REPORT

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WELLMA-2

SYNTHESIS REPORT

Project acronym: WELLMA-2

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Title

WELLMA-2 Synthesis report

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Thank you!

Summary

Objective of this synthesis report is to summarize the main achievements of the WELLMA-2 project. Based on the preparatory phase WELLMA-1 (2007-2009), the main project phase WELLMA-2 (2009-2012) included extensive laboratory, pilot-scale and field site investigations aiming at optimizing the operation and maintenance of drinking water production wells with respect to costs, energy efficiency and sustainability.

The main reason for inefficient well performance is so-called well ageing. Deposit formation due to multiply correlated biological, chemical and/ or physical clogging processes in and around the well cause a decrease in performance. Thus, the inter-disciplinary WELLMA-project team aimed at improving the efficiency of drinking water production wells by providing a scientific basis to support operators in their efforts to reduce well ageing. This included the development of guidance and recommendations for an adapted and well-planned operation scheme and maintenance strategy to sustain or reinstall the well performance.

Well ageing processes were intensively studied at a multitude of vertical drinking water production wells located in Berlin, Germany and near Bordeaux, France. Thereby, classical monitoring and diagnosis methods, such as pumping tests and TV inspections, but also newly developed own experimental setups, such as the in-situ measurement of oxygen, depth-oriented water sampling or the exposure of object slides and bio-reactors for biofilm growth were applied.

This synthesis report follows the project outline featuring four work packages dealing with

1. the identification of ageing types and the site-specific ageing potential from optimal data processing of site and well characteristics to provide decision support for the diagnosis and subsequent optimisation of well operation, monitoring and maintenance,
2. field methods and experimental setups applied within the WELLMA-project to investigate mixing processes, oxygen uptake and biofilm formation,
3. the impacts of intermittent operation on the uptake potential and distribution patterns of oxygen, and
4. the efficiency of hydrogen peroxide treatments for preventive well maintenance against biochemically induced iron ochre formation and the oxygen uptake potential correlated to the decomposition of H_2O_2.

Intermediate data were presented at various occasions at scientific and practice-oriented conferences, e.g. the Association for General and Applied Microbiology (VAAM), the International Water Association (IWA) Groundwater conference, International Association of Hydrogeologists (IAH), Berlin-Brandenburger Brunnentage, Wasser Berlin etc. and in related papers. A publication list is given at the end of this synthesis report.

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Glossary

Production well	(Vertical) filter well used for drinking water abstraction, usually consisting of borehole, casing, screen and gravel pack, equipped with a submersible pump
Observation well	(Vertical) filter well used to monitor groundwater quantity and/ or quality; typically 2" diameter casing and screen (of max. few metres length)
Recharge source	Recharge sources of drinking water abstraction wells can be - naturally replenished groundwater (GW) - (river)bank filtrate (BF) - (managed) aquifer recharge (AR)
Static water level (Rest water level in Figure 1)	Equilibrium water level in the well, when no water is taken from the well [m below reference]
Dynamic water level (Pumping water level in Figure 1)	Steady-state water level in the well, when the well is operated [m below reference]
Specific capacity	Qs; Yield per meter drawdown as a function of time and discharge; Abstraction rate Q [m^3/h] divided by corresponding drawdown s [m] [m^3/h*m]
Well performance	Maximum rate of yield for given conditions, usually maximum discharge rate for given drawdown
Well ageing	Biological, chemical and/ or physical processes reducing the performance, usually due to the deposition of clogging material in the screen, gravel pack and/ or adjacent aquifer
Preventive maintenance	(Chemical) treatment of production wells to preserve their performance, typically involving a disinfectant agent to reduce biochemical clogging, e.g. hydrogen peroxide
Well regeneration	Mechanical or chemical methods to reinstall the well performance by removing deposits from the screen, gravel pack and adjacent aquifer

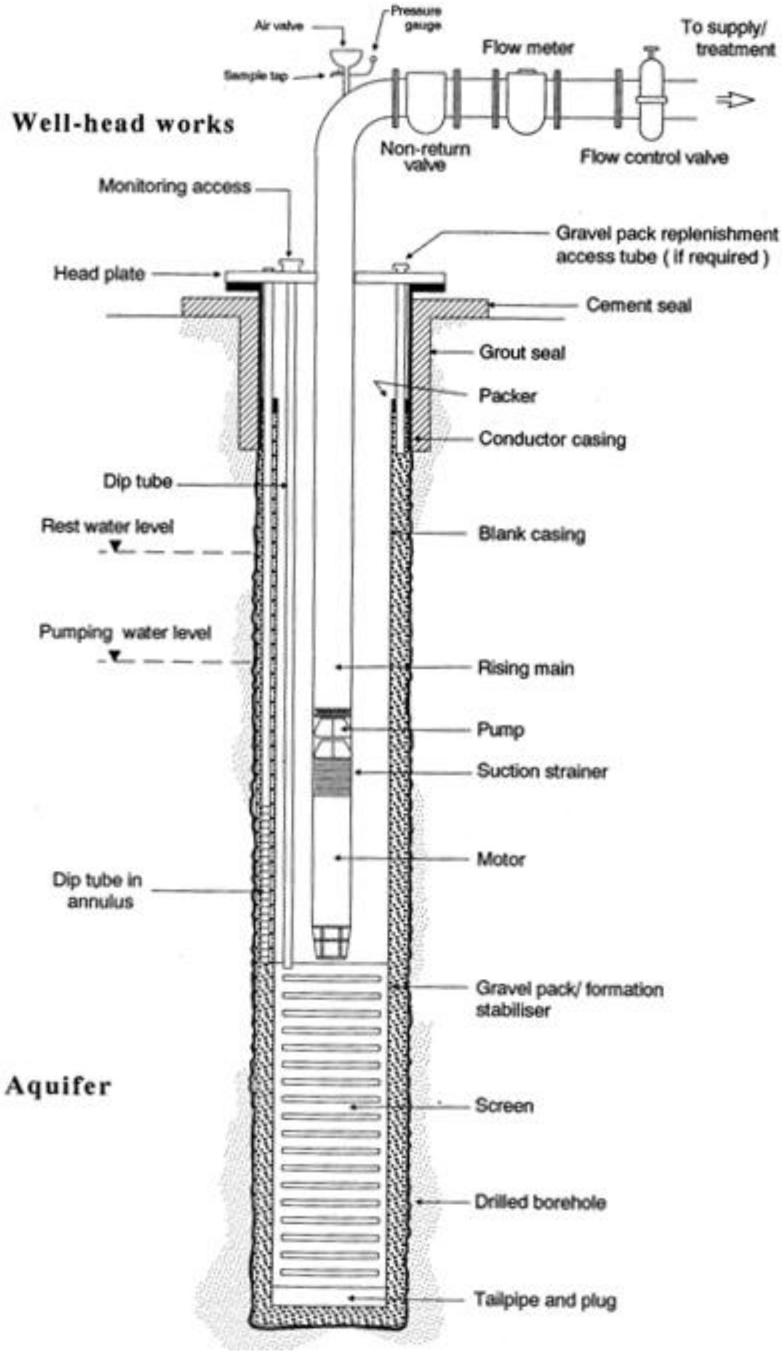

Figure 1: Terms and nomenclature [after HOWSAM et al. 1995]1

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[1]HOWSAM, P., et al. (1995). Monitoring, maintenance and rehabilitation of water supply boreholes. London. Construction Industry Research and Information Association.

Part A
The ageing potential of wells

Well ageing involves a multitude of biological, chemical and physical processes. Key factors determining the type, extension and location of clogging deposits are the geology of the exploited aquifer, hydrochemical properties of the abstracted water, well design and operation. Thus, it should be possible to pre-diagnose the occurrence of deposit formation processes from the presence of their pre-requisites and their triggers induced by well design and operation.

Objective of WELLMA-2 was therefore to define the set of key parameters, with which the ageing potential of wells can be evaluated from given site and well characteristics. Based on this well-specific ageing potential and the assessment of the current well condition, operational parameters, e.g. maximum discharge rates or numbers of switching, and qualitative monitoring indicators, methods and measurement frequencies could then be recommended.

1 Key parameters and triggers of ageing

As they imply different pre-requisites and site conditions and lead to different monitoring requirements, the ageing potential was defined separately for each of the following ageing types:

1. Carbonate scaling,
2. Forms of corrosion (oxidative, galvanic and bio-corrosion),
3. Iron ochre formation,
4. Biofouling (in terms of mass accumulation of biomass, slimes, EPS ...),
5. Sand intake (and abrasion), and
6. Colmation.

Using a top-down approach (Figure 2), for each ageing type, first a general process description and definition of pre-requisites was developed from reference textbooks[2], practical experience of the involved partners, and the WELLMA-1 hypotheses. Secondly, sub-processes and triggers inducing these processes in drinking water production wells were identified. These triggers were then related to site and well characteristics by defining the main indicators, which enable to recognize changed conditions in wells. Finally, enhancing conditions were described for each ageing type and trigger.

Final effect	**Ageing type**
Principle	What happens in general? What is the <u>general</u> chemical or mechanical process?
Pre-requisites	What <u>basic conditions</u> need to be fulfilled?
Sub-process	By which processes are basic conditions changed in general?
Trigger	<u>How are these changes induced in a well</u>?
Coefficient	How relevant is this change compared to the other triggers?
Main indicator	<u>How do we recognize changed conditions in the well</u>?
Enhancing conditions	Are there aquifer or well properties, or operation modes enhancing the occurrence of changes?

