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STATE OF THE ART
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Colophon

Title

WellMa 1 - Tasks x.1: State of the art of

(1) The distinction of well ageing types and their extension
(2.1) Monitoring and diagnosis
(2.2) Maintenance,
(3.1) Well design and construction
(3.2) Operation

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Abstract

The overall project *WellMa*, which stands for well management, aims at the optimization of the operation and maintenance of drinking water abstraction wells.

For this purpose, in addition to a statistical analyses of well data (☞ report D 1.2) and first field investigations to compare various diagnosis methods (☞ report D 1.3), a review of literature during the preparatory phase WellMa1 should answer the following questions:

(1) Which processes affecting the well performance and conditions can occur?

(2) Which correlation exists between well ageing and well characteristics?

(3) How can such well ageing be recognized at an early stage?

(4) What is the state of the practice to restore a good performance and condition?

(5) What can be done during well design and construction to prevent well ageing?

(6) How can well operation be adjusted to slow-down well ageing processes?

Based on textbooks, standards and professional articles published in large number since the middle of the nineties, the state of the art was gathered and compared to current practice at BWB and Veolia to identify possibilities for improvement and specify the need for further investigations to be proposed for WellMa2.

1) Three well ageing types involving different processes could be identified. These are chemical, biological and physical clogging. They are closely linked to the characteristics of the exploited aquifer, such as the physical properties of the formation or the chemical composition of the groundwater.

2) The evaluation of these site-specific aquifer characteristics, the impacts from well design and the observed effects on the well performance and condition and their development with time of operation should be used to specify the individual ageing potential for each well site.

3) The early recognition of well ageing implies the need to monitor wells (1) regularly and (2) with comparable methods. As suitable indicators, the development of water levels and discharge rates to calculate the specific drawdown and specific capacity, the pump surveillance and the visible condition of the well interior could be identified.

4) Both, the assessment of the ageing potential and the monitoring of a reference value describing the state of the well lead to the specification of maintenance requirements. Generally, three strategies could be identified, ranging from sheer operation, over reactive maintenance to regular condition assessment and preventive treatment. Concerning the choice of maintenance method, key criteria must always be the well design, its state of construction, the well ageing type and location. Up to now, patterns linking well characteristics and the success of maintenance could not be identified. Thus, maintenance relies on practical experience and the willingness to discuss limitations and disadvantages of methods as open as the advantages on side of the rehabilitation companies.

5) For well design and construction, the technical standards were summarized, describing the necessary steps for proper dimensioning, drilling, choice of materials and final well development. Not only the avoidance of nonconformities and the careful evaluation of the advantages, but also the restrictions of different well design alternatives, e.g. for the accessibility of rehabilitation, assure an optimal well ageing prevention and well operation.

6) Furthermore, well operation could be identified as a key element and critical factor co-determining the lifetime, but at the same time the economic efficiency of a well. It is always a compromise between demand, technical possibilities and economic considerations, for which reason general standards or technical guidance are not available so far. They need to be developed individually considering present well ageing processes and the quantification of impacts.

Comparing the state of the art with current practice at BWB and Veolia, room for improvement could primarily be identified for monitoring and subsequent data processing for both, operational parameters (to assess well performance and condition), and maintenance (to evaluate the success of applied treatments).

Based on the recommendations derived on this state of the art review, within WellMa2 the effects of measures for preventing and treating well ageing shall be quantified so that the benefits can be assessed for future optimized well management.

Kurzfassung

Ziel des Projekts *WellMa* (engl. well management - Brunnen Management) ist die Optimierung des Betriebs und der Instandhaltung von Brunnen zur Trinkwassergewinnung.

Eine Literaturstudie während der vorbereitenden Phase WellMa1 sollte zusätzlich zu einer statistischen Analyse von Brunnendaten (☞ Bericht D 1.2) und ersten Feldversuchen zum Vergleich verschiedener Diagnosemethoden (☞ Bericht D 1.3) die folgenden Fragen beantworten:

(7) Welche Prozesse haben einen Einfluss auf Leistung und Zustand des Brunnens?

(8) Welcher Zusammenhang besteht zwischen Brunnenalterung und den Eigenschaften des Brunnens?

(9) Wie kann solch eine Brunnenalterung schon in einem frühen Stadium erkannt werden?

(10) Was ist der Stand der Praxis zur Wiederherstellung einer guten Leistung und eines guten Brunnenzustands?

(11) Was kann während Planung und Bau eines Brunnens zur Vermeidung von Brunnenalterung unternommen werden?

(12) Wie kann der Brunnenbetrieb angepasst werden, um Alterungsprozesse zu verlangsamen?

Basierend auf Fachbüchern, Regelwerken und Fachartikeln, die seit der Mitte der 90er Jahre in großer Anzahl veröffentlicht wurden, wurde der aktuellen Stand von Wissenschaft und Technik zusammengetragen und mit der aktuellen Praxis bei BWB und Veolia verglichen. Daraus wurden Verbesserungspotentiale identifiziert und weitergehende Untersuchungen für WellMa2 vorgeschlagen. Die Ergebnisse der Literaturstudie können wie folgt zusammengefasst werden:

1) Drei Arten der Brunnenalterung mit jeweils unterschiedlichen zugrunde liegenden Prozessen konnten identifiziert werden. Dabei handelt es sich um chemische, biologische and physikalische Verstopfung. Sie sind eng verknüpft mit den Eigenschaften des genutzten Aquifers, wie beispielsweise den physikalischen Eigenschaften der Bodenformation und der chemischen Beschaffenheit des Grundwassers.

2) Die Erhebung dieser Aquifereigenschaften, die Einflüsse aus der Bauart des Brunnens und die beobachteten Auswirkungen auf Leistung und Zustand des Brunnens sowie deren zeitlichen Entwicklung während des Betriebes sollten verwendet werden, um das individuelle Alterungspotenzial eines jedes einzelnen Brunnenstandorts zu spezifizieren.

3) Für die frühzeitige Erkennung der Brunnenalterung ist es notwendig, Brunnen (1) regelmäßig und (2) mit vergleichbaren Methoden zu überwachen. Als geeignete Indikatoren stellten sich die Entwicklung der Wasserstände und Pumpraten zur Berechnung der spezifischen Grundwasserabsenkung und der Brunnenkapazität, eine Kontrolle der Pumpe sowie die optische Überwachung des Brunneninneren heraus.

4) Die Beurteilung des Alterungspotenzials und die Überprüfung eines, den Zustand des Brunnens beschreibenden Referenzwertes ermöglichen die angepasste Instandhaltung. Im Allgemeinen konnten drei Strategien ermittelt werden, vom Betrieb ohne Instandhaltungsmaßnahmen über Pflege bei Bedarf bis hin zur regelmäßigen Zustandsüberwachung und präventiven Behandlung. Bei der Wahl der Instandhaltungsmethode muss immer auf die Bauart des Brunnens, den Bauzustand und auf Art und Lage der Brunnenalterung geachtet werden.

Bisher konnte kein Zusammenhang zwischen den Brunneneigenschaften und dem Erfolg der verschiedenen Methoden identifiziert werden. Daher beruht die Instandhaltung vor allem auf praktischer Erfahrung. Wünschenswert ist die Bereitschaft seitens der Brunnenregenerierungsunternehmen, Anwendungsgrenzen und Nachteile der Methoden ebenso offen zu diskutieren wie deren Vorteile.

5) Für die Planung und den Bau eines Brunnens wurden die Technischen Standards zusammengefasst. Sie beschreiben die notwendigen Schritte zur Dimensionierung, Bohrung, Materialauswahl und dem Brunnenausbau. Nicht nur die Vermeidung von Fehlern bei Plaunung und Bau und Einbeziehung der Vorteile, sondern auch die Beachtung von Nachteilen der verschiedenen Brunnenausbau-Alternativen, z. B. hinsichtlich der Instandhaltung, sichert die bestmögliche Vorbeugung vor Brunnenalterung und einen optimalen Betrieb.

6) Der Brunnenbetrieb konnte als Schlüsselelement und kritischer Faktor ermittelt werden, der die Lebensdauer und gleichzeitig auch die wirtschaftliche Effizienz eines Brunnens entscheidend mitbestimmt. Er stellt immer einen Kompromiss zwischen Nachfrage, technischen Möglichkeiten und wirtschaftlichen Überlegungen dar, weshalb bisher noch keine allgemeingültigen technischen Standards verfügbar sind. Diese müssen daher individuell entwickelt werden, unter Berücksichtigung vorhandener Brunnenalterungsprozesse und ihrer Auswirkungen.

Aus dem Vergleich des Standes von Wissenschaft und Technik mit der aktuellen Praxis bei BWB und Veolia konnte vor allem für die Überwachung und anschließenden Datenverarbeitung, sowohl für Betriebsparameter (zur Bestimmung von Brunnenleistung und -zustand) als auch für die Instandhaltung (zur Auswertung des Erfolgs der angewandten Behandlungen) ein Verbesserungspotential identifiziert werden.

Basierend auf den Empfehlungen aus dieser Bestandsaufnahme sollen in WellMa2 verschiedene Maßnahmen zur Prävention und Bekämpfung der Brunnenalterung untersucht und deren Nutzen für einen optimierten Brunnenbetrieb quantifiziert werden.

Résumé

L'ensemble du projet *WellMa*, abréviation de well management, a pour objectif l'optimisation de l'exploitation et de la maintenance des puits d'eau potable.

Pour cela, en plus d'une analyse statistique des données sur les puits et d'un premier champ d'investigations comparant les différentes méthodes de diagnostic, une revue littéraire élaborée pendant la première phase WellMa 1 devrait apporter des réponses aux interrogations suivantes :

(1) Quels processus affectent la performance et l'état du puits?

(2) Quelle corrélation existe–t-il entre le vieillissement du puits et ses caractéristiques ?

(3) Comment peut-on au plus tôt détecter de tel processus de vieillissement?

(4) Qu'est-il fait en pratique pour retrouver de bonnes performances et un bon état ?

(5) Que peut-on faire pendant la conception et la construction du puits pour prévenir ce vieillissement ?

(6) Comment peut-on adapter l'exploitation du puits pour ralentir ces procédés de vieillissement ?

Basés sur la littérature et les articles courants et professionnels publiés en grand nombre depuis le milieu des années 90, l'état de l'art a été fait et comparé à la pratique actuelle du BWB et de Veolia pour identifier les possibilités d'améliorations et spécifier les besoins en vue des investigations plus poussées du projet WellMa 2.

1) Trois types de vieillissement faisant intervenir différents processus ont pu être identifiés. Ce sont des procédés chimiques, biologiques et physiques. Ils sont liés aux caractéristiques de l'aquifère exploitée comme aux propriétés physiques de la formation et à la composition chimique de l'eau souterraine.

2) L'évaluation des caractéristiques de l'aquifère propres à chaque site, les impacts sur la conception du puits, les effets observés sur les performances et l'état du puits et leur évolution avec le temps d'exploitation devraient être utilisés pour déterminer le potentiel individuel de vieillissement de chaque site.

3) Pour pouvoir déceler au plus tôt le vieillissement du puits, cela nécessite (1) des contrôles réguliers et (2) l'utilisation de méthodes comparables. Comme indicateurs adaptés, on a pu identifier les niveaux d'eau et les taux de décharge pour calculer le rabattement du niveau d'eau spécifique et la capacité spécifique, la surveillance de la pompe et l'état visuel de l'intérieur du puits.

4) L'évaluation du potentiel de vieillissement et le contrôle d'une valeur de référence décrivant l'état du puits permettent de déterminer les besoins en maintenance. En général, trois stratégies peuvent être identifiées, allant du simple fonctionnement, en passant par la maintenance, à l'évaluation régulière de l'état et le traitement préventif. Concernant le choix de la méthode de maintenance, les critères clés doivent toujours être la conception du puits, son état de construction, le type de vieillissement et la location du phénomène. A ce jour, les modèles reliant les caractéristiques du puits et le succès de la maintenance n'ont pas été mis en évidence. Ainsi, la maintenance est basée sur la pratique et les discussions des limitations et désavantages des méthodes comme des avantages au côté des entreprises de réhabilitation.

5) Pour la conception du puits et sa construction, les critères techniques ont été résumés, ils décrivent les étapes nécessaires au bon dimensionnement, forage, choix des matériaux et développement final du puits. Non seulement en évitant les non-conformités et en évaluant minutieusement les avantages mais aussi en se restreignant les différentes alternatives de conception de puits, par exemple pour l'accessibilité de la réhabilitation, on assure une prévention optimale du vieillissement du puits et son fonctionnement.

6) De plus, le fonctionnement du puits a pu être identifié comme élément clé et facteur crucial déterminant la durée de vie, mais aussi l'efficacité économique d'un puits. C´est toujours un compromis entre demande, possibilités techniques et considérations économiques, c'est la raison pour laquelle des critères généraux ou des conseils techniques ne sont pas suffisants. Il faut les développer un par un en tenant compte des procédés actuels de vieillissement du puits et de la quantification des impacts.

La comparaison de l'état de l'art avec la pratique actuelle au BWB et Veolia met en évidence des possibilités d'améliorer le contrôle et par le traitement de données qui suit en ce qui concerne les paramètres opérationnels (pour évaluer les performances du puits et son état) ainsi que la maintenance (pour évaluer le succès des traitements appliqués).

Basés sur les recommandations provenant de cet état de l'art, les effets des mesures de préventions et de traitement du vieillissement des puits devraient être quantifiés afin que les profits puissent être évalués lors de futurs managements de puits.

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Thank you!

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Chapter 1 Introduction

Wells represent the immediate interface between groundwater being a resource and its use for water supply. But, during their lifetime, they are affected by well ageing processes. Many mechanisms are involved and their interaction is complex and differs from well to well. Therefore, no management, maintenance or monitoring strategy can be transferred from one site to another without a good understanding of basic processes and key parameters.

Because of the limited number of adequate sites, ecological and economic reasons, less wells are built new, so that maintenance and value retention of existing wells become more and more important. The perception of wells changed from being disposable, cheap to replace and minimal in maintenance requirements to expensive to replace, sustainable and requiring ongoing preventative maintenance (ALFORD & CULLIMORE 1999). Nowadays it is widely recognized that drinking water wells need not only to be designed and constructed according to technical standards, but also need proper monitoring, operation and maintenance strategies to extend their lifetime and energy efficiency. This is supported by a large number of publications and technical guidelines available since the 90s. Literature on well management as well as patents for rehabilitation technologies come to a high proportion from Germany, The Netherlands, UK, USA, Canada and Australia. However, the authors draw similar conclusions, which will be summarized within this report.

GROSSMANN (2000) concluded from a literature review (mainly German and Dutch papers) that there are many site-specific case studies about well ageing effects and successful rehabilitations, but no sufficient investigation of the processes and mechanisms leading to a loss of well capacity. However, as stated above, this would be the basis for the optimization of operation and maintenance. Three fundamental aspects could be concluded, which remained actual since then:

1. The documentation, processing and employment of operating data are in most cases insufficient. More output can be gained from available data alone.
2. The type and composition of deposits in the well interior needs to be investigated to choose and assess the most useful rehabilitation strategies.
3. A standardized reference basis is needed to assess the success of any maintenance or rehabilitation measure and to compare different methods and technologies.

According to HOWSAM, MISSTEAR et al. (1995), current practice is highly variable. What has been learnt from own practical experience supports this statement.

Reacting to a problem with a water well means to:

- observe the symptoms
- determine the cause (microbial, chemical or physical)
- develop a method to remediate the problem
- apply the remedial practice
- determine whether that treatment has been successful
- develop and apply a monitoring program
- react quickly to control any repetition of the problem

(ALFORD & CULLIMORE 1999)

Hence, monitoring is a crucial part in well operation and maintenance and links all investigations in this field. Furthermore, well management should be “acting” instead of “reacting”.

Within the proposed first phase of the project WellMa, the current state of the art concerning well management should be evaluated. Four work packages were defined:

1) the distinction of different clogging types,
2) maintenance planning and maintenance methods,
3) prevention of well ageing by design, construction and operation and
4) impacts of well operation and maintenance on the water quality.

This report presents the current state of the art for work packages 1 to 3. (For work package 4, please refer to report D 4.1). The following chapters are intended to give an overview about possible strategies. They are sorted according to the work packages.

The aim of the present report was to review worldwide literature containing standards and best practice for well management and to investigate

- parameters that are linked to well ageing and indicate ageing processes
- technologies and schedules to monitor these parameters
- methods for well maintenance
- the impact of design and construction on well ageing and
- the impact of well operation on well ageing

to conclude the room of improvement, which will serve as a basis for the development of individual operating guidelines for BWB and Veolia in WellMa2.

At the same time, this report establishes the basis for the proposed research during WellMa2 aiming at understanding well ageing processes to optimize operation and maintenance of vertical drinking water abstraction wells.

The objective of this state-of-the-art study was not to write another textbook. There are various available, coming to a large part from US American, Canadian and German authors. They provide best practice guidance on well monitoring, maintenance, rehabilitation, design and construction and especially encourage the development of integrated strategies covering these aspects.

As different authors use varying terminology, some definitions need to be specified. These are:

Discharge	Q	Also referred to as yield or abstraction rate. Volume of water pumped from a borehole per unit of time, usually in m³ per hour
Well performance		Also referred to as well capacity. Maximum rate of yield for given conditions, usually for a given drawdown
Specific capacity	*Qs*	Abstraction rate Q divided by drawdown s, describes the yield per meter drawdown [m³/ h* m], is a function of time and discharge
Entrance resistance	*Δh*	Difference in water level [m] between the abstraction well and an observation well in the gravel pack during abstraction
Monitoring		Routine investigation and analysis of quantitative, qualitative and structural condition of a well construction

Diagnosis	Deduction of reasons for any change in well performance
Well maintenance	Process, carried out on a regular basis, and intended to preserve a level of performance by keeping the components in good repair
Rehabilitation	All measures aimed at the removal of mineral and organic deposits from the well interior to restore it to its original level of performance
Preventive treatment	Measures, carried out on a regular basis, aimed to preserve a good level of performance by slowing down well ageing processes

Unless it is noted otherwise, wells are referred to as vertical filter wells constructed with a casing, screen and gravel pack behind the filter screen. In Chapter 5, other design types are described briefly to explain differences, advantages and disadvantages of the various well designs.

Chapter 2 Well ageing

The construction of a well always interferes with the natural system of aquifers and groundwater. Both, soil and water contain different amounts of chemical and organic compounds as well as particles and colloids. Their compositions and concentrations depend on the site characteristics and the travel times through the unsaturated and saturated zone. As wells link the mainly anoxic groundwater with the oxic surface, impacts to the geochemical balance of the water-soil-system are most likely. Therefore, well ageing can be slowed-down, but not prevented entirely.

Well ageing, that is a decreasing capacity, indicated most commonly by less discharge for a given drawdown or higher drawdown for a constant discharge. It is related to physical, chemical or microbial processes as well as to operational, structural or mechanical factors, which lead either to the build-up of mineral encrustations, biomass or particle accumulation or to material deterioration (corrosion). Some of these processes are due to errors in well design or construction. This applies especially to sand intake and corrosion. Others depend on water chemistry and/or well operation. Figure 2-1 shows, which parts of a well can be affected:

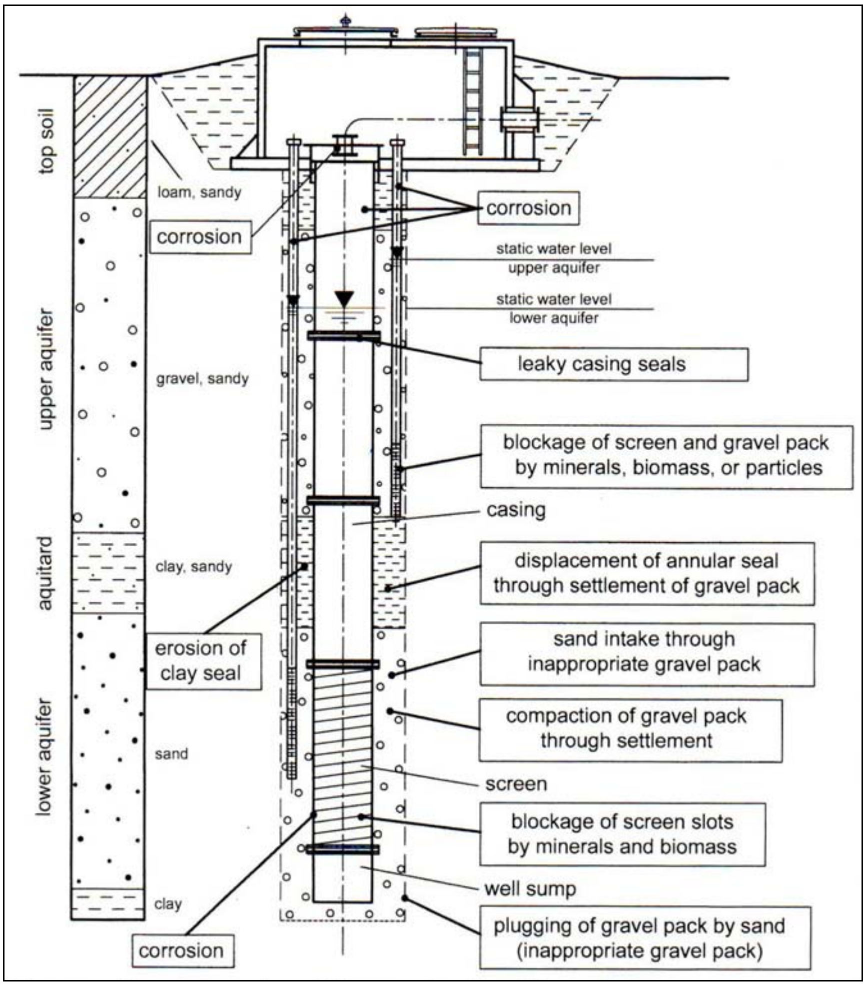


Figure 2-1: Parts of a well, which can be affected by ageing [from Houben & Treskatis 2007:4]

The dominant processes are determined by the geology and hydrology. Hence, the distribution of causes and ageing types differs from country to country, but follows the distribution of different aquifer types. For Germany, The Netherlands, Australia and the United States figures can be found at HOUBEN & TRESKATIS (2007). They also summarize the most common problems for specific aquifer types (Table 2-1):

Table 2-1: Aquifer types and common ageing mechanisms [from HOUBEN & TRESKATIS 2007:50]

TABLE 2.6 The Most Common Ageing Phenomena in Wells and Maintenance Intervals

Aquifer type	Most common problems*	Maintenance frequency**
Alluvial (porous unconsolidated gravel-sand formations)	▪ Silt, clay, sand intrusions ▪ Mineral incrustations (ochre) ▪ Biofouling ▪ Casing failure (corrosion)	2–5 years
Sandstone (fractured-porous aquifer)	▪ Fissure plugging ▪ Casing failure (corrosion) ▪ Sand intrusion (suffosion)	5–10 years
Limestone (karst or fractured aquifer)	▪ Fissure plugging by clay, silt ▪ Carbonate incrustations	6–12 years
Basaltic lavas	▪ Fissure and vesicle plugging by clay, silt ▪ Mineral incrustations	6–12 years
Interbedded sandstone and shale	▪ Low initial yields ▪ Fissure plugging by clay, silt ▪ Casing failure (corrosion)	4–7 years
Metamorphic rocks	▪ Low initial yields ▪ Fissure plugging by clay, silt, or mineral incrustations	12–15 years
Consolidated sedimentary rocks	▪ Low initial yields ▪ Fissure plugging by clay, silt, or mineral incrustations (ochre)	6–8 years
Semiconsolidated sedimentary rocks	▪ Silt, clay, sand intrusions ▪ Mineral incrustations (ochre) ▪ Biofouling ▪ Fissure plugging	2–5 years

*Excluding pumps and declining water table.
**Shorter intervals in wells with high incrustation potential is recommended.
Modified after Driscoll (1989).

