KOMPETENZZENTRUM WasserBerlin

# REPORT

Contract: WELLMA-1

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# EXTENDED SUMMARY
# Project acronym: WellMa1

by
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# Colophon

**Title**

Extended summary of the results and conclusions of the preparatory phase of the WellMa project [WellMa1: Nov. 07 - Dec. 08]

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# Chapter 1
# Introduction

The optimization of well management includes all decisions for well operation, monitoring and maintenance to keep performance and water quality as good as possible.

Because many mechanisms are involved and their interaction is complex and differs from well to well, it needs a good understanding of basic processes and key parameters to transfer knowledge into the development of guidelines and recommendations.

The overall WellMa-project aims at the development of such guidelines for BWB and Veolia to slow down well ageing processes and avoid quality deterioration. Therein, WellMa 1 was the preparatory phase with the objective to recommend methods (incl. diagnosis, rehabilitation etc.) for further investigations and to find suitable sites for further field work from

- Literature studies to define the state of the art,
- Advanced statistical analyses of well data to identify well ageing indicators and parameters to describe processes and group affected wells and
- Field investigations to compare methods and tools for diagnosis and monitoring

# Chapter 2
# State of the art (D X.1)

## 2.1 Summary: Well ageing and well management (WP1 to WP3)

Maintenance and value retention of existing wells become more and more important. Hence, the perception of wells has changed from being disposable, cheap to replace and minimal in maintenance requirements to expensive to replace and requiring ongoing preventative maintenance (ALFORD & CULLIMORE 1999).

### 2.1.1 Factors and processes

As wells interfere with the natural system of aquifers and groundwater, impacts to the balance of the water-soil-system are most likely, leading to so-called physical, chemical or microbiological *well ageing* processes.

The geology of the exploited aquifer, together with the qualitative properties of the abstracted water, the well design (dimensions and materials), construction (drilling method) and operation are the dominant factors determining type, extension and location of deposits (see Fig. 1).

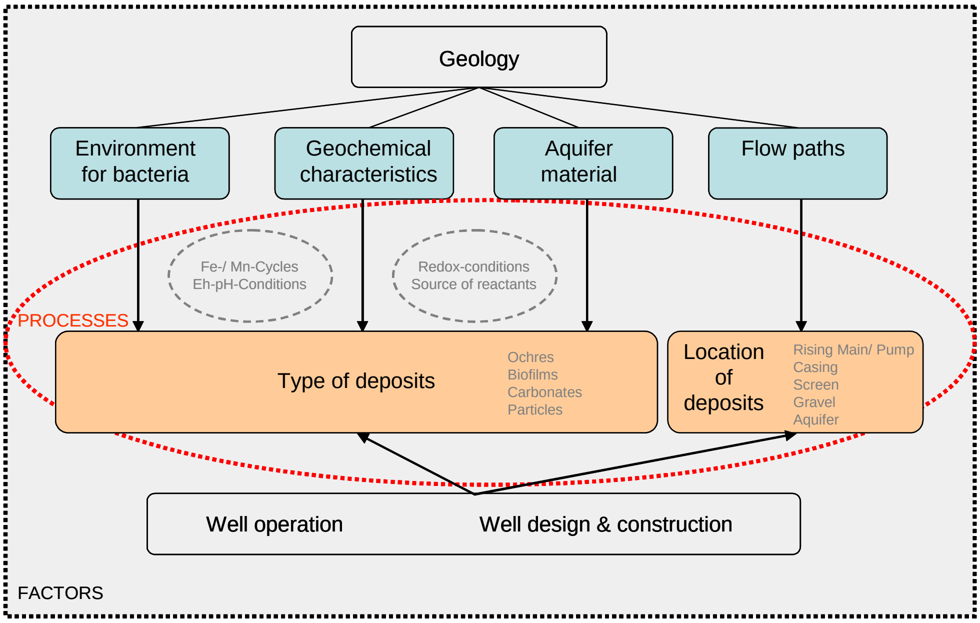



Fig. 1: Interaction of factors and processes leading to varying well ageing types and extension

### *Geology*

Well ageing processes represent the aquifer type and the hydrological characteristics as these components determine the present materials, pore spaces and flow paths. Thus, the geology is the decisive factor and the distribution of well ageing types follows the aquifer distribution (see table 2-1 of the full state of the art report).

Both, soil and water contain different amounts of chemical (iron, calcium etc.) and organic compounds as well as particles and colloids. Their compositions and concentrations set up the starting materials for any precipitation reaction (chemical clogging), colmation processes (physical clogging) and the living environment for bacteria (biological clogging).

Together with impacts from well operation, this may lead to clogging processes. They can be slowed-down, but not prevented entirely.

***Well design and construction***

A proper dimensioning (diameter, screen length, depth of screen sections in relation to aquifer and maximum drawdown etc.) and installation provided, well design and construction still yield some factors influencing well ageing processes, such as:

- the choice of materials and their physico-chemical and biochemical surface characteristics (e.g. susceptibility of steel screens to corrosion, provision of nutrients by PVC screens and drilling fluids)
- the sizing of the artificial gravel pack (e.g. too small grain size trapping particles or too large grain size enabling sand intake)
- inappropriate well development after construction (incomplete removal of drilling fluids, filter cake and fine materials)

Together with the aquifer characteristics, they determine type and location of deposits. Besides the potential to promote well ageing processes, well design and construction need to be considered as possible source of limitations to the applicability of rehabilitation methods. For example, PVC wells are less resistive and can therefore not treated with methods implying high mechanical forces, e.g. shock blasting or high-pressure jetting.

Thus, well design and construction provides room for improvement. If standardized approaches are developed, they need to be reviewed from time to time and adjusted in relation to ongoing monitoring, diagnosis and maintenance needs and recent technological developments.

***Well operation***

As well operation always changes the hydraulic conditions, it has a strong impact on the geochemical characteristics. Main factors are the increased flow velocity, mixing processes and the possibility of oxygen intake, leading primarily to an imbalance of thermodynamic equilibria. For biological clogging and sintering, the increase in temperature due to the pump operation is also considered a possible cause.

The parameters, which can be influenced, are

- the pump capacity and
- the operation schedule (continuous or periodic)

Generally, either by well design or by operation

- flow velocity should be kept as low as possible: to avoid turbulent flow,
- the dynamic water level should always remain above the screen section: to prevent oxygen intake and
- sudden water level changes, e.g. due to repeated switching, should be avoided

### 2.1.2 Well Maintenance

GROSSMANN (2000: Rehabilitation of drinking water wells - a literature review, *in German*) concluded that there are many site-specific case studies about well ageing types and successful rehabilitations, but no sufficient investigation of the processes and mechanisms leading to a loss of well capacity to transfer these results to other cases. Three fundamental issues were presented as “being open questions”, which indeed remained valid since then:

(1) The documentation, processing and employment of operating data are in most cases insufficient. More output could be gained from analyzing available data alone.

(2) Type and composition of deposits need to be investigated in order to choose and subsequently assess rehabilitation strategies.

(3) A standardized reference basis (e.g. Qs assessment before and after rehabilitation, carried out with constant conditions regarding discharge rates and durations) is needed to assess the success of any maintenance or rehabilitation measure and to compare different methods and technologies.

Hence, proper monitoring and documentation are crucial parts of any well management linking well construction, ageing processes, operation and maintenance (see Fig. 2).

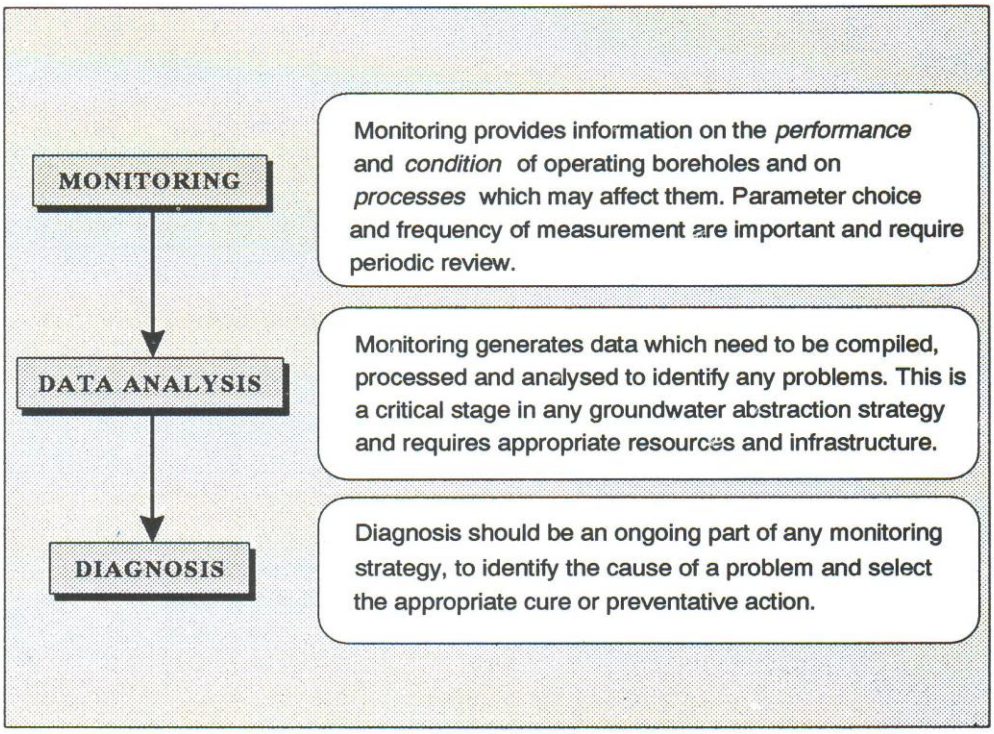



Fig. 2: Summary of purpose and principle of well ageing diagnosis [from HOWSAM, MISSTEAR et al. 1995:85]

Monitoring is subdivided into

(1) Continuous data recording during operation (well performance) and

(2) Discontinuous measurement in regular intervals, or whenever the continuous monitoring reveals a decrease in performance for additional information on causes and location (well condition and diagnosis)

The requirements with regard to parameters and schedules need to be developed adjusted to the site conditions and the well characteristics considering always a combination of methods. A general strategy is summarized by HOWSAM (1995: Monitoring, maintenance and rehabilitation of water supply boreholes, *in English*).