Figure 2: Workflow for the definition of ageing processes and their key parameters

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[2] *to name the most important ones (in the order of appearance)*: *CLARKE 1980; DRISCOLL 1989; HOWSAM et al. 1995; APPELO et al. 1996; CULLIMORE 1999; MCLAUGHLAN 2002; DVGW 2007; HOUBEN et al. 2007*

Pre-requisites and main indicators for the triggers and enhancing factors may be parameters from

		e.g.
-	aquifer geology	coverage, sediment composition, presence of carbonates, static water level etc.
-	well design and construction	depth of the screen top, casing and screen material, total well depth etc.
-	raw water chemistry	carbonic acid equilibrium, iron content, chlorine or sulphate concentration etc.
-	well operation	dynamic water level, discharge rate, number of switchings etc.

Table 1 summarizes all dynamic parameters from operation and raw water chemistry, which were identified as triggers and enhancing factors.

Accordingly, the ageing types involving chemically or biochemically induced precipitation processes, namely carbonate scaling, oxidative corrosion and iron ochre formation, are typically triggered by changes in water chemistry and operational parameters leading to mixing, e.g.

- dewatering of the screen top (or confining layer, if present)
- frequent water level fluctuations, or
- turbulent flow conditions due to high discharge rates,

while the ageing types involving physical processes, namely sand intake and colmation, are depending on constructive properties and operation, e.g.

- weak construction materials,
- wrong design and construction (gravel pack, screen position, ...) and
- particle mobilisation due to over-exploitation.

A brief summary of the identified key parameters is given in the sub-chapters below.

Table 1: Parameters from well design, operation and raw water chemistry representing triggers and/ or enhancing conditions for well ageing

PARAMETER	THRESHOLD	CURRENT VALUE	TRIGGER FOR	ENHANCING CONDITION FOR
Dyn. WL above final depth of conf. layer	>= ?	?	iron ochre, carbonate scaling	
Dyn. WL above top of screen	>= ?	?	iron ochre, carbonate scaling, corrosion	
Dyn. WL above max. admiss. dyn. WL	>= ?	?		colmation, sand intake
Dyn. WL below stat. WL + 10m	<= ?	?		carbonate scaling
Current Q above admiss. Q	>= ?	?	colmation, sand intake	iron ochre, carbonate scaling, corrosion, sand i
Current Q above 75% of admiss. Q	>= ?	?		iron ochre, carbonate scaling, colmation, sand i
Current Q below 50% of admiss. Q	<= ?	?		carbonate scaling, biofouling
Current Q above crit. Q at vIn 0.02	>= ?	?	iron ochre, carbonate scaling	
Current Q above crit. Q at vIn 0.03	>= ?	?		colmation, sand intake
Switchings 1-6x per day	<= 2	?	sand intake	iron ochre, carbonate scaling, corrosion
Switchings 1-6x per week	<= 3	?	iron ochre, corrosion	
Switchings 1-3x per month	>= 4	?	carbonate scaling, biofouling, colmation	
Fe tot [mg/L]	>= 0,2	?	iron ochre formation	
Fe diss. [mg/L]	>= 0,2	?	iron ochre formation	
O2 [mg/L]	0,1 - 1	?	biofouling, corrosion	
Eh [mV]	-50 - 150	?	biofouling, corrosion	iron ochre formation
EC [µS/cm]	>= 700	?	corrosion	
Temp [°C]	>= 10	?		biofouling
Temp [°C]	>= 20	?	biofouling	
TSS [mg/L]	>= 0,3	?	sand intake	
TSS [mg/L]	>= 5	?	abrasion	
Turbidity [NTU]	>= 2	?	sand intake	
SO4 [mg/L]	>= 150	?	corrosion	
Cl [mg/L]	>= 200	?	corrosion	
NO3 [mg/L]	>= 0,1	?	biofouling	
NH4 [mg/L]	>= 0,01	?	biofouling	
DOC [mg/L]	>= 2	?	biofouling	
DOC [mg/L]	>= 5	?		iron ochre formation
Odour	= 1	?	corrosion	
Ryznar index	>= 7	?	carbonate scaling	

Above threshold — Insufficient data — Below threshold

1.1 Carbonate scaling

Carbonate scaling is a chemical phenomenon that mainly involves the precipitation of calcium carbonate in wells due to sudden changes of the physical or chemical conditions in the water. This leads to an under-saturation of the water in dissolved CO_2, which shifts the carbonic acid equilibrium towards carbonate precipitation.

Groundwater quality

Calcium is a constituent of the groundwater and its presence is a pre-requisite for carbonate scaling. Hence, aquifers naturally presenting high calcium contents (karsts, sedimentary basins…) show a high carbonate scaling potential.

Parameters directly or indirectly linked to operation

The *hardness*, *alkalinity* and *pH* of the water are very closely linked to the concentration of dissolved CO_2. Therefore, any operational process leading to the degassing of CO_2 such as dewatering, pressure release due to pump switching or turbulence in the well will enhance carbonate scaling.

Temperature also has a decisive impact both on CO_2 solubility as well as on chemical reaction constants (pK_2 and pKs). Any increase in temperature will enhance carbonate scaling. This effect can be triggered for instance by a long-time pump operation (motor heat) or by mixing cold groundwater with warmer water (different aquifer, riverbank filtrate…).

Furthermore, carbonate scaling can be triggered by *mixing incompatible waters* (different aquifers, river bank filtrate, ...).

1.2 Corrosion

Corrosion is the destructive attack of a metal (i.e. black steel) due to the interaction with given environmental conditions. It is predominantly a chemical phenomenon, which may severely damage well systems. It involves a chemical, electrochemical or biological attack of the well materials due to the nature of the groundwater, to the presence of gases (O_2, CO_2), to the nature of casing materials or to the action of microorganisms.

Groundwater quality and well materials

Electric conductivity (EC) and the c*hlorine content* are characteristics of the groundwater. Their presence is necessary to ensure that water is conductive (electrochemical corrosion).

For contact corrosion i.e. the galvanic effect, a pre-requisite is the existence of *two different metals* in the well materials.

Sulphur, which is also a natural content of groundwater especially in thermal waters or waters from gypsum-rich rocks, is required for bio-corrosion, where sulfate-reducing bacteria induce corrosion via H_2S-production, creating an electron transfer potential.

Parameters directly or indirectly linked to operation

Dissolved CO_2 and O_2 contents are influenced by operation. Dewatering, frequent pump switching, relevant water level variations and high flow velocities tend to increase these parameters and are thus triggers for chemical corrosion. On the contrary, low flow velocities and anaerobic conditions are favourable for bio-corrosion.

Temperature also has an impact on CO_2 solubility as well as on chemical reaction constants. Temperature can be altered for instance by long-time pump operation or by mixing cold groundwater with significantly warmer water from a different aquifer. An increase in temperature will potentially trigger electrochemical corrosion.

1.3 Iron ochre formation

Iron ochre formation is induced by the coincidence of oxygen and dissolved divalent iron. The iron is oxidized and precipitated as hydroxide deposits. The reaction is determined by pH and Eh conditions.

Groundwater quality, aquifer and well characteristics and recharge sources

Groundwater characteristics must contain dissolved iron and must provide the stability of precipitates, i.e. pH between 6 and 9, and Eh between -50 and +150 mV, which can be presumed for most of the groundwater used for drinking water production.

In general, *unconfined conditions* provide less protection from unwanted oxygen intake. As the aquifer has a free groundwater surface, oxygen uptake from water level fluctuation due to well operation accelerates ageing due to mixing.

Leaky aquifers represent points of contact of different waters, where mixing reactions will occur in the well surroundings. Because *bank filtrate or artificially recharged water* may contain oxidizing species such as oxygen itself or e. g. nitrate, mixing with iron-rich ambient groundwater results in precipitation of hydroxides, as well.

Parameters directly or indirectly linked to operation

The parameters, which can be influenced, are the pump capacity and the pumping strategy (continuous or intermittent). Both, oxygenation and the flow velocity are strongly dependent on the well operation scheme. Air entrapment from *frequent water level fluctuations* and potentially *turbulent flow* enable oxygen uptake and accumulation in the upper groundwater layers.

If the *water level* is allowed to fall below the top of the screen, a seepage face can develop, which will promote cascading. Dewatering of the confining layer leads to pressure changes and subsequent shifts in thermodynamic equilibrium. Both processes will trigger enhanced iron ochre formation.

1.4 Biofouling

Biofouling can be defined as the undesired accumulation of biological deposits on a surface (VIDELA 2002). Such biofilm accumulations are sufficient to reduce water flow and/or quality. Thus, they increase the risk of clogging and/ or corrosion.

Groundwater quality and recharge sources

Groundwater characteristics must be favourable for the development of micro-organisms, i.e. *pH* between 6 and 9, *Eh* between -50 and +150 mV. Besides, t*emperatures* above 10°C are needed to observe significant biofouling, and higher temperatures accelerate the process.

Waters with *high dissolved oxygen content* will likely enhance iron oxidation and slime production in the gravel pack. Finally, a *high proportion of bank or surface water filtrate* also increases the potential for biofouling as it increases the risk of organic compounds, contaminants or microorganisms to be present in the groundwater (waters with high BDOC content).