Hence, the site conditions determine factors, which on their side induce processes leading to different ageing products. However, due to interaction and overlaying influences and processes, the resulting types and extensions vary.

The following scheme (Figure 2-2) is intended to visualize the complexity of well ageing:

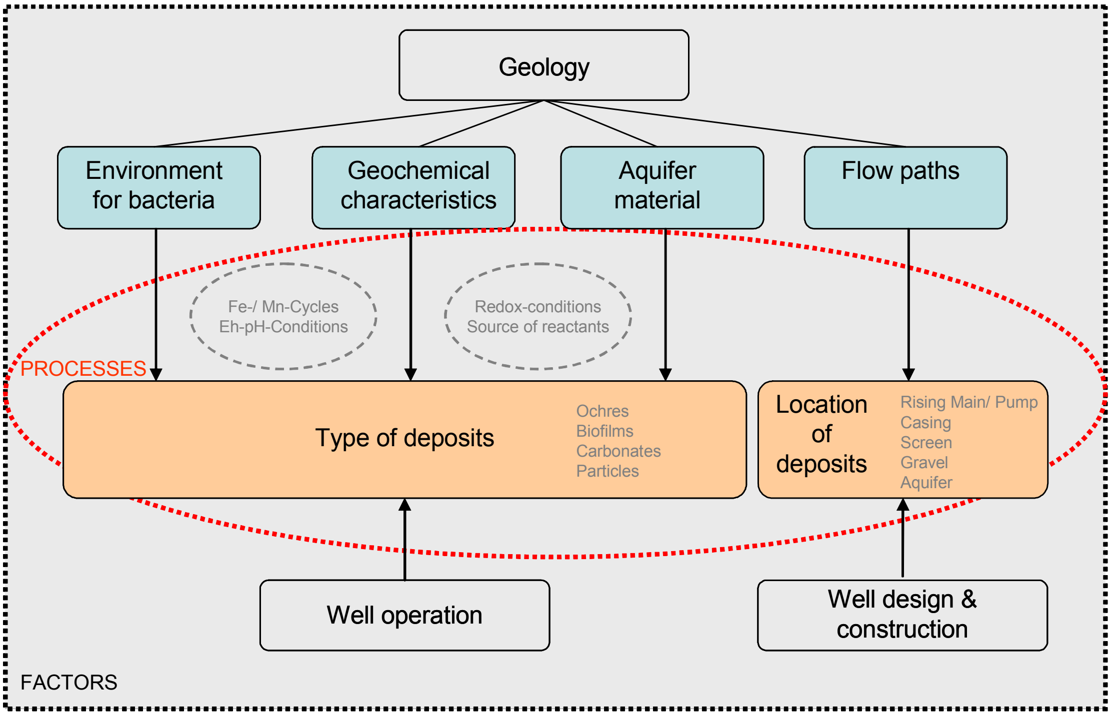


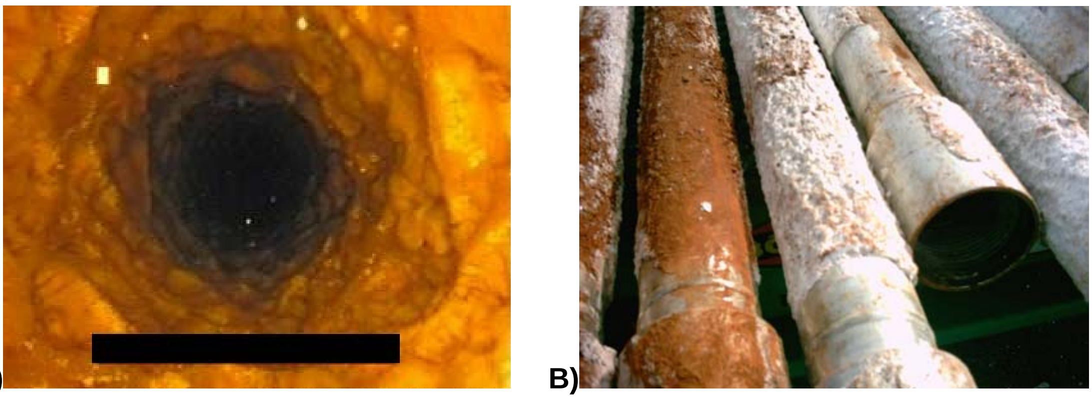
Figure 2-2: Interaction of factors and processes leading to varying well ageing types and extension and possibilities to influence them

2.1 Types of deposits

Apart from The Netherlands, all above named countries claim the build-up of incrustations to be the predominant process for well ageing. Therefore, chemical and microbiological clogging are the most relevant mechanisms.

2.1.1 Chemical clogging

The term describes the deposition of precipitates within the screen casing, rising main, gravel pack or at the pump due to the occurrence of chemical reactions. Two main types can be distinguished depending on site geology. These are (Iron) ochre formation and sintering (Picture 2-1 A and B):



A) B)

Picture 2-1: Types of chemical clogging TV inspection - A: Iron ochre [TV inspection, picture by E. Höhndorf], B Sinter [Rising main, picture by A. Wicklein]

Iron ochre formation is induced by the presence of oxygen and dissolved divalent iron. Due to mixing of waters from different depths or redox layers or due to the intake of atmospheric oxygen because of water level fluctuations, the iron is oxidized and precipitated as hydroxide deposits. The reactions are determined by pH and Eh conditions and can be described with the following equations:

[1]	$FeCO_3 \Leftrightarrow Fe^{2+} + CO_3^{2-}$	Source of dissolved divalent iron within the aqifer
[2]	$4Fe^{2+} + O_2 + 10H_2O_2 \rightarrow 4Fe(OH)_3 \downarrow + 8H^+$	Amorphous iron deposit
[3]	$Fe(OH)_3 \rightarrow FeOOH + H_2O$	Iron ochre

from HOUBEN & TRESKATIS 2007p67 [after STUMM & MORGAN 1996]

Generally, reaction kinetics follows the path:

$$Fe^{2+} \xrightarrow{Oxidation} Fe^{3+} \xrightarrow{Hydrolysis} Fe(OH)n \xrightarrow{Precipitation} \alpha Fe(OH)_3 \xrightarrow{Cristallisation} Fe_2O_3$$

from WIACEK 2005 p28 [after EHRLICH 2002]

Additionally, the reaction is autocatalytically enhanced. The same effect is used for iron removal in water treatment plants, where clean gravel is not as effective as already slightly iron-covered one (HOUBEN & TRESKATIS 2007). This is due to the sorption of Fe^{2+} at the surfaces of already precipitated iron oxides, which then provide reactants for further build-up of deposits. Details are described by various authors investigating the reaction kinetics, e.g. TAMURA, GOTO et al. 1976, APPLIN & ZHAO 1989, HOUBEN 2003.

Ochre samples from operating wells often consist of a mixture of different oxides and hydroxides. They represent different ageing states and overlaying processes. For example due to the similar geochemical behaviour, iron ochres do also contain varying amounts of manganese. A good indicator is the colour of the deposits. Red colour means a predominance of iron oxides and hydroxides, while brown colour shows the presence of manganese. Black colour is more difficult as it can be manganese as well as iron sulphides. Again, the geological background is an important factor to determine if it is iron oxides, iron sulphides or manganese oxides. Because of the bad crystallisation state, mineralogical analyses are often difficult, while the colour can be used to assess the maintenance needs depending on the type of deposits.

A striking fact is the presence of layers within the clogging deposits forming annular rings (WICKLEIN, personal communication 03.09.08; HOUBEN 2003; HOUBEN 2006; HOUBEN & TRESKATIS 2007). They are believed to represent changing conditions caused by different pumping regimes or seasonal influences, for example temperature variations, which on their site influence parameters like oxygen content, pH and flow velocity. The mechanisms are not yet understood ad should be included in further detailed research.

Sintering describes the formation of calcium carbonate deposits precipitated due to a change in the carbonate/ bicarbonate equilibrium because of a pressure release and following CO_2-degassing during pumping. It can occur only in calcitic aquifers. Although it is described in most standard literature on well ageing issues, HOWSAM, MISSTEAR et al. (1995) state, that it is firstly not often observed in practice and secondly temperature, pressure and flow conditions measured in wells are not sufficient enough to enhance the precipitation of carbonates.

HOUBEN & TRESKATIS (2007) on the other hand, give examples and claim turbulent flow conditions at the aquifer-gravel/ gravel-screen boundaries responsible for degassing and stress additionally the factor temperature, especially due to heat-production by the pump engine.

Both types of chemical clogging are linked by different authors to the activity of certain bacteria. Up to now there is no clear distinction into sheer chemically or microbiologically formed incrustations or combinations of chemical reactions and biological catalysis effects.

2.1.2 Biological clogging

Certain specialized bacteria, also called iron-related bacteria (IRB), use the oxidation of divalent to trivalent iron as their energy source. Again, the oxidation reaction leads to the precipitation of iron oxide deposits. Such **iron-oxidizing bacteria**, are long known, e.g. *Gallionella* or *Leptothrix.* Others were just recently becoming subject of research, e.g. *Siderocapsa* or *Siderococcus*. They either convert iron enzymatically or bond it from organic complexes to their surfaces. Details of their metabolisms still need to be investigated. However, their metabolic activities are restricted to certain pH values and iron and oxygen contents. Different authors give varying ranges (Table 2-2). Therefore, the predominant species depends on the pH-Eh-conditions (Figure 2-3).

Table 2-2: Living conditions for iron bacteria [from HOUBEN & TRESKATIS 2007p79]

	Reference			
	Hanert (1968, 1974, 1981)	Hässelbarth & Lüdemann (1967)	Driscoll (1989)	Summary
pH	6.0−7.6	5.4−7.2	6.0−7.6	± Neutral
Redox potential (mV)	200−320	−10 ± 20	200−300	Slightly oxic
Dissolved oxygen (mg/liter)	0.1−1.0	> 0.005	0.1−1.0	Slightly oxic
Dissolved iron(II) (mg/liter)	ND*	0.2−1.2	1.0−25	Normal
Dissolved CO_2 (mg/liter)	(Present)	(Present)	>20	Normal

ND* = no data available.

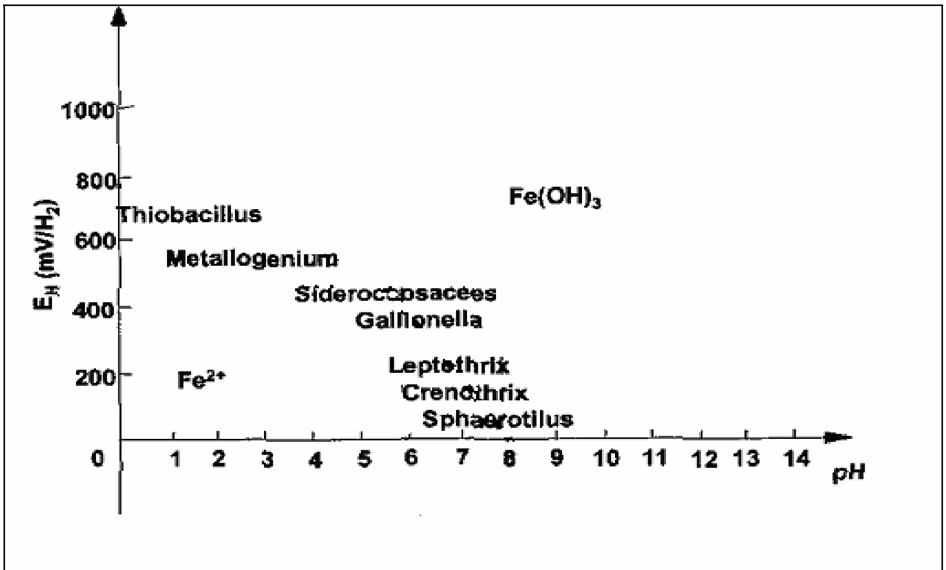


Figure 2-3: The occurrence of iron bacteria depending on the pH-Eh-conditions [modified from the figure contained in the Veolia-comments on the extended summary]

Remarkably is that the ratio between biomass (cell growth) and iron conversion lies between 1:10 to 1:120, depending on the environment and the ageing of the deposits (HOUBEN & TRESKATIS 2007; UHLMANN 1982). This shows that firstly, the energy gain is very low and secondly, flow velocities and thus constant supply of nutrients, oxygen and iron are limiting factors.

Even more relevant for well ageing is the fact, that these biological deposits consist not only of iron oxides, but to a large part of protective coatings (slimes) and minerals trapped within.

Most iron related bacteria are also slime-forming and most slime forming bacteria are iron-related (MANSUY 1999). They build a biofilm.

Such **biofilms** in drinking water abstraction and/ or infiltration wells are observed and investigated worldwide. They are subject in several textbooks, e.g. ALFORD & CULLIMORE 1999; BARTETZKO 2002; CARLSON, VUORINEN et al. 1980; CHAPELLE 2000; CULLIMORE 1999; CULLIMORE 2000; EHRLICH 2002; HÄSSELBARTH & LÜDEMANN 1967; HORN & NEU 2004; HOWSAM 1990; LEGAULT 1999; MANSUY 1999; SMITH 1992; SWWI 2000; UHLMANN 1982. As the bacteria find favourable conditions within these protective environments, they grow quickly.

Biofilm development starts with an initial colonization, followed by a rapid growth leading to a more or less balanced stabilization phase, where die-off and detachment equal re-growth. Limitations to growth are set by available nutrient concentrations and flow velocities. The latter is a crucial factor as low flow velocities enable attachment but limit nutrient supply while high flow velocities provide enough nutrients but lead to a detachment from passed surfaces. Thus, the thickness of biofilms is always limited to a threshold, which is determined by the surface characteristics, predominant bacteria and the flow velocity.

Biofilms are always attached to surfaces. Materials and their surface characteristics have great influence at speed and rate of colonization. The detailed mechanisms and interactions are not fully understood yet and therefore subject of several investigations, though up to now focus for the water sector is more on drinking water distribution systems and domestic installations (e.g. FLEMMING, ULRICH et al. 2000). However, materials are similar, especially the use of copper pipes, PVC or stainless steel. Furthermore, the gravel pack of a well can be compared to sand filters from water treatment, where biofilm development and composition is currently investigated for example by Prof. Szewzyk of the TU Berlin.

In the context of wells, material surfaces and bacteria, another process needs to be looked at. This is **biocorrosion**. Corrosion in general has two effects on well construction. Firstly, it weakens the structure as it causes holes and secondly, it again leads to the deposition of reaction products within the open area of screen and gravel pack.

The most common cause for biological induced corrosion is the presence of sulphate-reducing bacteria (SRB), which affect protective hydrogen films at steel surfaces. These bacteria form hydrogen sulphide (H_2S), which reacts with ferrous iron (Fe^{2+}) under precipitation of a mixture of iron sulphides and iron oxides. As sulphate-reducing bacteria can only survive in anoxic conditions, they depend on the presence of protective biofilms.

Biocorrosion (in the sense of material deterioration by biologically induced degradation in general) is not restricted to metallic materials. Wood-based screens can be degraded by specialized bacteria and fungi, too. In PVC screens and rubber-based seals, stabilizers and plasticizers might represent a nutrient source to biofilm populations, where degradation makes them become brittle.

2.1.3 Physical clogging

Physical clogging is the accumulation of particulate matter in the pores along the flow paths of water entering a well. Particles are solids, suspended in groundwater. Their sizes range from 0.01 to 100 µm (0.01 to 10 µm are colloids, 1 to 100 µm are suspended particles). They can consist of colloidal humic substances, carbonates, iron oxides, microorganisms or silicates, such as clay minerals (DE ZWART 2007).

The relocation of particulate matter can be caused by different processes (HOWSAM, MISSTEAR et al. 1995):

- drilling fluid invasion into the adjacent aquifer and resulting blockage of pore space by clay minerals (drilling mud) during drilling
- inter-mixing of aquifer horizons with different grain sizes due to wash-out during drilling and development
- inter-mixing of gravel pack and aquifer material due to poor installation or too heavy development
- mitigation of fine materials from the aquifer into the gravel pack or well itself

The first three processes are due to design and construction and can be avoided by proper planning and completion of a well. Remarks will be included in Chapter 5.

The latter one is meant by physical clogging in a narrower sense and will be briefly described here:

Physical clogging is determined by aquifer and particle properties. Relevant are:

- pore size
- grain shape
- sorption forces (surface charge)
- particle size
- surface charge of particles

Due to pumping, the flow velocity in the well surrounding is increased. This mobilizes particles, which are then transported towards the well. Depending on the factors, particles are either accumulated:

- at the boundary from coarse to fine layers, where pores are too small for large particles. This layer of large particles blocks also smaller ones, which otherwise would be able to pass the pores (outer colmation or cake filtration).
- within an inhomogeneous porous medium, where larger particles are trapped at smaller pores (inner colmation).
- due to bridging, when at least two particles, which alone would be small enough to pass the pore, reach it at the same time and collide. The bridged particles then block the pore space for other small particles and they accumulate.

In wells, the aquifer near the borehole, the boundary at the transition between aquifer and gravel pack and the gravel pack itself are vulnerable for particle accumulation. Therefore, the grain size of the gravel pack needs to be carefully chosen according to the aquifer grain distribution. Further details are included in chapter 5.

The only process, which cannot be avoided by proper construction, seems to be bridging. The mechanisms and how it can be treated by adapted operation and rehabilitation measures is subject of ongoing research, e.g. by the KWR Watercycle Research institute (former KIWA Water Research). Some details can be found in chapter 6.

2.2 Location of deposits

The location of any deposits depends on the dominant process and its required environmental conditions. As stated in the introduction, a well always changes natural conditions. The mechanisms are not yet fully understood. Hence the distribution of resulting material accumulations is still subject of research and a growing number of available publications.

As the flow towards a well is inhomogeneous, so is the distribution of deposits. Changes in flow condition, e.g. switching of a well, induce changes in redox state and/ or chemical composition, due to degassing, turbulent flow, oxygen uptake etc.

Chemical clogging occurs wherever water with different chemical conditions (i.e. containing reduced irons and oxygen) is mixed. Such mixing processes are induced either by the presence of redox boundaries or by turbulent flow conditions. Chemical clogging does not naturally follow a direction from the inner to the outer parts or from top to bottom. If there appears to be a growth direction, this is mainly due to the relocation of boundary conditions by the previously deposited reaction products.

Wells represent **favourable environments for iron-related bacteria**. These are adapted to low oxygen conditions, because they are able to use other chemical sources for energy gain and protect themselves by slimy coatings. Such biofilms grow only at surfaces. The surface characteristics of the underlying materials may enhance or deteriorate the speed of growth. The constant supply of nutrients with the fresh groundwater due to the abstraction further enhances biologically induced clogging. Therefore, **biofilms** can be located at any surface present in a well: the pump, screen or artificial gravel pack.

Particles in groundwater have different origin. Their transport is determined by particle sizes, surfaces and grain size distribution of aquifer and gravel pack. Boundaries between grain sizes (aquifer-gravel/ twofold gravel pack etc.) are most vulnerable for colmation processes.

The **vertical distribution** of deposits is determined by the inhomogeneities of the aquifer and by geochemical redox zonation. The **horizontal distribution** is determined by flow paths and flow conditions following mainly sediment layers of the aquifer.

According to the mechanisms, chemical and biological processes lead to deposits wherever water from different redox zones is mixed or turbulent flow changes the conditions. This can be in the aquifer near the well, the gravel pack or screen or along the flow in the casing, at the pump or even the rising main. Meanwhile, physical processes correspond to filtration and are therefore limited to the filter parts, which are the aquifer near the well, where flow velocities change, the gravel pack and the screen. Most deposits are located in the zone with the most changes, that is:

(1) between top of the screen and static water level, especially near the pump intake and
(2) at boundaries (aquifer-gravel and gravel-screen).

All well ageing processes can be influenced by well design, such as the right choice of screens, geometry of screen slots, gravel grain size, length of the filter sections etc. Please do also refer to Chapter 5.

The following table (Table 2-3) summarizes the vulnerable parts of well constructions.

Table 2-3: Parts of a well affected by the different ageing processes [modified after HOWSAM, MISSTEAR et al. 1995p22]

	Clogging type	Prerequisites	Aquifer	Gravel pack	Casing	Screen	Pump	Rising main
Chemical	Ochre formation	Mixing Turbulent flow (Redox condition)	V	V	V	V	V	V
	Sintering	Turbulent flow Temperature changes (CO_2 degassing)	-	V	V	V	V	V
Microbiological	Iron-oxidizing bacteria	Constant supply of nutrients, Fe and O_2	V	V	V	V	V	V
	Biofilm accumulation	Flow velocity Nutrient supply	V	V	V	V	V	V
	Biocorrosion	Anaerobic environment Sulfate-reducing bacteria	-	-	V	V	V	V
Physical	Outer colmation	Gravel pack pore sizes to small for aquifer particles	-	V	-	-	-	-
	Inner colmation	Inhomogeneous grain distribution	(V)	V	-	-	-	-
	Bridging	Flow velocity Particle load	V	V	-	(V)	-	-
Structural	Sand intake	screen openings and gravel pack too large for aquifer material	-	(V)	-	V	V	-
	Abrasion	Sand intake	-	(V)	-	V	V	-
	Corrosion	Interface of different metals Mechanical damage to protective coating	-	-	V	V	V	V

V occurrence; - no occurrence; (V) occurrence under certain characteristics

Methods for monitoring and diagnosis will be described in the next chapter.

<u>Summary D1.1: Distinction of well ageing types and their extension</u>

As wells impact the natural balance of aquifers and groundwater, chemical, microbiological and physical changes will always occur. Well ageing can therefore not be entirely prevented, only slowed down.

The type and location of well ageing deposits is determined by the geology, as it defines the geochemical and sedimentary lithological characteristics and thus the environment for bacteria and flow paths.

According to the mechanism of deposition, chemical, biological and physical clogging are distinguished.

<u>Checklist</u>:

1. Evaluate the aquifer characteristics and site conditions to assess the general ageing potential:
   - ☞ Are there sources for chemical clogging: Presence of dissolved iron or calcium, oxygen intake, mixing?
   - ☞ Are the geochemical conditions favourable for iron-related bacteria: Presence of slightly oxic conditions, normal iron content and neutral pH?
   - ☞ Are there sources for physical clogging: inhomogeneous unconsolidated aquifer, presence of clay layers?
2. Consider the well history, background conditions and practical experience with similar well settings:
   - ☞ Well history: Old data and documentation of previous maintenance or rehabilitation measures might include diagnoses of the observed effects and an assessment of the success and sustainability of the measures.
   - ☞ Background: Are there natural causes for the observed loss in performance: Overall decrease of static water table, e.g. due to over-exploitation or more wells in operation?
   - ☞ Practical experience with similar well settings: Which further measurements and analyses are needed to diagnose type and extension of well ageing?
3. Evaluate the well condition by direct methods (see chapter 3):
   - ☞ Are there visible deposits? What is their colour and texture? Which parts of the well are affected?
4. Apply a weighting of the evaluated factors to determine an individual well ageing index.

Chapter 3 Well monitoring as basis for diagnosis and maintenance planning

Well monitoring describes the observation of wells with the aim to detect any deterioration of the well construction, its condition and performance or of the aquifer condition as early as possible to be able to maintain or restore the initial performance and condition as quickly as possible. This implies two different objectives:

(1) the detection of deterioration and

(2) the diagnosis of their causes

Both objectives can only be achieved, if monitoring is conducted on a regular basis, because only time-series of the monitored parameters will reveal the development of the well performance and condition with operation. In addition, it requires a good documentation and subsequent data processing (Figure 3-1).

