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ADVANCED STATISTICAL ANALYSES OF WELL DATA

Project acronym: WellMa1

by

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Title

Detailed analysis of clogging types, extension and variations: Advanced statistical analysis of well data

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Abstract

WELLMA-1, WP 1.2 includes a statistical analysis of Berlin and French well data. The aim is to identify parameters by which the extent of iron related clogging can be assessed and which can be used for grouping the wells for further investigations.

The data analysis is based on data on well construction, water chemistry and well operation for about 615 wells in Berlin and 47 in France.

The approach is first to do a descriptive analysis of the datasets. It shows amongst others that the French data are not extensive enough to be included in further statistical analysis. They were therefore interpreted individually and added as annex to the report.

In the second step, a reliable indicator for iron related clogging in the Berlin wells is identified. This is done by testing the significance of differences in parameters recommended by BWB (Qs, number of H_2O_2-treatments and results of TV-camera inspections) that indicate either *intense clogging* or *no clogging*. The analysis of the reduced dataset reveals that TV-camera inspections are the most reliable clogging-indicator for the Berlin wells for statistical analysis with the current database.

Thirdly, the relation of all available constructional, hydro-chemical and operational parameters is checked for four different stages of clogging indicated by the TV-camera inspections. It can be stated that most wells reveal increasing clogging with increasing well age and decreasing depth of the first filter. Clogged wells are characterized often by lower iron and higher manganese and nitrate concentrations, a higher mean total discharge and more operating hours than wells without clogging indication.

Finally, the clogging indicator is evaluated by a multiple linear regression. For this, the dependent variable *clogging* is linked to the ten variables, which are obviously related to clogging processes. Although all comprised parameters are partly related to the clogging intensity of the wells, only well age, depth of the first filter, iron and manganese concentrations as well as operating hours and total discharge have an explanatory value for clogging. However, their total explanatory value of 20% of the variance in clogging is low.

Either the most relevant parameters to identify clogging are missing or the selected parameters reveal too much data variability. This can be due to temporal and depth oriented variations what could not be included in the recent analysis. Measurements in mixed raw water cannot characterize all processes involved in iron related clogging.

Therefore, several recommendations of well operation and monitoring are given to improve the explanatory power of the data. The most important ones are the development of a more detailed matrix for the evaluation of well condition by TV-camera inspections and an improvement of measurements of specific capacity *Qs* by constant discharge rates and fully documented initial step pumping tests.

Groups of wells that would be useful for more detailed field investigations and further data analysis are:

- wells with different depth of the first filter
- wells with significant differences in mean discharges (and similar construction and number of switchings).
- wells with different amounts of switchings
- wells with similar number of switchings but different filter lengths or pump capacities,
- wells of different age, but otherwise same construction and operational characteristics.

Kurzfassung

WELLMA-1, WP 1.2 beinhaltet die statistische Analyse von Berliner und französischen Brunnendaten. Das Ziel besteht darin, Parameter zu identifizieren, anhand derer das Maß der Eisen induzierten Brunnenverockerung bewertet werden kann. Diese sollen zur Gruppierung der Brunnen entsprechend ihrer Verockerungsneigung herangezogen werden.

Die Datenanalyse beruht auf Daten über den Brunnenausbau, die Wasserchemie und den Brunnenbetrieb von 615 Brunnen in Berlin und 47 in Frankreich.

Zuerst wird eine deskriptive Analyse der Datensätze vorgenommen. Sie zeigt unter anderem, dass die französischen Daten nicht umfassend genug sind, um in die weitere statistische Analyse aufgenommen zu werden. Sie wurden deshalb individuell interpretiert und dem Bericht als Anhang beigefügt.

Im zweiten Schritt wird ein zuverlässiger Indikator für eiseninduzierte Verockerung in den Berliner Brunnen ermittelt. Dies erfolgt durch das Prüfen der Daten auf signifikante Unterschiede anhand der durch die BWB empfohlenen Parameter zur Identifikation von Verockerung (Qs, Anzahl der H_2O_2-Behandlungen und Ergebnisse der Kamerabefahrungen), die entweder eindeutig *intensive Verockerung* oder definitiv *keine Verockerung* anzeigen. Die Analyse des reduzierten Datensatzes zeigt, dass Kamerabefahrungen bei der statistischen Analyse des derzeitigen Datenbestandes der zuverlässigste Verockerungsindikator für die Berliner Brunnen sind.

