.08
180
160
140
120
100
80
60
40
20
0
Beta
Dapi
Gamma
Dapi


STOborg19-/90V 06.03.08
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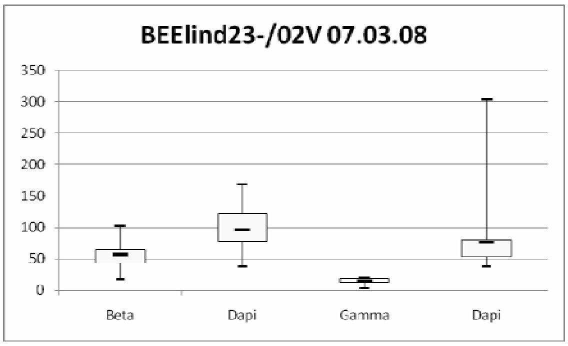
300
250
200
150
100
50
0
Beta
Dapi
Gamma
Dapi


BEElind23-/02V 07.03.08
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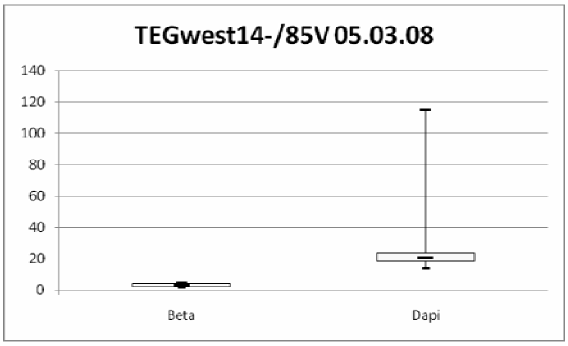
200
150
100
50
0
Beta
Dapi
Gamma
Dapi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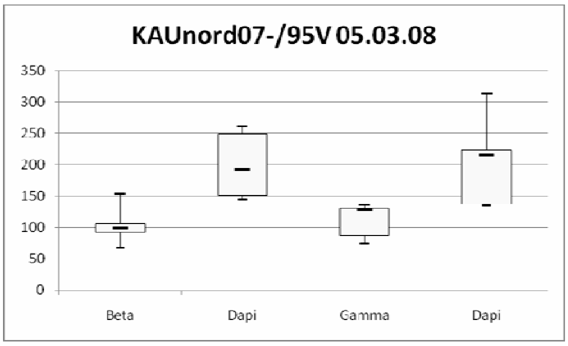
120
100
80
60
40
20
0
Beta
Dapi


KAUnord07-/95V 05.03.08
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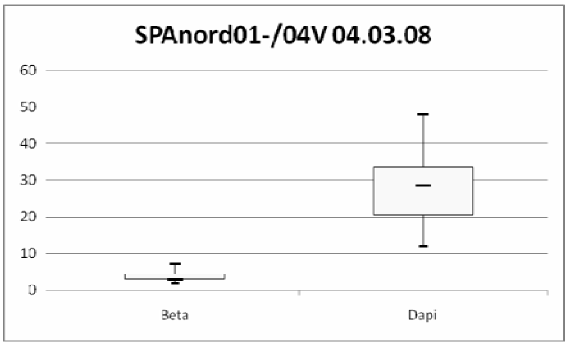
150
100
50
0
Beta
Dapi
Gamma
Dapi


SPAnord01-/04V 04.03.08
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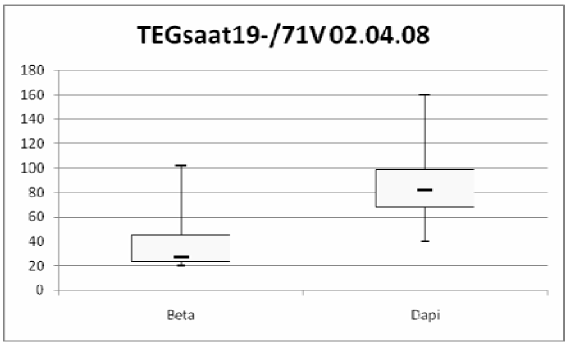
50
40
30
20
10
0
Beta
Dapi