Recommendation for the investigated BWB and Veolia wells will be given in chapter 6 of this extended summary.

To slow down ageing processes (preventive measures) or restore the well performance after deterioration (rehabilitation), maintenance methods are applied. The methods for preventive treatment and rehabilitation are more or less the same. The difference lies in the moment and the intensity of application.

For the right selection of methods needs to be considered:

(1) the nature of the problem (well condition and diagnosis of involved processes)

(2) the location and extension of deposits

(3) restrictions and limitations coming from the well construction or the constructive state of the well

A large variety of technologies is available. For details and descriptions, please refer to textbooks (e.g. HOWSAM, 1995; HOUBEN & TRESKATIS 2007), the internet (e.g. www.groundwaterscience.com/free-article-library.

Generally, preventive treatment aims at slowing down microbiological and chemical processes. Hence, the technologies must be able to prevent growth of bacteria and hardening of incrustations. Most widespread are disinfection methods using strong oxidants such as $H_2O_2$ (as applied in Berlin and at other Veolia sites). Rehabilitations aim at the removal of deposits from the entire well. Therefore, they need to be able to reach the full extent of the gravel pack and to disconnect (mechanical measures) or dissolve (chemical methods) the deposits.

Basis for successful and sustainable rehabilitations is:

(1) the consideration of practical experience: Documentation of past maintenance events

(2) the application as early as possible: Definition of a trigger point (operational parameter, which is monitored on regular basis), e.g. 20% loss of performance (decrease in specific capacity Qs compared to the initial value right after construction)

(3) the removal of all debris to prevent rapid re-growth: Extensive pumping and well redevelopment

## 2.2 Microbial contamination (WP4)

From a bibliographic study on existing cases of microbial well contamination, published cases should be compared to the situation in Berlin to analyse the possible origins of microbial contamination. Therefore, the following issues had to be investigated:

- Identification of relevant bacteria
- Evaluation of sources
- Assessment of pathways into a well
- Parameters from well design or well operation that increase the risk of contamination
- Techniques and analytical methods that can be used to determine the sources and pathways

Worldwide publications could be found dealing with microorganisms within the groundwater. Hence, it is by no means an unfavourable environment, quite the contrary, many bacteria have adapted to the special conditions present underground. The following statements summarize the findings of the literature review:

- Microbial occurrence and the composition of microbial communities in groundwater are variable depending on the heterogeneous properties of the soil and the aquifer.
- Major determinants for microbial abundance and activity in groundwater are nutrition supply, availability of dissolved oxygen and energy sources. Environmental factors like temperature, pH, hydrostatic pressure, dissolved salts influence microbial persistence.
- The same processes and factors that influence the quality of groundwater should also be relevant for well water. Wells represent in addition a specific habitat for microorganisms with different attachment surfaces, increased water flow, and availability of space.
- Under the oligotrophic conditions often present in groundwater and wells, most microorganisms are attached to surfaces.
- It is not feasible to track faecal contamination by determining the multitude of different pathogens with variable characteristics. Instead, bacteria are tracked, which generally are most abundant in faeces (like *E. coli*), thus indicating faecal pollution. This indicator principle has been universally accepted. It is agreed upon that the occurrence of faecal indicator bacteria does not always coincide with the presence or absence of pathogenic bacteria and even more so for pathogenic viruses and protozoa. Usually the abundance of indicators is taken as a measure of probability for the presence of pathogens. Debate remains about the use of bacteriophages as indicators for the presence of pathogenic viruses. The correlation of indicator to pathogen should be assessed for each specific environment because of their different transport and survival characteristics.
- The introduction of microorganisms into the subsurface occurs with recharge water, typically from precipitation or infiltration of surface waters. Major sources of microbial pollution in groundwater were reported to result from leakages of sewer facilities, from animal wastes, from faecal contamination of surface soil and surface water (human, animal, wildlife). Additional contamination, specific for wells, may arise from unhygienic manipulations during operation and/or monitoring procedures.

- Depending on the subsurface material, such as pore sizes, presence of canals, hydrophobicity of surfaces, migration velocity can be very different. Once below the water table, the vertical movement diminishes. Further migration is determined by the direction and velocity of the aquifer flow. During the passage, the distance of microbial migration is dependent on various processes such as filtration, dispersion, attachment to surfaces, and die-off.
- Important for the assessment of pathways, with respect to the speed and distance of microbial subsurface passage, is a detailed knowledge of the structural conditions of the aquifer and the survival times of the microorganisms involved.
- Various biochemical, microbiological, and molecular methods have been developed and are ready to be used for the determination of the types, abundance, and metabolic activities in microbial communities, for the tracing of faecal pollution with indicator microorganisms, and for the detection of specific pollution sources.
- Sensitivity of wells to contamination is principally a function of the hydrogeological and geochemical site characteristics of the specific location of the well, the overlaying saturated and unsaturated subsurface zones, the distance to potential contamination sources and the correct functioning of wellhead protection, ascertained by best management practices during operation and monitoring.

# Chapter 3
# Advanced statistical analysis of well data (D 1.2)

## 3.1 Method

One part of the work package "*diagnosis methods*" was the statistical analysis of existing data sets from well fields in Berlin and France. In accordance to the proposed project strategy, the data analysis was structured into three different steps:

(1) Identification of a reliable clogging indicator,

(2) Linkage of parameters related to clogging processes to identify trends and

(3) Conclusions for grouping wells for further investigations.

As the majority of the underlying data originate from Berlin wells, which are believed to be affected to 80% by microbiological clogging, the following conclusions refer to iron-related clogging processes. The different French sites were only integrated in the descriptive data analysis and no further statistics was carried out because the number of samples was too small and inhomogeneous. However, a site-specific investigation was conducted, which is given in the appendix of the full report.

For the identification of a reliable clogging indicator for further statistical analysis i) TV inspections, ii) the changes in specific capacity (Qs) and iii) the number of H2O2-treatments were related to constructional, hydrochemical and operational parameters of the Berlin wells.

To obtain first trends, a reduced dataset of wells with a good distinction related to clogging or no clogging was used. The classified TV-camera inspections showed the most significant distinction between clogged and non-clogged wells, according to existing knowledge of iron related clogging processes. For example, the clogging status shows significant trends depending on the distance to the next surface water, iron-, manganese- and nitrate-concentrations, mean monthly operating hours and mean total discharge. However, one major constraint is that the TV inspections only visualize clogging on the well interior, and not in the gravel pack.

Next, the percentage of a mean yearly reduction in the specific capacity (Qs) was calculated to compare differences in well condition. The parameter Qs has the advantage that it delivers a metric quantification of well performance, but also the limitation that it is a comparable measure only in confined aquifers or for a constant discharge rate, as there is only a linear relation between discharge and drawdown for these cases. Therefore, pumping tests made at different discharge rates - as practiced commonly by BWB and Veolia – are not fully comparable. This might be one of the reasons, why the relations between clogging processes and Qs changes reveal less clear results than for TV camera inspections, whereas in theory this indicator would be very well suited to show the effects of different clogging processes

Finally, the number of preventive H2O2-treatments was tested as an indicator for clogging for the Berlin wells (as rproposed by BWB). However, this showed that the differentiation between cause and effect of clogging is problematic and this indicator did not correspond to the theory of clogging processes. Therefore, H2O2-treatments do not seem to be an appropriate clogging indicator for the statistical analysis.

## 3.2 Conclusions

After the identification of classified TV-camera inspections as the most reliable clogging indicator for statistical analysis, the four defined classes ranging from no clogging (0) to intense clogging (3) were linked to the available parameters of well construction, hydrochemistry and well operation. In this way, general trends of parameters that are linked to clogging processes were detected:

(1) Most wells reveal increasing clogging with rising well age and decreasing depth of the first filter.

(2) Clogged wells show lower iron and higher manganese and nitrate concentrations compared to non-clogged wells.

(3) Wells with a higher mean total discharge and more operating hours tend to clog to a greater extent.

However, a final quantification between clogging state and related parameters by a multiple linear regression led to a poor result. Only 20 % of the variance in clogging could be explained by the independent parameters, whereas 80 % of the variance is still unknown. Hence, there is still a lack of knowledge if the most relevant parameters are missing or if the known parameters reveal too much variability in measurements. For example, hydrochemical data vary not only over time but also with well depth, depending on the hydraulics in the well. Therefore, a single value measured in the mixed raw water cannot characterize depth-orientated variations induced by well operation.