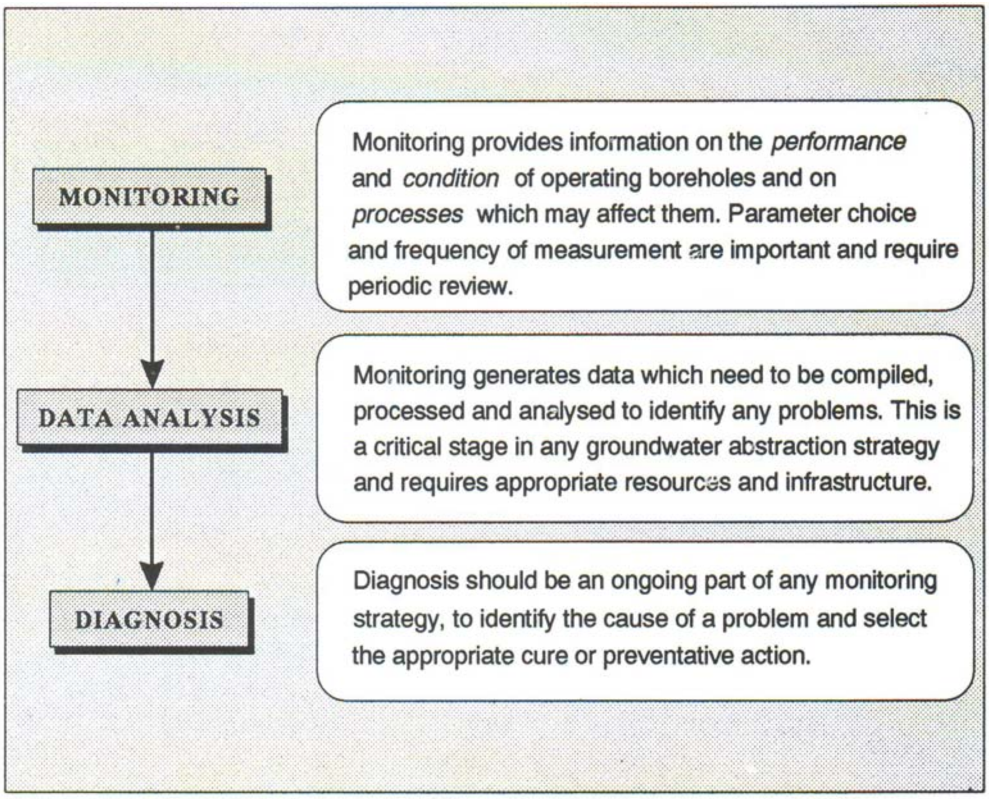


Figure 3-1: Summary of purpose and principle of monitoring and diagnosis [from HOWSAM, MISSTEAR et al. 1995p85]

Both need furthermore a well-documented initial assessment as reference point including the documentation of master data, performance and water quality of each individual well right after construction or start of operation.

Technical standards are available, e.g. the DVGW bulletins (Germany) or ASTM Standard guides (USA) stating the need of “a regular control of ageing-relevant parameters”. However, they can only provide some general recommendations for intervals and schedules and do not contain a specification of the parameters, because these need to be developed adjusted to site conditions, well design and operation.

3.1 Key parameters

Considering the site conditions leads to the determination of the starting point for any monitoring and subsequent diagnosis from answering the following questions:

(1) Which basic data are necessary and available to characterize the well construction?

☞ Geological log, well log, hydraulic dimensioning

(2) How do the geological site conditions influence the geochemical parameters within the aquifer, the groundwater and the abstracted raw water?

☞ Redox conditions, presence of iron, Carbonates etc.

(3) Which correlation exist between hydrochemistry and

- Rate of clogging
- Composition of deposits
- Crystallisation state of deposits

(4) Where are the deposits located?

The interpretation leads to the ageing potential of the well side.

Afterwards, minimum requirement is to keep record of the well performance by measuring water levels and discharge rates to provide early warning (☞ objective 1). Any occurrence of a decrease is then followed by the identification of the occurring problem (☞ objective 2) and the recognition, which maintenance technology needs to be applied and where (pump, well interior, gravel pack, aquifer).

According to that, the key parameters (as similarly proposed by HOWSAM, MISSTEAR et al. 1995, see Figure 3-2) are:

<u>for monitoring</u>:

- Water levels: Variation of static water level, drawdown, entrance resistance Δh
- Well yield: Q-s-curve (compared to a previous state), Qs-development with time in operation, calculation of aquifer and well loss

<u>and for diagnosis:</u>

- Condition of the well interior: Pump, rising main, casing, screen
- Condition of the gravel pack (compared to a previous state): Pore space, permeability, active sections of intake
- Chemical site characteristics, which represent (1) the redox-conditions, (2) mineral stabilities and (3) the living conditions for microorganisms: O_2, NO_3-N, pH, Eh, Fe, Mn, Ca, HCO_3, DOC, AOC, T

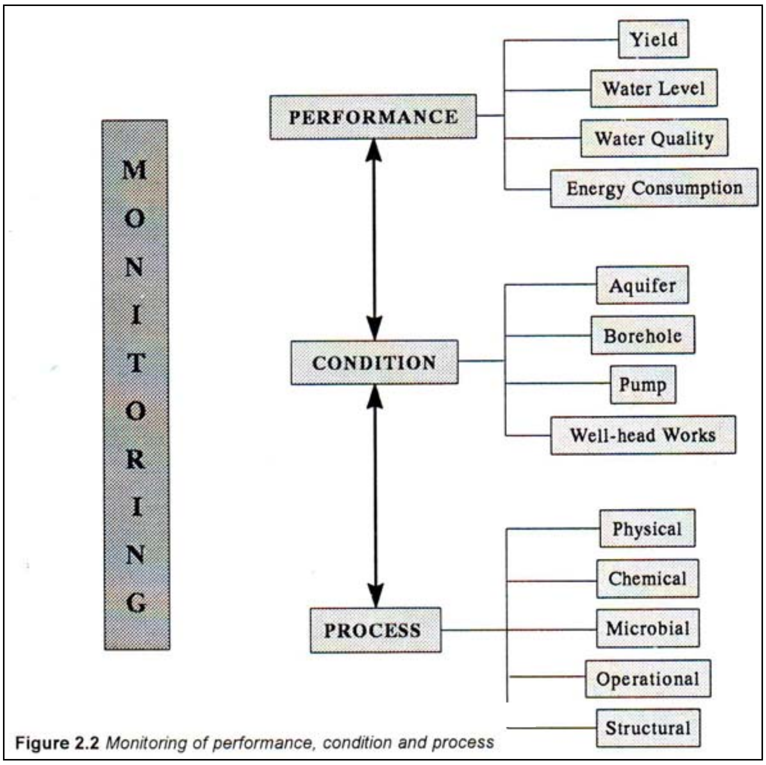


Figure 3-2: Levels and key parameters of monitoring and subsequent diagnosis of performance, condition and processes [HOWSAM, MISSTEAR et al. 1995p21]

To diagnose the well ageing type, location and extension of the deposits, it is necessary to check:

(1) What has been observed during monitoring?

  ☞ E.g. increasing drawdown, sand intake, occurrence of deposits

(2) Which parts of the well are affected?

  ☞ See Table 2-3

Additionally, it should be evaluated:

- How long ago is the last monitoring or maintenance event?
- Were there any changes in the overall operation scheme since then?
- Is the observed loss in performance really due to well deterioration or might it be a depletion of the aquifer itself?

3.2 Methods

As for all condition assessments, diagnosis of the well condition should always start with the simple and quick methods, followed step by step by more detailed investigations to refine the results and to localize the detailed causes of deterioration. The following tables summarize available methods and tools (Table 3-1 and Table 3-2).

Unfortunately, in most cases a direct access to clogging deposits is not given. The methods are either restricted in their range, e.g. TV inspections are only able to inspect the well interior, but not the gravel pack, or they base on indirect investigations, e.g. deterioration of the raw water quality indicating ageing processes. Hence, a combination of different methods can lead to clearer results.

Table 3-1: Information obtained from different monitoring tools

	Diagnosis tool/ Parameter	Information value	Useful combination
Performance	Step discharge test	Q-s-curve and further calculation of Qs, aquifer loss and well loss	Previous tests to follow up the development with time
	Short pumping test	Maximum drawdown s for one discharge rate Q to calculate Qs	Previous tests, if unconfined aquifer condition - with the same discharge rate Q to compare and follow up the development with time
	Entrance resistance Δh	Localization of deposits: either between inner and outer gauge or behind the outer gauge	Previous measures for time-series Packer-Flow
Condition	TV inspection	State of construction, Occurrence of deposits within the well interior	All performance measurements If no visible deterioration: GG.D and Packer-Flow
	GG.D	Bulk density of the gravel pack to conclude the porosity -> shows accumulation of fines	Flow/ Packer-Flow to assess the impact on water intake
	NN	Water content of the gravel pack to conclude the porosity	Flow/ Packer-Flow
	Flow	Percentaged distribution of intake along the screen section	Drillers log for grain size distribution of the aquifer GG.D Recovery time from pumping tests
	Packer-Flow	Permeability of the gravel pack near the screen	Flow for evaluation of intake distribution
Processes	O_2	Redox conditions	TV to detect presence of deposits
	NO_3-N		dto.
	Eh		dto.
	pH	Living conditions for bacteria Stable state conditions for precipitates (Eh-pH-diagrams)	-
	Fe	Presence of starting material for precipitation or biological transformation	More detailed sampling campaigns, e.g. sampling of deposits or depth-oriented geochemical logging Together with the presence of oxygen iron indicates mixing and instable redox conditions
	Mn		
	Ca, HCO_3		
	DOC	Living conditions for bacteria	-

Table 3-2: Applicability of monitoring tools for the different ageing types and extensions

	Diagnosis tool/ Parameter	Chemical clogging	Biological clogging	Corrosion/ Abrasion	Colmation
Performance	**Discharge rate Q/ Volume**	yes, deposits decrease open area and therefore increase entrance resistance	yes, deposits decrease open area and therefore increase entrance resistance	no	yes, particles block pores and therefore increase entrance resistance
	Dynamic water level/ Δh	yes	yes	no	yes
Condition	**TV inspection**	yes	yes	yes	no
	GG.D	partly, only if comparable with old data (preferably initial test after start of operation) no distinction of origin of deposits	no, clogging deposits have a high water content	no, but Caliper-log, needed for interpretation of GG.D, shows decreasing thickness of screen and casing	partly, *see first column*
Processes	**Biofilm collector**	partly	partly	no	no
	Particle counting	partly, if particles itself are filtered and analysed	partly, if particles itself are filtered and analysed	no	yes, high load of fine particles increases clogging probability
	O_2	yes, describes the redox conditions consumption by reaction -> low O_2 content present	yes, describes the living environment consumption by bacteria -> low O_2 content present	no	no
	pH	low pH = autocatalytic effects high pH = hydroxide precipitation	6.0 - 7.6	low pH accelerates corrosion	not relevant
	Eh	0-600	200 - 300	low Eh for biologically induced corrosion	not relevant
	Fe	yes, especially mass balance calculation with adjacent observation wells could hint iron-uptake in deposits	yes, low iron content compared to adjacent observation wells shows uptake by bacteria	no	no
	HCO_3	> 300 mg/l raise potential for carbonate precipitation	partly, living conditions/ nutrient supply	no	no

3.2.1 Routine monitoring

Due to limited resource and budget availability, routine monitoring is in most cases restricted to tracking the water level development and the pump performance. The additional evaluation of the well condition, e.g. with TV inspections, is performed on demand, only and used for diagnosis.

In accordance to the well performance monitoring after HOWSAM, MISSTEAR et al. 1995 (see page 14) regular measurements include the:

- Volume of abstracted water
- Operation hours of the well
- Dynamic water level
- Energy consumption of the pump
- Pressure head at the pump

A typical data sheet, as used by the BWB, should therefore include:

Waterworks: ____________

Gallery: ____________

Well No.: ____________ Reference point for depth measures: ____________

Date	Meter reading			Operating hours	Discharge rate	Discharge head	Water level			Last switching	Pump	Remarks
	old	new	Difference		Q actual		well	gravel pack	ηh	Hours since	Electricity consumption	
	[m³]			[h]	[m³/h*m]	[bar]	[m below reference]		[m]	[h]	[A]	

Figure 3-3: Data recording from performance monitoring at the BWB [translated after SCHMOLKE 2002p123]

For a proper monitoring of well performance, the following points need to be considered:

- For data accuracy, the dynamic water level needs to be taken after it has reached stable state. The well should be in operation for more than two hours (HOWSAM, MISSTEAR et al. 1995).
- For subsequent data processing, i.e. Q-s-calculations, the static water level is needed. To obtain it, the well needs to be taken out of operation. The rest period depends on the well and aquifer characteristics, but should not be less than two hours.
- The static water level needs to be controlled and compared to historic data (☞ aquifer condition) for any calculation of drawdown. Variations can be caused by different operation of adjacent wells or a general change within the aquifer (e.g. a general decrease due to over-exploitation).
- For unconfined aquifers, the relation between discharge and drawdown is non-linear ((☞ aquifer characteristics). Measurements can only be compared, if either discharge rate Q or drawdown s is held constant.

Discharge rates and water levels in the inner and outer gauge should preferably be measured automatically. Data processing includes plotting and interpretation of the data.

If water levels are taken with constant discharge rates, they can be plotted directly for comparison and evaluation of trend lines indicating constant or decreasing performance. From the records of static water level, dynamic water levels in the well and the gravel pack and discharge rate Q, Qs-curves are the most convenient interpretation tool.

Figure 3-4 contains for example the Qs-development of a well operated by Veolia, where the records (green dots) were taken with an increased frequency during the overall time of operation. Data in the red window are for more or less constant discharge rate and show the development of the well capacity based on monthly measurements. The green dotted line represents the trend line for the chosen time span.

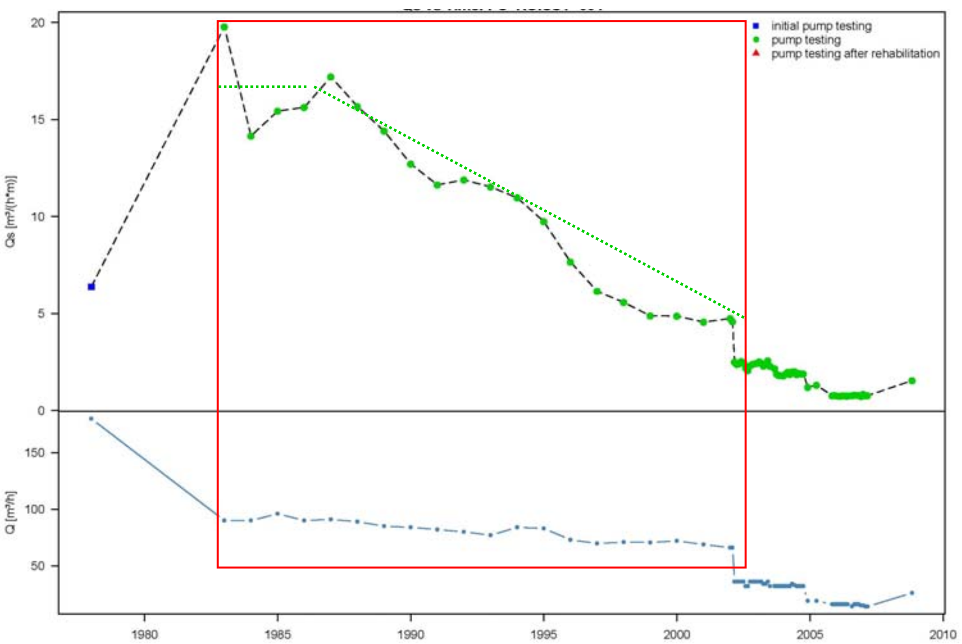


Figure 3-4: Example of a Qs-plot. For better comparability, the lower part contains information on the related discharge rate.

Recent presentations by Aquatune (company working on process automation and optimization, www.aquatune.de) and KWR (former Kiwa water research) described water level measurements with 4 seconds-intervals. However, they showed mainly that there is much variation in the water levels with low amplitudes and short time periods. More important to monitor well ageing processes is, what can be concluded from the overall trend line. An interval of one record per month together with the assessment of the general aquifer condition e.g. by including data of an observation well is regarded to provide the requested information.

The use of the entrance resistance Δh, that is the difference between the water level in the gravel pack and in the well, is controversially discussed by different authors.

As stated in Table 3-1, Δh is principally used to distinguish the location of deposits. However, in practice the value is very much dependant on a proper well construction, especially the vertical installation of the gauge within the gravel pack and the existence of a pressure compensation between the well interior and the atmosphere (SCHMOLKE 2002; *Please do also refer to the WellMa1 D1.2 report on the advanced statistical analysis of well data.*). The measurement and calculation of Δh is therefore though recorded, but not used to assess well ageing at the BWB wells (see also chapter 3.4.1).

3.2.2 Methods for diagnosis

Beside well performance monitoring, diagnosis requires additional information about the well condition and involved processes, which are obtained by extra measurements on demand.

Whenever the continuous monitoring reveals a decrease in performance, these additional measures are for example:

- Short pump or step-discharge tests
- TV inspections
- Hydrochemical and microbiological water quality assessment
- Particle and/ or microbiological sampling
- Borehole geophysical investigations, e.g. flowmeter and packer-flowmeter logging

with the objective to reveal the type and location of the deposits causing the loss of performance.

As summarized in Table 3-2, the choice of methods must be adapted to what is already known about the site-specific ageing potential and occurring processes. For example, TV inspections are only useful, if the deposits are located within the well interior only and biofilm collectors or BART will only provide information on the presence of bacteria and biologically induced ageing processes. A description of these methods is included in report D 1.3 of WellMa1.

3.2.3 Recent developments

In general, monitoring should be as easy and quick as possible. This is best achieved by in-situ monitoring without the need for extensive analyses for diagnosis.

For example, biological clogging would in theory best be monitored by optical sensors, as suggested e.g. by FLEMMING (2003). He distinguishes between devices, which

(1) detect the deposition and changes of thickness, but cannot differentiate between microorganisms and abiotic components. These are e.g.

- fiber optical devices,
- differential turbidity measurement or
- redox electrodes at the surface, on which a biofilm grows

(2) detect the deposition and can distinguish between biotic and abiotic components, e.g.

- FTIR-ATR-spectroscopy
- Detection of auto-fluorescence of biomolecules

(3) provide detailed information about the chemical composition of the deposits

- FTIR-ATR-spectroscopy using the entire spectrum of medium infra-red

In fact, all presented devices work currently only at laboratory scale. In practice tests, i.e. the optical cells were also affected by clogging and could not measure permanently. However, the approach should be further assessed.

RUBBERT & TRESKATIS (2008) used the entrance resistance to characterize the well condition of 64 wells of a well field in Germany, which are known to be affected by chemical and biological clogging. They concluded, that Δh increases first linear and changes with progressing well ageing to exponential growth. Furthermore, they state that the point of change in the curve marks the necessity for maintenance and recommend taking measures every two weeks to be able to recognize the point of change as early as possible. Further assessment will be necessary to evaluate the usability and reliability and is proposed to be included in the *WellMa* project (*Please refer to the extended summary containing also the proposed tasks for WellMa2*).

3.3 Schedule

HOUBEN & TRESKATIS (2007) (after JANSSENS, PINTELON et al. 1996) classify schedules into:

- preventive, status-oriented and interval-dependent: monitoring plan with predefined parameters
- damage-oriented: after decrease (or disruption of operation)
- breakdown-oriented: reconstruction after total failure

As stated above, a successful monitoring schedule is described by the first strategy.

Figure 3-5 and Table 3-3 give an overview about the recommended schedule for monitoring of well performance, well condition and ageing processes.

Of course, the parameters and investigation frequencies need to be reviewed from time to time to adjust information value, needs and intervals.

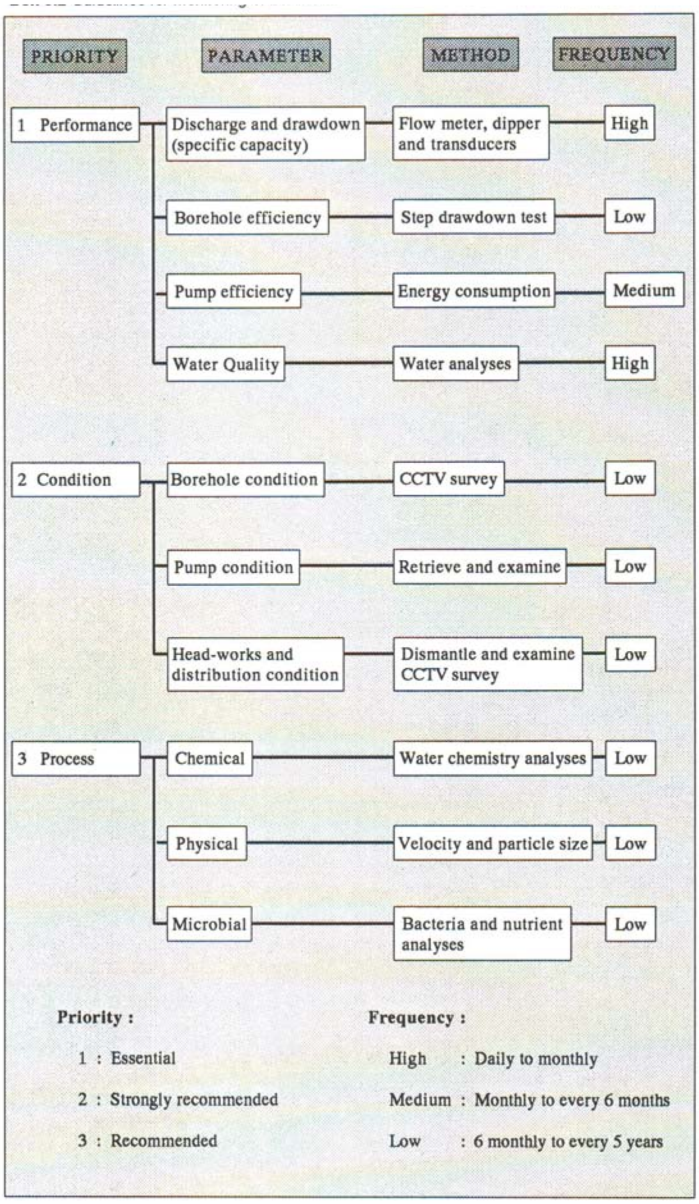


Figure 3-5: Guideline for monitoring by HOWSAM, MISSTEAR et al. 1995p86

Table 3-3: Recommended schedule and obtained information by monitoring well performance, condition and water quality parameters

	Monitoring method	Interval	Significance
	Switching	Record of all switching operations	Stress applied to the well Relevant for assessment of performance and quality data
Well Performance	**Discharge rate Q**	Preferably automatically and continuously with record of one value each day If manually -> minimum once a month	Deposits decrease open area and therefore increase entrance resistance, which causes higher drawdown for same discharge rate or lower discharge for same drawdown
	Dynamic water level		
	Δh - measurement		Together with information on discharge and drawdown, Δh indicates position of deposits: low Δh = deposits "behind" outer gauge/ high Δh = deposits between well interior and outer gauge
	Pump - power consumption	Regularly during operation	Higher energy consumption stands for a higher entrance resistance
	Pump test	Depending on practical experience DVGW W125 -> twice a year	Changes of static water level, dynamic water level Recovery time Q-s-curves to compare with initial performance
Well condition	**TV inspection**	Depending on practical experience DVGW W125 recommends every two years	Visual inspection of the well interior for damages due to corrosion of failure of well construction Visual inspection for deposits, sand intake, tightness of sealing etc.
	GG.D	On demand	Together with tv inspection and pump tests to find explanations for performance decreases, which are not related to deposits in the well interior
	Flow		Detection of possible aquifer deterioration (e.g. fine material blocking the flow paths)
	Packer-Flow		Measure for the permeability of the gravel pack, should be compared to initial data
Processes	**O_2**	At least once a year, If possible at least once depth-oriented	Check, if conditions are preferable for biological or chemical clogging
	pH, Eh, Cond., Temperature		dto.
	Main cations and anions		Basic data to evaluate precipitation potential (e.g. modelling with PhreeqC)
	Turbidity/ Particle load	Turbidity: Regularly Particle load: On demand, if turbidity is increasing	Check for sand intake and suspended solids and analyse their origin Relevant to assess the potential for physical clogging
	Biofilm collector	Installation in the well or a bypass (e.g. flowcell, robbins-device, glass slide)	Check clogging potential of surfaces in contact with the raw water Possibility to easy sampling and visual/ microscopic inspection
	BART (IRB, SRB)	Once a year together with raw water sampling for chemical analysis	Clogging potential, which is due to the occurrence of certain bacteria, here: iron-related bacteria for biological clogging and sulphate-reducing bacteria for biocorrosion

3.4 Room for improvement

The comparison of the state of the art from literature with the current practice and own practical experience reveals a gap between theoretical technical standards on the one and practical application on the other side. This applies especially to monitoring and documentation, which are the basis for all other parts of an integrated well management strategy

3.4.1 Current practice

Both, BWB and Veolia, monitor the operational parameters

- volume of abstracted water
- operation hours
- dynamic water level
- energy consumption of the pump
- pressure head at the pump

Calculated values are the mean discharge rate Q [in m³ per hour] and the pump operating point (on the pump's characteristic curve).