Parameters directly or indirectly linked to operation

Stable environmental conditions enhance most of the biofouling processes, among these, especially stable flow conditions. This means that wells with *long resting periods* as well as *constant and moderate* flow rates are potentially prone to biofouling. On the other hand, *well switching* or *high flow velocities* may trigger changes in water temperature and an increase in dissolved oxygen content through turbulence, but these effects are generally counterbalanced by a negative impact on biofilm development by detachment of biofilms shreds due to shear forces.

1.5 Sand intake and abrasion

Pre-requisite of groundwater quality and well materials

Groundwater and/or aquifer characteristics must be favourable for particle mobilization. A *high particle load* shown by elevated total suspended solids (TSS) or turbidity is the major indicator for sand intake. The abrasion process is enhanced by the use of *soft/weak well materials* such as PVC, copper or wood.

Parameters directly or indirectly linked to operation

High flow rates and *high intake velocities* will accelerate the mobilization of particles from the well surroundings. Hence, operation of the wells at *high discharge rates* or *inadequate well design* (pump capacity in accordance with well geometry) is likely to enhance sand intake. Inadequate *initial well design* (of the filter pack or the screen) or inadequate *initial well development* will lead to an incomplete filtration and ultimately to sand intake.

Parameters leading to an increased mobilization of suspended solids will also enhance abrasion. Hence, *high flow rates* and *high intake velocities* are likely to enhance abrasion. An inadequate size of the gravel pack relative to the aquifer grain size distribution may lead to abrasion problems from sand intake (DVGW 2001, 2002).

1.6 Colmation

Groundwater and aquifer characteristics

Groundwater and/or aquifer characteristics must be favourable for well colmation. Major pre-requisite to any colmation mechanism is a *high particle load* of the raw water.

Parameters directly or indirectly linked to operation

High flow rates and *high intake velocities* are parameters that accelerate the mobilization of particles from the well surroundings, and ultimately colmation, e.g. from bridging of particles. Hence, operation of the wells at *high discharge rates* and/ or *inadequate well design* (pump capacity in accordance with well geometry) is likely to enhance colmation problems.

Repeated switchings on the other hand, are reported to reverse bridging. Thus, they can help to reduce colmation. According to VAN BEEK (2010) no clogging will occur, as long as, on average, the particle amount removed by switching equals the volume accumulating during abstraction periods. This however needs to be determined for each individual well from comparing Qs-curves and TSS loads with and without switching.

2 Decision support for an optimized operation and monitoring

The quantification of clogging rates to be expected from hydrogeological, chemical and operational characteristics of the well, together with the assessment of the current well condition from quantitative and qualitative monitoring data were integrated into a decision matrix defining a global indicator. From this, monitoring and maintenance needs were derived and recommendations were determined for

- the maintenance of wells already affected by ageing, based on the well performance development
- operation, and
- monitoring.

The selection of specific key parameters depended on the ageing types, because different ageing types require different measures.

For optimized operation, the previously identified limits for discharge rates and number of switchings were transferred into well-specific recommendations for optimized operation stating e.g.

- a minimum and maximum number of switchings per week or month e.g. in case of the potential for colmation and/ or iron ochre formation, or
- a maximum discharge rate to prevent over-exploitation or turbulent flow e.g. in case of the potential for sand intake or carbonate scaling.

For monitoring, three levels of activity were identified, being

1. a minimum monitoring schedule of operational parameters, when the well is in good condition and ageing potential is low,
2. semi-annual to annual monitoring parameters for currently absent pre-requisites and triggers enabling the early identification of degradation, and
3. monthly to quarterly monitoring for confirmed pre-requisites and triggers to become aware of overstepping thresholds and to subsequently initiate maintenance as early as possible.

The minimum monitoring schedule is based on the numerous available textbooks and technical standards (see footnote on page 2 for example references) and thus includes the recommendation to record at least:

- total discharge (per day/ month/ year),
- (daily/ monthly) operation hours,
- pump power consumption (per day/ month/ year),
- one pumping test per year to record static and dynamic water levels at a constant discharge rate and to evaluate the specific capacity of the well, and
- total suspended solids (or turbidity) (annually) to identify physical processes and/ or corrosion.

For some of the identified triggers, it has to be noted that they are relevant for different ageing types, for which they have sometimes opposite effects. Best example is the "number of switchings", where a high value is beneficial in case of physical clogging, but has an adverse effect for all other clogging types. Thus, all ageing types should be evaluated, when aiming at optimizing operation, monitoring and maintenance.

Part B
Methods to study ageing processes

Ageing processes in drinking water production wells have been studied for more than 100 years now leading to a series of state-of-the-art monitoring and diagnosis methods, which are applied routinely nowadays. However, these methods typically focus on recognizing and diagnosing losses of performance rather than understanding the processes within wells itself, so that there is still room for improvement.

Objective of the WELLMA-project was to quantify ageing rates in relation to well characteristics. Focus was on iron ochre formation, but methods should be transferable to ageing processes in general and thus the methods should be applicable for different lithological and hydrochemical settings and well designs.

Within WELLMA-2, field investigations and experiments on a technical scale were applied to study redox processes, the impacts of operation and preventive maintenance. Aim of the following chapters is to describe the investigation approaches and to obtain conclusions regarding the general applicability and transferability of these methods.

1 Depth-oriented sampling

Based on the recommendations derived from the short-term monitoring and oxygen measurements during the preparatory project phase WELLMA-1, method development within WELLMA-2 focussed on a better understanding of the redox processes in wells. Special interest was to determine the redox cline and contact zones between (deep) anoxic, iron-bearing and (shallow) oxic water within the screened section of vertical filter wells (Figure 3). Thus, a methodology for depth-oriented sampling was developed to study mixing processes in drinking water abstraction wells during operation.

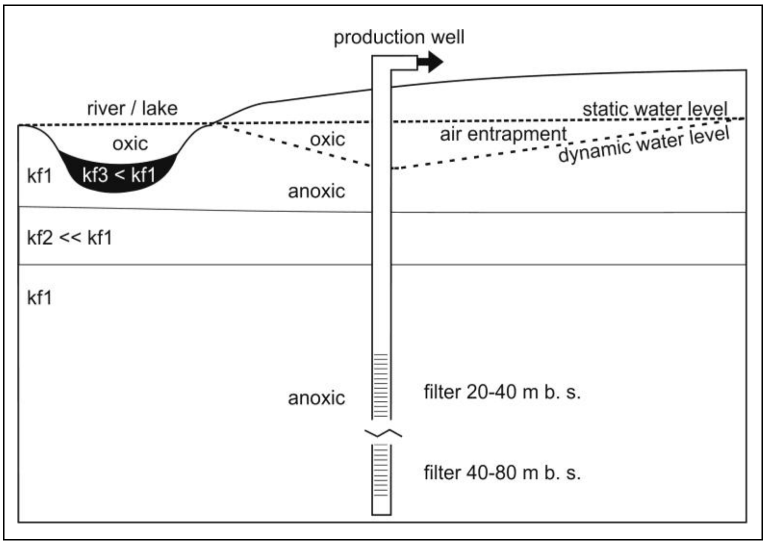

Figure 3: Conceptual model of the studied water supply system with river bank filtration/ artificial recharge and shallow, oxic on top of deeper anoxic water [Appendix 1 of TAUTE et al. 2013].

1.1 Methodology

Sampling aimed at determining the hydrochemical composition of the raw water at different depths within a well to assess mixing processes and changes of saturation. The well should be in operation during the whole procedure. Within WELLMA, the method was successfully applied at several locations including quaternary sandy aquifers and tertiary carbonate aquifers.

Water samples were taken with a Grundfos MP1 sampling pump installed in the monitoring access tube. Sampling always started at the lowermost depth, proceeded upwards and finished with a sample from the tap on the well head. The top of screen and depth of the pump intake were always included (Figure 4).

The sampling depths were selected based on

i) the geological log of the well to represent the different geological units and
ii) flow meter log to represent the intake distribution.

Samples for laboratory analysis of main cations and anions were always taken after physico-chemical parameters temperature (T), electrical conductivity (EC), pH, redox potential (Eh) and dissolved oxygen remained constant for 20 minutes.

Pre-requisites for depth-oriented sampling were an access tube suitable for a mini pump, a geological log of the well and a flowmeter log. Results interpretation included the computation of depth-related raw water compositions and the graphical plot of these chemical parameters against depth, including saturation indices to indicate the potential for precipitation or dissolution reactions.