Concerning operational data, at BWB the measurements of operating hours and total discharge can be subject to high errors, depending if they are measured by direct or indirect methods. For example in some waterworks, operating hours are calculated by electricity consumption of the pump. In other waterworks, meters are measuring the exact operating hours. The same can be noticed for total discharge measurements. Some waterworks have flow meters which themselves also tend to clog, others use inductive measurements or electricity consumption. Therefore, most data have a limited comparability in the sense of statistics because they are subject to different errors in measurements.

Recently, Rubbert & Treskatis (2008) made similar investigations and came up with the conclusion that trends can be detected but not be translated to the individual case. Too many factors including natural, operational and economical reasons lead to the observed high variability. Therefore, it needs

(1) measures to reduce the variability in the data and

(2) the development of a matrix system with an individual weighting of factors and the evaluation of time-series of measurements

The implementation in daily monitoring and operation routine will be discussed with the technical staff of BWB and Veolia based on the following recommendations.

## 3.3 Summary of the descriptive data analysis of the French sites

With regard to the results of the statistical analysis of the Berlin well data, the French data basically seem to follow the general trends relating well ageing processes to parameters such as iron and oxygen concentrations, mean discharge, operation hours etc.

For more detailed assessments and multivariate linear regressions, the data need to be completed and validated first. To assess the wells further and to draw conclusions about potential interactions, recommendations for monitoring and diagnosis are in general the same as for Berlin or any other site.

Because the TV inspection as indicator for the occurrence of clogging is restricted to investigate the well interior only, a combination of both, TV inspections and pump tests is necessary to monitor the well performance. Especially with regard to physical clogging, flowmeter measurements were very useful to link well deterioration to certain aquifer layers.

As at all sites, iron hydroxides, carbonates and biofouling were claimed to be responsible for well ageing, the minimum chemical parameters are accordingly pH, Eh, Ca, $HCO_3$, $O_2$ ($NO_3$) and Fe. At least once, sampling should be depth-oriented to assess shares of water with different chemical composition and redox zones. In combination with flowmeter measurements, mixing processes can be discovered.

The sampling and/ or monitoring interval depends on the rate of ageing and cannot be given in general but has to be decided for each well individually. Altogether, these monitoring methods do also present first diagnosis of ageing types and extents, which are necessary to plan any rehabilitation measure or adaptation of operation.

The database at hand now can be used as basis to draw up an overall well management database on side of the technical directions of Veolia Eau. After filling all available data and their validation, it can be used for further statistical investigations as well as for daily operation and decision support.

In addition, after validation, the data should be further analysed with regard to the trends identified during task 1.2 of WellMa.

As all of the French well sites represent unique features, the selection of sites for the field investigations needs to be discussed with the technical directions.

As also concluded for the Berlin wells, the final selection of sites for field investigations is proposed to be carried out in the beginning of WELLMA-2 corresponding to its detailed objectives. These will be determined in close discussion with the technical directions of Veolia and BWB.

# Chapter 4
# Comparison of methods (D 1.3)

## 4.1 Methods and main results

One of the objectives of the preparatory phase WellMa 1 was to assess available methods for clogging diagnosis and monitoring with regard to their information value and applicability. Therefore, a large variety of methods was tested at three chosen wells. They can be divided into:

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, which are extensively described in textbooks and technical bulletins (*see full state of the art report for references*), 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 lay on the assessment of redox conditions, the living environment and the composition of bacteria communities in biofilms. To increase the significance of the evaluation, additional 17 wells were included into the hydrochemical and microbiological investigations by the universities.

Table 4-1 summarizes the scope of investigations:

Table 4-1: 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 | |

### 4.1.1 *Hydrochemical analyses [FUB]*

***Method***

These investigations covered the determination of physico-chemical parameters (pH, redox-potential, $O_2$-content, conductivity and temperature) and the concentrations of main cations and anions in water samples of 19 different BWB wells.

In order to obtain information on the optimal sampling interval, measuring and sampling intervals were set to one minute during the first ten minutes after switching on the pump, followed by increasing intervals. The duration depended on the stability of the field parameters. The values had to be stable for one hour.

Hydrochemical field parameters were measured quasi continuously in a flow-through chamber (Figure 3-1). Critical parameters like $HS^-$, $NH_4$, $NO_2^-$, colour, clouding and $HCO_3^-$ were determined on site. 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.

Fig. 3: Sampling devices for the short term monitoring for microbiological and hydro-chemical water sampling. Measuring system with flow-through cell for hydrochemical field parameters [FUB 2008]

Besides the filtered cation sample, an unstrained, acidified sample was taken for the investigation of particulate iron and manganese in the water. The drawdown within the well was measured with an electric contact meter at sampling times.

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 were finished.
- The last sample represents the steady state with stable field parameters.

Anion and cation analyses were carried out in the laboratory of the FU Berlin.

***Results***

From the hydrochemical analyses, it became apparent that the abstracted well water is not in a thermodynamic equilibrium. We proved the presence of oxygen (up to 10mg/l) and nitrate (up to 14 mg/l) under redox conditions where they should be absent in an equilibrium state (see Fig. 4). Fe and Mn are present in zones, where they should be oxidized (and thus not dissolved) in equilibrium, but then in some cases depleted in zones of low redox-potentials (see Fig. 5).

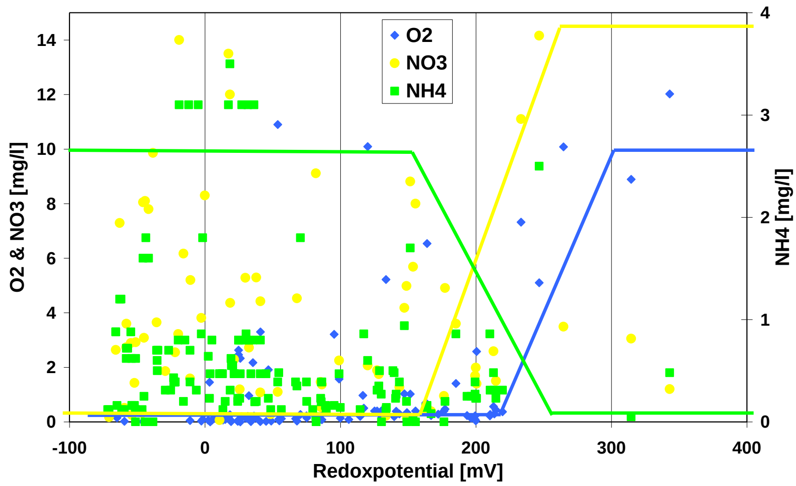



Fig. 4: Plot of $O_2$, $NO_3$ and $NH_4$ against the redox potential for all well samples. The lines show the expected values for stable thermodynamic conditions [FUB 2009]

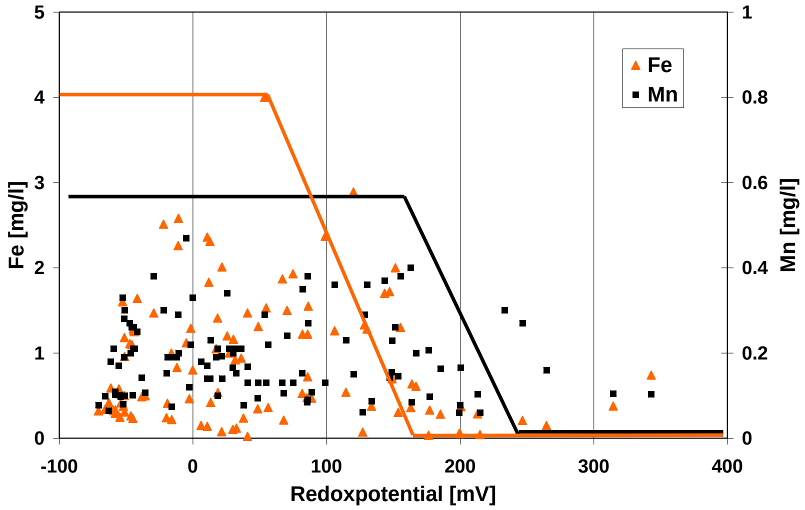



Fig. 5: Plot of Fe and Mn against the redox potential for all well samples. The lines show the expected values for stable thermodynamic conditions [FUB 2009]

These conditions are most probably caused by the mixing of anaerobic iron-bearing groundwater and oxygen-containing surface-near water and provide chemical conditions for ochre incrustations.

However, as the analyses were done for the already-mixed water, an improvement of the methodologically approach would be to extend measurements to depth-oriented sampling to assess the original redox zonation and equilibrium conditions within the well. This will also lead to the identification of preferred zones for the precipitation of chemical clogging deposits.

### 4.1.2 Microbiological investigations [TUB]

The microbiological investigations included the sampling of water and deposits as well as the growth of biofilms. The methodological development was part of the sub-project *WellMaDNA*, but applied in the course of task 1.3 of WellMa1, too.

***Sampling***

In order to retrieve undisturbed biofilm samples from inside the wells, a sampling device had to be developed.

Alongside a 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, which were adjusted to the size of the standpipes (Fig.1).