At BWB, all wells are equipped with a piezometer in the gravel pack. Thus, additionally Δh, the difference of the water levels inside the well and within the gravel pack, is recorded. At current date, all measurements are performed manually once every three months. Because, the static water level is not measured regularly, the Qs development is evaluated only before and after rehabilitation measures.

Hydrochemical parameters are evaluated once a year involving a full analysis for pH, Eh, oxygen, the main cations and anions.

At Veolia, the monitoring strategy differs from region to region and does not only depend on the number of wells, but also on the local authorities, type of contract etc. Remarkably, a growing number of the wells are equipped with data loggers for automatic water level measurements. One data set each day is recorded. Additionally, a software tool has been developed, which scans the data sets for rest periods of the well to use the measured static water levels for the calculation of Qs.

The hydrochemical monitoring is limited to various campaigns focussing on certain problems only, e.g. nitrate concentration. Thus, not all necessary parameters are evaluated regularly.

Triggered by a loss of performance, expressed by a decreasing specific capacity Qs, again both, BWB and Veolia assess the maintenance needs: At BWB, the evaluation of the well condition implies a TV inspection and a short pumping test (fixed duration: two hours). At Veolia, instruments are TV inspections, step discharge tests, gamma ray (GR) and flowmeter logging. Eventually, water samples are taken and analysed for clogging-related bacteria. The extent of the investigations differs from region to region and depends amongst other factors on the severity of the deterioration. Please do also refer to chapter 4.4.1.

3.4.2 Recommendations

Room for improvement at operator's side mainly exists with regard to

- the regularity of measurements and standardization of the procedure (☞ monitoring strategy),
- data processing and analysis and
- subsequent adjustment of the monitoring strategy

The results of the statistical analysis carried out during WellMa1 (Report D 1.2 of WellMa1) support this finding: 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 maintenance and operation.

As already applied at BWB and Veolia, each diagnosis attempt should start with a flowmeter logging and a TV inspection, both comparatively quick and simple methods providing a good basis for subsequent data interpretation. Further monitoring methods need to be selected considering the present well ageing type or the ageing potential of the site:

The occurrence of chemical clogging requires the monitoring of the main hydrochemical parameters pH, Eh, oxygen and temperature. Additionally, iron and manganese or for carbonate environments calcium and hydrogen carbonate, need to be evaluated. Based on the above-described assessment of the redox-zonation and geochemical modelling, changes can be related to thermodynamic equilibriums and the occurrence of precipitation or solution processes.

Biological clogging can only occur, if the geochemical conditions are favourable for the related bacteria. The parameters to monitor are therefore pH, Eh, oxygen, TOC, DOC, T, and for iron-related clogging the iron content.

Physical clogging processes remain difficult to detect, because they are hidden behind the screen. If there is a loss of specific capacity, which can be related neither to an overall aquifer yield decrease nor to the presence of visible deposits, the process of eliminating possible causes leaves physical clogging behind. The diagnosis is restricted to indirect methods revealing the presence of either particles in the abstracted water (particle counting) or the accumulation of fine materials (typically clay) within the gravel pack or near-well aquifer (gamma-ray logging). If there is a source for physical clogging can be concluded from checking the drillers log and the cross section of the well for the presence of fine sediment layers and the position of the screened section to evaluate the clogging potential.

For the proposal of <u>tasks for WellMa2</u>, practical experience drawn from own research but also from published case studies (please see e.g. GROSSMANN 2000 for examples) show that it seems generally to be favourable to focus on:

(1) clogging deposit instead of raw water samples

(2) depth-oriented sampling instead of tap sampling of already mixed raw water together with

(3) geochemical modelling for theoretical quantification and

(4) time-series of previous measurements (well history) instead of singular investigations (diagnosis on demand)

(*Please do also refer to the conclusions from the field investigations report D 1.3*)

The evaluation of the presence and activity of clogging-related bacteria in water or biofilm samples is currently investigated in the course of <u>WellMaDNA</u>. Existing applications base on cultivation, e.g. microscopic analysis or BART (<u>B</u>iological <u>A</u>ctivity <u>R</u>eaction <u>T</u>est). Because certain clogging-related bacteria are known to be viable, but not cultivable, DNA methods will extent the reliability of detection.

In this context, temperature measurement should be considered to be performed locally at the pump to assess the expectedly higher variations due to the pump operation, which might be favourable for the bacteria, but not represented by measuring at the well head.

Summary D 2.1.1: Maintenance planning

> Any maintenance planning requires well monitoring. It must start together with initial operation. Basis for any well assessment are regularity and good documentation.
>
> The initial diagnosis of site conditions and well characteristics leads to the monitoring requirements and is needed to adjust the monitoring strategy.
>
> Indicators for the occurrence of well ageing processes are water levels, the well capacity and visible well condition and their development with time in operation.
>
> Discharge rates and water levels during operation should be monitored continuously to identify the need for preventive or restoring maintenance at an early stage.

Checklist:

1. Start monitoring together with initial operation. If not done so, evaluate all available well information to set a reference point for future comparison.
2. Store all information in an individual well file containing master data and a service history.
3. Take into account general considerations:
   - ☞ Choose methods according to type and location of the expected ageing processes: assessed from aquifer characteristics, hydrochemical site conditions, presence of iron-related or biofouling-bacteria etc.
   - ☞ Organize necessary resources: data loggers/ transducers or personnel to perform the measurements in the given interval, data sheets for recording etc.
   - ☞ Determine the workflow clearly: responsibilities, data sheets, recording and storage, data analysis, reporting and decision-making etc.
4. Start with simple and quick methods to follow the well performance development: Regular recording of discharge rates, operation hours, dynamic water level in inner and outer gauge, pump surveillance
5. If performance decreases beneath a reference value, start diagnosis:

   a Is there a failure of equipment: Pump failure, damages to casing or screen, sudden sand intake?

   b TV inspection

   --- if no visible deposits, damages or leakages ---

   c Step discharge or at least short-pumping test to assess Qs and recovery time

   d Packer-Flow to assess permeability of the near-screen gravel pack

   e Evaluation of the "well history" and overall development of the regional groundwater level

   --- if visible deposits ---

   f Descriptive characterization: colour, structure, location etc

   g Sampling and characterization: Presence of bacteria, mineralogical analyses, calculation of saturation indexes etc

Chapter 4 Maintenance of vertical filter wells

Well maintenance covers preventive treatment and rehabilitation measures (reactive treatment). The applied methods are more or less the same. The difference lies in the moment and the intensity of application. Hence, preventive treatment implies a regular scheme, while rehabilitation is a reaction to deterioration. The latter is therefore often linked to a more forceful measure. In the following, the methods are discussed regardless the objective of application.

The growing awareness and interest in maintenance is reflected by the increasing number of patents, textbooks and papers on this issue. However, regardless the apparently high number of patented technologies, there are only a few basic principles, namely mechanical and chemical methods to clean a well in order to keep or restore its performance.

Appendix B gives a compilation of well rehabilitation technologies. Most patents have been developed by US American and German companies with a focus on the removal of deposits from chemical and/ or microbiological clogging. Remarkably, there is a clear distinction between the further development of chemical methods in the USA and mechanical methods in Germany. Obviously, stricter regulations and extensive authorization procedures for the use of environmentally hazardous chemicals in groundwater in Germany has induced a high innovation potential for the replacement of chemical methods by mechanical and hydromechanical technologies.

So far, no pattern to relate well characteristics, ageing types and certain rehabilitation methods has proved to be successful in any case. Each maintenance, either preventive treatment or rehabilitation has to be planned individually considering the:

- hydrogeological background
- constructive condition of the well
- ageing type and extension
- maintenance history of the well with its performance development, previous rehabilitations and their success
- changes in operation mode etc

In general, the aim of well rehabilitation is to remove any deposits from the interior of the well and if necessary from the gravel pack and the adjacent aquifer (see chapter 2.2). In the latter case, the methodological approaches need to reach behind the screen and as far as possible into the gravel pack.

A research project sponsored by the DVGW-German Technical and Scientific Association for Gas and Water (DVGW) (see chapter 4.2.2) has revealed, that most hydromechanical rehabilitation methods are not able to fully penetrate the gravel pack (EICHHORN 2003). In the following, each technology will be discussed with regard to its advantages, disadvantages and limitations due to geology, well design and construction.

4.1 Methods

All methods can be divided into three steps: (1) Separation, (2) Removal and (3) Control of removal. According to the mode of action for separation, methods are either mechanical or chemical (Table 4-1).

Table 4-1: Overview and classification of common rehabilitation methods

Mechanical			Other	Chemical		
Classical	**Hydro-mechanical**	**Impulse**	**Thermal**	**Inorganic acids**	**Organic acids**	**pH-neutral agents**
Brushing	Isolation Surging	Shock blasting	CO_2 injection	Hydrochloric acid	Acetic acid	Aixtractor
Bailing	Low pressure jetting	Ultrasound	Heat/ Pasteurization	Chlorine	Sulfamic acid	
Mech. Surging	High pressure jetting	Compressed air		Phosphoric acid	Oxalic acid	
		Knallgas		Hydrogene peroxide	Citric acid	

Each rehabilitation technology has to be accompanied by succeeding intensive pumping to remove detached deposits, because otherwise they might function as a source of re-growth.

Removal and control can be either continuously, parallel to the process of separation, or discontinuously after the separation process. The control of removed material sets the stop criterion: Treatment can be stopped, if clean water is abstracted. Treatment must be stopped, if there is a sudden increase in particles or if gravel is abstracted as this indicates a failure of the well construction.

For more detailed descriptions of different rehabilitation methods please refer to Appendix B and textbooks, e.g. BORCH & SMITH 1993; HOUBEN & TRESKATIS 2007; MANSUY 1999. They contain the most widespread chemical and mechanical methods.

As stated by HOUBEN & TRESKATIS 2007, many rehabilitation companies use self-developed, patented techniques. Due to competitiveness, they rarely provide information on the detailed mode of action, technical parameters and even on limitations for use. A reliable monitoring and diagnosis together with practical experience, both of the well operator and the contractor, are therefore essential.

4.1.1 Mechanical well rehabilitation

Mechanical methods work by creating shear forces. They can be further subdivided into classical pure mechanical, hydromechanical, thermal and impulse technologies, according to the power transmission mechanism (Table 4-2).

Table 4-2: Mechanical rehabilitation methods

Method		Principle	Restrictions
Pure Mechanical	**Brushing**	Vertical or rotational movement of brushes, Material and diameter of the brushes selected according to well design and material	Limited to well interior Damage to protective coatings of the screen or casing possible
	Surge block	Vertical movement of a packer leading to a piston effect displacing water into the gravel pack (down) and back into the well (up)	No possibility to control the force of application

Hydro-mechanical	**Isolation pumping**	Pump between two packers to intensify hydraulic force, Pump discharge and packer spacing according to nominal discharge rate with the aim to reach a five times higher entrance velocity	Mobilization of fine material from the aquifer may lead to relocation and subsequent colmation Not suitable for pre-glued gravel pack screens High volume of water is abstracted
	Closed-circuit pumping **(here with water only, also possible with chemicals)**	One or more chambers with separate injection and extraction causing a circulation around the separating packers and thus through the gravel pack (see Figure 4-1)	high flow forces at the screen because of the short sections (flow around the packer) might damage the screen
	Low-pressure jetting	Separation by thin and fast water jets injected by nozzles Pressure < 5 bar Flow rates between several tens to hundreds m^3/h	High pressure loss between source, nozzle and screen, therefore less effective in the gravel pack High consumption of fresh water
	High-pressure jetting	Separation by water jets injected by rotating nozzles Pressure >> 10 bar Flow rates up to 20 m^3/h	Potential to damage the screen More effective at screens with high open area than on slot-bridge screens High consumption of fresh water
Impulse	**Detonating gas** **(Electrolysis)**	By electrolysis, hydrogen and oxygen are generated By ignition, “Knallgas”-reaction is started, causing steam bubbles, which implode leading to a piston effect	Potential to damage the well
	Compressed air/ nitrogen **(Impulse generators)**	Repeated sudden release of compressed gas to generate pressure waves	Impulse strength can be regulated
	Explosives	Use of TNT to generate gases (reaction product) leading to a rapid volume increase	Potential to damage the well construction Transport and handling need special training Gas development at the well head
Sound energy	**Ultrasound**	Use of magneto-restrictive oscillator blocks to generate low-frequency, high-energy ultrasound waves. WILKEN & BOTT (2002) claim better efficiency with higher pressure/ well depth due to resonance effects or liquefaction of thixotropic fluids (biofilms) KIWA (2004) state a decreasing efficiency due to less cavitation	Not suitable for pre-glued gravel pack screens, where the glue is dissolved and for very inhomogeneous aquifers because of material relocation, which might lead to colmation

Thermal	**CO_2 injection**	1) Injection of gaseous CO_2 to displace the water. 2) injection of liquid CO_2 (12 bar, - 40°C). The pressure release causes a phase transformation with rapid volume increase. The low temperature causes frost shattering.	High amount of CO_2 necessary Parts of the injected CO_2 will resolve and change water quality, especially pH. Gas development at the well head
	Use of heat	Water heated to 54°C and recirculated over several days with or without chemicals to prevent biofouling	High amount needed of fuel or power to generate thermal energy. Heat can actually enhance growth away from the thermal shock zone, as well as cause drying and shrinking clays such as bentonite grout.

Some of the described mechanical devices can also be used to inject chemicals, e.g. closed-circuit pumping systems and impulse generators.

In general, only the screened sections of a well are treated. Usually, this is done section by section (corresponding to the length of the device) from the top of the screen to the bottom.

4.1.2 Chemical well rehabilitation

Chemical methods were the first technologies for well rehabilitation. Advantages are the efficiency, the inclusion of the filter gravel into the cleaning process and the flexibility to choose type, concentrations and residence time of the agent according to the nature of the problem. The chemical solvents applied are either inorganic or organic acids or pH-neutral agents. The methods differ in the composition of the chemical agent and the mode of application.

First chemical well rehabilitations were done by adding an acid to the water column and waiting for one to three days for the acid to solve the incrustations. Compared to the chamber devices in use nowadays this required large volumes of chemicals. The time-span was chosen with regard to the degree of ageing and from practical experience. Main disadvantage for this comparatively simple approach is that the chemicals will exit the well with natural groundwater flow gradient, flowing through the permeable areas instead of doing their solution work in clogged sections (HOUBEN & TRESKATIS 2007). Further development of the methodology included:

(1) Broadening the range of chemical solvents

(2) Application of dissolution tests prior to the application in the well to select amount, concentration and residence time.

(3) Optimization of the application technology to make sure, that only the minimum required amount of chemicals would be used and that all added solvent would subsequently be removed from groundwater and aquifer

1) <u>Chemical solvents</u>: As described before, ochre incrustations are the most abundant well ageing deposits. They are insoluble at neutral pH. Typical chemical agents are therefore acids. Beside acids, pH neutral agents are available, which are able to reduce iron and manganese oxides. Table 4-3 contains a list of chemicals in use for well rehabilitation:

Table 4-3: Chemicals used in water systems for cleaning and disinfection [modified after ROMIEU 2006]

Group	Chemical	Effectiveness	Safety/ Operational aspects/ Limitations
Organic acids	**Acetic acid** **(CH_3COOH)**	Excellent biocide and biofilm dispersing acid Major component of brand name mixtures specified for biofouling Variation: glycolic or hydroxyacetic acid	Safety: relatively safe to handle Acidizing to pH < 2 with sulfamic acid recommended
Organic acids	**Sulfamic acid** **(H_3SO_3N)**	Effective against carbonate scales, Acid enhancer for acetic acid Not effective alone against biofouling or metal oxides	Safety: Relatively safe to transport and handle because of solid form Less aggressive than HCl.
Organic acids	**Other organic acids** **(e.g. oxalic or citric acid**	Oxalic acid is also effective as a primary acidizer in low-Ca water.	Safety: Safe to transport Handling depends on form (typically granular solids). Form insoluble precipitates in high-Ca waters
Inorganic acids	**Hydrochloric acid** **(HCl)**	Powerful for removing mineral and inorganic metal oxide scale. Ineffective against biofouling Damages stainless steel	Safety: Extremely hazardous to handle Volatile liquid Not recommended for preventive maintenance
Inorganic acids	**Phosphoric acid** **(H_3PO_4)**	Effective against metal and mineral hydroxides Less effective against biofouling Leaves phosphate residue behind, which represent a nutrient source for bacteria	Safety: Extremely hazardous to handle Liquid Not recommended for preventive maintenance
Oxidants	**Chlorine** **(Cl_2)**	Biocide Typically sodium or calcium hypochlorite Used as "shock" treatment to limit and remove biological encrustation	Safety: Powerful oxidant that reacts with organic compounds, causing chemical alteration forms that are more difficult to treat, or potentially explosive situations with eruption of chemicals at the surface
Oxidants	**Hydrogen peroxide** **(H_2O_2)**	Powerful disinfectant and oxidant Breaks down to form H_2O and O_2	It has been used with some effectiveness in removing well biofouling The resultant oxygenation can actually enhance microbial growth
Oxidants	**Ozone** **(O_3)**	Used in piping system treatment to repress biological activity	Handling: Storage and transport under pressure needed, making it largely impractical for rehabilitation

As for mechanical methods, most chemicals for well rehabilitation are patented and sold under certain brand names, e.g. “Herli”, “Carrela” or “Aixtractor”. Their composition is not described in detail.

Inorganic acids provide less material for bacterial growth than organic acids and/ or additives. HCl and H_2O_2 are most widespread, as they have the advantage to dissolve iron and manganese as well as carbonates. They are the main ingredients of the available brands offered by rehabilitation companies (see also Appendix B).

2) Dissolution tests: The selection of chemical agents is done by dissolution tests. In the laboratory, deposit samples are exposed to different chemical solvents possible to use. Aim is to find the agent with the highest efficiency, i.e. the highest reaction rate, which is defined as the chemical conversion caused in a defined time span).

For the choice of chemicals additionally need to be considered:

- corrosive effects
- required additives
- expenditure for neutralization and disposal
- possible enhancement of microbial growth
- toxicity and handling
- cost-efficiency

[after HOUBEN & TRESKATIS 2007p264]

3) Application technology: Effort has been undertaken to avoid dispersion of the chemicals into the aquifer. This is done by packer-systems that can either be single-chamber systems with packers on top and bottom (Figure 4-1 A) or closed circuit pumping system consisting of two cylindrical chambers separated by packers (“Gravel washer” Figure 4-1 B):

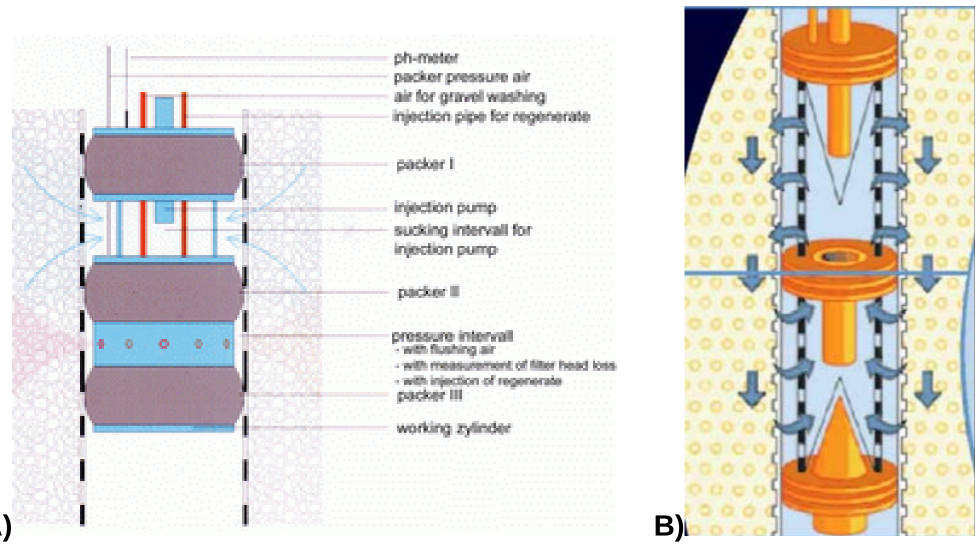


Figure 4-1: Flow scheme of gravel washers - A) Device with one chamber, step 1: injection of chemical, step 2: removal of chemical agent and debris by abstraction from this section [www.brunnenservice.de, 09/2008] B) Closed-circuit two chamber system with continuous circulation around the middle packer [www, 05/2007]

4.1.3 Preventive treatment

Preventive treatment usually aims at slowing down microbiologically induced processes that lead to clogging. Hence, the technologies must be able to prevent growth of bacteria and hardening of incrustations. Therefore, regular disinfection of the well interior is the most widespread method. This is done by adding strong oxidants (see Table 4-3), which transform biomass into carbon dioxide and water. As for chemical rehabilitation, inorganic acids are most often used. These are usually chlorine-containing agents or hydrogen peroxide. The latter method is used at approximately half of the wells in Berlin. Depending on the rate of clogging, treatment intervals vary between twice a month to once every two months. It was further investigated during WellMa1 option H_2O_2.

Other methods are

- The frequent application of heat (Pasteurization) and
- Installation of sources of ionizing radiation (Cs137) within the well

for the prevention of biological clogging

- Lowering of the pH with e.g. HCl to increase the iron solubility and decrease the bacteria activity and
- Installation of reaction inhibitors, e.g.humic substances to complex dissolved iron

to prevent both, biological and chemical clogging and

- The generation of electric currents using the (steel) casing as anode to change surface polarity, which prevents the attachment of deposits
- Use of permanent magnets to prevent sintering (the mechanism still subject of discussion)

to decrease the potential for chemical clogging.