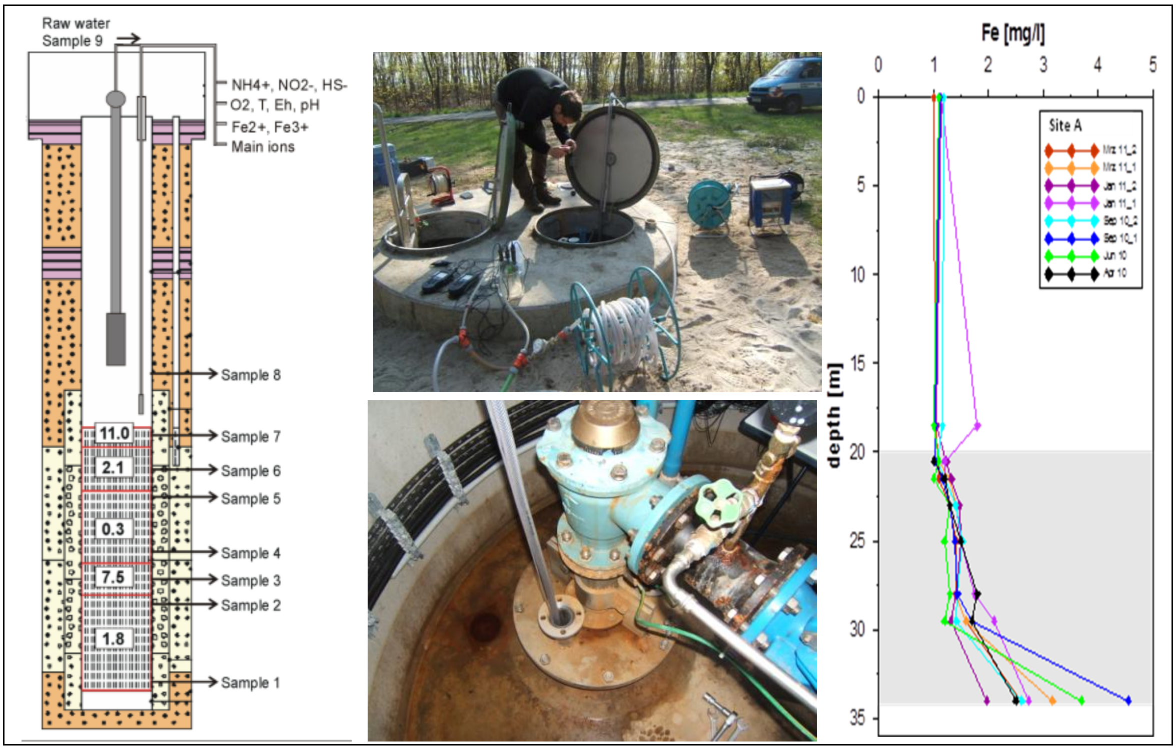

Figure 4: Scheme of depth-oriented sampling (left), procedure in the field (middle) and results interpretation (right). Sample depths correspond to the intake distribution indicated in the red boxes [MAIWALD et al. 2011]

Within WELLMA, five wells representing different hydrogeological boundary conditions were sampled quarterly to determine not only the variations in the chemical raw water composition with depth, but also with the seasons (long-term changes). In addition, each sampling campaign included one depth-oriented sampling directly after start of pumping after one week of rest and another campaign after one week of uninterrupted operation to assess mid-term changes in the raw water composition due to operational impacts.

1.2 Assessment of the obtained information value and applicability

Although more time-consuming compared to tap sampling, depth-oriented sampling yielded the expected insight into changes of the raw water composition and resulting saturation states along the intake section of the wells.

The method was successfully applied at an additional well in a consolidated aquifer in a carbonate context proving the general transferability. There, due to insufficient access at the well head, sampling was carried out with a bailer instead of a pump. Resting and operating conditions could not be compared, but zones of high variation in raw water composition and corresponding saturation states were identified.

Thus, the method was applicable in both

- shallow and deep wells
- unconsolidated and consolidated aquifers
- wells tending to carbonate scaling and/ or iron ochre formation.

Remarkably, in all investigations a zone of high variation in the chemical raw water composition was observed for the section between top of the screen and the pump inlet emphasizing the impact of flow conditions on the thermodynamic equilibrium. The method provided in-situ measurements for this zone, which is typically affected by visible deposits, which was not obtainable from tap sampling before. Saturation indexes could be calculated per depth and mixing processes due to operation could be assessed.

2 In-situ oxygen measurements

Objective of the oxygen measurements within WELLMA-2 was to quantify the oxygen input from different sources to develop adapted recommendations for an optimized operation. The investigations focussed on the impact from intermittent operation, but also on recharge sources, the effect of aquifer coverage, seasonal variations, and impacts from neighbouring wells and preventive maintenance with hydrogen peroxide. Two well sites, in addition to the one transect investigated during WELLMA-1, were equipped with observation wells in two directions vertically to the well field orientation. Continuously measuring oxygen probes (optodes) were installed in the well and the transect observation wells in different depths. The results were used in a 2D-flow and transport model based on Modflow2000 (HARBAUGH et al. 2000)[3] to compare different recharge and operation scenarios regarding their oxygen uptake potential (→ Part C1.2).

2.1 Optodes

Optodes are optical sensor devices made of a thin fibre optic. The measuring principle is based on a phase shift detection between LEDs and an oxygen-sensitive foil (Figure 5).

Their main advantages are a high resolution of 0.005% air saturation, their flexible design regarding lengths and permanent installation and their cost-effectiveness. Within WELLMA, optode components and measuring equipment of PreSens - Precision Sensing Germany were used.

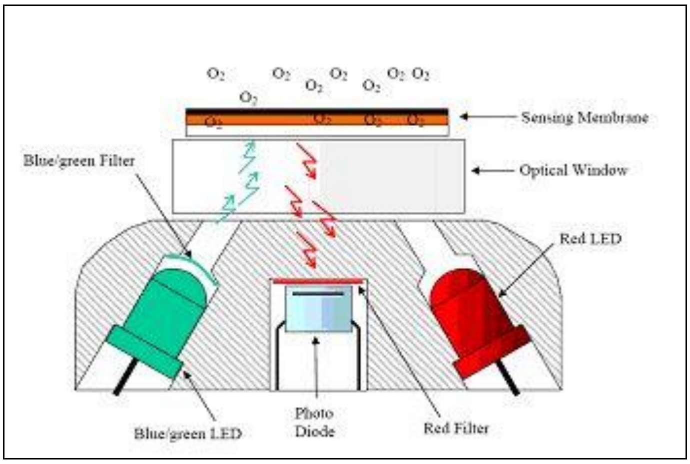

Figure 5: Principle of oxygen measurement with optodes [www.coastalwiki.org, accessed 06/2013]

2.2 Transect design

Primary target was to investigate differences between the recharge sources for typical well settings in the Berlin context. The transect observation wells were thus directed towards bank filtration (BF) or artificial recharge (AR) and to their opposite sides (GW).

Concerning the depth profile, of special interest were

- the zone of water level fluctuations (between resting and pumping water level),
- the upper part of the screen, and
- the lower part of the screen.

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[3] HARBAUGH, A. W., et al. (2000). MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model - User Guide to Modularization Concepts and the Ground-Water Flow Process. U. S. Geological Survey.

Therefore, multilevel observation wells were constructed. Screen and optode installation depths followed the geological log and the design of the wells (Figure 6). A dense optode network was installed especially in the zone of water level fluctuations, because of the primary objective to study the impacts from intermittent operation on the uptake and distribution of oxygen.

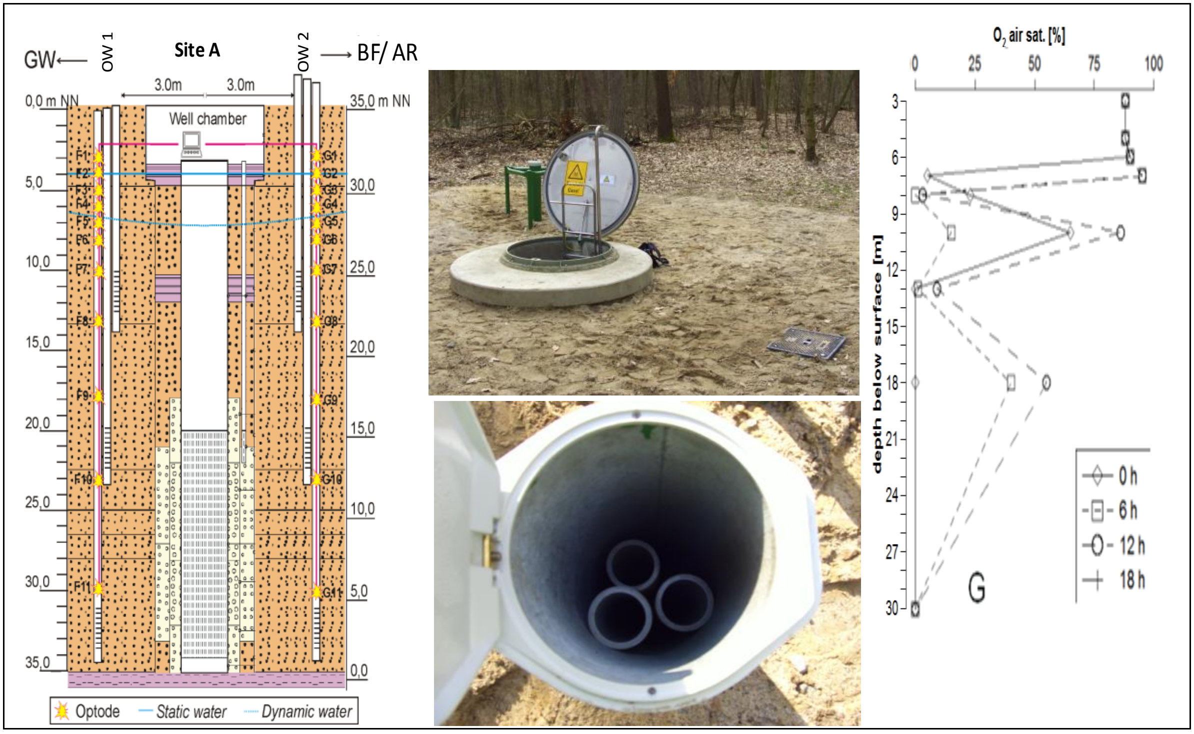

Figure 6: Transect design and location of optodes for in-situ oxygen measurements (left), field installations (middle) and results interpretation for one of the optode chains (right) [MAIWALD et al. 2011]

2.3 Methodology

The optode measurements mainly involved pump tests with specific switching schedules for the production well and its neighbouring wells in the well field. These tests were repeated quarterly to assess additionally seasonal variations.