TEGsaat19-/71V 02.04.08
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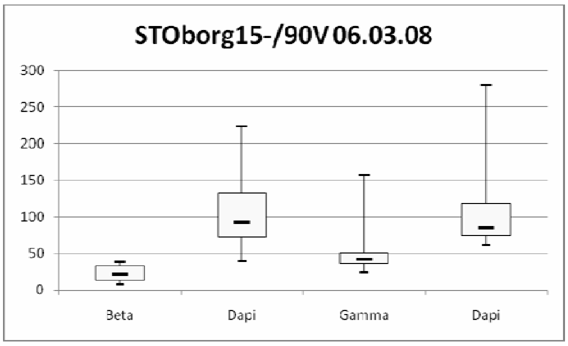
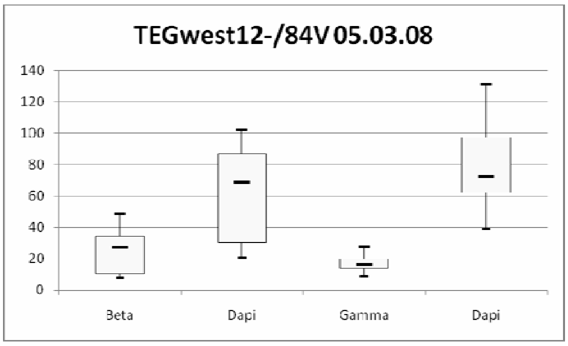
160
140
120
100
80
60
40
20
0
Beta
Dapi


STOborg15-/90V 06.03.08
300
250
200
150
100
50
0
Beta
Dapi
Gamma
Dapi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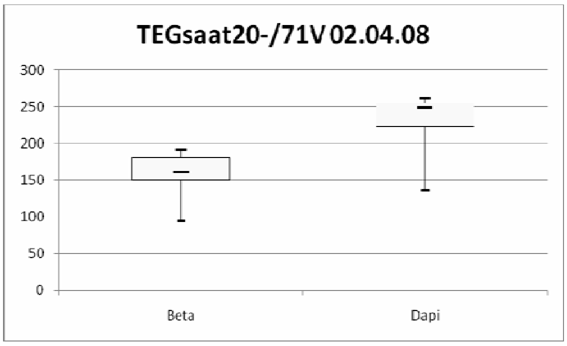
140
120
100
80
60
40
20
0
Beta
Dapi
Gamma
Dapi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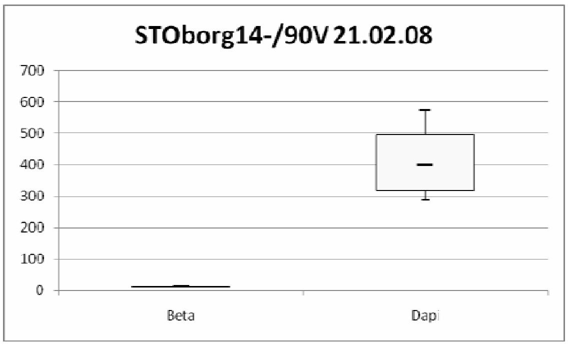
150
100
50
0
Beta
Dapi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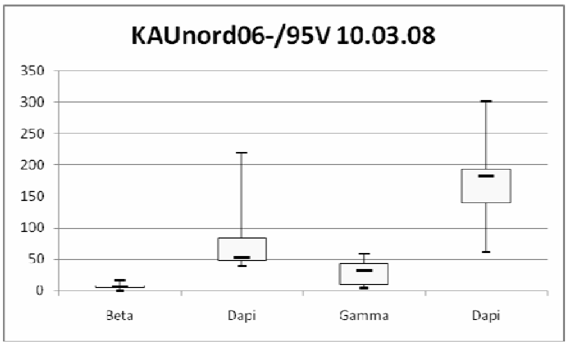
700
600
500
400
300
200
100
0
Beta
Dapi