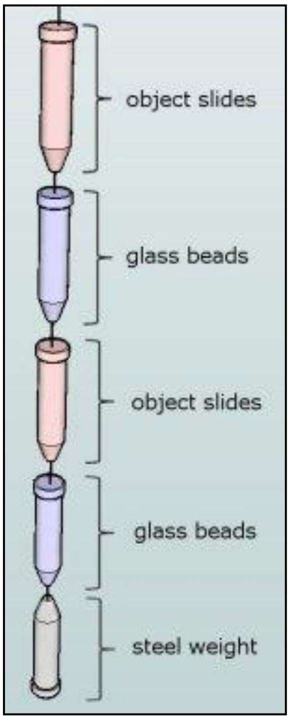



Fig. 6: Sampling device [TUB 2009]

***Results***

- The sampling device made it possible to collect undisturbed biofilm samples without the need of additional construction work or opening of the wellhead. It proved to be easy to handle and suitable for the task.
- The exposure duration has an impact on the biofilm community attaching to the object slides. The first tests indicate that an exposure of seven weeks is sufficient to see iron bacteria on the object slides.
- The pump should always be deactivated before handling the sampling device, in order to prevent it from being sucked into pumps without safety grid.

***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: modified *Leptothrix* medium and groundwater), two replicates per medium.

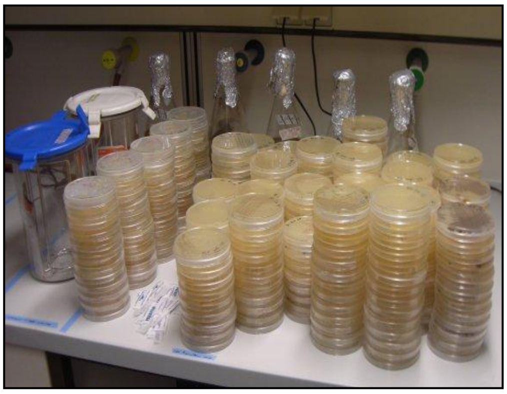


Fig. 7: Cultivation and isolation [TUB 2009]

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.

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. The PP was incubated and slower growing colonies that developed were subsequently subcultivated for an additional period of time.

### *Results*

- The method allowed us to gain reference cultures for a denaturing gradient gel electrophoresis (DGGE, molecular fingerprinting method separating DNA-sequences), primer- and probe design.
- In order to successfully cultivate the iron bacteria of the different wells, new culture media had to be developed based on water of the respective wells.
- Pump sludge, as well as glass beads proved to be the most promising inocula.
- The fact that the best cultivation results where achieved with media based on well water, hints to a correlation between ochre forming and chemical composition of the well water.

### *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).

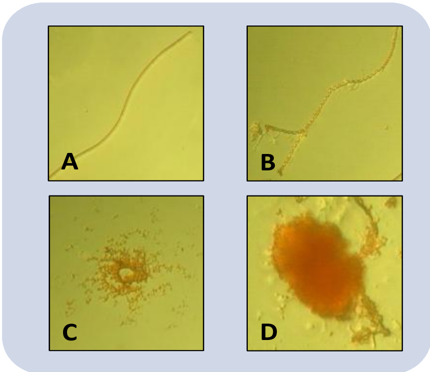



Fig. 8: Morphotypes [TUB 2009]

### *Results*

- It was shown that each well contains a different set of morphotypes of iron bacteria.
- While some wells contain mostly sheath forming bacteria, others contain corona forming and cell agglomerates. This could have a strong impact on the type of ochreous deposits that will form on the filter area and inside the gravel pack.
- The type of ochreous deposit could strongly depend on the dominant type of iron bacteria inside the well. First results of correlations with chemical data, indicate that the morphological structure of the biofilms correlates with the chemical conditions of the well. Adjustments in well operation could be a method to influence these conditions and the community structure. This has to be further investigated.

### *DNA Probes*

Many iron bacteria are part of the group of the Beta-proteobacteria, a class in the bacterial phylogenetic system, which 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, Thiobacillus and Gallionella.

Using the FISH (Fluorescence 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 labelled 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.

***Results***

- The method will allow correlating specific probe signals with iron incrustations. This will be an important tool, to evaluate the potential for the formation of ochreous deposits by the respective organisms.
- First results indicate a correlation between well operation and ratio of Beta-proteobacteria on the slides.
- There could be a potential for manipulating the bacterial community of the well and the form and thickness of the ochreous deposits, simply by activating or deactivating the pump for extended periods of time. Further data on this has to be acquired.

***Molecular biological trials***

During the progress of the project, more than one hundred and 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 by polymerase chain reaction (PCR), cloning and DGGE trials have begun.

***Results***

- The results of the first DGGE trials show similarities but also differences between populations of different wells. First patterns in community composition emerged.
- The DGGE method, in combination with the other methods, has the potential to allow the identification of indicator organisms, which correlate with the respective ochreous deposits.
- It was observed that many of the biofilm samples yielded only low amounts of DNA, compared to the water samples. The exposure time of the glass beads will be extended in future experiments.
- 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.

### 4.1.3 BART [UWT]

***Method***

This method was developed by Canadian researchers investigating biofouling. It is a cultivation-based screening method providing information on the presence and activity of bacteria groups, which are known to be relevant for well biofouling. The test itself consists of nine sampling kits (one for control) with selective nutrients aiming at:

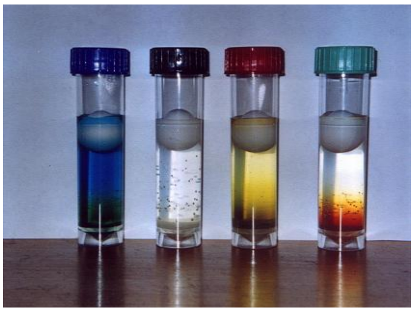


Fig. 9: IRB BART test kits

- Iron-related bacteria (IRB)
- Sulphate-reducing bacteria (SRB)
- Slime-forming bacteria (SLYM)
- Nitrifying (N) and Denitrifying (DN) bacteria
- Heterotrophic Aerobic Bacteria (HAB)
- Fluorescent pseudomonas (FLOR)
- Micro-Algae (ALG)

We chose IRB, SRB and SLYM at water and clogging deposit samples from the three wells to assess the potential of biologically induced deposition of iron hydroxides.

***Results***

BART showed the presence of iron-related bacteria and slime-forming bacteria in all investigated water and clogging deposit samples. However, the bacteria could not be further classified.

To finally assess the significance of the BART results, one of the water as well as the clogging samples from the finished test-kits were included into the cultivation trials and DGGE investigations by the Technical University part. Here, only a weak correlation between the DGGE patterns could be determined. It remains unclear, if BART really is able to represent the activity of iron-related bacteria, which are known to be not cultivable. The ongoing identification and classification with the molecular biological methods will reveal the specification of the bacteria represented by BART.

### 4.1.4 Particle counting [KWR]

The application of particle counting was promoted by KWR (former Kiwa), who successfully used the method to determine physical clogging of wells. 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 (Fig. 10A). In the 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 (Fig. 10B). 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).

On the other hand, 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, particle counting has never been tested before.

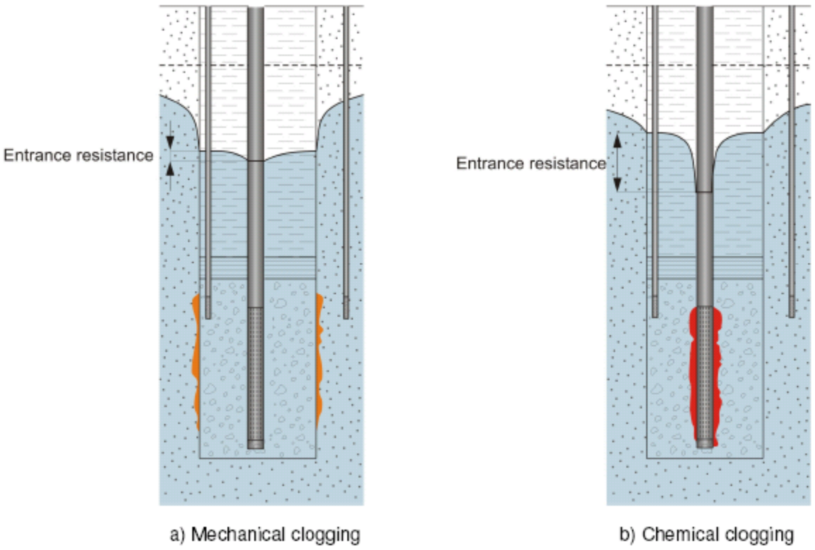



Fig. 10: Clogging types; A. Mechanical clogging; B. Chemical clogging [KWR 2009]

The three chosen wells were operated for 3-and-a-half days following a schedule of 24hours operation followed by 3hours rest. Particle concentrations and their size distributions in the abstracted water were recorded, as well as hydraulic head and discharge of the well and operation of neighbouring wells. The results from these experiments were analyzed and compared to results from similar studies on (Dutch) mechanically clogged wells.

***Results***

The first attempts to better understand the role of particles in abstracted water from biologically / chemically clogged wells led to the following conclusions:

- 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 responded to switching off the pump. A similar response is possible in the other two wells, but this was not recorded due to technical limitations;
- 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 are 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.