However, they all have certain disadvantages, do not meet regulations or are not fully understood yet and are therefore not very widespread. For more details regarding the application of the above-named methods, please refer to e. g. HOUBEN & TRESKATIS (2007).

4.1.4 Recent developments

As stated above, the growing interest in well maintenance is reflected by the technological development and a growing number of methods and patents. Rehabilitation companies constantly improve their technologies and the way of application. Their main objective is the improvement of the operating distance. However, at the same time they need to consider the possibility of damages to the well construction and are therefore limited in the employed forces.

Certain technologies were developed or thought of for direct application within the gravel pack. These are for example:

- the use of thin nozzles to be pushed from above into the gravel pack for washing it. However, they are not recommended as they damage the clay sealing.

- the installation of a removable gravel pack, which can be taken out for washing or be replaced. However, no practical case has been reported so far.

- the implementation of satellite boreholes to apply chemicals from outside the well. 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.
  If there is a gauge in the gravel pack and the Δh indicates that the deposits are located between the outer gauge and the well interior, the application of chemicals to the gauge together with slight pumping should be considered.

4.2 Choice of method

HOWSAM, MISSTEAR et al. (1995) distinguish between three steps to approach maintenance technology selection and application. :

(1) solution looking: list all technologies and indicate how they might be applied,
(2) standard recipe: list all borehole problems and offer cure for each or
(3) match the solution to the problem: list aims and requirements.

The first two are one of the purposes of this report giving the state of the art for well ageing types (step 2, chapter 2) and appropriate rehabilitation technologies (step 1, this chapter), while step (3) corresponds to the development of a guiding manual, which is the objective of WellMa2.

Generally, the selection of a suitable and promising method for any well rehabilitation requires the precise knowledge of the well characteristics and the present ageing types. Key criteria are

- the well design, especially the diameter and material of the filter tube, and
- the location and extension of the deposits

The decision should be made by the well operator together with the rehabilitation company based on previous experience. However, the selection procedure is subjective and often the costs are one of the decisive factors.

An objective comparison of technologies is often difficult, as not only the methods themselves in their action and the wells in their physical and hydrological properties are different, but also the way of assessing the success because there is no uniform basis. Especially chemical rehabilitations are often evaluated by calculating the amount of removed iron (chemically dissolved iron or calcium, which originates from the deposits), but this does neither allow to conclude the total amount of deposits nor to compare different methods or wells. Here, regularly performed short pumping tests with constant discharge rates are the better alternative as they provide comparable measurements of the specific well capacity and its performance development. Other useful measures to assess the success of a rehabilitation are TV inspections or borehole geophysical logs of the permeability (Packer-Flow) before and after.

In addition to the increase in the yield of the well, it is important to increase the interval between rehabilitations. This is known as sustainability of the method. Its assessment needs the long-term documentation of the maintenance history and the review of success for the different applied methods. This allows comparing methods and subsequently relating the success to specific well characteristics and enables to select a suitable procedure for future application.

4.2.1 Restrictions from site and well characteristics

Well design components and/ or hydrochemical site conditions might present a source of limitations to the application of well rehabilitation techniques. In general, the state of the well with regard to materials and construction must be good enough to withstand the employed forces. This applies especially to mechanical (shear forces), but also to chemical methods (dilution effects at coatings or surfaces).

The more forceful a method, the higher is the risk to damage the well structure. Some methods can therefore not be used with certain well construction materials as summarized in Table 4-4. Especially for chemical rehabilitation methods, additionally the hydrochemical raw water parameters need to be evaluated to prevent e.g. the dissolution of silicates (clay sealing/ artificial gravel pack) or the reprecipitation of calcium carbonate (CLEANWELLS 2004). Dissolution tests with clogging samples are necessary to select the chemical agent, its dosage and reaction time (see chapter 4.1.2).

Table 4-4: Applicability of rehabilitation methods with regard to well construction [after HOUBEN & TRESKATIS 2007, after DVGW 2001]

Construction	Mechanical rehabilitation methods										Chemical rehabilitation methods		
	Brushing	Over-pumping	Surge blocks	Low pressure jetting	High pressure jetting	Short-circuit pumping	Detonating gas/ compressed air	Explosives	Ultrasound	CO2 injection	Single chamber devices	Multi chamber devices	Multi chamber devices with reversal flow
Casing	++				++			-	-				
Wire-wound screen	++	++	+	++	++	++	++	++	++	++	++	++	++
Slot bridge screen	++	++	++	++	++	++	++	++	++	++	++	++	++
PVC screen	++	++	++	+	+	+	++	-	++	++	++	++	++
Ceramics	++	++	+	++	+	+	+	-	++	+	+	++	++
Laminated wood (OBO)	++	++	-	+	+	+	+	-	++	-	+	++	++
Preglued gravel pack	++	+	-	-	+	-	+	+	+	-	+	++	++
Single gravel pack		++	++	++	++	++	++	++	++	++	++	++	++
Differentiated gravel pack		++	+	-	+	+	+	+	+	+	+	+	++
Depth-differentiated gravel pack		++	+	+	+	+	+	+	++	+	++	++	++

Key:

++	Fully applicable and useful
+	Applicable and partially useful, Check for potential damages of the well construction required prior to treatment
-	Not applicable or not recommended
no entry	Application not useful or not possible

Special cases are re-screened wells. They are practically not treatable with the modern hydrochemical methods, if there is a gap between the old and the new screen. If the in-liner is not backfilled with gravel, all induced energy will disappear before it reaches the outer screen or even the gravel pack of the well.

Important factors for the operating distance of the method and the removal efficiency of the debris are the pore space and permeability. Thus, hard rock formations or gravel aquifers are in theory better to rehabilitate (HOUBEN & TRESKATIS 2007). However, in practice this has never been systematically validated. Furthermore, the open pore space is only one of many interacting factors influencing the success of any rehabilitation method.

Rehabilitation-induced problems might include damages to the well construction, microbial contamination or changes of the water quality. Therefore, each rehabilitation should be started and ended with

(1) an inspection of the well to assess the constructive state and

(2) a water sampling for chemical and microbiological approval.

4.2.2 Investigations to assess the efficiency of mechanical rehabilitation methods within the gravel pack (DVGW W 55/99)

Initiated by the revision of the technical bulletin W 130 “Well rehabilitation”, in 1997 a research project was proposed by the technical committee “water abstraction” of the DVGW to replace the subjective assessment of the efficiency of different mechanical well rehabilitation technologies by the owners of the patents by an objective scientific investigation.

The project was carried out by the “Dresdner groundwater research centre” (DGFZ) in the years 2000 - 2003. Main purpose was the rating of the penetration efficiency of selected rehabilitation technologies on a technical scale. By definition, the assessment of the rehabilitation efficiency was not part of the project. The well type focussed on is a vertical filter well in unconsolidated aquifers, equipped with an artificial gravel pack.

A report (in German language) is available from the DVGW. Its main contents shall be summarized here:

The following rehabilitation technologies were included in the investigation programme:

- an isolation pumping device
- a low-pressure jetting device
- various high-pressure jetting devices
- various impulse generators with detonating gas (DWI), compressed air/ nitrogen (Preussag and Pigadi)
- a closed-circuit pumping chamber (A.B.S. Aqua Brunnen Service) and
- two ultrasonic devices (Sonic Umwelttechnik and Vormann)

(Please do also refer to table Table 4-2, Table 4-5 and Appendix B.)

Two test facilities were available:

(1) a well test facility of the E+M Bohr GmbH (Etschel + Meyer) consisting of a cylindrical “well” of 0.5m diameter and 3.0m length with a wedge-shaped outer segment with 1.0m edge length representing the near-well aquifer and

(2) a model well of the IBB GmbH consisting of a column with 1.0m diameter and 3.0m height, which was equipped with a screen (350mm) and a single gravel pack (300mm thickness, 3.15-5.6mm grain size)

1) The smaller of the both columns was used to investigate

- structural changes due to loosening or compaction within the gravel pack and the near-well aquifer induced by the impulse technologies and
- the attenuation of the pressure wave to confirm the penetration efficiency

For this reason, first geo-electrical resistance sensors were installed in different distances in the gravel pack and the simulated near-well surrounding to measure the water saturation and porosity. Afterwards, vibration pick-up probes were installed to measure the frequency and amplitude of the pressure wave with increasing distance to the screen and transition from the gravel pack to the natural aquifer formation.

2) The model well was used to investigate the flow conditions behind the screen. Therefore, pressure transducers were installed in the gravel pack in six distances and eleven elevations. From the measured pressures in vertical and horizontal direction, the flow field was calculated and displayed.

The comparatively high thickness of the gravel pack (300mm) was chosen to prevent vertical boundaries, which would have influenced the flow field. Thus, the absolute penetration efficiency was evaluated. The impact from a vertical boundary, i.e. the contact zone between the artificial gravel pack and the natural aquifer formation, was subsequently evaluated from a mathematical model.

In general, the use of clean gravel pack materials and the dimensions of the gravel pack (too small in test facility 1 and too large in test facility 2) limit the transferability to aged wells and their rehabilitation.

With regard to the geo-electric resistance measurements, the authors stated that although a compaction could be measured, the penetration depth could not be investigated detailed enough for a assessment of the tested devices.

For the impulse technologies and the ultrasonic devices, it was stated that an inducement of a flow was not expected. Thus, only the attenuation (2nd test series in facility 1) was investigated.

All results are summarized in Table 4-5.

Additionally, the impact on the flow field of all devices tested in facility 2 was modelled using a two-dimensional aquifer-simulation-model (ASM [Kinzelbach, W. & Rausch, R. 1995]).

An interesting result was the comparison of the flow induced in a single and a twofold gravel-pack. It showed that all devices were only able to induce sufficient flow within the inner gravel pack.

Together with the measured high attenuation within the gravel pack for the jetting devices, impulse technologies and the ultrasonic probes, the project made clear that the effectiveness of the hydromechanical rehabilitation technologies is mainly restricted to the gravel pack. Most devices work very good within the first few centimetres behind the screen. The ability to penetrate the gravel pack is reflected by the ranking in Table 4-5, where the induced acceleration indicates the efficiency right behind the screen and a low attenuation indicates the efficiency near the contact zone to the adjacent aquifer.

Because of the competitiveness of rehabilitation companies and the fact that some companies were involved in the project steering committee, the investigations were not without controversy. Nevertheless, purely from the measured acceleration and attenuation, for gravel pack wells the Pigadi device showed the best penetration efficiency.

Table 4-5: Investigations at the DGFZ to assess the efficiency of hydromechanical well rehabilitation devices [after EICHHORN 2003]

Device	Supplier	Benchmarking data	Comments	Results		Ranking [2)]		Results
				Test facility 1 **geo-electric resistance**	Test facility 1 **pressure probes**	**Induced acceleration [the higher, the better]**	**Attenuation [the lower, the better]**	Test facility 2 **Flow field**
Low-pressure jetting	NDSK (Brunnenbau Wilschdorf)	Q: 90 m³/ h Working pressure: 1,5 bar Exit speed (nozzles): 10 m/s	No vibrations induced, thus purely mechanical method	Compaction of the gravel directly behind the screen resulting in 4-10% less permeability	not tested			Inducement of an intense vertical flow around the jet rim, restricted to the first few centimetres behind the screen
High-pressure jetting	HRH (Aqua Brunnen Service)	Q: 5,4 m³/h Working pressure range: 50-240 bar Exit speed (nozzles): ?	First test indicated generation of vibrations with a frequency of 500 to 700 Hz	Compaction of the gravel all along the gravel pack, but not relatable to flushing (see comment)	High attenuation in the gravel pack Distinct reflection at the contact zone	**6**	**5**	Range of influence restricted to screen and screen openings
	WellJet (Aquaplus)	Q: 5,4 m³/h Working pressure range: 50-300 bar Exit speed (nozzles): ?	Both high-pressure devices showed similar results. There is only little difference in their effectiveness.	see above	see above	**7**	**6**	see above
Impulse generator	JET Master (E+M Bohr)	Q: 5,4 - 9,0 m³/h Working pressure range: 100-500bar Exit speed (nozzles): ?	High acceleration directly behind the screen	Compaction, restricted to the gravel pack Removal of fine sediment	Inducement of shock waves with a frequency of 500 Hz and an inharmonic amplitude	**4**	**2**	No inducement of flow
	"Pulsator" (PST)	"knallgas"-technology	[1)] Expectations before performing tests: No fluid flow, but propagation of a sound wave Thus, investigation of the attenuation	Compaction, restricted to the gravel pack	Distinct attenuation, especially at the contact zone Occurrence of a high-frequent spurious oscillation with app. 10 kHz	**5**	**4**	not performed (see comment [1)])
	Hydropulse (Pigadi)	compressed nitrogen Working pressure range: 40-60 bar Pulses per second: 1-3		not tested	Highest initial oscillation (200 Hz) of all impulse technologies Highest acceleration. Little attenuation. Occurrence of a high-frequent spurious oscillation with app. 10 kHz	**1**	**1**	not performed (see comment [1)])
	WellReg (Aquaplus)	compressed air Working pressure range: 10/ 20 bar Pulses per second: ?		not tested	Acceleration similar to "knallgas" device	**8**	**3**	not performed (see comment [1)])
Ultrasonic device	Swing stick (Vormann)	Stick of 1m length with oscillators at both ends Rated power: 2x 1,5 kW Frequency: 25 kHz		not tested	Harmonic oscillation. High acceleration. Little attenuation.	**2**	**7**	not performed (see comment [1)])
	Block oscillator (Sonic)	Block with 2x 160cm² Rated power: 2x 1 kW Frequency: 20 kHz		not tested	Harmonic oscillation. Acceleration and attenuation in a similar range as with the high-pressure device	**3**	**8**	not performed (see comment [1)])
Closed-circuit pumping chamber	A.B.S.		No classical hydromechanical device, but tested for the occurrence of traction and discharge effects	not tested	not tested			Good penetration of the gravel pack. Even distribution of flow all along the device. Highest efficiency in the first few centimetres

[2)] Ranking from high to low
Rank 1 is given to the best device (high acceleration, low attenuation)

4.3 Development of maintenance strategies

For well operators, three different basic approaches exist:

(1) No maintenance: This implies usually a shorter lifetime and earlier reconstruction need, but there is no effort and no cost for prevention or rehabilitation.

(2) Monitoring and reactive treatment: While operating the well general operational parameters such as total discharge, energy consumption of the pump and operating hours are monitored continuously. Further measurements are performed on irregular basis, either if one of the observed parameters reveals deterioration or if there is human or financial spare resource. This is the most widespread approach.

(3) Regular well condition assessment and preventive treatment: Here, performance and condition from the beginning of well operation until current date are documented and the development with time can be used to reveal processes affecting the well performance. Preventive measures aim at slowing down these processes and rehabilitations can be planned according to the well history and performance development. Hence, they are applied early enough to provide sufficient improvement of the well performance and thus increase the total lifetime of the well. This should be the preferred approach.

The maximum tolerable loss of performance for initiating a rehabilitation measure (i.e. a reactive treatment), indicated by comparing the actual specific capacity Qs with its initial value (Qs_{ini} =100%), varies in literature between 10% (MCLAUGHLAN 2002) to 50% (VAN BEEK 1995). In general, the higher the loss of performance has become the more complex and more costly is the restoration. Practical experience has furthermore shown that wells with less than 50% remaining capacity will age more rapidly in the future.

To plan and schedule a successful maintenance strategy (third approach) it needs an individual assessment of the ageing potential of the well site from its documentation and monitoring (see Chapter 3 for details). The higher the ageing potential, the higher the frequency of preventive and reactive treatment must be.

Recently, RUBBERT & TRESKATIS (2008) have presented an example of the development of such a risk matrix to derive the (site-specific) well ageing potential, which could then be used to schedule maintenance needs (intervals and methods). They proposed to define a maximum tolerable drawdown or another ageing indicator for each well field, which’s overstepping triggers a maintenance operation. Technical standards define a loss of capacity of 10 to 20% in Germany and up to 50% in the USA and the Netherlands as maximum tolerable loss of performance. Above that value, a rehabilitation is believed not to be successful and sustainable enough to be economic.

This approach could be further followed up, e.g. by developing software-based decision support systems.

The comparison of costs and the assessment of the benefits of the different strategies base on a mean expected lifetime of a well and all life-cycle costs (energy consumption, maintenance etc.) on a yearly base.

Own experience with calculation of a few site-specific examples (WIACEK 2005) showed that indeed regular rehabilitations depending on the specific capacity development (☞ approach 2) were more economic than reconstructing the well after half of its achievable lifetime (☞ approach 1).

However, as most of the costs depend on site conditions and well dimensions, such cost-benefit-assessments need to be done individually for each well site.

For the BWB, SCHMOLKE (2002) stated that with regular and preventive maintenance and gentle operation, the normative lifetime can be doubled, which lowers the amortisation costs (per year). Hence, reducing efforts for well maintenance seem to be economically not reasonable.

4.4 Room for improvement

Room for improvement exists again mainly with regard to the documentation of maintenance measures. In general, the more data are recorded and plotted for evaluation, the higher is the gain of experience for future rehabilitations.

However, as the open discussion of the success or rather the failure of rehabilitation methods touches commercial interests of the involved rehabilitation companies, up to now an objective comparison remains difficult.

4.4.1 Current practice

The maintenance strategy of the BWB includes regular rehabilitation (i.e. reactive treatment) and, if the wells have a high ageing potential and are affected by biological clogging, preventive treatment with H_2O_2. Thus, it is a mixture between the above-described second and third approach.

All maintenance measures are exclusively done by Pigadi, the well service branch of the BWB. Depending on the well condition, they apply either their hydropulse technology or shock blasting. The maintenance procedure is standardized and includes:

- for rehabilitations

  (1) a rest period of at least 24 hours
  (2) a short pumping test of two hours duration with the installed operation pump to evaluate the specific capacity of the well before rehabilitation
  (3) a TV inspection to assess the condition of the well interior and to check casing and screen for damages
  (4) mechanical cleaning followed by isolation pumping and/ or airlift to clean the sump pit
  (5) shock blasting or hydropulse in the screened sections
  (6) isolation pumping for redevelopment

  on demand: cleaning of the piezometer in the gravel pack, sealing of leakages, maintenance work at the well head

  (7) a TV inspection after the rehabilitation to check for damages
  (8) a short pumping test of two hours duration with the installed operation pump to evaluate the specific capacity improvement

All technical data of the well and the installed pump, the performed diagnosis and maintenance measures and the results of the pumping tests are recorded in a maintenance report, which is then included in the well file.

On average, each well is rehabilitated every five to seven years. The interval is determined by practical experience and the quarterly monitoring. Chemical rehabilitation methods are not applied because of their environmental impacts.

- for the preventive treatment with H_2O_2

(1) taking the well out of operation at least 24 hours prior to treatment
(2) application of a specified volume of 1% H_2O_2 solution with a high-pressure nozzle, which is moved up and down along the filter section
(3) allowance of 24 hours contact time
(4) switching on the well and pumping for minimum two hours

The needed volume of H_2O_2 is calculated from the water volume within the well and a target concentration of 300mg/l H_2O_2. The decision, which wells are to be included in the preventive treatment, bases on the TV inspections. The wells with a distinct presence of biological clogging are treated once a month. Most wells are treated every two months. Approximately half of the BWB wells require preventive treatment to extend the rehabilitation interval.

The maintenance strategy of Veolia is driven by the second of the above-described approaches. The wells are regularly monitored and treated, if they show deterioration.

Due to the differences from region to region, as already mentioned in chapter 3.4.1, each rehabilitation is planned individually. Because of the different geological contexts, clogging types as well as well designs vary much more. Therefore, the diagnosis of type, location and extent of well ageing and the well condition is the first important step for maintenance.

Generally, hydromechanical methods are not very commonly used, yet. Standard methods for rehabilitation are

- mechanical cleaning, e.g. brushing, isolation pumping, surging or air lift and
- acidification with hydrochloric or sulfamic acid

The chemical rehabilitation is applied either on the open well or under pressure. The choice of the chemical agent, the contact time, need for additives (e.g. corrosion inhibitors) and the mode of application are determined according to the geological site condition, hydrochemical properties of the raw water and the well condition.

Because of the known negative impacts of chemical well rehabilitation, e.g.

- dissolution of protective coatings of casing and screen and subsequent enhanced corrosion
- dissolution of carbonate aquifer material and subsequent caving
- formation of unwanted reaction by-products
- dangerous handling

the interest in hydromechanical methods led to first tests with the CO2 injection method (Aquafreed) and impulse technolgies, such as Airburst or Hydropulse. For detailed description of these methods, please refer to Appendix B.

4.4.2 Recommendations

With regard to the choice of rehabilitation methods, it is not possible to give general recommendations. However, the evaluation of present available data with regard to the success of applied measures should reveal, if there are patterns regarding the well characteristics and the applied methods.

Therefore, the increase in the specific capacity (after rehabilitation) calculated in relation to

(1) Qs before the rehabilitation and
(2) the initial specific capacity Qs_{ini}

should be compared with parameters such as

- screen material
- screen diameter
- well depth
- presence (and thickness) of an artificial gravel pack and
- the clogging type

For this purpose, it needs the willingness to cooperate both on sides of the well operators as well as the rehabilitation companies as it involves talking about unsuccessful cases, too.

For WellMa2, It is proposed to investigate the distribution of the loss of capacity to the different affected parts of a well to allow the assessment of the importance of the single steps of a rehabilitation measure.

According to its results, e.g.

- pump maintenance intervals might need to be shortened or
- the well redevelopment might need to be further improved to provide an efficient removal of all debris from the rehabilitated well

With regard to preventive treatments, according to SCHMOLKE (2002) the scientific investigation of the efficiency of the H_2O_2 treatment and parameters for the selection of wells, which need to be treated, has been neglected so far. Currently, all decisions base on practical experience. The proposed investigations of option H_2O_2 of the WellMa-project aim at enlarging the understanding of the benefits and possible disadvantages of this method.

Summary D 2.2.1: Maintenance methods

Maintenance methods are applied either preventive, implying a regular scheme, or reactive to restore a good well performance and condition. In general, mechanical and chemical methods can be distinguished. Each rehabilitation consists of three different steps: pre-cleaning, treatment and redevelopment of the well. To schedule maintenance events the ageing potential of a well (site) has to be evaluated and a reference parameter has to be monitored. Typically, the specific capacity is used. The loss of performance, indicated by the specific capacity development, should not exceed 20%. If the remaining capacity is less than 50%, a rehabilitation will most probably not lead to the desired success and sustainability. The selection of a suitable and promising method for any well rehabilitation requires the precise knowledge of the well characteristics. Key criteria are the well design (diameter and material), and type and location of the deposits.

Checklist:

1. Know the specific capacity development of your well (site).
2. Identify the cause for decrease: clogging type, location and extension.
3. "Match the solution to the problem" (HOWSAM): Define a maintenance strategy with preventive treatments and/ or regular rehabilitation.
4. Gather practical experiences with different methods: from previous rehabilitations, similar well sites and the rehabilitation company.
5. Check the well condition prior to the application of rehabilitation technologies:
   - ☞ Is the well construction stable enough to withstand the applied forces?
   - ☞ Is the selected method adjusted to the well characteristics, ageing type and location?
     - a for chemical rehabilitations: Has a dissolution test been performed with deposit samples from the related well?
     - b for mechanical methods: Is the method able to reach the deposits in the gravel?
6. Redevelop the well after rehabilitation to completely remove all debris.
7. Evaluate and record the performance and condition before and after rehabilitation and track the sustainability (by regular monitoring of the well performance).