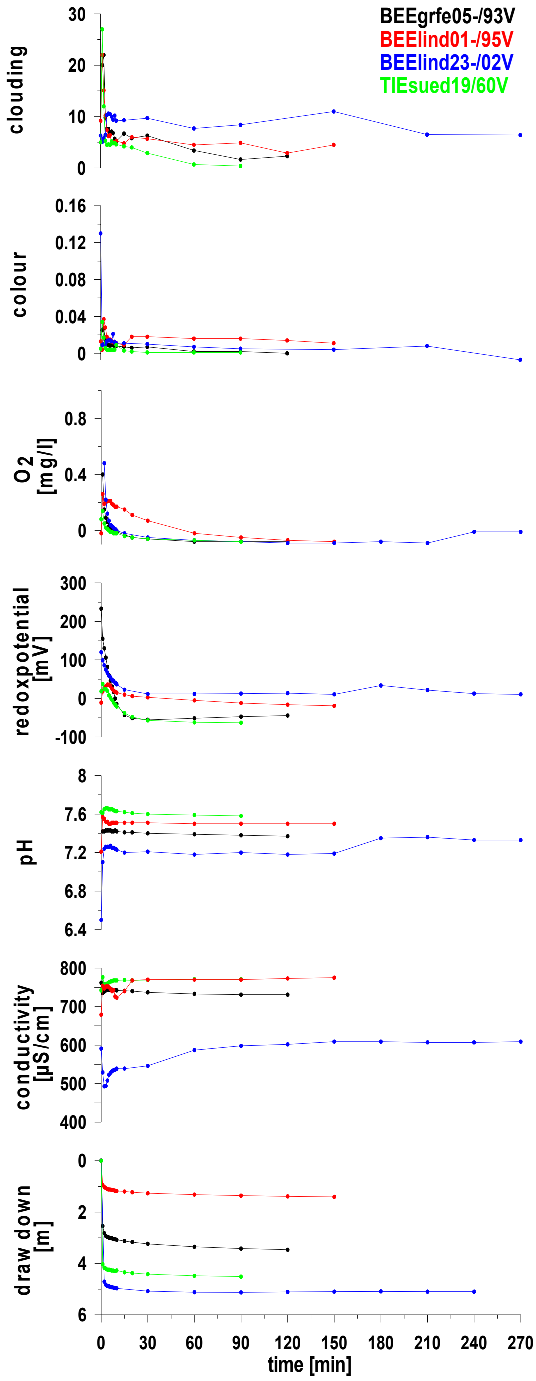

KAUnord06-/95V 10.03.08
350
300
250
200
150
100
50
0
Beta
Dapi
Gamma
Dapi

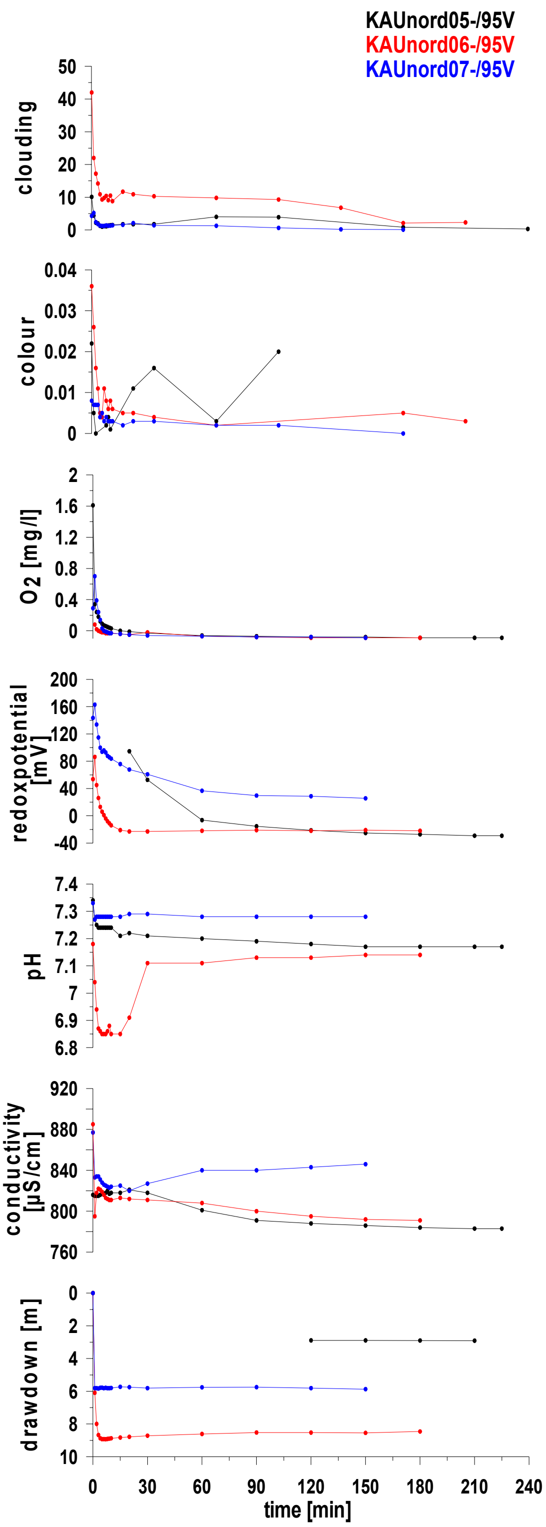
Appendix D