### 4.1.5 Well condition analysis

***Methods***

The following methods were applied to the three abandoned wells and the operation well of the transect before and after $H_2O_2$ treatment:

- three step discharge test
- TV inspection
- Gamma-gamma density scan and Neutron-neutron log to assess the condition of the gravel pack
- Flow and Packer-Flow meter to assess the hydraulic conditions

***Results***

The evaluation of the well performance with a **three-step pumping test** with stationary conditions for each step led to the determination of:

- the specific capacity Qs to be compared with the initial Qs and its development with time in operation and before/ after rehabilitation measures
- the aquifer loss component and the well loss component of the drawdown
- the significance of $\Delta$h to indicate the location and extension of clogging within the gravel pack

The determined **specific capacities (Qs)** indicate a significant deterioration of all four investigated wells with remaining 25 to 74% of their initial capacity. The well loss component of total drawdown (non-linear component due to turbulent flow condition within the gravel pack of a well) could be calculated for one well only. The other three wells showed negative values already for the initial state. The **calculation of the $\Delta$h-values** showed no differences between water levels in the inner and outer gauge for three of the four wells, which indicates the absence of clogging deposits between the screen and the first centimetres of the gravel pack (see Fig. 10). Only well STOborg19 had a $\Delta$h of 12 cm. This is at the same time the well with the highest loss of performance.

Pumping tests and well condition analyses (TV inspections and borehole geophysical logging) vary in their correlation for the four investigated wells. Generally, the **TV inspections** gave no hints on clogging deposits along the filter screens. In all investigated wells, the deposits were located between the dynamic water level and the top of the filter with highest accumulation near the pump intakes. However, the colour and structure of the deposits along the casing varied for the steel and the PVC wells. Fig. 11 shows the results of TV inspections of a steel well (pictures A to C) and in contrast, a PVC well (pictures D to F).

While the steel well, which was last rehabilitated in 2003, showed only slight incrustations at the top of the screen, the PVC well, last rehabilitated in 2007, showed clearly more deposits. Noticeable is the partial clogging within the screen section, while the casing shows deposits in all directions.

The conclusion that there is an **impact of material** is supported by practical experience by BWB, which state that wells made of copper, show less ageing. However, such correlations could not be identified by the statistical analysis, but should be included into further assessment.

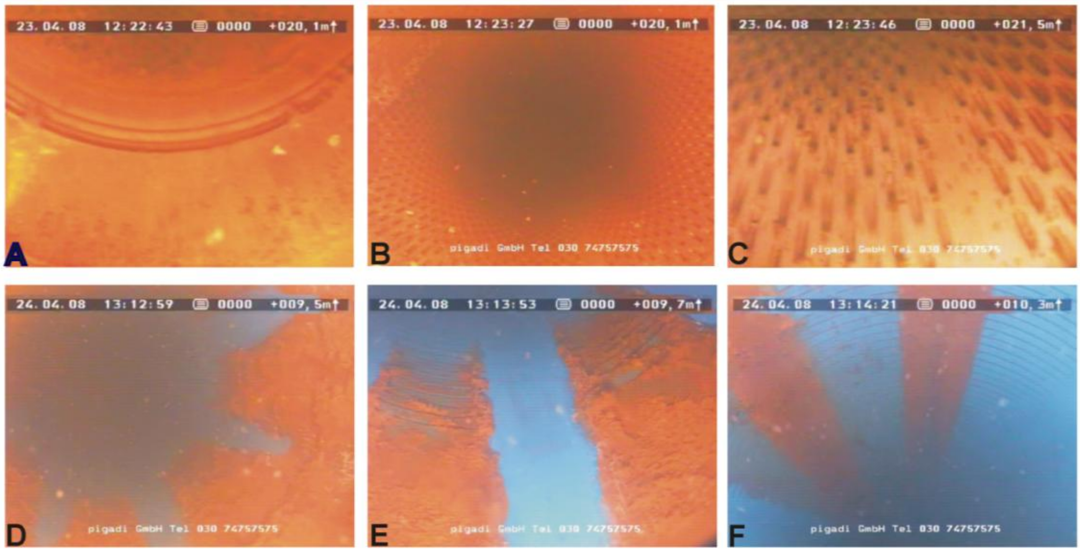



Fig. 11: TV inspections of the wells TEGhzk22 (A-C), made of steel and STOborg15 (D-F), made of PVC [KWB 2009 based on pigadi reports]

Beside the visible deposits in the casing, the **gamma-gamma measurements (GG.D)** indicated the accumulation of fine materials within the upper two metres of the gravel pack for all four wells, which is between the top of the screen and the clay sealing (upwards). Thus, the area between the dynamic water level and the top of the screen seems to be affected by ageing processes reaching from the well interior into the gravel pack.

A correlation to the geological situation within the aquifer could be determined in the way that the **distribution of water intake** (FLOW) represented layers of the aquifer varying in their grain sizes. Sections with coarse sediments showed a higher intake than sections with fine sediments.

The assessment of the permeability of the gravel pack with the **packer flow meter** measurements showed correlation either with the GG.D or with the Flow. Hence, it provided an indication for the presence of deposits within the filter gravel when it correlated with the GG.D and not with the flow meter measurement. A correlation with the flowmeter, but not with the GG.D refined the correlation with the aquifer sediment layering. For all other cases, an initial assessment would be needed for comparison.

## 4.2 Conclusions and evaluation

### 4.2.1 Comparison of 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 $\Delta$h-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.

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. 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 characterization of the abstracted particles to determine their origin to distinguish between bacteria, precipitates of chemical clogging processes and fine sediments with a potential for physical clogging and colmation processes.

### 4.2.2 Processes leading to bio-chemical well ageing

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 Fig. 12).

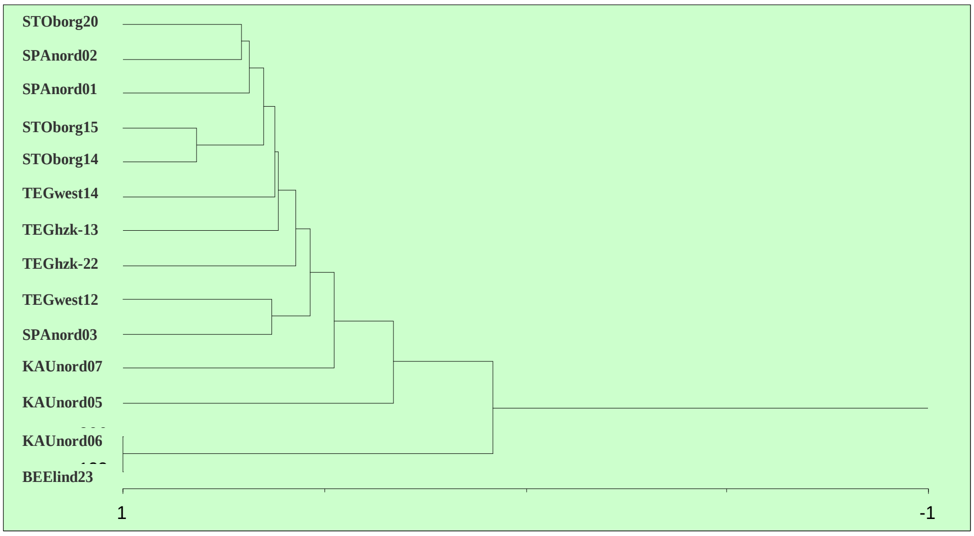



Fig. 12: Cluster analysis for STM-wells based on hydrochemical parameters and DGGE bands [TUB 2009]

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 Fig. 13).

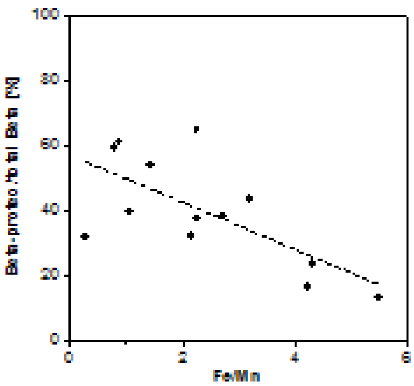



Fig. 13: Correlation of the ratio of beta-proteobacteria to the total cell count with the Iron-Manganese ratio [TUB 2009]

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
# First field investigations in Berlin wells to asses the impacts from switching (Option $O_2$) and $H_2O_2$ treatment on well ageing processes (Option $H_2O_2$)

## 5.1 Methods and main results

### 5.1.1 Experimental setting

21 selected wells, among them 1 transect, 3 wells planned for abandonment and 17 production wells with different well designs and capacity development, were investigated with regard to geochemical changes and the microbiological colonization during operation and rest periods.

In addition, one well site was equipped with transect of five multi-level observation wells to provide a high-resolution observation network to investigate the impacts of operation and maintenance on the near-well surroundings (see Fig. 14). The transect was used to investigate the oxygen intake due to

(1) Operation and subsequent oscillation of the groundwater table and

(2) $H_2O_2$ treatment for preventive maintenance.

Each of the multi-level observation wells consists of three 2-inch piezometers, with filter screens from 5-7m, 11-13m and 14-16m below surface and is equipped with a set of $O_2$ optodes to measure the oxygen distribution. Further optodes were installed in different depths of the operation well (see Fig. 14).