Chapter 5 Well design and construction

Any successful prevention of well ageing processes starts with planning and well design based on the exploration of the aquifer conditions to determine

- the aquifer type: unconsolidated/ consolidated or pores/ fissures
- depth and thickness of the water-bearing layer(s)
- the permeability
- the aquifer yield Qa (volume of water per time unit) and
- hydrochemical parameters: raw water type (main cations and anions, oxygen, pH, Eh, conductivity, temperature)

The objectives of a site-specific well design (DRISCOLL 1986) are:

1. Attainment of a high well capacity, adjusted to the aquifer yield
2. Abstraction of water with high hydrochemical and microbiological quality
3. Preservation of the protective properties of the aquifer and its covering
4. Abstraction of sand-free water
5. Achievement of a high durability
6. Guarantee of efficient and cost-effective operation

Hence, a proper well planning and design must include the determination of the best aquifer section(s), materials for construction, drilling technique and well dimensions.

A wide range of textbooks is available containing the theoretical background for the calculation of inflow, range of the cone of depression, technically available volume of water, needed diameters and filter size etc.

For well design and construction manuals please refer to e. g. BIESKE 1984; CLARK 1988; EPA 1975; FRICK & RUMÖLLER 1997; HARLAN, KOLM et al. 1989; NGWA 1975; PETTY & AL 2000; RIES 2006; RUBBERT 1997; THOLEN 2006; TRESKATIS 2005; VASSMER 1999.

Standards are available, too, e.g. DINs for screen materials and artificial gravel packs, DVGW rules for dimensioning and drilling in Germany, AFNOR standards for drilling and well construction in France, or NGWA and EPA manuals for the US.

Generally, planning a well must include the following steps (CONRAD 2002):

Planning:

1. Determination of the demand
2. Evaluation of the hydraulic characteristics of the chosen aquifer
3. Dimensioning: Borehole diameter, screen diameter, materials, design of gravel pack etc.
4. Selection of the drilling method (with regard to the geology, needed depth etc.)

Construction:

5. Drilling
6. Installation of casing, screen, dip tubes and gravel pack
7. Equipment with pump, rising main etc.
8. Construction of the well head (cement grout, connections etc.)

Well development:

9. Well development and initial pumping test
10. Record of all data in a well-specific file

The main elements of a well are its screen and the casing, the seal, the pump and rising main. Depending on the formation, an additional element might be an artificial gravel pack.

Wells in consolidated rocks do not necessarily need tubing or gravel pack. They can be constructed as an open borehole, equipped with a pump. However, due to weathering, they might be not as long living as expected. In addition, it is not possible to seal off unwanted water-bearing layers, e.g. with different hydrochemical characteristics. Thus, nowadays most wells are equipped with tubing or tubing and gravel pack.

Variable are the depth of the well, the diameter of the borehole, depth and length of casing and screen and, if installed, the grain size of the gravel pack. Together with the depth of the water table, these are the main dimensions characterising a well. 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.

5.1 Dimensioning

According to HOUBEN & TRESKATIS (2007), well dimensioning defines the adjustment of the intake capacity to the available groundwater supply. Aim is to provide sand-free water and minimized hydraulic entrance losses, achieved by a low flow velocity at the screen openings. This will also avoid well ageing.

The intake capacity Q_F of a well results from the overall aquifer yield and the technical setting of the well, described by the area of water intake, which is a function of the diameter and length of the screen section (hydraulic design). The maximum allowed flow velocity, which is a function of the permeability, determines the maximum pumping rate. To secure the function and effectiveness, the well should optimally be operated with three quarters of this capacity, which is the nominal capacity. If that does not meet the demand, diameter and screen length need to be adjusted accordingly.

5.1.1 Definition of diameter and length of the screen

In practice, the well diameter calculated with regard to the demand and the hydraulic design is often too small to accommodate the pump, screen and annular space.

Typically, the pump size (diameter) is taken to define the screen diameter (technical design). It is recommended to have at least 100 mm space available for sufficient circulation. Then, the borehole diameter is determined. The standard ratio between the screen and the borehole diameter lies between 1.5 and 2.0. Generally, the annular space should be as small as possible to guarantee the efficiency of development and rehabilitation measures, but at the same time big enough to secure proper installation and prevent contact between the screen and the borehole wall.

The screen length depends on the thickness of the aquifer. Ideally, a well should fully penetrate the aquifer. This adds to an even intake distribution. The minimum dimensions of the screen can be calculated based on the above-described intake capacity and optimum discharge rate together with the critical flow velocity, determined empirically by SICHARDT:

<u>for unconfined aquifers</u>:

$$Qf = 2r \cdot \pi \cdot h \cdot \frac{\sqrt{kf}}{15}$$

<u>for confined aquifers</u>:

$$Qf = 2r \cdot \pi \cdot M \cdot \frac{\sqrt{kf}}{15}$$

with kf -	Permeability of the aquifer	[m/ s]
h -	Dynamic water level at given discharge	[m]
r -	Radius of the well	[m]
M -	Thickness of the aquifer	[m]

[after BIESKE 1998]

For details, please refer to e.g. CLARK 1988, DRISCOLL 1986 or DVGW 2005.

The top of the screen must always be under water. In addition, the submersible pump is usually placed in a cased section above the screen. Thus, the top of the screen is determined by the dynamic water level at maximum discharge, taking into account possible changes of the static water level, and adding a backup, plus the needed space for the pump.

Mixing of different aquifer horizons has to be prevented by blind casing sections and sealing off the annular space to prevent mixing of water with different hydrochemical properties, which could enhance well ageing processes.

5.1.2 Well screen materials

The main parameters relevant for the choice of screen types and materials are the physico-chemical and biochemical surface properties and the geometry of the openings.

Technical criteria for the selection of the most suitable screen type are:

- Mechanical strength
- Durability
- Resistance against aggressive water and corrosion
- High entrance area to provide sand-free water and laminar flow condition
- Cost-effectiveness
- Handling
- Availability and
- Accessibility for rehabilitation

after FRICK & RUMÖLLER 1997

Nowadays, wells are usually equipped either with PVC or with wire-wound stainless steel tubing. This is current practice at BWB and Veolia.

Both have horizontal slot openings, which grant a good accessibility for well development and redevelopment after rehabilitation events. Their width needs to be adapted to the aquifer or the gravel grain size. Different standardized sizes are available. Older wells can feature wooden screens, copper or ceramics. These materials were used because of their corrosion-resistance compared to steel.

PVC wells are cost-effective, easy to handle and unsusceptible to corrosion. With regard to ageing, it has been stated that depositions tend to be more evenly distributed. On the other hand, they have less open area and are less resistive to high mechanical forces, e.g. during rehabilitations.

A clear advantage of the wire-wound Johnson screens is their variability with regard to the slot width. Hence, they can optimally be adapted to the gravel grain size, which lowers the entrance velocity and slows down well ageing. The higher open area furthermore increases the effectiveness of development and rehabilitation as less energy is lost.

The importance of the open area is subject of discussions, because the positive effect of its increase to the entrance flow velocity is limited. CLARK (1988) states for unconsolidated formations that an open area of the screen of more than 10% does not increase the inflow, because the aquifer itself has an open area of only approximately 9%. Hence, the open area of the screen should be equal or slightly higher than that of the aquifer. Further details can be found in e.g. BIESKE 1984; CLARK 1988; MANSUY 1999 or DRISCOLL 1986.

With regard to ageing, the surface characteristics are important. The surface should be as smooth as possible, free of nutrient providing substances (e.g. plasticizers) and resistant to any forces applied e.g. during maintenance.

As the materials for well construction are standardized, this should theoretically apply to all above named screen types. Practical experience however has shown differences in the clogging rates, which needs to be further investigated. Here, physical properties and interactions with micro-organisms are of interest for the attachment of deposits and biofilms. An additional life-cycle assessment for the Johnson screens is needed to clarify the cost effectiveness.

5.1.3 Gravel pack design

Gravel packs are necessary for unconsolidated formations. They can be either artificial or naturally developed. They support the casing and provide filtration of fine-grained particles from the aquifer.

Basis for their effectiveness is a proper sizing. It starts with the determination of the mean grain size of the aquifer sediments by a sieve analysis. This leads to the definition of the needed gravel grain size distribution.

The right dimensioning is always a compromise, because two opposing requirements need to be fulfilled (HOUBEN & TRESKATIS 2007):

(1) It must be fine enough to hold back formation particles and

(2) It must be coarse enough to minimize the energy loss and allow effective desanding.

Standards (DIN, DVGW, US EPA, US ArmyCofE) referred to by HOUBEN & TRESKATIS (2007) set the gravel pack to be four to six times coarser than the mean grain size of the aquifer.

For poorly sorted or very fine-grained aquifers, a twofold gravel pack might be necessary. Two grain sizes are used with the finer one outside and the coarse one towards the screen. The factor between the outer and inner grain size distribution should be between four and six, too. Using a twofold gravel pack provides the possibility to extend the screened section to cover several sediment layers with varying shares of fine sediments. On the other hand, it represents an additional boundary, both for the inflowing water and the achievable operating distance of maintenance technologies, resulting in an energy loss.

In well-sorted aquifers on the other hand, a gravel pack can be developed from the natural aquifer sediments simply by desanding (see also chapter 5.2.2). The removal of the fine grain stabilizes the formation and increases the laminar flow. Such natural gravel packs are widespread in the US.

The most widespread well design alternatives with regard to the different design elements, their dimensioning, and types and materials are summarized in Table 5-1:

Table 5-1: Well design elements and execution alternatives [modified after RUBBERT 1997]

Element	Parameter	Alternatives	Advantages	Disadvantages
Design procedure for determination of the main dimensions	Basis for determination	Components to be installed (pump < screen diameter < annular space < borehole diameter)	Technical design, adapted to demand and construction needs Quickest design method	Maximum aquifer yield and technical intake capacity of the well need to be considered
		Aquifer yield and maximum intake capacity (borehole diameter minus two*thickness of the gravel pack = screen diameter)	Hydraulic design, adapted to maximum possible abstraction Considers the aquifer yield	Demand and head loss due to installation components (technical intake capacity) need to be considered
		Demand and technical intake capacity (screen radius = Qf / critical flow velocity * aquifer thickness*2π)	Hydraulic design, adapted to demand and aquifer properties	Size of the pump and space for gravel pack installation (if necessary) need to be considered
Well depth	Aquifer depth	Near-surface	Lower costs for drilling and casing due to lower depth	Higher risk of inflow from the surface, leading to oxygen uptake and/ or microbiological contamination
		Deep	Protected against leakage or inflow from the surface	Higher costs for drilling and construction Higher costs for maintenance measures
	Position of the static water level	Artesian	Low energy costs for pumping	Technically more challenging with regard to drilling and well head installation
		Unconfined	-	Not protected against inflow of surface water Even if the well is properly grouted, there will be a vertical flow component within the near-well aquifer
		Confined	Protected against leakage or inflow from the surface	
Position of the pump	Depth of intake section	In casing above the screen	Lower energy consumption	Intake highest in the upper metres Risk of dewatering
		In a blind section within the screen	More homogeneous inflow from upper and lower screen sections	Higher costs for rising main installation and pump energy
		In tail pipe below the screen	Protected against dewatering	Pump more exposed to abrasion due to sand intake Higher costs for rising main installation and pump energy

Screen depth	Expected drawdown	Little (0.50 to 2.00 metres)	Low hydraulic head resulting in a lower flow velocity (prevention of turbulent flow)	Higher risk of dewatering, if static water level decreases
		Medium (2.00 to 10.00 metres)	Longer casing provides better protection against inflow from the surface	Higher costs for materials and construction Higher hydraulic head
		High (10.00 to 20.00 metres)	-	High hydraulic head. High energy costs. Higher costs for drilling and materials
Screen position	Top of the screen	Above dynamic water level	-	Chemical clogging due to alternating exposure to air and water
		Below dynamic water level	Protected against air exposure	-
Screen length	Use of the whole aquifer thickness	Screen covers whole aquifer (fully penetrating well)	Lower flow velocity (prevention of turbulent flow) Decreased risk of sand intake Buffer capacity for the reduction of permeability due to ageing processes	Higher costs for drilling and construction due to higher depth Higher costs for maintenance
		Screen covers aquifer only partly (incomplete well)	Lower costs for drilling and construction	High flow velocity Uneven intake distribution Less yield
	Number of screen sections	One screen section = one water-bearing layer	Lower costs for materials and construction Less effort for gravel pack determination	Inhomogeneous aquifer properties are not considered
		Selective screening within one water-bearing layer	Exclusion of unwanted impacts, e.g. clay horizons	Higher effort for determination of exact position and construction
		Multiple screen sections covering different water-bearing layers (separated by impermeable layers)	Higher yield with one well	Mixing of groundwater with different hydrochemical properties, e.g. due to diffusion during rest periods, resulting in enhanced chemical clogging
Screen type	Material	Stainless steel (Johnson screen)	High variability of slot width Stable to corrosion and forces applied during maintenance	Expensive
		PVC	Cheaper than stainless steel Lightweight	Lower open area
		Coated steel	-	Risk of corrosion as soon as protective coating is damaged
		Older materials (OBO, ceramics, copper)	Stable to corrosion and forces applied during maintenance	Heavyweight, thus bad handling Not produced anymore

	Geometry of the openings	Horizontal slots, fully open	Higher open area providing laminar flow conditions and better access for maintenance	-
		Vertical bridges, louver	Higher tensile and compression strength	Lower open area resulting in increasingly turbulent flow conditions Additional diffraction and/ or reflection for hydromechanical maintenance methods
Artificial gravel packs	In consolidated formations	No gravel pack	Lower drilling diameter resulting in lower costs	High risk of turbulent flow due to the sudden change
		Gravel pack	Borehole support to prevent damages to the casing from weathering	-
	In unconsolidated formations	No gravel pack	Natural development of the near-well aquifer possible	Natural development needed to provide filtration function
		Gravel pack	Filtration function	Additional pore space for ageing deposits Less accessible for maintenance
	Extent	Screened sections only	-	Particle movement with the vertical component of the inflow can lead to colmation processes Settlement processes within the gravel pack cannot be balanced
		Pile-up (screened sections plus 1m up and down)	Filtration is provided considering the vertical flow component due to the hydraulic head	No access to clean the bottom part
	Grain size	One grain size for the whole screen length	Less effort for material provision and depth-oriented installation More homogeneous inflow	Because grain size must be adapted to the finer layers ineffective for the higher permeable layers Higher risk of colmation
		Depth-differentiated grain size	Optimal use of aquifer sections with high permeability	Disproportional inflow to the well from the sections with the most permeable gravel pack Exact depth-oriented installation necessary to prevent particle mobilisation from the finer to the coarser section and subsequent settlement and/ or colmation
		Two-fold gravel	Higher slot width possible for fine-grained aquifers reducing turbulent flow Less effort for material provision and installation	Larger distance between borehole wall and screen resulting in less effective cleaning and sand removal

Sealing (Grouting) towards the surface	Sanitary protection	Lining with protective casing	Good protection along the entire upper part of the borehole (Often required by the local authorities)	To prevent vertical flow along the outer casing additional grouting between lining and borehole wall is recommended
		Clay sealing	Easy transport and installation (solid form) Good protection after set (swelling)	Hydrochemical properties of the water need to be considered Not suitable above the water table
		Grout sealing	Nowadays good handling (solid, mixture with clay to provide swelling) Good protection, if installed with sufficient thickness	Hydrochemical properties of the water determining for durability and impermeability Whole casing section should be grouted to prevent flow around
Back-filling of blind sections	Support	With drilling material	-	Even distribution not provided due to the different, inhomogeneous grain sizes leading to bridging and subsequent settlement (high risk of collapse and damages to the casing)
		With clay or grout	Protective properties Sealing of different water-bearing horizons to prevent mixing	-
Accessibility for monitoring	Installation of gauges (piezometers)	Within the artificial gravel pack	Provision of access for sampling and measurements during operation Provision of gravel pack monitoring Localisation of ageing deposits	Possibly larger drilling diameter necessary Possibly disturbance of gravel pack installation
		Near the well	Provision of access for sampling and regional water level monitoring	Installation costs

5.2 Construction

Constructing a well includes all steps from establishing the construction site to

- drilling,
- equipment of the borehole with all installations and
- well development.

As for well design, construction standards and a wide range of textbooks are available, e.g. DVGW W 117 and W 118, NGWA 1975, BALKE 2000; BIESKE 1998; CLARK 1988; DRISCOLL 1986; PETTY & AL 2000; SEGALEN, PAVELIC et al. 2005. They contain detailed descriptions of drilling methods, construction materials and the steps of installation. In the following, the most important points will be summarized:

During drilling, samples need to be taken to adjust the planned well design to the actual aquifer characteristics, if needed.

All data, such as e.g. the driller's log, sampling depths, sieve curve analyses, water levels etc. need to be recorded and stored in the well file for later well assessment.

5.2.1 Drilling methods

Drilling methods have been developed according to the various geological conditions, ranging from hard rock formations such as granite or dolomite to unconsolidated sediments such as soft sands or alluvial gravel.

In general, they can be divided according to their mode of action in percussive or rotary methods and according to the need to use drilling fluids in dry or fluid methods. Each features different technological properties.

The selection of the best drilling tool requires practical experience, a good understanding of the geological site characteristics and knowledge about the limitations, advantages and disadvantages of the methods. The latter are summarized in Table 5-2.

In addition, the way of drilling implicates the need to remove barriers formed during drilling, where they were needed to stabilize the borehole for the installation of casings and screens. Depending on the drilling method, such barriers are due to either the drilling fluid forming a so-called mud cake (direct rotary drilling) or a “plaster”-effect caused by scratching along the borehole wall (percussion drilling/ cable tool).

Dutch researchers reported a relation between the drilling method and the rate of ageing (TIMMER, VERDEL et al. 2003) for 22 investigated wells all situated in one well field: Wells drilled by using the cable-tool were less affected by ageing than wells drilled with the reverse-circulation rotary drilling. From the investigations including particle measurements, sampling of sediments and subsequent sieve analyses as well as microbiological analyses parallel to rehabilitation measures it could be concluded that the drilling fluids used for rotary drilling induced a high potential for biological ageing processes. Thus, the effective removal of drilling fluids, forming a mud-cake at the borehole wall is a decisive factor to prevent a fast loss of capacity. This is the subject of well development.

Table 5-2: Drilling methods [after DVGW, BALKE 2000; BIESKE 1998; DRISCOLL 1986]

Drilling method		Mechanism	Limitations	Advantages	Disadvantages
Dry / Percussive	**Driven Wells**	Well point is directly hammered into the ground	- Maximum depth 15 m (in sandy grounds)	- Simple application	- Only useable in sandy grounds - No sampling possible
	Cable Tool	Repeated lifting and dropping of a heavy string of drilling tools or weights into the borehole pulverises material at the bottom	- Depths up to 400 m and diameters up to 900 mm possible - Difficult or sometimes even impossible in soft or cohesion-less soils	- Useful for deep holes when a hydrostatic head from drilling mud is unacceptable - Good sampling	- The larger the diameter, the less depth can be reached - Relatively slow - Pulverised material must be removed with a bailer
Dry / Rotary	**Hollow Stem Auger**	Rotating of sections of auger casing (auger flights) are turned into the subsurface while rotating of the auger flights carries the soil to the surface	- Depths of 60 m with 10 mm diameter or 25 m with 25 mm diameter achievable - Most effective in stable soil	- Hole is drilled and cased simultaneously, well installation directly through the auger - Hole can be advanced without use of fluids	- Difficulty of drilling significantly increases with depth - Cobbles and boulders might cause problems
	Air Rotary	Similar to Direct Mud Rotary Drilling, but instead of drilling fluid compressed air is used to carry drilling cuts to the surface	- Maximum depth 400 m, maximum diameter 600 mm - Well suited for difficult materials	- Fast and efficient - Suitable for high depths and high hole diameters - No need for fluid	- Usually need of a drill casing supporting the sides of the borehole
Fluid / Rotary	**Direct Mud Rotary**	Drill bit on the bottom of a string of drill rods is rotated in a borehole, drilling fluid circulates in the borehole (pumped down through the string of rods) and carries drilling cuts to the surface	- Maximum depth 400 m, maximum diameter 600 mm - Not useable if excess hydrostatic heads cannot be tolerated	- Fast and efficient - Suitable for high depths and high hole diameters	- Fluid can seal the sides of the borehole - Usually need of a drill casing supporting the sides of the borehole - No undisturbed samples
	Dual-Wall Reverse Circulation	Similar to Rotary Drilling, but the transport medium is pumped down between the outer casing and the inner drill rods and up through the drill rods	- Maximum depth 400 m, hole diameters up to 1500 mm - Suitable both for unconsolidated and consolidated formations	- Higher hole diameters can be achieved - Continuous collection of the cuttings	- Fluid can be flushed into the aquifer leading to colmation - No undisturbed samples
Fluid	**Wash Boring**	Water is pumped down the drill rods under pressure and carries the soil up to the surface	- Restricted to low depths and sandy grounds	- Simple and safe application	- Only useable in sandy grounds - No sampling possible

5.2.2 Well development

Well development describes the desanding and stabilization of the formation directly adjacent to the borehole (if existent, it includes the gravel pack) to reverse damages, material intrusion and compaction caused by drilling. Main objective is the removal of sand and fine particles, which will otherwise impede the inflow leading to a quickly decreasing well performance.

Any insufficient well development after construction will affect the subsequent operation. Three processes are involved:

(1) The mobilisation of fine particles due to the well operation might induce colmation processes at the aquifer-gravel pack boundary or within the gravel pack.

(2) Sand intake on the other hand, if not removed during well development, might damage the pump or lead to deposition within the well or the rising main.

(3) Remaining drilling fluid containing organic substances might provide a nutrient source for bacteria and biofilms, thus enhancing biological ageing processes

Methods to develop a well are overpumping, backwashing, mechanical surging, airlifting or jetting. The application is similar to the appropriate rehabilitation technologies basing on these mechanisms, where it fulfils the same objective - the removal of deposits and fine material blocking the pore space.

Overpumping involves a minimum 1.5 times higher discharge rate than during normal operation, and reaches usually maximum one metre around the screen. The efficiency is enhanced by using packer discs for isolation pumping. Due to the enforced high flow velocity towards the well it might lead to bridging of fine particles, which will then be remobilized during normal operation and lead subsequently to sand-intake (DRISCOLL 1986). More effective are therefore backwashing, airlifting or surging, where reversing the flow direction helps to break down bridging.

Based on the results of numerical fluid mechanics modelling and field tests, a new device for well development and desanding was presented by Pigadi and GCI GmbH. It bases on isolation pumping, but has thicker packer sections. The 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. It can be used for well development after construction as well as for a redevelopment after rehabilitation measures.

Well development might be used to naturally develop a highly permeable zone from the formation sediment (DRISCOLL 1986) by removal of particles smaller than the screen openings. Because the induced forces are highest near the screen, grain sizes will grade from coarse-grained to a mixture between coarse and medium sized to original aquifer mixture. This stabilizes the sediment and prevents further movement of particles. However, it works only in rather sorted and coarse-grained aquifers (see chapter 5.1.3).

Well development is followed by the start of operation with a pump test confirming the initial capacity and the abstraction of sand-free water.

5.2.3 Potential nonconformities

As already mentioned in Chapter 2, well design and construction are important factors influencing the productive lifetime and ageing potential of a well. Although well design and construction are standardized, all steps of planning, designing and constructing a well yield sources for errors and improper workmanship, which are in most cases irreversible and lead to a shorter lifetime, shorter maintenance intervals and higher energy consumption for water abstraction.

A careful planning and design with regard to the site selection and aquifer characteristics provided, the most common errors are made during well construction. Their impacts and consequences are summarized in Table 5-3.