Im dritten Schritt wird die Relation aller verfügbaren hydrochemischen, Ausbau- und Betriebsparameter zu allen vier verschiedenen anhand der Kamerabefahrungen identifizierten Verockerungsgraden geprüft. Es kann festgestellt werden, dass die meisten Brunnen mit zunehmendem Alter und abnehmender Tiefe des ersten Filters in zunehmendem Maße Verockerungen aufweisen. Verockerte Brunnen sind oft durch niedrigere Eisen- und höhere Mangan- und Nitratkonzentrationen sowie eine höhere mittlere Fördermenge (Q Mittel) und mehr Betriebsstunden gekennzeichnet als Brunnen ohne Anzeichen von Verockerung.

Schließlich wird der Verockerungsindikator durch eine multiple lineare Regression evaluiert. Dafür wird die abhängige Variable Verockerung zu den zehn unabhängigen Variablen in Relation gesetzt, die offenbar eine Beziehung zu Verockerungsprozessen aufweisen. Obwohl alle einbezogenen Variablen partiell eine Relation zur Verockerungsintensität der Brunnen zeigen, haben nur das Brunnenalter, die Tiefe des ersten Filters, die Eisen- und Mangankonzentrationen sowie die Betriebsstunden und die mittlere Fördermenge einen erklärenden Wert für die Verockerung. Ihr gesamter erklärender Wert mit nur 20% der Gesamtstreuung der Verockerung ist jedoch niedrig.

Entweder fehlen die relevantesten Parameter für die Identifikation der Verockerung, oder die ausgewählten Parameter weisen eine zu hohe Streuung auf. Das kann auf zeitliche und tiefenbezogene Schwankungen zurückzuführen sein, die in der vorliegenden Analyse nicht berücksichtigt werden konnten. Zudem können Messungen in vermischtem Rohwasser sicher nicht alle Prozesse charakterisieren, die mit der eiseninduzierten Verockerung zusammenhängen.

Deshalb werden verschiedene Empfehlungen zum Brunnenbetrieb und zur Brunnenüberwachung gegeben, um den Erklärungsgehalt der Daten zu erhöhen. Die wichtigsten sind die Entwicklung einer detaillierteren Matrix für die Bewertung des Brunnenzustands mittels Kamerabefahrungen sowie eine Verbesserung von Messungen der spezifischen Ergiebigkeit *Qs* durch konstante Pumpleistung und vollständig dokumentierte Stufenpumpversuchte am bei Abnahme eines neu gebauten Brunnens.

Gruppen von Brunnen, die bei folgenden Felduntersuchungen und weiterer Datenanalyse nützlich wären, sind:

- Brunnen mit unterschiedlicher Tiefe des ersten Filters
- Brunnen mit signifikanten Unterschieden in der mittleren Fördermenge (aber gleichem Ausbau und gleicher Schalthäufigkeit).
- Brunnen mit stark unterschiedlichen Schalthäufigkeiten.
- Brunnen mit gleicher Schalthäufigkeit aber unterschiedlichen Filterlängen oder Pumpkapazitäten.
- Brunnen unterschiedlichen Alters, aber gleichem Ausbau Bauweise und mit gleichen Betriebskennwerten.

Résume

WELLMA-1, WP 1.2 comporte une analyse statistique de données de puits à Berlin et en France. L'objectif est d'identifier les paramètres permettant d'évaluer l'étendue du phénomène de colmatage ferrique et de classer les puits, afin de réaliser des études plus poussées.

L'analyse des données repose sur des données de construction, d'exploitation et hydrochimiques pour 615 puits à Berlin et 47 en France.

L'exercice prévoit, dans un premier temps, une analyse descriptive des ensembles de données. Il met, entre autres, en évidence que les données françaises ne sont pas suffisamment détaillées pour les inclure dans l'analyse statistique. Elles ont ainsi été analysées individuellement et insérées dans une annexe du présent rapport.

Dans un deuxième temps, un indicateur fiable de colmatage ferrique dans les puits berlinois est identifié. L'on y parvient en examinant la signification des différences de paramètres recommandés par BWB (Qs, nombre de traitements H_2O_2 et résultats d'inspections télévisuelles) qui indiquent soit le *colmatage intense*, soit le *non-colmatage*.

L'analyse des ensembles réduits de données montre que les inspections télévisuelles sont l'indicateur de colmatage le plus fiable pour les puits berlinois pour une analyse statistique avec la base de données actuelle.

Dans un troisième temps, les liens entre tous les paramètres de construction, d'exploitation et hydrochimiques disponibles sont vérifiés pour quatre phases distinctes de colmatage constatées pendant les inspections télévisuelles. On constate que la majorité des puits présente une tendance au colmatage croissant avec l'âge des puits et liée à la faible profondeur du premier filtre. Les puits engorgés se caractérisent par des concentrations faibles en fer et plus élevées en manganèse et en nitrate, un débit moyen total plus élevé ainsi que plus d'heures d'exploitation que les puits ne présentant pas d'indices de colmatage.