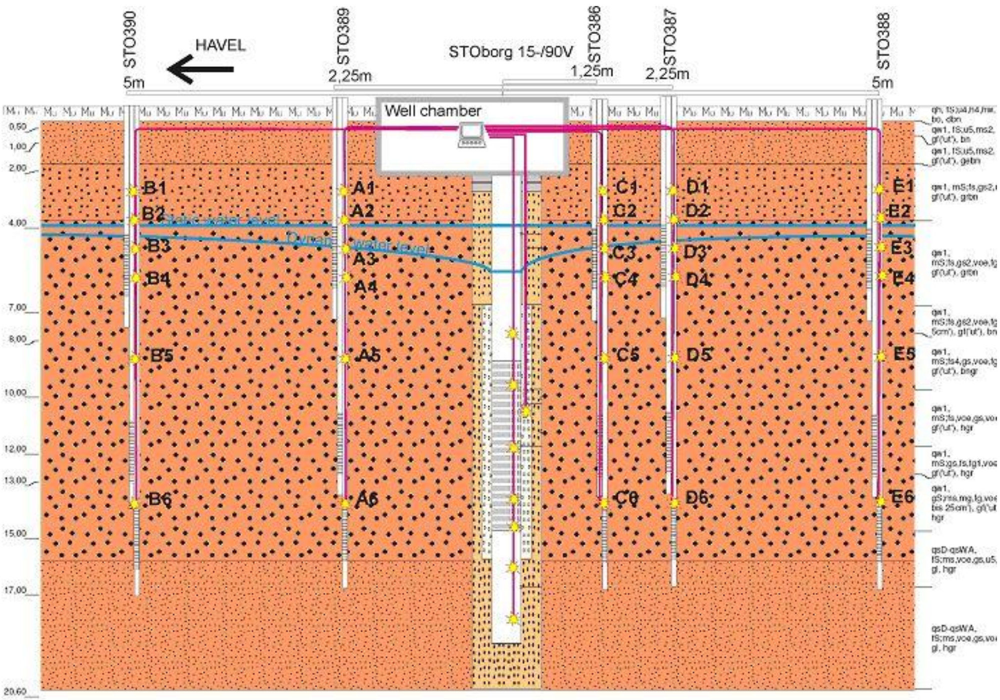



Fig. 14: Schematic cross section of the transect. The yellow dots mark the optodes installed for oxygen measurements [FUB 2008]

The investigations at the transect included a TV inspection, a step discharge test and borehole geophysical logging at the operation well before and after $H_2O_2$ treatment as well as hydrochemical and microbiological sampling of the well and the piezometers.

### 5.1.2 Impact of switchings (Option $O_2$)

***Short-term monitoring of geochemical conditions within the operation wells***

The impact of switchings was assessed by monitoring short-term variations in hydrochemical parameters during the initial phase of pumping. The methodology for sampling and measurement parameters and frequency was chosen in accordance to the hydrochemical investigations described before.

All 21 investigated wells were included. To provide comparability, the following fixed sampling procedure was applied:

(1) The shut-down of the well and its two neighbour wells for minimum one week before the sampling

(2) The start of sampling simultaneously to switching on the well

(3) A sampling interval of one sample every minute for the first ten minutes, then after 15, 20, 30 min, and subsequently every half an hour

(4) A continuation of sampling until stable physicochemical conditions were reached for: pH (±0.05), redox-potential (±10), $O_2$ (=0), conductivity (±10), temperature (±0.5), (variations within one hour)

According to this procedure, the samples represent:

(1) the condition in the well during shutdown

(2) the immediate starting phase

(3) the conditions after the first quick changes due to turbulent flow and drawdown

(4) the steady-state condition during normal operation.

The drawdown within the wells was measured with an electric contact meter at sampling times. The sampling and analyzing procedure were the same as for the hydrochemical analyses described in chapter 4.1.1.

***Results***

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 pH, redox-potential, $O_2$-content, conductivity and temperature seem to be significantly influenced by the switching operation.

***Oxygen intake in the well surrounding***

The first investigations at the transect focussed on the oxygen input caused by groundwater oscillation due to well operation. Therefore, a short pumping test (one discharge rate, 3.5 hours duration) was carried out at the transect accompanied by optodes measurements within the production well and all multi-level observation wells.

One optode in 1.25 m distance to the well at 5m depth below surface was selected for further discussion (optode C3 in Fig. 14). Under static hydraulic conditions, this optode is situated in the groundwater-saturated zone. During well operation, it falls dry due to the development of cone of depression.

### *Results*

Fig. 15 shows the observed oxygen concentration and draw down in relation to the time after the start of the pumping test.

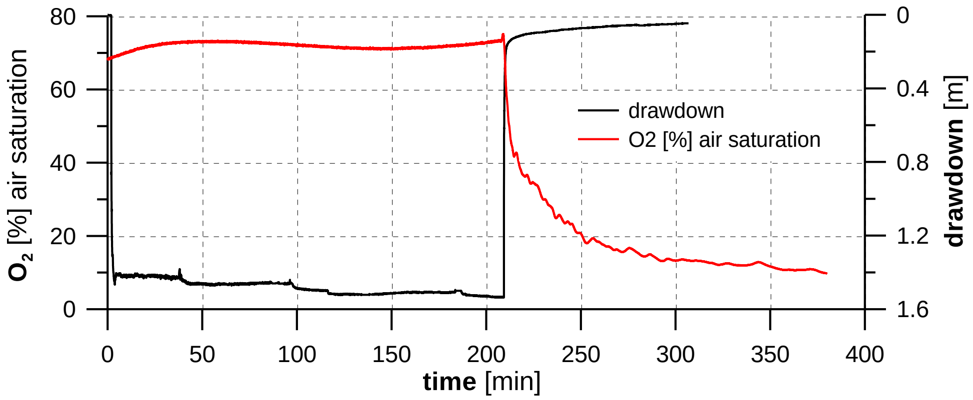



Fig. 15: Recorded oxygen saturation and drawdown during a short-term pumping test at well STOborg15 [FUB 2009]

During pump operation, the oxygen saturation was constant at around 70 % (related to air saturation), which corresponds to the development of an unsaturated zone in the vicinity of the optode.

The recovery of the water table due to switching off the pump (after 210 minutes) led to a rapid decrease of air saturation due to the water level rise. However, air saturation remained constant at around 10 % (corresponding to about 1 mg/L oxygen concentration) for three hours after complete recovery.

Thus, repeated switching enhances the oxygen intake in the well surrounding and might lead to the precipitation of iron ochres.

### *Mass-balance calculation for iron concentrations*

To estimate the clogging potential, the precipitation of ochre was theoretically quantified by balancing the Fe-concentrations of abstracted water from the production well and from the surrounding groundwater as observed in the observation transect.

Fe-concentrations were calculated for bank filtrate and groundwater entering the production well. In a first step, the discharge rates were determined for every sub zone of the aquifer profile, based on hydraulic conductivities (see

Fig. 16 left side). Secondly, the mixing ratio of different water types based on the analysis of electrical conductivities and stable isotope data was added.

### *Results*

The characterisation of Fe-concentrations in the well and its vicinity are shown in

Fig. 16. The mixing ratio of bank filtrate and groundwater is 2:1. Measured Fe-concentrations of abstracted well water are about 1.6 mg/l, whereas calculated Fe-concentrations flowing towards the well are about 1.75 mg/l.

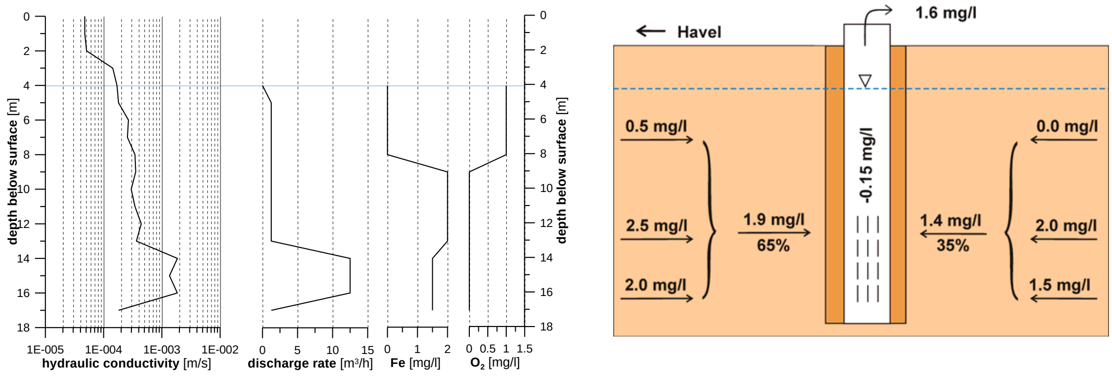



Fig. 16: Characterisation of Fe-concentrations of different groundwater layers mixing in well STOborg15 [FUB 2009]

Thus, the balance calculation reveals a loss of around 10% Fe, which corresponds to approximately 7g Fe per hour assuming an overall discharge rate of $50 m^3/h$.

### 5.1.3 Impact of $H_2O_2$ treatment

***Method***

Hydrogen peroxide is stable under normal conditions, because of high threshold energy. However, due to the presence of catalysts $Fe^{3+}$, $Mn^{4+}$ or $Cu^{2+}$ in groundwater, the reaction rate increases sharply. In the well, the inserted hydrogen peroxide dissociates in a catalytic reaction to oxygen and water.