Development of field parameters during the short-term monitoring

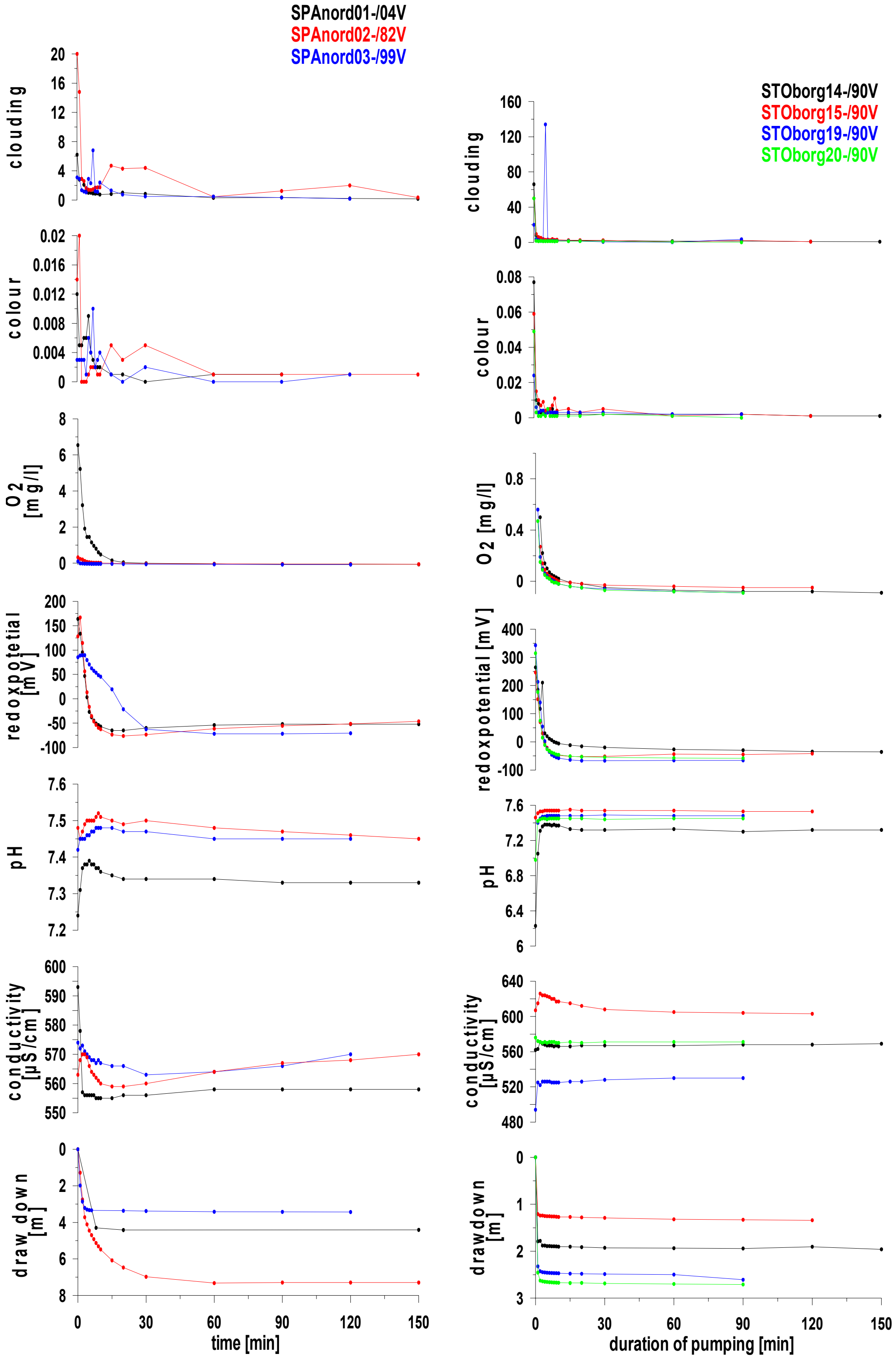
(a) Wells from galleries Beelitzhof Großes Fenster und Tiefwerder Süd.

b) Wells from gallery Kaulsdorf Nord.