The occurrence of such errors can be prevented by a close cooperation between the well owner and the drilling company, the implementation of a quality assurance procedure including site inspections, keeping of records about the drilling method, use of drilling fluids, sampling etc. and the ongoing adjustment of well design and construction to the findings during drilling progress.

Table 5-3: Sources of well construction errors and their consequences [modified after WALTER 2002p202]

Insufficiency	Impact	Consequences
Selection of materials without consideration of raw water properties	Chemical reactions between installation materials and water contents	Occurence of corrosion or dissolution effects and subsequent failure of the construction
Damage to coatings during handling and installation of equipment	Water gets in contact with underlying material (usually steel), which should be protected	Occurrence of corrosion and subsequent failure of the construction
Too fine-grained gravel pack	Decreased capacity Higher drawdown for nominal yield	Higher energy consumption due to increased pressure head Higher risk for colmation
Too coarse-grained gravel pack	Ongoing sand intake	Abrasion at the pump Higher risk for colmation due to particle mobilisation
Leaky sanitary protection (grouting)	Influx of surface water	Higher risk for bacterial contamination Oxygen intake leading to precipitation of mineral deposits
Leaky casing connection points	Influx of infiltration water	see above
Leaky grouting between different aquifers	Mixing of groundwater from different depths with different chemical properties	Precipitation of mineral deposits
Use of wrong **lubricants**	Alteration of water chemistry Provision of nutrients to microorganisms	Mixing reactions Enhancement of biofouling
Poor capacity of filter sections due to **improper desanding**	Decreased well performance/ higher drawdown Higher risk of sand intake	Higher energy consumption due to increased pressure head Pump abrasion
Too small **diameter of the rising main**	High flow velocity	Higher energy consumption
Too small **cable diameter** for energy supply of the submersible pump	High energy loss	Higher energy consumption

5.3 Ageing prevention by design and construction

Main factors of well ageing, which can be influenced by well design and construction, are:

(1) the control of flow velocity changes and prevention of turbulent flow conditions

(2) the prevention of mixing of water from different depths or aquifers with different hydrochemical properties

(3) the prevention of exposure of the screen to air

(1) The flow velocity is a function of the volume (discharge rate) and the permeability along the flow path of the water. The latter depends on the open area. These are

- the pore space in sedimentary aquifers or the width of the fractures in fissured aquifers,
- the screen openings and
- the pore space of the gravel pack (if present).

In horizontal direction, critical points are all boundaries, where the permeability changes. Sudden velocity changes along the flow path are avoided by choosing the largest possible open area for screens and grain size for gravel packs.

With regard to gravel pack improvement, a recent development is as the use of glass beads instead of quartz gravel 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 clogging properties and behaviour during rehabilitation should be further investigated.

In vertical direction, the pressure head is lowest directly at the pump and increases with increasing distance. To homogenise the inflow vertically, suction flow control devices (SFCD) have been developed. They consist of a perforated tube attached to the pump to enlarge the intake area. A description can be found in BORCH & SMITH (1993) or HOUBEN & TRESKATIS (2007).

In new or freshly rehabilitated wells, the additional energy loss, caused by passing the SFCD is compensated by the gain due to the reduction of turbulent flow conditions. It benefits to an even intake distribution. On the other hand, the SFCD represents an additional surface, which will be affected by ageing deposits itself. In that case, it increases the entrance loss compared to an aged well without SFCD. It can therefore be recommended for wells, which are affected by physical clogging or sand intake, but not for biologically or chemically clogged wells.

2) The prevention of mixing is achieved by

- limiting the screen depth to one intake section,
- installing proper sealing between different water-bearing horizons or
- separating the abstraction to more than one well, each penetrating a different depth (cited in HOUBEN & TRESKATIS 2007, p333f).

Each of these solutions implicates some disadvantages: Limiting the screen length reduces the overall capacity. Sealing between different water-bearing horizons must include blind casing, but also a grouting of the annular space, which must adjoin the borehole wall. Any leakage will induce a vertical flow.

Splitting two or more screen sections to the corresponding number of separate partially penetrating wells was tested by Dutch researchers (van Beek & Brandes 1977). It requires a precise knowledge about the reduction zones and their changes due to pumping. Because it was less effective than expected, both in terms of ageing prevention and overall yield, it has not been implemented in practice. Horizontal or radial collector wells follow a similar approach as they take water from one water-bearing layer, only (☞ constant hydrochemical properties).

3) To prevent oxygen uptake, the top of the screen must always be covered by water. Hence, during well design the maximum drawdown needs to be considered. It is preferable to use confined aquifers rather than unconfined or to apply a minimum depth for the first screen section (depending on the permeability of the overlying formation). This furthermore benefits towards securing the raw water quality.

5.4 Room for improvement

Most important for a proper well design and construction is a good knowledge or careful evaluation of the site conditions to minimize the impact of the well properties on well ageing processes.

The evaluation of determining factors such as the

- aquifer depth and thickness
- occurrence of confining layers
- grain size distribution of unconsolidated formation
- hydrochemical properties of the different water-bearing layers

has already improved a lot together with the technical development of hydrogeological exploration and drilling methods.

A recent development in that context is for example the "Fluid Finder", developed by the EDI Drilling Company (www.edipower.com). It allows a better adaptation of the well design to the hydrochemical properties of the different penetrated water-bearing layers because of an easier sampling during the drilling process.

Nowadays, the optimization of the well site selection and dimensioning of the well is done with the help of flow models, which allow the assessment and comparison of different possibilities. However, this does not replace practical experience, a good cooperation between all participants and the quality assurance during all steps of construction.

5.4.1 Current practice

At BWB, well design and construction are to a certain degree standardized, mainly due to economic reasons and material provision. As all wells are situated in the same quaternary aquifer complex (please refer to chapter 2.1 of the report D 1.3), the site conditions determine variations in the gravel grain size and the well depth.

The well diameters lie between 200 and 400mm. Casing and screens are made of copper, ceramics, steel or PVC in the older wells. Since approximately 1995, stainless steel wire-wound Johnson screens together with a twofold gravel pack are used for new wells. The top of screen is usually below 20m and the total screen length at around 25m. Depending on the homogeneity of the aquifer it might be divided into two to four screen sections. Since 2005, the clay sealing has been extended to the top of the gravel pack for an enhanced protection against surface water intake. For a more detailed overview of the well dimensions of the BWB wells, please do also refer to chapter 3.1 of the report D 1.2.

Drilling is done as far as possible without drilling mud. If necessary, only water is used as drilling fluid to prevent the formation of mud cakes. For well development, isolation pumping is used. Currently, the new device developed by Pigadi (see chapter 5.2.2) is tested.

To assure a good construction quality, all wells are logged with borehole geophysical methods after construction:

- caliper-log (CAL) to assure the verticality and uniformity of casing and screen from the top to the bottom

- gamma-gamma (GG.D) to evaluate inhomogeneities in the porosity of the gravel pack or the accumulation of fine materials
- flowmeter (FLOW) to assess the initial intake distribution

Each well construction ends with a step test. All data are recorded in a well file, but currently in hardcopy only. The BWB is currently in the process of digitalisation and development of adequate database storage.

For their sites, Veolia on the other hand is not the well owner, because in France these are the communities. Therefore, they have less influence on well design and construction, but might be involved as consultants.

Because of the different geological contexts, the well design is much more variable. In consolidated formations, wells are designed either as open boreholes or they have a protective casing, either with or without a stabilizing gravel pack. Diameter and well depth differ. In unconsolidated aquifers, all wells are constructed with an artificial gravel pack. The screen materials in use follow the general technical development. In relation to the year of construction, ceramics, black steel, PVC or stainless steel are most common. Current standard is the stainless steel wire-wound Johnson screen, too. Especially for the old wells, not all data are available.

In reference to Figure 7 (page 21 of the report D 1.2), the data from 11 well fields available to us, already show the high variability. Further data need to be evaluated in the course of WellMa2 to continue searching for patterns (see also next chapter).

5.4.2 Recommendations

Both, from the statistical analysis (please refer to report D 1.2) and the evaluation of current practice, it could be concluded that possibilities for a proper protection against surface water intake need to be further evaluated. This implies e.g. adjusting the depth of the screen or extending the protective clay sealing (as done since 2005 by BWB) or lining.

In reference to Table 5-1, further design alternatives should be assessed from the point of practical application with regard to their benefits and disadvantages. This applies especially to

- the use of twofold gravel packs
- the use of naturally developed gravel packs, if the site conditions allow this possibility
- the optimization of the piezometer installation
- the use of glass beads instead of quartz gravel
- a comparison of PVC and stainless steel screens regarding costs and durability

To which extent these tasks can be included in WellMa2 as laboratory and field investigations or theoretically using flow models, or will be fulfilled by the technical divisions of BWB and Veolia, needs to be discussed with the technical committee.

Finally, the further maintenance and extension of the database and implementation of digital well files is strongly recommended. The data availability provided, this will allow the intensified search for patterns between the ageing susceptibility and well characteristics, for example

- taking up the Dutch investigations of the impact from the drilling method on well ageing (see chapter 5.2.1) or
- comparing the different design possibilities in consolidated formations,

which contributes to the optimization and development of guidelines for best practice.

Summary D 3.1.1: Slow-down of ageing by design and construction

Design and construction determine the flow velocity and inflow distribution. Thus, they influence the location of ageing deposits. The configurations, dimensions and choice of materials for well construction are set by a variety of economic, technical, quantitative and qualitative requirements. The hydraulic and technical design need to be evaluated for each new well site individually. Feedback from operation and maintenance, i.e. about the well ageing potential of the site should be considered.

Checklist:

1. Develop a quality assurance protocol for all steps of design and construction:
   - ☞ Make a schedule, name the responsible parties (consultancy, own technical division, contractor), prepare minutes, data record sheets etc.
2. Start planning with the determination of demand.
3. Take time for proper design and planning to avoid construction-related ageing problems.
   - ☞ Are the hydraulic characteristics of the chosen aquifer suitable to meet the demand with reasonable effort regarding the well number and dimensions? If not, look for solutions other than drilling a new well.
   - ☞ Are the materials suitable for the hydrogeochemical site conditions and the expected raw water type?
4. Adapt the technical design of the well:

$$Pump \cdot size \xrightarrow{+100mmm} Tube \cdot diameter \xrightarrow{*1,5 to 2} Borehole \cdot diameter$$

$$Mean \cdot grain \cdot size \cdot of \cdot the \cdot aquifer \cdot se\dim ent \xrightarrow{*4 to 6} Gravel \cdot pack$$

5. Select the drilling method with regard to the geology, needed depth etc.
6. If necessary, adapt design and dimensions to the actual aquifer properties, determined during drilling.
7. After drilling and installation of all parts of the well, develop the well (desanding and activation).
8. Test the initial specific capacity. Ideally, carry out initial caliper and GG.D log, flowmeter and packer-flowmeter measurement as basis for later well condition assessment.
9. Record all data in a well-specific file.

Chapter 6 Well operation

Efficient and economic well operation is the key element of an integrated well management (Figure 6-1).

At the same time, it seems to be a critical factor co- determining the lifetime of a well, because once a well is constructed, operation and maintenance are the only possibilities to influence its lifetime.

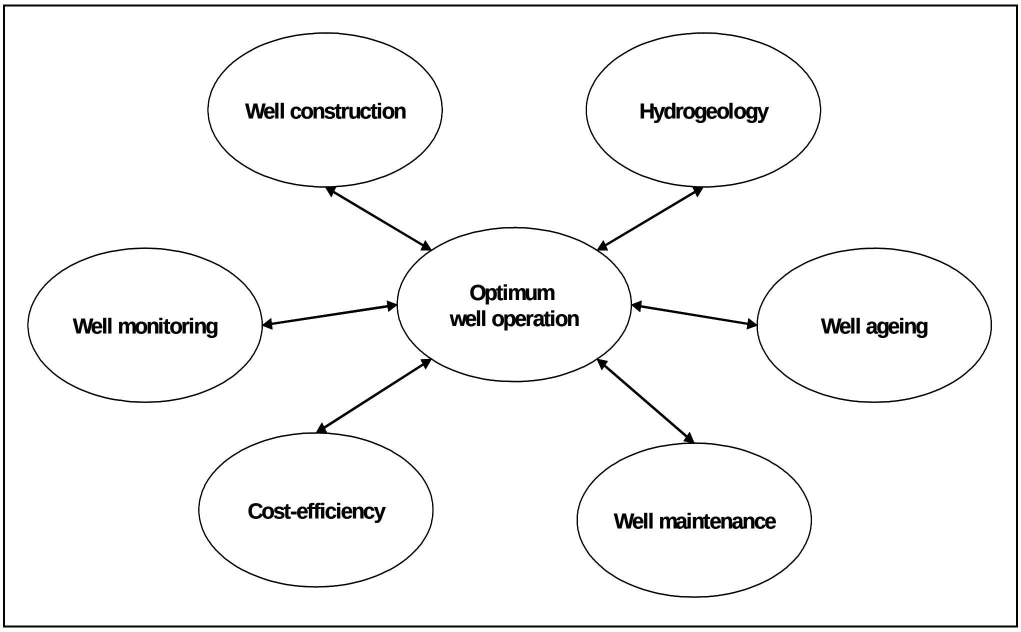


Figure 6-1: Key elements of an efficient well management [modified after WICKLEIN & STEUßLOFF 2006]

Well operation is always a compromise between

- the demand,
- site-specific opportunities and
- technical possibilities

Furthermore, it is economically driven. The costs of operation (material and equipment, energy consumption, maintenance needs) and the achieved benefit (water supply with sufficient quantity and quality) determine, if a well is efficient or not.

As well operation always changes the hydraulic conditions, it has a strong impact on the hydraulic and hydrogeochemical characteristics. Together with the site conditions, it determines the ageing potential of a well.

The parameters, which can be influenced by operation, are

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

However, as any change might prevent one process, but at the same time enhance another, it always needs practical experience and the careful consideration of the site-specific circumstances.

In contrast to well design, construction and maintenance, there have been only a few approaches for standardization or technical guidance, e.g. BERGER 2004 or DVGW 2004, which focus in fact more on the importance of implementing a monitoring strategy instead of giving technical guidance for an optimized operation.

Further publications consider mainly the economic side of well operation, e.g. BAILEY 2007; HANSEN 2006; SCHULZ 1999; WALTER 2002; WALTER 2007.

Beyond it, the following overview aims at the evaluation of the potential to prevent or at least slow down well ageing by an adjusted operation. An additional cost-benefit-evaluation is proposed to be part of WellMa2 to assess the advantages of the recommended optimization approaches in practical application.

6.1 Impact of well operation on ageing

The main factors for an enhanced well ageing are the increased flow velocity, mixing processes and the possibility of oxygen intake, the latter two leading primarily to an imbalance of the thermodynamic equilibrium, which enhances biological and chemical clogging. The effects depend on the site characteristics.

Generally, either by well design or by operation

- the 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,
- water from different horizons should not be mixed (primarily by well design) and
- sudden water table fluctuation should be minimized

A more detailed review considering the different well ageing types is given below:

6.1.1 Chemical clogging

In reference to chapter 2, the most important parameters influencing the potential for **iron-related chemical clogging** are the presence of oxygen and dissolved iron at pH-conditions leading to the precipitation of iron hydroxides. For oxygen intake due to well operation, three sources are possible:

1) <u>Mixing of groundwater from different sources</u> (i.e. bank filtrate and ambient groundwater): Due to well operation, water is abstracted from different directions. Especially at riversides, oxygen-bearing bank filtrate and iron-bearing landside groundwater will meet within the abstraction well. In accordance to the Eh-pH-diagram (Figure 6-2 left), iron hydroxides will precipitate.

Because of the constant delivery of starting materials for the reaction during operation, this process is more affected by the duration of abstraction and the volume of water (☞ mean discharge) than by the number of switchings.

For the Berlin wells, modelling has furthermore shown that the bank filtrate-share is not constant for one well due to highly transient flow conditions along the well field. It depends on the operation schedule of neighbouring wells, the duration of abstraction, the discharge, seasonal influences etc. Thus, the mixing processes can be influenced by the operation scheme of the well gallery.

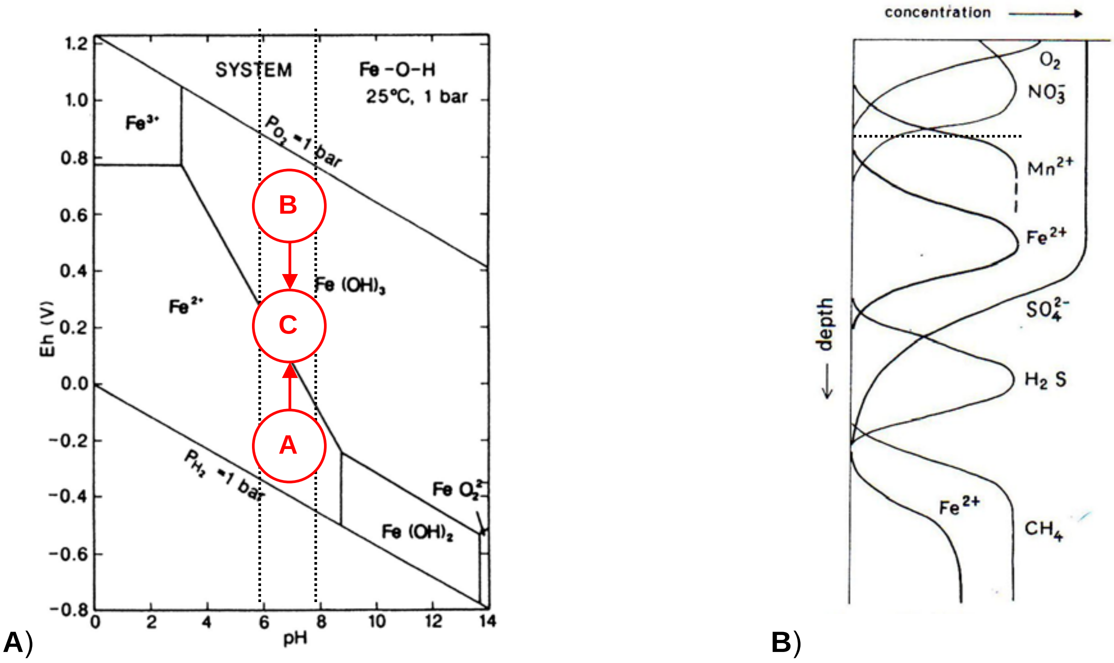


Figure 6-2: On the left: Eh-pH-diagram for the stability fields of iron species, A: Ambient groundwater, B: Bank filtrate, C: Mixed raw water; On the right: Depth-related groundwater composition reflecting the sequence of redox processes [after APPELO & POSTMA 1996]

2) The redox profile: In undisturbed aquifers, the redox conditions change with depth due to biological activity taking up first the available oxygen introduced from the unsaturated zone. Thus, there is a vertical layering, with oxygen-rich water at the top and oxygen-free, but iron-bearing water below (Figure 6-2B, right).

Well operation causes a vertical flow towards the pump intake resulting in mixing water from different depths within the well. Again, in accordance to the Eh-pH-diagram, this will lead to the precipitation of iron hydroxides.

Because of the formation of a steady state during constant operation, the redox boundary is re-established after a certain time of operation, but moves away from the well into the aquifer. Within the well, mixing takes place, i.e. near the pump intake, where the vertical flow component is highest.

Each switching operation disturbs the redox boundary. Because of its location, switching on enhances mixing within the well and switching off within the gravel pack. Hence, to prevent vertical mixing, the number of switchings should be reduced.

3) Atmospheric oxygen is present underground in the unsaturated zone. Due to the start of pumping, each time the water table is lowered and air is taken into the cone of depression. Even if the water level is always kept above the top of the screen, this oxygen is taken up by the groundwater, because as soon as the well is switched off, the water table rises and the groundwater filling the cone of depression mixes with the entrapped air bubbles (Figure 6-3).

Thus, each switching operation moves atmospheric oxygen down to the initially saturated zone leading in the presence of dissolved iron and neutral pH to enhanced chemical clogging.

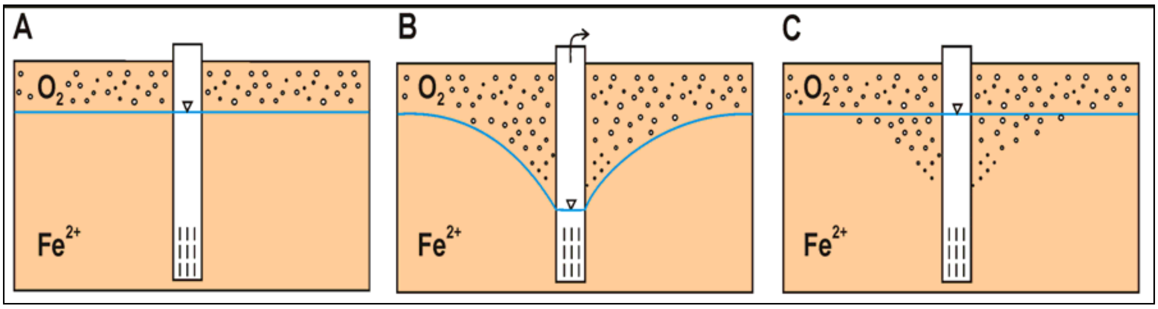


Figure 6-3: Schematic diagram of oxygen input due to air entrapment as a result of well operation: A: undisturbed hydraulic and hydrochemical conditions. B: Oxygen entry into the temporary unsaturated zone of cone of depression during well operation. C: Air entrapment due to recovery after shutdown of pump [taken from Report D 1.3, KWB 2009]

To prevent operation-induced oxygen uptake and subsequent chemical clogging, HOUBEN & TRESKATIS (2007) describe the possibility to insert inert gas to replace oxygen. However, as this would require airtight sealing, the technical effort would be very high and regular monitoring would not be possible. No case of practical application has been reported.

For **sintering**, the state of the carbonic acid system is the decisive factor. The most important parameter is the CO_2 pressure within the groundwater. With regard to well operation, three effects occur, which change the equilibrium state, because they lead to CO_2 degassing:

(1) the increase in temperature due to the pump operation

(2) the occurrence of turbulent flow conditions

(3) the head pressure release due to abstraction

With a decreasing CO_2 pressure, less calcite can be hold in the dissolution and will therefore precipitate.

Both, the temperature increase and the occurrence of turbulences are local effects primarily at the pump. Thus, from pump operation and chemical reaction kinetics, carbonate clogging would be restricted to deposits at or near the pump.

In contrast, the overall pressure release due to abstraction is not restricted to the pump or even the well and might lead to calcite precipitation within the range of influence within the aquifer.

However, the mechanisms are still subject to research. Furthermore, the only process, which can be influenced, is the occurrence of turbulent flow, which is prevented by applying a maximum allowed intake flow velocity for the calculation of the intake area (screen dimension and width of the openings).

6.1.2 Biological clogging

The impacts of well operation on clogging-related microorganisms are complex and the mechanisms are not yet fully understood. The most obvious factors are:

(1) the constant delivery of nutrients

(2) the increased temperature, at least at the pump surface and

(3) the flow velocity changes

Clogging related bacteria are sessile. They can be attached to all surfaces present in a well, i.e. the pump, casing and screen, where they build biofilms, which protect the cell surfaces and function as a nutrient trap.

1) The enhanced flow towards a well during operation periods increases the nutrient supply. Especially for iron-related bacteria, nutrients are not only nitrate, phosphate and carbon sources, but also dissolved iron or manganese. Thus, together with the constant delivery of some oxygen, the conditions in an operated well are favourable for iron-related bacteria.