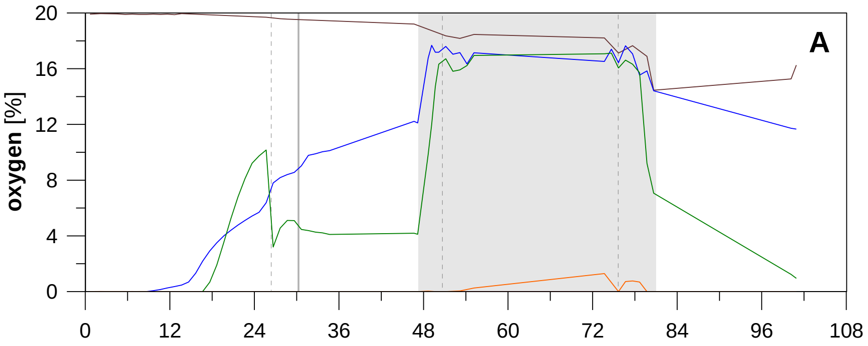
$$2\,H_2O_2 \rightarrow 2\,H_2O + O_2$$

The impact of $H_2O_2$ was observed during und subsequent to the treatment in the operation well and the observation wells of the transect. The amount of released oxygen from $H_2O_2$-dissociation in the saturated zone was determined with the installed oxygen optodes.

***Results***

The investigation showed a strong impact of $H_2O_2$ treatment on the physico-chemical conditions in the vicinity of the treated well.

All optodes within the saturated zone showed a sharp increase in oxygen shortly after the application. Within the operation well, up to 100% air saturation were reached a few minutes after the $H_2O_2$-input decreasing slowly back to partially stable condition. In the observation wells (Fig. 17), the measurements showed increasing oxygen concentrations with increasing contact time. The start of pumping led to a decrease of oxygen with time in operation.



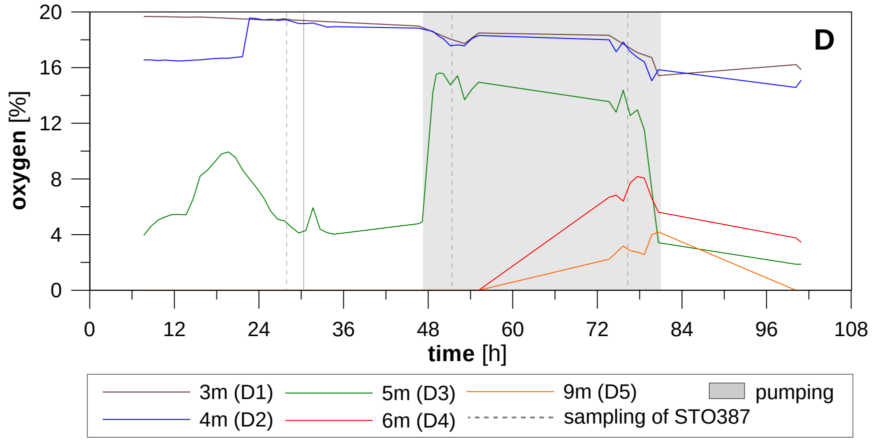



Fig. 17: Oxygen concentrations in the observation wells A (2.25m towards Havel river) and D (2.25m towards landside) [FUB 2009]

## 5.2 Conclusions and evaluation

### 5.2.1 Impact of switchings

From the **short-term monitoring** it became apparent that stable physicochemical conditions in the wells are not reached until 120 min after start of operation. For a comparison of different well states and sites, a sampling of wells in two phases is recommended:

- For a characterisation of the initial hydrochemical conditions right after pumping start, a sample should be taken within the first 5 min of operation.
- For a characterisation of stable conditions, a second sample should be taken after a minimum of 120 min of operation.

The investigations at the transect led to a theoretical model of **oxygen intake due to the start of operation** as described in Fig. 18:

During drawdown, air enters the unsaturated cone of depression (Fig. 18B). After shutdown of the operation pump, the cone of depression is filled up again entrapping air bubbles, which are remaining in the pore space (Fig. 18C). Now the gases from these bubbles can be dissolved by the ground water and enter the well during the next operation.

This process reoccurs each time the well is brought into operation and shut off again. Thus, frequently operating wells abet under the above-described hydrochemical conditions the precipitation of dissolved iron and the clogging of wells.

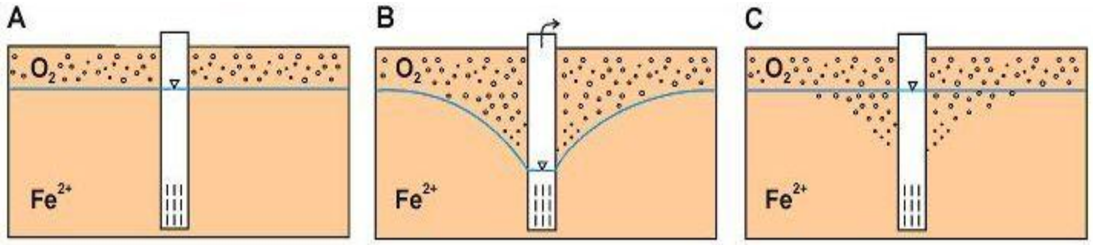



Fig. 18: Schematic diagram of oxygen input due to air entrapment as a result of well operation [FUB 2009]

The results of the **iron mass balance calculation** provide a valuable indication to quantify the dimension of precipitation rates of Fe. The calculated loss in iron concentration is in all probability due to precipitation of iron hydroxides in the well and its vicinity.

### 5.2.2 Impact of $H_2O_2$ treatment

The measurements indicate a mushroom-shaped spread of oxygen dissociated from $H_2O_2$ (Fig. 19) while the well is not operated. Switching on the pump apparently results in a displacement of oxygen into deeper zones of the aquifer resulting in a change of physicochemical conditions.

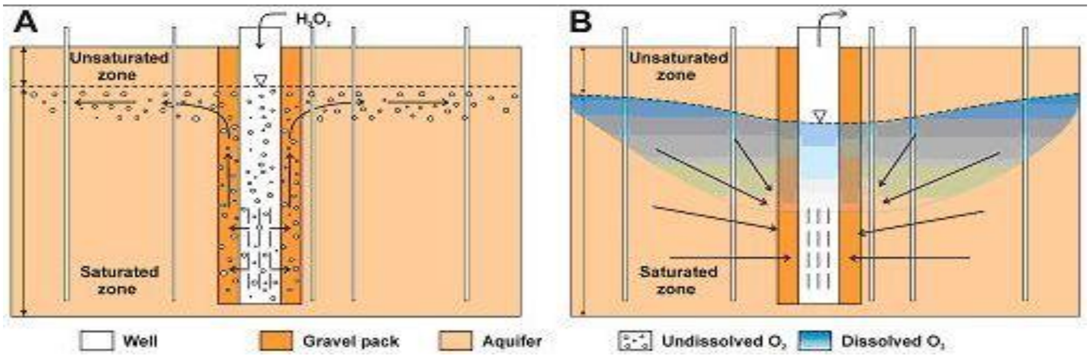



Fig. 19: Schematic view at the spread and distribution of oxygen during (A) and after (B) H2O2-treatment [FUB 2009]

The additional input of oxygen might enhance biological as well as chemical clogging counteracting the benefit provided by the disinfection. Further investigations will be required proving this thesis.

**Switching** seems to be one of the crucial factors leading to mixing processes, oxygen uptake and thus an increased ageing potential. This is already being considered by BWB, reflected by grouping the wells with into continuously running and intermittently operated ones, based on the occurrence of visible deposits (TV inspection). However, a quantification of switching effects in terms of evaluating the amount of oxygen intake and subsequent reaction kinetics has never been done.

Therefore, further investigations should include:

- Depth-oriented sampling to assess the redox boundaries
- Online optodes measurements during switching off to assess the oxygen distribution and following consumption
- Calculation of saturation indices and geochemical modelling to quantify the precipitation rates
- Hydrochemical and microbiological investigations to compare regularly switched and continuously operated wells

Furthermore, it needs to be considered that changes in operation might prevent one process, but enhance others. Therefore, the assessment of impacts from switching should also consider possible benefits, e.g.:

- Modelling of flow velocity peaks during switchings to assess shear forces affecting (1) the attachment of biofilms to surfaces and (2) the mobilisation of particles

In addition, possible benefits from using **frequency-controlled submersible pumps** should be evaluated as their operation yields the potential to prevent sudden water table fluctuations. With such pump types, changes in the total volume abstracted from a well gallery can be distributed to all wells of the gallery, leading to only small variations of the water table within the single wells.

For a reliable **analysis of the oxygen concentration**, oxygen-probes based on optical measurement principles are recommended. Here, the installed optodes at the transect could serve for comparative measurements and allow the evaluation of the occurrence of negative impacts from the long-term exposure, e.g. clogging of the optical sensor.

Especially for the **preventive treatment with $H_2O_2$** there seems to be a gap between theory and the observations in practice. As stated above, $H_2O_2$ acts as disinfectant, but provides at the same time a source of oxygen. To further assess the benefits of preventive $H_2O_2$ treatment, the following investigations are recommended:

- Laboratory investigations with deposit samples and $H_2O_2$ :dissolution tests
- Laboratory evaluation of the impact of $H_2O_2$ on micro organisms: disinfection effectiveness
- Tank and field investigations (transect) with different $H_2O_2$ concentrations and amounts: correlation of the range of oxygen distribution

In addition, operation wells of the BWB should be included, e. g. by comparing otherwise identical wells, one being treated, the other not or to assess the impact of stopping the treatment at one of two wells, which are identical in their design and operation parameters.