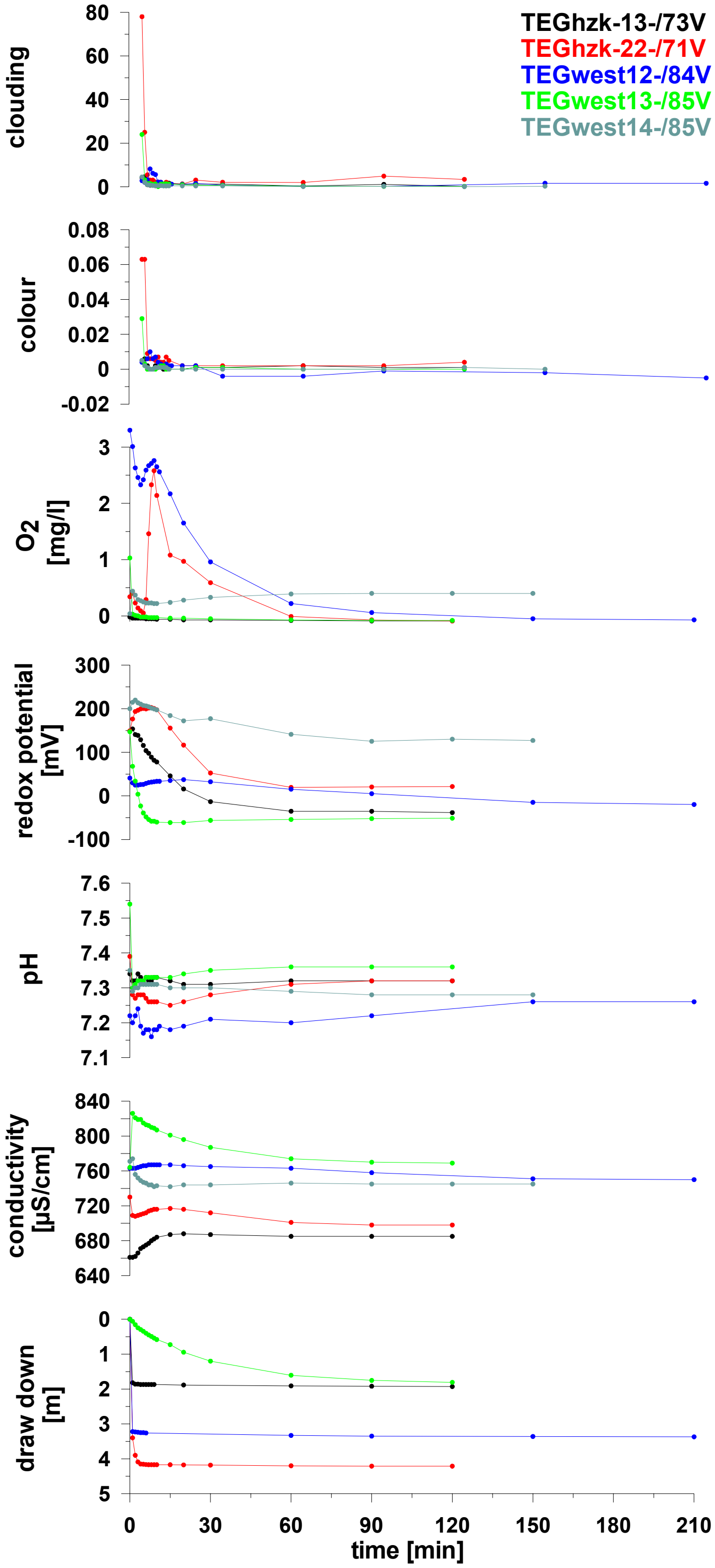


(c) Wells from gallery Spandau Nord. (d) Wells from gallery Stolpe Borgsdorf.



L

(e) Wells from galleries Tegel Hohenzollernkanal and Tegel West.



Appendix E
Operating pumps of the wells

Photographs courtesy of Oliver Thronicker,
Technical University, Berlin.

Photo 1. TEGhzk-13

Photo 2. TEGhzk-22

Photo 3. STOborg19-/90V