Results interpretation included graphical plots of oxygen air saturation with time and against depth. These curves were further interpreted with regard to distribution patterns, replacement of oxygenated layers with time and operation, as well as balance calculations for the different recharge sources and relations between drawdown and oxygen uptake etc.

2.4 Assessment of the obtained information value and applicability of the method

Optodes and transects proved their applicability for long-term measurements of oxygen. Both, time-dependent changes and depth-related movement and accumulation of oxygen due to operation could be quantified and further used in model-based simulations of different operation and recharge source scenarios to quantify the effect of different design and operation measures. .

Such continuous measurement was performed for the first time in drinking water abstraction wells in Berlin. Because of the permanent installation of the optodes in different depths and in different intake directions, further individual sampling campaigns could easily be scheduled requiring only

- the (re)connection of the optodes to a data logger (called "fibox") and
- the set-up of an operation schedule for the specific objective.

3 Experimental setups on technical scale

Experiments on a technical scale aimed at studying the processes of biochemically induced iron ochre formation under controlled environmental conditions. Beside column and tank investigations, which are not described here as they followed standard procedures, WELLMA-2 led to two specific experimental setups for targeted investigations of mixing processes and key parameters for clogging under controlled environmental conditions.

3.1 Model well tank

Special feature of the model well tank constructed at the FU Berlin within WELLMA was the up-scaling from mid-sized laboratory tanks to the real dimensions of drinking water abstraction wells. To obtain realistic radial flow conditions, a wedge-shaped design was chosen comprising a segment of 1/12 of a full circle.

The investigations focussed on the impacts of clogging deposits on the permeability and porosity in the gravel pack and the adjacent aquifer material. Varying switching intervals and pumping rates were applied to assess their impacts on the precipitation rate.

3.1.1 Model well tank design and measurement equipment

Corresponding to a typical vertical filter well, the model well tank included from the inside (well interior) to the outside (aquifer): (I) a stainless steel casing with a wire-wound screen, (II) an inner gravel pack, (III) an outer gravel pack, (IV) an aquifer section and (V) a vertically divided recharge chamber (Figure 7).

The tank was filled with conventional filter gravel and sand and aquifer sediments from a drilling site in Berlin. The gravel pack compartments were sealed with clay on top corresponding to the annular sealing of wells.

Measurements included:

- the determination of the hydraulic flow field from 44 piezometers installed in the gravel pack and aquifer compartments
- pumping rate, inflow and outflow rates
- oxygen distribution from a network of 22 oxygen-sensitive optodes (→chapter 2)
- dissolved and total iron in the in- and outflow (sampling)
- the determination of the effective porosity via tracer tests with NaCl.

At the end of each investigation period, screen, gravel packs and aquifer were sampled for deposit analyses involving micro-section analyses and the determination of the loss on ignition, iron and manganese contents.

Altogether three investigation periods were carried out: (1) a calibration phase in the lab, (ii) operation in the laboratory with pre-conditioned tap water and (iii) installation at a drinking water production well and operation with iron-bearing groundwater.

The operation of the tank in the laboratory setup with tap water proved the general applicability of the tank and its installations. The succeeding field phase covered a period of 390 days with two experimental phases. Within phase 1, re-aeration processed due to different operation schemes were determined. Phase 2 aimed at generating deposits to determine clogging rates and preferred locations and their impacts on the hydraulic flow field.

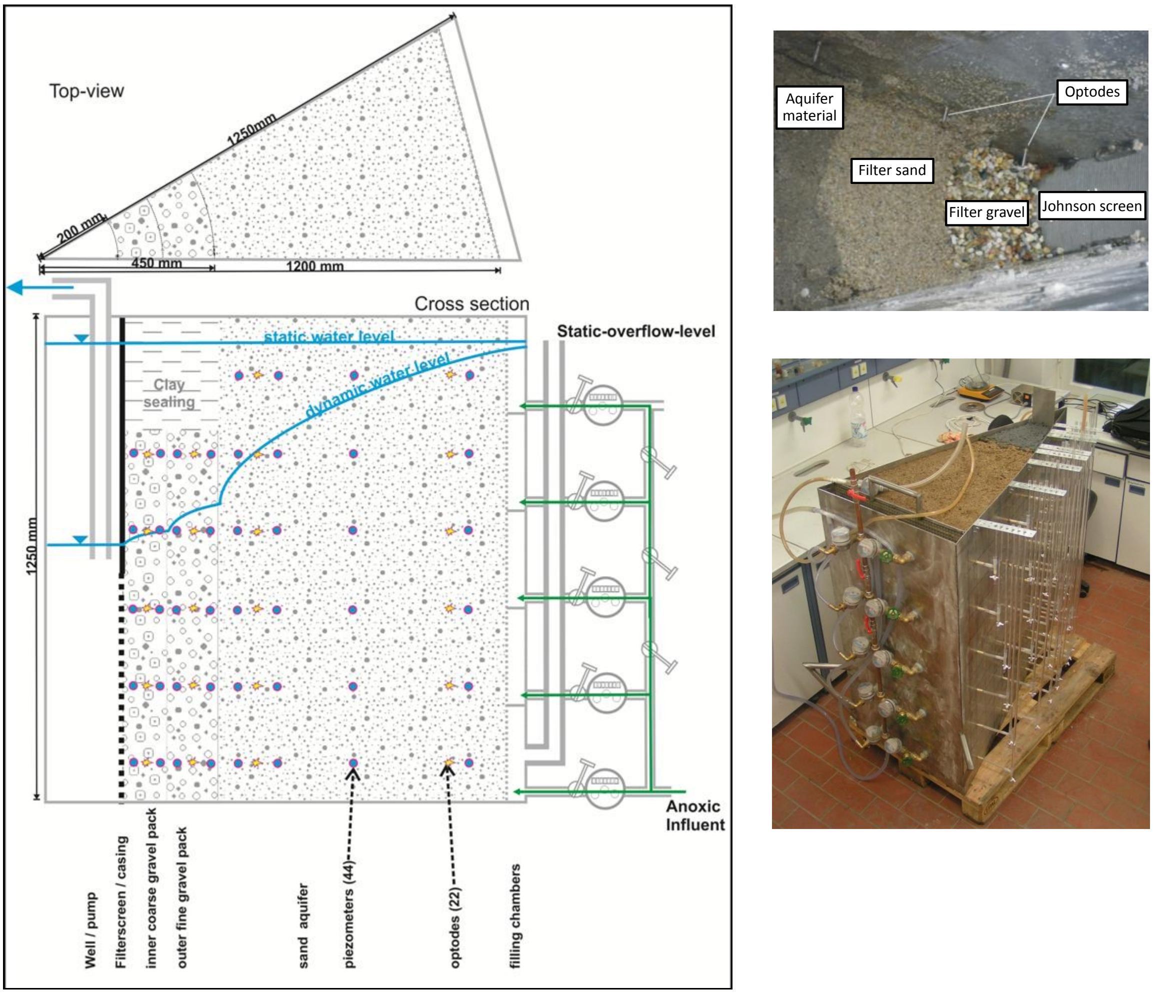

Figure 7: Model well tank design with measurement equipment.

3.1.2 Assessment of the obtained information value and applicability

In the laboratory, stable conditions providing a constant supply of dissolved iron could not be obtained because of the fast (re-)precipitation of iron in contact with air before reaching the tank. The succeeding field phase, at which the model well tank was fed with raw water from a drinking water production well containing no oxygen and iron concentrations of about 1.8 mg/L, was however suitable to simulate the iron and manganese ochre formation processes in drinking water abstraction wells.

The redox-sensitive parameters showed no dependency on the discharge rates, but switching clearly induced oxygen inflow from water level fluctuations, which was rapidly consumed by precipitation processes. Sampling at the inflow and outflow, and deposit sampling at deinstallation allowed balance calculations for iron and manganese showing that nearly 60% of iron and 3% of manganese were removed during the tank passage.

Compared to real wells, clogging processes appeared to be accelerated by high flow rates and the high ratio of iron in groundwater compared to oxygen. The tank investigations were thus well applicable to confirm the dependency between clogging rates and reactant supply. The hydraulic flow field reflected the deposition of iron and manganese hydroxides in the zones providing the main recharge to the well.

For further investigations, it was recommended to (i) shorten the screen section to prevent direct aeration from dewatering, (ii) compact the filling at installation to prevent later settlement and (iii) de-sand the tank after installation. Potential further applications include e.g. the comparison of different gravel pack designs and operation schemes.

3.2 Mini column installation

The mini-column investigations involved a down-scaling of laboratory column experiments allowing (i) to install columns directly at production wells and (ii) enabling parallel experiments with up to 18 columns.

Within WELLMA, two investigation setups were realized:

i) comparison of conventional gravel and sand materials with glass beads, and

ii) application of hydrogen peroxide, used as agent for preventive maintenance, to sand-filled, clogged columns to optimize treatment.