# Chapter 6
# Recommendations

## 6.1 Well monitoring

As stated in the previous chapters, well management relies on an integrated monitoring and diagnosis strategy. Therefore, the most important recommendations aim at optimizing **monitoring and diagnosis**:

- regular measurements with standardized procedure (monitoring strategy),
- data processing and analysis and
- subsequent adjustment of the monitoring strategy

> ⇨ Only a well-planned monitoring and subsequent data processing and analysis will reveal the potential to understand processes and interactions and to identify room for improvements for well operation.
>
> ⇨ Such a schedule needs to be developed together with further statistical approaches in close discussion with the well operators.

The results of the statistical analysis carried out during WellMa1 (chapter 3) support this finding.

Generally, it would be useful to reduce data variability by **more accurate and comparable measurements**. Certainly, it will not be possible to convert measurement strategies for the short term, but in the long term, it will be valuable to use the same measurement technique for all parameters. One example is the automatic recording of operating hours and total discharge.

Furthermore it seems to be useful to carry out a terminal **validation of the operational parameters** $\Delta h$, operating hours and total discharge. The reduction in data variability will increase the comparability and so the relation to clogging tendency.

A strong recommendation is to develop a detailed **classification matrix for the evaluation of well condition by TV-camera inspections**, because this will lead to a systematic description of well condition already at the point of recording as a valuable parameter for further comparable data analysis. Currently the classification is only based on four stages of clogging and does not differentiate between types and locations of incrustations. Presumably, a more detailed code could reveal a better correlation to well performance data. Our recommendation would be a matrix with a classification of the intensity of the visible deposits in combination with a classification of the deposits' location distinguishing between the three possibilities filter-screen, pump or riser and well casing. **These classifications need to be assessed already in the field**. Whereas in the work report some more details about colour and structure of the deposits could be included, in the database only a classification index would be recorded. The definite development of a matrix should be done in cooperation with experts from the technical directions, e.g. staff responsible for executing the TV inspections.

**Qs** is still seen as **the best operational monitoring parameter** but its measurement could be improved to make it comparable. In WELLMA-1, KWB and FU Berlin encouraged the **digital recording of initial pumping tests** for the Berlin well data. Those data will be available in the future for a more detailed evaluation of the specific capacity Qs of individual wells. Furthermore, it can be rechecked if the hydraulic conditions in the aquifer are confined or unconfined. The examination of the French data showed the value of such an assessment.

In the best case, **pumping tests** should be done for **the same duration and discharge rate** to be comparable. Furthermore, a more regular measurement of Qs for the Berlin wells– like in France - would be favourable. Variations of single values can then be compensated by trend analysis over the respective period.

The idea is to **combine Qs measurement it with a classification matrix via TV-camera inspections** to come to an optimized evaluation of well condition in the future.

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.

Only continuous or regular measurement and subsequent data processing provides an early identification of deterioration.

Firstly, a reference value, which triggers intervention needs to be defined. This could either be a maximum tolerated drawdown (for a specified discharge rate), $\Delta h$ or loss of performance or simply the presence of clogging deposits (or corrosion etc.) discovered during TV inspection.

The earlier countermeasures are started, the higher is the success and sustainability. Therefore, a detailed **monitoring schedule** needs to be developed with regard to the identified **reference value** on the one hand and the consideration of available technical and personnel resources on the other. It must include **operational parameters** (if not measured continuously) to assess the **well performance** and regular additional investigations to evaluate the **well condition**.

## 6.2 Well operation

Considering the results of the data analysis for well design and operation, it is recommended to **avoid well construction with filters less than 20 m under top ground surface**.

Furthermore, it seems to be favourable to **lower operating hours and mean total discharge** to reduce the loads of iron, manganese and nutrients for the individual well. Besides, it lowers the variation of the operational conditions. However, the observed relations need more detailed investigations.

## 6.3 Well construction

Regarding **well design and construction**, the statistical analysis yielded one recommendation:

- The top of the screen section(s) should be below 20m below surface.

In addition, this contributes to an enhanced protection against the contamination by pathogens, as was concluded from the bibliographic study for work package 4. Therefore, it has already been implemented into the well design standard of BWB.

During literature review, some recent approaches for (1) well design and (2) a better accessibility for rehabilitation methods were considered to be of interest and shall therefore be mentioned here:

1. The use of glass beads for artificial gravel packs (Ochs Bohr GmbH, Nürnberg): Advantages are the homogeneous grain size distribution and thus porosity, a better resistance to abrasion and fracturing, the absence of impurities (undersized particles as well as organic compounds), smoother surfaces inhibiting the attachment of biofilms or precipitates.
   The benefits should be further assessed including the evaluation of clogging properties and behaviour during rehabilitation.

The possible inclusion of field investigations testing these approaches within the scope of WellMa2 needs to be discussed with the technical staff of BWB and Veolia.

2. The use of the "symmetrical double surge chamber" (GCI and Pigadi, Berlin): Based on the results of numerical fluid mechanics modelling and field tests, a new device for well development and desanding was presented. Advantage is an improved operating distance resulting in higher transport velocities and activation of the complete artificial gravel pack up to the near-well aquifer.

As this device is developed in co-operation with Pigadi, it has already been tested at BWB and Veolia wells. The transfer of results and a possible accompany of further field tests by scientific investigations within the scope of the WellMa project needs to be discussed with the persons concerned.

3. The equipment of new wells with "satellite boreholes" within the near-well aquifer for the application of chemicals from outside the well (HOWSAM 1995):
   The advantage lies in the greater hydraulic gradient towards the well. Chemicals will attack young and therefore least severe clogging outside first and will make better progress towards the well.

The proposal might be considered for the construction of a new well in France. As BWB do not apply chemical rehabilitation methods, the approach needs not to be considered for further field work and the development of guidelines for well construction for Berlin.

## 6.4 R&D Transfer

For a better understanding of well clogging, it seems to be useful to observe especially the detected parameters related to clogging: **depth of the first filter, mean total discharge, iron concentrations and well age**.

(1) For WELLMA-2 it is suggested to monitor if shallow wells reveal more clogging tendency. Therefore, wells with the same construction and operation characteristics but with **differences in its depth of the first filter** will be analysed. An additional data analysis for the identified outliers (i.e. wells, which do not show clogging, although their filter is close to the surface and vice-versa) of this correlation is recommended.

(2) A second suggestion is to choose two wells with a **significant difference in its mean discharge** but a similar construction and switching scheme. To investigate the hypothesis that wells with a higher mean discharge tend more to clogging, the well with less mean discharge needs to be non-clogged, the one with the high discharge needs to be clogged. For the outliers as well a data analysis would be useful.

(3) Thirdly, it is proposed to investigate operational stress on wells by **different number of switchings**. Therefore, two wells with the same discharge rate will be selected. One will be switched very often and the other one as little as possible. The one with a high number of switchings is supposed to have intense clogging whereas the other has to be not clogged. This will be accompanied as well by a data analysis of outliers.

(4) Because operational stress is also caused by high flow velocities, which by themselves depend on the ratio between discharge and intake area (screen length), another two wells will be chosen to focus on the dependency on clogging at **different flow rates**. Here, two wells either with the same number of switchings, mean discharge but different filter length or with different pump capacities will be sampled. The well with the short filter (or high pumping rate and same filter length) is supposed to clog more due to a higher flow velocity and respectively higher stress than the one with the long filter.

(5) **Furthermore,** a depth**-oriented recording of iron, manganese, nitrate and oxygen** in the well and its catchment should be done in WELLMA-2. This includes measurements upstream of and in the well to be able to calculate mass balances of the hydro-chemistry.

(6) Finally, the relevance of **well age** needs to be analysed by a data analysis for the individual case considering filter materials and well construction.

(7) At the moment, the classified TV-camera inspections yield only static information from the last inspection date. For further investigations, **the time series of all available TV-camera inspections** should be implemented in the database to see if it is possible to use the clogging rate to differentiate the wells.

The current analysis showed that it is preferable to focus on a small but defined dataset with reduced data variability. Therefore, it seems to be useful to include only wells with extensive information of camera inspections. Subsequently the strength of any identified trend can be rechecked with a more extensive dataset as it was done during our analyses.

Subsequent data analysis can be used to investigate if different clogging characteristics correspond to typical site conditions, well construction or operation types. Having more detailed information about the development of clogging and their differentiations will help to adjust well management.

Furthermore, the recording of visible clogging deposits can be compared with Qs-measurements, because the disadvantage of TV-camera inspection as a diagnosis tool is, that it works only for visible deposits.

A better knowledge on the control of clogging needs less multivariate interaction of all influencing factors. This might compete with the technical and economical interest of well operation. Therefore, the implementation of all recommendations for well monitoring, diagnosis and further investigations needs to be evaluated in close discussion with the operators.

Further field investigations should aim at:

(1) Method validation

- The evaluation of the use of $\Delta h$ 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

The development of the horizontal core sampling device should be followed after, to use ct-scans of the cores to validate the borehole geophysical methods and particle counting.

(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