Enfin, l'indicateur de colmatage est calculé par régression linéaire multiple. A cette fin, la variable dépendante *colmatage* est liée aux dix variables qui sont associées aux processus de colmatage. Bien que tous les paramètres inclus soient en partie liés à l'intensité de colmatage des puits, seuls l'âge du puits, la profondeur du premier filtre, les concentrations de fer et de manganèse, ainsi que les heures d'exploitation et le débit total sont d'une valeur explicative du phénomène de colmatage. Toutefois, leur valeur explicative totale de 20% de la variance du colmatage est faible.

Il se peut que les paramètres les plus pertinents fassent défaut pour identifier les cas de colmatage, ou encore que les paramètres sélectionnés présentent une trop grande variabilité des données. Ceci s'explique par les variations dans le temps et la profondeur qui n'ont pu être introduites dans cette étude récente. Les mesures dans l'eau brute mélangée ne sauraient caractériser tous les processus liés au colmatage ferrique.

En conclusion, plusieurs recommandations d'exploitation et de surveillance de puits sont présentées dans le but d'améliorer la puissance explicative des données. Les plus importantes concernent au développement d'une matrice plus détaillée permettant de juger l'état des puits moyennant des inspections télévisuelles et l'amélioration des mesures de débit spécifique Qs à débit constant accompagnées d'essais initiaux de pompage par palier bien documentés.

Les groupes de puits qu'il serait opportun d'approfondir dans le cadre d'études sur le terrain et d'analyses de données à venir sont les:

- puits à profondeur différente de premier filtre
- puits présentant des différences significatives de débit moyen (mais similaires dans leur schéma de construction et cycle de commandes marche/arrêt de la pompe, en anglais « switching »)
- puits avec un nombre distinct de pompes ;
- Puits doté d'un nombre semblable de pompes mais de longueurs de filtres ou de capacités de pompage différentes;
- Puits d'âge différent mais de schémas de construction et d'exploitation semblables.

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Chapter 1
Introduction

The *WELLMA-1* project, funded by the Berlin Water Company (BWB) and Veolia Water, aims at the development of practical methods and models to support operation and maintenance of drinking water wells for optimizing well management (WELLMA).

Work package 1 will provide a detailed insight and analysis of clogging, their extension and variations at selected sites to identify the nature and variability of the clogging affecting wells. Amongst other methods, a statistical analysis of well data from Berlin and French field sites was carried out. The results are subject of this report.

Single processes of well clogging are well known, however, there is still a lack of information how to detect it in an early stage to prevent a well from accelerated well ageing. Some extensive datasets of waterworks in Berlin and France are available. The aim of the statistical analysis of well data is to identify parameters, which can be used as an indicator for clogging processes. Wells with similar clogging behaviour and/ or site conditions will be classified. These criteria will be a basis for a selection of wells for further investigations in *WELLMA-2*.

According to the project proposal the tasks of the statistical analysis are:

- Identification of a clogging indicator
- Identification of trends for processes and interactions related to clogging
- Choice of wells in Berlin and France

The focus in the data analysis in *WELLMA-1* is on iron related clogging, because it was identified in both Berlin and France. In Berlin, it is supposed to be the most relevant type of clogging. Hence, well monitoring and data management are focussed to data, which are able to describe this clogging type The data analysis is based on the knowledge that iron related clogging is an effect either of redox-processes (chemical clogging) or of bacteriological induced iron oxidisation (biological clogging). Therefore, the most important parameters influencing chemical and biological clogging processes need to be considered in the data analysis (DVGW 1970, DVGW 2001, BARTEZKO 2006). For more details, see Chapter 2 of the *State-of-the-Art report*.

Referring to the potential influencing factors of clogging, the data analysis is based on three types of data, which are available:

- well construction (year of well construction, number and type of aquifer, number, depth and material of filter screens, distance to next surface water etc.)
- water chemistry (Eh, pH, O2, Fe, Mn, NO3, SO4, DOC)
- operational data: performance and maintenance of the wells (filter entrance resistance *Δh*, total discharge, total operating hours, specific capacity *Qs*, rehabilitations)

Additional information is :

- date of preventive H_2O_2-treatment, camera inspections and pump-switchings for the Berlin wells
- initial pumping tests (step pumping tests) to measure the initial performance of the French wells

In discussions with *BWB* and *Veolia* it turned out that current well management is based on a mixture of scientific knowledge and practical experience. So, the aim of the statistical analysis was to verify some of the current hypotheses in the context of well-clogging:

Well construction:

- Clogging increases with well age.
- Clogging depends on well construction (depth, filter screen material, number of filters etc.).