On the other hand, prolonged rest periods may not prevent bacterial growth, but the present communities change. Instead of iron-related bacteria, which rely on the above-described slightly oxic conditions and nutrient supply, anaerobic bacteria will occur. These are mainly slime-forming bacteria inducing biofouling processes.

2) Temperature influences the community structure as well. In an abstraction well, this applies especially to the surface of the submersible pump. In any case, biofilms will attach at the pump, but according to the temperature gradient, the microorganisms differ (Figure 6-4). Bacteria adapted to higher temperatures will settle near the pump engine, where the temperature is increased, while bacteria, which cannot survive higher temperatures, will settle at other parts of the pump.

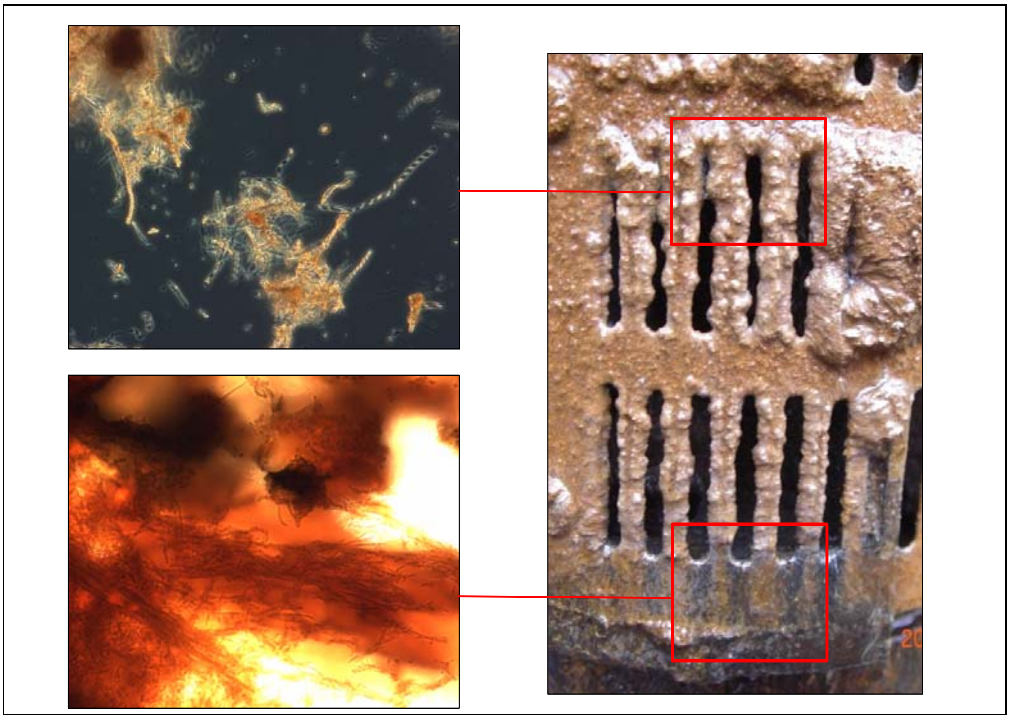


Figure 6-4: Microscopic analysis of two biofilm samples, both from the same submersible pump app. 1o cm away from each other, representing different bacteria morphotypes [from Thronicker&Szewzyk, 2008, presentation at the KWB]

Further details need to be investigated, yet, e.g. by monitoring the range of temperature changes at the pump in correlation to the occurring bacteria, as this might give the opportunity to prevent biological clogging by an adjusted operation scheme.

3) A constant flow velocity results in an equilibrium between attachment and detachment of cells in a biofilm. Switching induces turbulent flow conditions, under which oxygen and nutrients are better assimilated, which is favourable for biofilm growth and iron-related clogging. On the other hand, under such high flow conditions patches of mature biofilms may detach. Thus, the switching frequency and the flow velocity determine the thickness of the biofilm (BARTETZKO 2002).

For more details regarding biofilms and well operation, please do also refer to chapters 2.1.3 and 5.2 of report D 4.1.

6.1.3 Physical clogging

As described in chapter 2.1.3 of this report, physical clogging is caused by the mobilization of fine particles with the increased flow towards a well during abstraction. Three processes can be distinguished:

(1) Sand intake, if the particles can pass the pores,

(2) Colmation, if the pores are too small and the particles are trapped or

(3) Bridging and thus a reduced permeability, if the particles, which would normally pass the pores, collide and can therefore not pass.

The ability to mobilize particles is determined only by the flow velocity, which was one of the reasons to introduce a critical flow velocity for the calculation of the hydraulic design of a well (see chapter 5.1).

Thus, apart from well design and construction errors, sand intake and colmation are usually related to overexploitation with discharge rates higher than the maximum tolerable discharge.

However, even if a well is properly designed and constructed and operated with moderate flow velocities, physical clogging can occur due to the build-up of particle bridges, as Dutch researchers found (DE ZWART 2007).

Fine particles, which are mobilized at normal flow conditions and would normally be able to pass the gravel pack, are trapped, if they reach the pore at the same time and hinder each other.

The investigations led to the conclusion, that particle bridging is reversible by frequent switchings, as switching on and off the pump generates a flow impulse due to the sudden change of the hydraulic head, while on the other hand, constant operation establishes the bridges, making it harder to remove them (Figure 6-5).

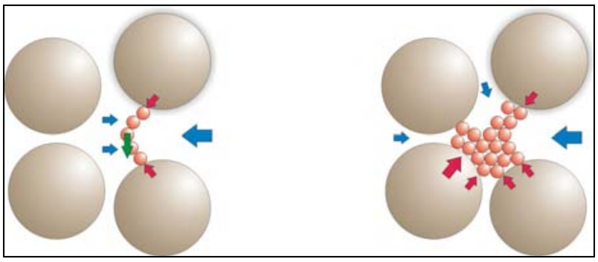


Figure 6-5: Particle bridge, formed in the gravel pack under flow from left to right (small blue arrows), on the left: recently formed particle bridge, which can be broken by a reversed flow (big blue arrow), on the right: well established particle bridge after some time of abstraction [from DE ZWART 2007]

Thus, wells in inhomogeneous, sandy aquifers with a high potential for such physical clogging should be switched on and off frequently to remove particle bridges and maintain a good permeability of the gravel pack.

Summarizing the impacts of well operation on ageing processes, in theory it can be concluded that:

- The achievement of longer and lower discharge rates and reduction of the number of switchings will decrease the ageing potential for chemically clogging wells.
- Biological clogging cannot be avoided by operational measures, but the community structure can be influenced. Continuous operation will lead to iron-related clogging, while rest periods induce biofouling (i.e. slime-forming, anaerobic bacteria). Switching enhances nutrient supply, but at the same time, the detachment of biofilm patches.
- If there is a source for physical clogging, bridging can be reversed by frequent switching, because the high flow impulses due to switching on are able to destroy bridging and remove fine particles, which increases the porosity and thus permeability.

6.2 Room for improvement

Well operation is one of the most difficult parts of well management, if not the key element, because it merges the requirements from demand, technical possibilities and economic efficiency (balance between effort and output).

Additionally, as stated at the beginning of this chapter, beside the site characteristics well operation needs to be considered as a critical factor for the assessment of the individual well ageing potential (HOUBEN & TRESKATIS 2007).

Altogether, this makes it difficult to develop standardized approaches, which is also reflected by the fact that there are no standards or technical guidelines so far. However, room for improvement can be concluded from comparing the state of the practice with what has been learned from the outputs of WellMa1:

6.2.1 Current practice

At BWB, apart from some siphon wells still in operation, all wells are equipped with a submersible pump with a fixed capacity (range between 50 and 250 m³/h; *for more details, please refer to report D 1.2*).

Because most wells are located near to surface waters (rivers Spree and Havel), mixing processes of riverbank filtrate and landside groundwater as well as mixing of different redox layers are quite common. Thus, the potential for biological and chemical clogging is high. Years of practical experience led to the current operation scheme aiming at fulfilling the above-described requirements

- to maintain low flow velocities and
- prevent oxygen uptake and mixing as far as possible.

According to SCHMOLKE (2002) all wells of the BWB are operated at only 50% of their maximum intake capacity to reduce the stress to the well building itself by keeping the flow velocities low. In addition, according to their ageing susceptibility, concluded from TV inspection results and the energy consumption development, the wells are sorted to one of the following three groups:

- Wells, which need to be rehabilitated very often (average 3 years) are constantly running wells. They produce the base demand and are switched on and off as little as possible to lower the ageing susceptibility.
- Wells, which are less affected by clogging processes (rehabilitation interval on average at 7 years), are frequently switched wells. They supply the peak demand and are switched every 1 to 7 days.

- All wells, which do not belong to one of the two other groups, are classified to be "medium" running wells (average rehabilitation interval of 5 years). They are in operation for intervals between 1 week and 1 month.

In general, regardless the group, there have to be at least 24 hours between two switching operations at one well. Furthermore, a maximum number of switchings per day has been determined for the galleries.

Together with well design and maintenance, despite the high clogging potential an average lifetime of 30 to 40 years is reached.

From what has been learned by the author so far, at Veolia operation is to a large part driven by the demand. Often, the water supply of a town or region is relying on quite a small number of wells, only. Thus, the scope of possibilities is low. Overexploitation and lowering of the dynamic water level down into the screened sections might occur.

For further assessment, more information needs to be evaluated and discussed with the technical staff.

6.2.2 Recommendations

Generally, the basis for all optimization and improvement must be an integrated well management strategy, where feedback from operation is taken into consideration for the design and construction of new wells and the results of diagnosis and maintenance lead to an adjusted operation, as this is already done by BWB and Veolia.

In addition, a strong recommendation for the BWB would be to evaluate the grouping of the wells considering the costs for water abstraction, because taking into account the observed high potential for biological and chemical clogging:

- the operation of clogged wells as constant running wells leads to higher energy costs for the base demand, because of the increased drawdown due to ageing and
- the operation of new wells as frequently switched wells leads to a higher wear out of these wells and an increased ageing potential due to processes induced with switching (high head, peak flow velocity, turbulent flow conditions, vertical and horizontal mixing etc.)

For WellMa2, it is proposed to quantify the impacts of additional oxygen uptake due to switching on the precipitation of iron hydroxides by geochemical modelling and to investigate the occurrence of flow peaks during switching and their ability to mobilize particles or detach biofilms by flow modelling. Both approaches will help to assess e.g. the benefits of the use of frequency-controlled pumps.

The careful evaluation and assessment of operational changes together with the consideration of the different well ageing types will contribute towards the development of guidelines for an optimized well operation.

Summary D 3.2.1: Slow-down of ageing by well operation

Well operation needs to fulfil requirements from demand, technical possibilities and economic efficiency.

Any change in operation, which might prevent a certain process from occurring, might on the other hand enhance another.

Basis to develop an operational schedule must be the evaluation of the ageing potential, including the dominant ageing type and the occurring processes (e.g. mixing, turbulent flow) to determine how they can be prevented.

Checklist:

1. Operate the well with maximum 75% of its technical intake capacity to avoid exceeding the critical flow velocity.
2. Always keep the water level above the top of the screen to avoid exposure to air.
3. Plan storage capacity to avoid control of operation by peak consumption.
4. Carefully evaluate the present well ageing types to weigh up the impacts from operational changes:
   a Operate wells affected by chemical and biological clogging as constant as possible.
      ☞ Are there sources for physical clogging, e.g. clay layers?
   b Regularly switch wells affected by physical clogging to remobilize the particles (a proper well design and construction provided, otherwise think about reconstruction).
      ☞ Quantify the (additional) oxygen uptake, iron content and calculate the precipitation rate of iron hydroxides.

5. Evaluate the cost-benefit-ratio for different operation scenarios and compare e.g.
   a Low discharge rate and high operation hours vs. high discharge rate and low operation hours
   b Pumps with fixed capacity and frequency-controlled pumps
      ☞ Consider for example the additional drawdown (energy consumption) and impacts from switching.

Chapter 7 Summary and conclusion

The aim of this state-of-the-art report was to investigate

- well ageing types and their indicators
- a monitoring strategy to detect ageing on an early stage
- methods for preventive or reactive treatment
- the impact of design and construction and
- the impact of well operation on well ageing

In the following, the main results will be briefly summarized:

Above all, it needs to be considered that each well exhibits individual characteristics. In addition, the processes affecting the well performance as well as the measures to prevent or reinstall it are dynamic processes. Thus, well management implies to accept that optimal measures may not represent an overall optimum with respect to process and time.

The most important factor regarding the well ageing type (Chapter 2) is the geology of the exploited aquifer as it determines both, the lithological and hydrochemical characteristics. The sediment and groundwater 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).

> The desired aquifer and groundwater characteristics with regard to the quantitative and qualitative requirements coincide with the favourable environment for ageing processes. Thus, well ageing cannot be entirely prevented, only slowed down.

Because of the objective to actively manage a well (to slow down ageing), monitoring and maintenance strategies are needed.

Monitoring (Chapter 3) provides information on the well performance, its condition (with regard to the constructive state, visible ageing effects and the raw water quality) and possible causes for any deterioration.

Maintenance (Chapter 4) aims at preventing the performance decrease or restoring the well capacity and condition. For the right selection of methods needs to be considered:

(1) the nature of the problem
(2) the location and extension of deposits
(3) restrictions and limitations coming from the well construction or the constructive state of the well

> It is necessary to find the balance between costs (input) and benefits (output) with regard to the interval and choice of methods for monitoring and maintenance.

The impacts of well design and construction (Chapter 5) on ageing can be minimized by a proper planning including the choice of materials, dimensions and construction methods to provide low flow velocities, efficient filtration, protection against oxygen and surface water intake as well as qualitative deterioration etc.

On the other hand, well design and construction need to be considered as possible source of limitations to the applicability or efficiency of rehabilitation methods.

It is necessary to consider the technical possibilities, quantitative and qualitative requirements as well as economics to find the best well design and construction adapted to the site characteristics, operational needs and rehabilitation demands.

As well operation (Chapter 6) always changes the hydraulic conditions in a well, it has a strong impact on well ageing processes. Main factors are the increased flow velocity, mixing processes and the enhanced oxygen intake during operation. Their consequences depend mainly on the ageing potential of the site.

In general, prevention of one clogging process might enhance another. Thus, well operation implies the careful evaluation of the relevant site characteristics.

A balance needs to be found between opposing impacts, which prevent one process, but enhance at the same time another.

Additionally, the demand, technical possibilities and the request to operate the well cost-efficiently need to be considered.

Because an adjusted monitoring and diagnosis procedure is the basis for all other parts of an integrated well management strategy, amongst others WellMa2 should be used to develop new standard procedures for monitoring, test them in daily routine and assess the benefits compared to current practice.

This needs the determination of the site-specific well ageing potential and the definition of a reference value indicating the occurrence of the site-specific well ageing processes, which could either be a maximum tolerated drawdown (for a specified discharge rate), maximum Δh or loss of performance Qs or simply the presence of clogging deposits (or corrosion etc.) discovered during TV inspection. Subsequently, this parameter needs to be monitored, implicating a regular scheme and a defined method.

The application of selected rehabilitation methods at test sites, accompanied by an extended diagnosis before and after application to monitor the impacts, will allow concluding correlations to the geology, present ageing types and well design.

Further important aspects for WellMa2 are

- the distinction of different ageing processes in one well and their share contributing to the total loss of performance and
- the quantification of the impacts from well design and operation on the different well ageing processes

which will allow the linkage of all aspects of well management and the determination of an adjusted maintenance strategy and the optimization of well design and operation.

Appendix A
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Appendix B
Rehabilitation companies and their technologies

	Method	Description	Company	Advantages / Disadvantages
Mechanical methods	HRH Hydraulik-Rotations-Hochdruckverfahren	High pressure water with rotating cones (Rotation by …)	Aqua Brunnen Service (Germany)	Only suitable if well has no structural damages Pressure selection difficult, experience needed: too low = no effect, too high = possible damages
	WellJet™	High pressure water with rotating cones (Rotation by …)	AQUAPLUS (Germany)	Suitable for tubes from DN 80 to DN 1500 Specific cones for different kinds of tubes Possibility of monitoring Only suitable if well has no structural damages Pressure selection difficult, experience needed: too low = no effect, too high = possible damages
	WellPuls™	Pulsing high pressure gas (nitrogen / carbon dioxide)	AQUAPLUS (Germany)	Suitable for well cones with a diameter of 125 to 1500 mm Pressure and duration of gas pulses can be ceased for each kind of well material Only suitable if well has no structural damages
	Use of detonating gas	Oxyhydrogen-explosions release pressure waves	Celler Brunnenbau (Germany)	*see above*
	JET Master	High pressure water with rotating cones (Rotation by …)	Etschel Brunnenservice (Germany)	*see above*
	Airburst	Pulsing of high-pressure inert gas	Frazier Industries Inc, (Canada)	Adjustable energy release Different sizes for various well diameters Compared to other impulse technologies low pressure
	HAPETA™	Generation of turbulent stream by sudden relaxation of water	H.Pettenpohl (Germany)	No addition of chemical agents 2 to 4 procedures per minute possible suited for wells with a diameter of 100 to 2000 mm
	High Pressure Filter-Sleeve™	Sleeve is locked at the desired place of the tube and repairs holes, cracks and corrosion damage	Link-Pipe (USA)	Locking by air / hydraulic pressure instead of resin eases the work process Application takes 20 to 90 min Fast return to service

	Low Pressure Sleeve™	Internal repair method for rehabilitation of wells with differential pressure up to 5 psi (see above)	Link-Pipe (USA)	Locking by air / hydraulic pressure instead of resin eases the work process Application takes 20 to 90 min Fast return to service
	hydropuls™	Generation of pulses by sudden expansion of a compressed gas / liquid	pigadi (Germany)	Dissolved debris is directly pumped down at the generator Broad range of application Combination with Sprengschocken™ possible
	Sprengschocken™	Detonation causes a primary pulse as well as subsequent secondary pulses, which dissolve and remove incrustations	pigadi (Germany)	Broad range of application Matchless efficiency of dissolution also of mineralised incrustations Fast and economical application Combination with hydropuls™ possible
	Inlineschocken™	Combination of in-line procedures with Sprengschocken™, wall of the well is rebuild	pigadi (Germany)	Recommended to preserve wells and to improve their stability Reconstitution of the ability of the wells to be rehabilitated
	*Air*Schock™	Repeated sudden release of high pressure gas impulses in the well	ProWell (Israel)	High efficiency under all geological and technical conditions In combination with chemicals improvement of the dissolution efficiency
	SONIC Ultraschallsonde	Propagation of ultrasonic waves (pressure waves) with low frequency but high energy (20kHz/ 1000 W/cm²)	SONIC Umwelttechnik (Germany)	suitable for all materials and diameters (except screens with bonded gravel pack) detailed mechanisms unclear
	SONAR-JET	Combination of sound waves (30 kHz) and gas jetting to generate pressure waves moving from the well interior radially to the gravel pack	Water well redevelopers Inc. (USA)	Chemical-free Quick Possibility to damage the well structure
Combinatory methods	A.B.S. Kieswäscher	Combined cylindrical cleaning chambers for a stepwise chemical regeneration	Aqua Brunnen Service (Germany)	Individual cleaning of different sections of the tube Targeted access to the gravel Detailed monitoring of the cleaning process Economical application of agents Chemical agent is added to the groundwater Chemical agent needs certain time to work
	WellReg™	Combined cylindrical cleaning chambers for a stepwise chemical regeneration	AQUAPLUS (Germany)	Individual cleaning of different sections of the tube Detailed monitoring of the cleaning process Economical application of agents

Combinatory methods	KONTREG Master	Kieswäscher (“Gravel washer”)	Etschel Brunnenservice (Germany)	
	Switch Flow™	Combined cylindrical cleaning chambers for chemical regeneration of wells	pigadi (Germany)	Takes a few days Monitoring and readjustment of the rehabilitation agents possible Recommended subsequent to treatment with hydropuls™ or Sprengschocken™
	fluidpuls™	Combination of hydropuls™ or Sprengschocken™ treatment with chemical rehabilitation agents	pigadi (Germany)	Force of the pulse treatment is used to improve the penetration of agents Dissolved substances need to be pumped down subsequently
Chemical metods	BMR™	Betonite mud remover – agent which removes betonite mud and clays	CETCO (USA)	Ability to separate and disperse clay particles Contains no phosphates
	DPA™	Dry penetrating agent – cleaning of deposits consisting of mineral scale	CETCO (USA)	Safe to handle in dry form Much less corrosive on well materials than traditionally used chemicals (e.g. hydrochloric acid)
	LBA™	Liquid chelating agent – allows more dissolved minerals to be pumped to the waste	CETCO (USA)	Prevention of re–depositing of minerals Ability to penetrate and disperse debris layers Non-corrosive, non-toxic
	SC-200™	Liquid surfactant which enhances the dispersing efficiency of other well rehabilitation products	CETCO (USA)	Suitable for old and new wells Speeds penetration of cleaning products such as BMR™, DPA™, LBA™) Non-corrosive, non-toxic, non-flammable
	AIXTRACTOR x.0™	Well rehabilitation with different agents (neutral pH/ acidic; for removal of iron oxides, carbonates etc.)	cleanwells (Germany)	Suitable for different kind of filter material Reaction takes 45 min per segment Economical because of high efficiency
Other	Aqua Freed™	Use of gaseous and liquid carbon dioxide – combination of carbonic acid, freezing and agitation disrupts incrustations	Subsurface technologies (USA)	Successfully used on a high variety of wells, also in wells constructed using PVC or HDPE Good at slime dispersion, good at agitation, and also good at breaking up mineral scale Controlled injection of CO_2, monitoring

Appendix C
Research initiatives and Information sources on the www

Document	Key words	Author	Year	Organisation	Type of project	Results	Int.
BART website	Biofouling, Microbiology analyses, Monitoring	DBI	Akt.	Drocyon Bioconcept Inc. Canada	Commercial Website	Description of BARTs analyses, Bibliographie, Biological explanations,	@
Microbiology of well biofouling	Biofouling, Microbiology, Sampling, Monitoring, Maintenance	Cullimore C.	1992	Regina Water Research Institute	Book, public release	Understanding of the fouling microbiology, recommandations for Monitoring and maintenance	@
Operation and maintenance of extraction and injection wells – HTRW Sites	Maintenance, Monitoring, Management, Biofouling, Clogging, High hazard sites	Alford G. Smith S.A. Leach R.	2000	US Army Corps of Engineers	Pamphlet, public release	Maintenace program and schedule, conceptual background and framework	@
Well biofouling in Canada	Biofouling, Bacteria, field datas	Lebedin J. Dash T.	2003	Prairie Farm Rehabilitation Administration Canada	Public research, Website	Diagnostic, intensive analyse of 7 wells, recommandations	@
Well Rehabilitation Well Maintenance	Rehabilitation, technique, Chemical, Blended and Force treatments Monitoring, Sampling, Diagnostic, maintenance	Smith S.A.	2005	Smith-Comeskey Group Water Science	Public Information Website	Advanatges and disadavantages of all rehabilitation methods Monitoring and Management, cost-effectiveness	@ @
Sustainable Water Wells Initiative – Final Report	Sustainability, clogging, biofouling, construction, monitoring,maintenance, regeneration	Lebedin J. Novakowski Beatty B. Conboy M.J.	2006	SSWI Ontario Canada	Expert panel report, recommandations	Recommandations for action, monitoring, public awareness, research key points, actual methods to be used (rural residents, well aware)	@
Well clogging mechanisms in unconsolidated aquifers	Sand clogging, sand carriying flow, mechanical clogging	De Zwart A.H.	2002	KIWA Delft University Netherlands	Thesis Projekt-larger project	Thesis Program- end in 2006 Well clogging Prediction tool Other research projects	@