3.2.1 Methodology

The mini columns were constructed from plexiglas columns with 35 mm diameter and 100 mm length, which were connected to two 10L storage bottles providing an equal distribution of flow (Figure 8).

Figure 8: Mini columns before (top left) and after (bottom left) exposure and setup for installation at a drinking water production well (right) [SCHWARZMÜLLER et al. 2013]

To provide nearly natural conditions for clogging, the mini columns were installed directly at a drinking water production well supplying iron- and nitrate-bearing raw water.

The investigations involved:

- permeameter tests with different pressure steps
- tracer tests with NaCl to assess changes in the effective pore volume
- determination of volume and analysis of flushed material
- weighting and analysis of deposits remaining in the columns after flushing.

Permeameter and tracer tests were carried out before exposure to the well, after exposure (clogging) and between flushing experiments with different hydraulic pressure steps. In water and deposit samples, the loss on ignition, iron and manganese concentrations were determined. The columns in the setup focussing on the optimization of preventive well treatment with hydrogen peroxide were treated with hydrogen peroxide in different concentrations and treatment intervals during the exposure period at the well.

Results interpretation included graphical plots of the development of permeabilities and effective porosities after clogging and during flushing compared to the initial conditions before installation at the well. Loss on ignition, iron and manganese concentrations were set into relation to the flushing pressure steps and to the amount of deposits remaining in the columns to assess the effectiveness of potential hydromechanical regenerations.

Thus, (i) the optimal packing material with regard to clogging rate and effectiveness of flushing and (ii) the optimum hydrogen peroxide application scheme with regard to maintaining high permeability and removability of deposits could be evaluated.

3.2.2 Assessment of the obtained information value and applicability

The mini column experiments provided a low-effort approach to compare clogging rates and effects of deposits on the permeability on a small scale. Altogether, the methodology yielded the expected information. Both, the time-span needed for clogging and for the subsequent investigations was in the range of days. From the obtained results, recommendations regarding gravel pack materials, optimum treatment frequency and concentration of hydrogen peroxide treatments and effectiveness of hydromechanical regenerations depending on materials and previous preventive treatments could be concluded.

The small dimension and the geometry of the used columns and tubes led to a limited information value for the effective porosity calculated from the tracer tests and to limited transferability of measured permeabilities to natural systems. Thus, only relative changes of the porosities were compared, which, however, allowed the assessment of the best setup with regard to gravel pack filling material and optimal preventive maintenance.

Further experiments focussing additionally on microbial community characterisations are planned within the joint research project ANTIOCKER (2011-2014).

Part C
Sources and effects of oxygen in well operation

In the presence of iron(II)-containing groundwater and under typical pH-conditions of groundwater, the content of oxic species controls the iron oxide precipitation potential in drinking water wells. Based on the investigations during the preliminary project phase WELLMA-1, which included hydrochemical sampling campaigns and online measurements of geochemical parameters during start of pump operation and at constant conditions, oxic surface water originating i) from bank filtrate or artificial recharge and ii) from air entrapment by water level fluctuations induced by well operation were identified to be the most relevant sources of oxic species in wells.

Objective of WELLMA-2 was to quantify the oxygen distribution patterns under resting and operating conditions and to derive recommendations for optimum well operation to reduce the oxygen uptake potential.

1 Quantification of the oxygen uptake potential

Oxygen uptake and distribution patterns were compared by applying repeated direct oxygen air saturation measurements (optodes) at the three transect sites under specific operating conditions. Depth-oriented sampling focused additionally on assessing the redox states within a well with depth depending on the operation state and season. Preceding column experiments and the model well tank investigations (→ Part B, chapter 3.1) additionally refined the conclusions.

The experiments aimed at quantifying the oxygen input from different sources as the key driver for iron ochre formation and comparing natural oxygen supply depending on the recharge source and aquifer coverage with the impacts from operating the well and its neighbours.

1.1 Summary of field results

The investigations were carried out at:

- a transect site, at which a mixture of artificial recharge and bank filtrate are abstracted,
- a transect site, at which high portions of bank filtrate are abstracted,
- a transect site, at which a mixture of groundwater and bank filtrate is abstracted
- a production well abstracting groundwater and
- a production well abstracting artificially recharged groundwater and groundwater.

To assess the impacts of operation, at each field site, oxygen measurements and hydrochemical sampling were carried out under different operating conditions:

i) at start of an operation phase,
ii) after one week of uninterrupted operation,

and

iii) applying defined switching schemes for the investigated well and its direct neighbours.

From the results, the following conclusions could be drawn:

- ➢ Water level fluctuations due to switchings had a higher impact on the concentration of dissolved oxygen than the recharge source. The higher the drawdown, the more oxygen is taken up.
- ➢ Short-termed switchings (< 6-12 hours) had a minor impact on the oxygen uptake and distribution, because dissolution processes and subsequent aeration are slow.
- ➢ Of the investigated wells, the ones dominantly fed by groundwater showed high losses of performance and visible iron ochre formation on the top of the screen, which indicates that water level fluctuations are the main source of dissolved oxygen. Wells mainly discharging bank filtrate or artificially recharged water were less affected by a loss of performance and tended to develop oriented iron ochre formation in direction of the recharge source. Their precipitation rate is controlled by the oxygen load of the bank filtrate, which in turn depends on the travel time to the well.
- ➢ Bank filtrate showed much higher seasonal variations in redox conditions than groundwater.
- ➢ The concentration of dissolved oxygen in a well abstracting bank filtrate is mainly controlled by the discharge rate and number of operating wells in a well field.

- ➢ The oxygen uptake potential is strongly influenced by the location of a well within the well field and the distance to and operating condition and switching of its neighbours.
- ➢ Oxygen uptake can be minimized by distributing the total discharge of the well field to as many wells as possible applying equal, low discharge rates.

The rate of dissolved oxygen in artificially recharged water depends on oxygen consumption during infiltration. Thus, it is controlled by the travel time and influenced by seasonal variations (temperature, DOC ...). Artificial recharge in Berlin is additionally affected by pond operation and pond cleaning. Key parameters are

- the distance and hydraulic gradient between the well and the recharge source and
- the bank permeability.

The hydraulic gradient is generally influenced by operation. The oxygen uptake potential in wells abstracting high portions of riverbank filtrate or artificially recharged water can thus primarily be influenced by reducing the discharge rate. If possible, new wells in such well fields should be constructed with higher distance to the recharge source, which would probably also result in lower bank filtrate shares.

The rate of dissolved oxygen taken up from air entrapment due to switchings is depending on

- the thickness and permeability of the overlying sediments and
- the amplitude of drawdown.

Confined conditions and deep screens provide a natural protection of the wells against oxygenation. Concerning the amplitude of drawdown, the impacts of the operation scheme are more complex and interacting. Key parameter is the discharge rate, but also the location of the well within a well field, distance and operation state of its neighbours and the frequency of switchings.

To compare the impacts of geological conditions and well operation, the field results were transferred into a generic geological environment, as described below.

1.2 2-D flow and transport modelling

A MODFLOW flow and transport model was developed to determine minimum and maximum oxygen input rates for various hydrogeological scenarios. The boundary conditions were deducted from average values of the investigated field sites (Menz et al, in preparation, see also Figure 3).

The simulations included the comparison of different site characteristics:

- shallow (20-40m) and deep (40 to 80m) screens
- confined, semi-confined and unconfined conditions
- presence and absence of a clogging layer at the bank of a recharge source

as well as the test of typical and hypothetical operation schedules with varying

- discharge rates and resulting amplitudes of drawdown
- number of switchings (single or repeated change of water level)
- time lags between switchings (length of operating and resting periods)
- number of wells in operation.

The simulation results confirmed the hypotheses drawn from the field investigations. Both, oxic bank filtrate and air entrapment from repeated switchings provide a constant source of dissolved oxygen for subsequent precipitation processes.

The effect of switchings is up to twice as high as of bank filtrate intake, depending on i) the discharge rate and number of operated wells and ii) the travel time of bank filtrate towards the well. Figure 9 and Figure 10 illustrate these findings:

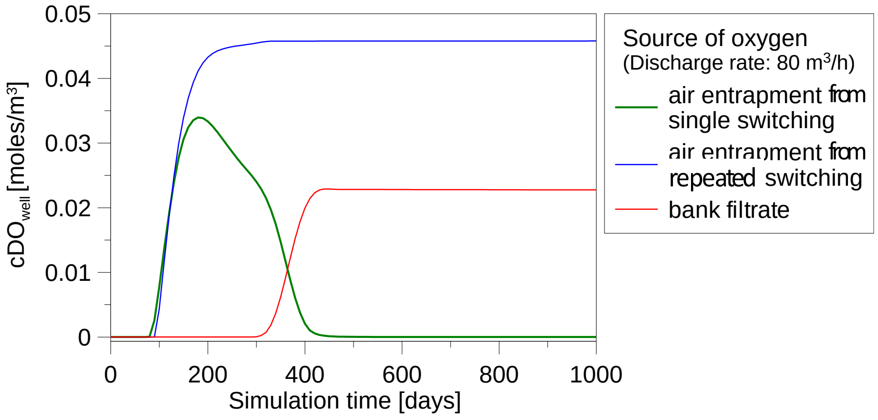

Figure 9: Comparison of simulated concentrations of dissolved oxygen (cDO) at the top of the screen related to the source of oxygen. Initial cDO in shallow groundwater and surface water was set to 10 mg/l and the discharge rate of the model well to 80 m^3/h.

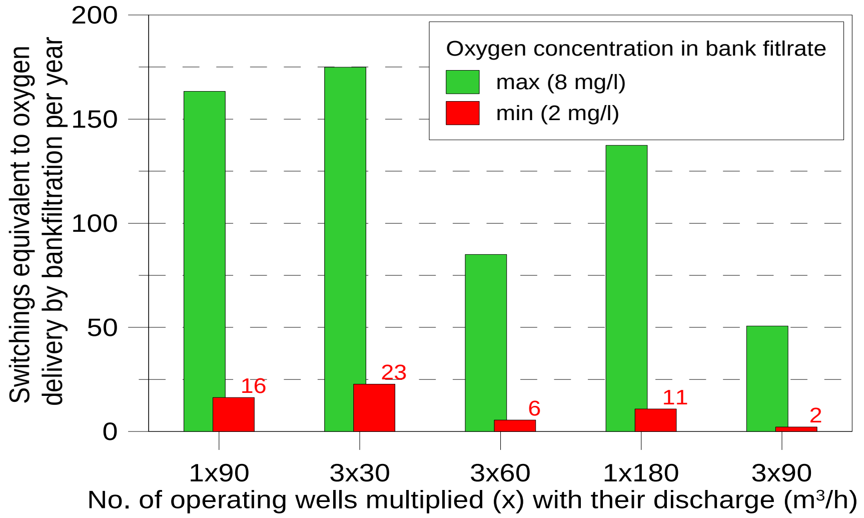

Figure 10: Comparison of the oxygen uptake potential of well switching and bank filtrate. The share of bank filtrate was set to 80%. Concentrations of dissolved oxygen in bank filtrate were set to 8 mg/l (max) and 2 mg/l (min) corresponding to field investigation results. Settings for drawdown, thickness of the oxic aquifer layer and distance between well and lake correspond to field settings.

2 Recommendations for well operation and design

The determination of the key parameters and their interaction led to a systematic classification approach and finally to the recommendation of specific operation and maintenance schemes depending on the well's location.

Based on the key parameters described above, a flow chart was developed to assess the potential for iron ochre formation due to oxygen uptake. Starting from aquifer coverage, distance to the neighbour wells, depth of the screen, initial oxygen content, recharge source and travel time of bank filtrate towards the well, clogging induced by i) well field interaction, ii) switching or iii) bank filtrate influence are distinguished and a constant or intermittent switching scheme and high or low discharge rate are recommended (Figure 11).

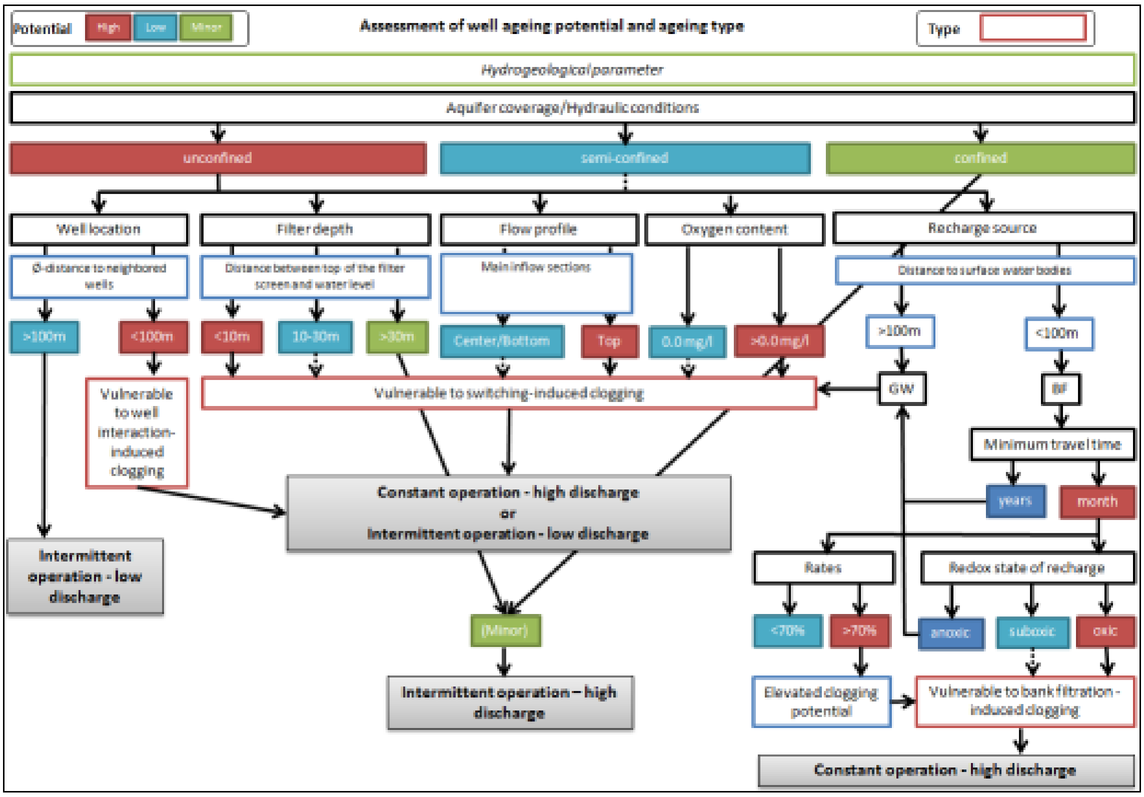

Figure 11: Well classification scheme

According to the WELLMA-2-investigations, thus

- In well fields abstracting groundwater or "old" bank filtrate, a reduced number of wells should be operated at low switching rates. Discharge rate can be high (considering maximum admissible discharge). As oxygen uptake from air entrapment in the zone of water table fluctuation is the main source of dissolved oxygen, a reduction of the number of switchings will reduce the iron ochre formation potential.
- In well fields abstracting high portions of bank filtrate (riverbank and artificial recharge), total discharge of the well field should be divided to as many wells as possible, applying reduced, constant discharge rates to increase the travel time. As dissolved oxygen derives from the recharge source and switchings, both, discharge and number of switchings should be reduced to decrease the iron ochre formation potential. Caution should be given to not reducing discharge too much as low flow velocities could on the other hand favour reducing conditions, which may induce other undesired processes such as e.g. manganese dissolution.

These results were further validated by a statistical analysis of available well data from Berlin (unpublished data) confirming that wells at high distance to surface waters abstracting groundwater from a confined, deep aquifer have the lowest ageing rate expressed as loss of specific capacity per year for the time span between initial operation and first regeneration.

In addition, larger well diameters and the use of speed-controlled pumps were recommended to further decrease the amplitude of drawdown and flow velocity within the aquifer and gravel pack, and larger distances between the wells in a well field were recommended to prevent overlapping cones of depression.

Part D
Efficiency of H_2O_2 for preventive well treatment

In order to reduce biochemically induced iron ochre formation of wells and pumps, a preventive maintenance strategy can be applied. It involves regular low impact well treatment. Typically, chemical disinfection agents are used to disturb the microbiological community and to keep precipitates in a soft, easier removable state.

In Berlin, since 1997 hydrogen peroxide (H_2O_2) is used for preventive well maintenance. In the presence of dissolved iron, it rapidly decomposes to water and oxygen radicals, the latter breaking up cell structures and thus killing bacteria. Practical experience confirmed structural changes of deposits at the pumps of treated wells and the within the wells itself (SCHMOLKE 2006). On the other hand, iron bacteria are known to possess an enzymatic protection against free radicals. At regular treatments, they furthermore may develop an H_2O_2-resistance (MANI et al. 1980; STEWART et al. 2000). Additionally, the release of oxygen is undesired in terms of clogging prevention.

Based on the field investigation results obtained within the preparatory phase WELLMA-1, the objective of the WELLMA-2 investigations was to further assess the effectiveness of preventive well treatment with H_2O_2 and to reduce the postulated undesired side effects of treatment by optimizing the application procedure.

1 Data acquisition methodologies and summary of results

Since the in-situ oxygen measurements during WELLMA-1 had revealed a sharp increase in dissolved oxygen shortly after the application of H_2O_2 and the formation of an oxygen reservoir in the well sump (SCHWARZMUELLER et al. 2011), extensive laboratory and field experiments within WELLMA-2 focused on:

i) the growth inhibition effects of H_2O_2 on iron bacteria in natural biofilms,
ii) the quantification of the potential improvement of the well performance, and
iii) the optimisation of the treatment procedure in order to minimize the formation of oxygen reservoirs within the well

Therefore, reaction tests, bioreactor and column investigations as well as pump tests and in-situ oxygen measurements during H_2O_2-treatment at one of the production wells with transect observation wells (→Part B, chapter 2.2) were conducted.

1.1 Efficiency of H_2O_2 against iron bacteria and biofilms

The microbiological experiments within WELLMA-2 included:

- growth inhibition tests with *Escherichia coli K12* as model organism and H_2O_2 treatment in the presence and absence of protective iron deposits,
- the comparison of the amount of oxygen released from bacterial decomposition of H_2O_2 with active and (heat-) inactivated iron bacteria,
- bio-reactor tests with naturally grown biofilms on the detachment mechanisms,
- bio-reactor tests with pre-treatment of naturally grown biofilms to overcome protective mechanisms, e.g. pre-treatment with EDTA to dissolve iron precipitates,
- population analyses of native biofilms from treated wells to determine adaptation mechanisms.

The investigations generally confirmed the protective mechanisms of catalase, an enzyme protecting bacteria cells against oxygen radicals, and of the iron or manganese precipitates deposited by the bacteria (THRONICKER et al. 2011). Thus, methods removing iron precipitates and/ or inactivating the catalase enzyme, e.g. by heating the test cultures first, made iron bacteria more susceptible to subsequent H_2O_2 treatment.

The investigated biofilms showed further a distinct population shift when repeatedly treated pointing towards a development of more H_2O_2-resistant populations. This could possibly explain the practical observations of changes of the structure and colour of deposits in treated wells compared to the previously untreated state or to untreated neighbour wells.

In addition, the following conclusions could be drawn:

- H_2O_2-concentration and the disinfection capability do not correlate.
- Bubble formation and related shear-forces are believed to be the main detachment mechanism. Bubble formation could also be observed in column experiments and in a TV inspection carried out during H_2O_2 treatment of a real well.
- Pre-treatment with EDTA had a positive effect on the H_2O_2 treatment efficiency. Iron precipitates were removed and the biofilm was destabilized, making the iron bacteria prone to subsequent disinfection.
- Pre-treatment with ethanol (oxygen consumption) shifted the biofilm population towards less-diverted and iron-reducing bacteria, destabilizing the biofilm and enhancing detachment.

1.2 Efficiency of H_2O_2 to maintain the well performance

Based on the oxygen measurements performed during WELLMA-1 (SCHWARZMUELLER et al. 2011), several column and field studies on the oxygen distribution patterns and effects of H_2O_2 on the well performance were carried out, including:

- tank and column experiments on H_2O_2-dispersion, potential bubble formation and oxygen transport mechanisms,
- in-situ oxygen measurements in the well, gravel pack and adjacent aquifer (transect) during and after H_2O_2-treatment (→ Part B, chapter 2),
- comparison of transport patterns in a well field under different operating conditions of neighbouring wells during and after treatment,
- pump tests before and after treatment to determine the specific capacity,
- mini column (batch) experiments on the optimum treatment concentration and frequency (→ Part B, chapter 3.2), and
- deposit analyses from tank, column and mini column experiments to assess changes in composition and structure.

All in-situ oxygen measurements clearly confirmed the formation and accumulation of oxygen from the decomposition of H_2O_2 inside the well. Transport was density-driven under static conditions and followed the hydraulic gradient, when neighbouring wells were operated, thus resulting in a horizontal displacement of oxygen into the gravel pack and aquifer. Reaction tests confirmed a strong reactivity in presence of iron deposits. The structural or mineralogical composition of iron minerals in deposit samples was not altered.

The mini column investigations, however, confirmed the practical experiences of well owners: In treated columns, the deposit formation rate was lower and iron and manganese precipitates could easily be removed by flushing, which was applied to simulate hydro-mechanical regenerations. Thus, H_2O_2-treatment was effective to preserve a good removability of iron ochres. Monthly and bi-monthly treated columns showed little differences except in the organic content of deposit samples, which was highest in the monthly treated columns. The removability clearly increased with the solution concentration, which was varied in the experiments between 0.03, 0.3 and 3.0 % H_2O_2 solution.

Altogether, the following conclusions were drawn:

- With regular H_2O_2-treatment, the gravel pack permeability could be preserved, because deposit formation rates are lower.
- At monthly treatments, the organic content in deposit samples was high, indicating the potential adaptation capability of biofilms as observed in the microbiological investigations.
- A less frequent treatment and/ or pre-treatment together with higher H_2O_2 solution concentration could improve the H_2O_2 efficiency.
- Dissociation rates of oxygen within the well decrease with time, most presumably due to the lack of supplementary iron delivery as long as the well is resting.
- Increased H_2O_2-treatment solution target concentration and decreased oxygen accumulation in the well sump could be obtained by narrowing down the application section.
- Static conditions should be obtained prior to H_2O_2 application in order to avoid oxygen displacement into the gravel pack and/ or aquifer.

These so-far obtained results were transferred into an optimized treatment procedure, as described below.

2 Recommendations for an optimized preventive well treatment using H_2O_2

In particular, the in-situ measurements of the oxygen distribution patterns led to the recommendation of an improved treatment application procedure. Main objective was to reduce the accumulation and long-term presence of oxygen within the well sump. Thus, it was recommended to target the application to a much narrower zone between pump intake and top of the screen. This would also increase the target concentration in the well, keeping the initial concentration for safety and handling reasons at 1% or 2%.

Further improvement could potentially be reached by additionally forcing the H_2O_2 to enter the gravel pack, e.g. by installing an inflatable packer at the screen top and applying the hydrogen peroxide solution, which is denser than water, above or by injecting H_2O_2 directly into the gravel pack via the monitoring access. Figure 12 summarizes the recommended optimized treatment application procedures.

Because of the comparative measurements with operating and resting neighbour wells, it was further concluded that neighbour wells in treatment should be grouped and maintained the same day, and untreated wells in the well field should be in constant operation during treatment to prevent a displacement of the oxygen plume.

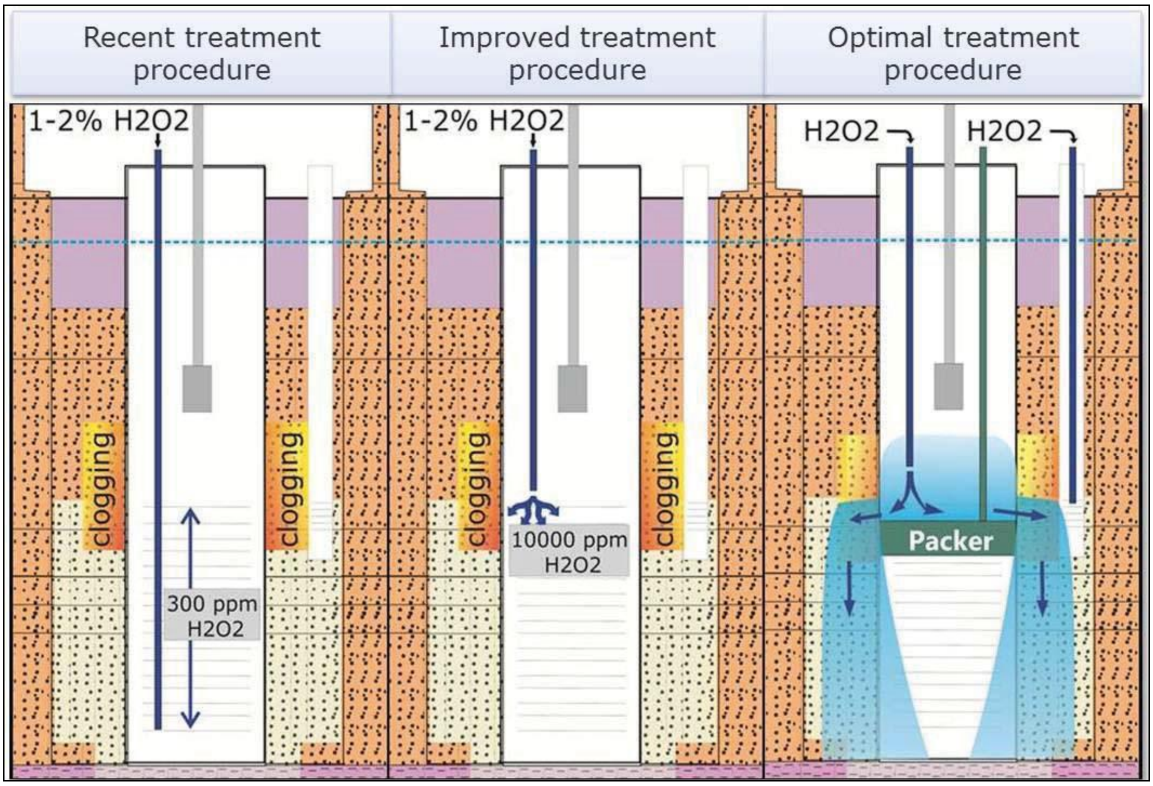

Figure 12: Comparison of old (left), and recommended improved (middle) and optimal (right) treatment application procedure

In a subsequent validation phase of the so-far obtained recommendations, three usually monthly treated production wells were selected, of which

- one was treated with the usual volume of 1% H_2O_2 solution following the "old" procedure,
- one was treated with the usual volume of 1% H_2O_2 solution following the improved procedure, and
- one was not treated for a period of one year.

Subsequently, pumping tests were carried out, showing a loss of specific capacities for all three wells, but confirming the expectations that

i) the untreated well showed the highest loss of specific capacity, and
ii) the well treated following the recommended procedure retained the best specific capacity.

These WELLMA-2 results have already been taken up in practice for one well field in Berlin, which is now treated completely with the improved application procedure. Further practical validation is thus expected including pump tests, pump recovery (for visual inspection and sampling), TV inspections and flow meter logs.

The microbiological pre-treatment studies are further continued in the scope of the ANTIOCKER-project, a joint research funded by BMBF and coordinated at the Chair of Environmental Microbiology at the Technical University Berlin.

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