Hydrochemistry:

- Clogging can be identified in hydrochemical characteristics (e.g. lower concentrations of dissolved iron, presence of oxygen).

Performance and Maintenance:

- Clogging can be classified by TV camera inspections.
- Clogged wells have a decreasing specific capacity (Qs) of more than 10% compared to their initial specific capacity (DVGW 2001).
- Clogged wells are reflected by preventive H_2O_2-treatments.
- Clogging increases with more frequent pump switching.

The approach is first to describe the characteristics of well construction, hydrochemistry, performance and maintenance. Out of these data, reliable clogging indicators are identified by a reduced dataset containing intensively *clogged* and definitely *non-clogged* wells. In the next step, this indicator is linked to a more extended dataset of wells, related to different stages of clogging. Afterwards the clogging indicator will be evaluated by linking the dependent variable *clogging* to independent variables, which are explanatory parameters for the clogging process.

Furthermore, the analysis is a means to improve data collection. It concludes in a first estimation what parameters are important to be measured or documented for the identification or assessment of well clogging.

The classification of wells in *clogged* and *non-clogged* wells is the basis for the selection of wells for *WELLMA*-2.

Chapter 2 Material and Methods

First, a short overview on the available data is given (chapter 2.1). The first step of data handling is the validation of the data and its description (chapter 2.2). The second step is the application of criteria what lead to comparable datasets for the investigated problem (chapter 2.3). For example, monitoring of well operation and water quality is carried out regularly, but the intervals depend on the water company, the data type and the well characteristics itself. So, the data represent snapshots of different conditions at a particular time. Finally, a short overview of the selected methods for the data analysis is given (chapter 2.4).

2.1 Data base

For the data analysis with focus on well clogging, the *Berlin Water Company (Berliner Wasserbetriebe BWB*) and *Veolia Water* in France provided extensive data of their drinking water supply wells.

- The requirements for wells to be included in the data base are the following:
- vertical filter well
- drinking water abstraction wells
- in operation between 1996 and 2006

These apply to 615 wells in Berlin and 47 exemplary wells in France.

The data are stored in two *MSAccess* project databases. They were collected and summarized from all available information provided by the responsible departments of *BWB* and *Veolia*. The Berlin data were already consolidated in 2006 by *BWB*. Some selected data were added in the beginning of 2007. The completion and validation of the database was carried out in 2008 by *KWB*. The integration of the French data was carried out in 2008 by *KWB* from available well documents and the laboratory database of Veolia.

All water supply wells were included in the database, regardless if they were put in operation before or after 1996. Therefore, the available data reflect wells of different ages. Consequently, there is less information for the younger wells – on the other hand the data are more complete because they comprise the full period of well operation.

The data summary of the Berlin wells is conform to the structure of the main BWB-databases for geological information (GCI-GMS), well management (WV) and laboratory data (LIMS) (MATHIE 2006).

For an easy comparability, the French data provided by Veolia Eau were adjusted to the structure of the existing project database of the Berlin wells. The data collection was coordinated by Boris David and Marc Alary of Veolia Eau Direction Technique. Well construction and performance data were mainly included in analogous well documents. The hydrochemical data were exported from a central database of Veolia Eau. Furthermore, some additional information was collected from the publicly available databases of the Bureau of Geological and Mining Research (BRGM) (http://infoterre.brgm.fr).

The two databases contain the following data:

1. Well construction including geology and the origin of the water
   - Material of the screen
   - Filter sections: number, length, depth
   - Diameter: borehole and screen
   - Coordinates: easting, northing, ground level elevation (masl)

- Year of construction
- Maximum allowable discharge rate/ well yield (according to the well performance test)
- Classification of the aquifer (stratigraphy)
- Lithology: Grain size/ soil texture of the aquifer material
- Aquifer-type: unconfined/ confined
- water source (groundwater/ bank filtrate/ artificial recharge)
- Distance to river (or lake) bank / recharge basin

2. Chemical Parameters
   - Time series of at least 17 parameters on water contents and conditions (Ca, Cl, electrical conductivity, DOC, Eh, Fe, HCO3, K, Mg, Mn, Na, NO3-N, NH4-N, O2, pH, SO4, Temp)
3. Performance
   - Rated power of the pump (if so: modifications, with date)
   - Total discharge
   - Total operating hours
   - Drawdown in the well and in the observation well in the gravel pack and calculation of Δh
   - Maintenance with special regard to rehabilitations
   - Date of rehabilitation / maintenance
   - Pumping tests: Well performance test before and after rehabilitation
   - Rehabilitation methods and maintenance activities (e.g. shock blasting, brushing, pump changes etc.)
   - Date and observations of camera inspections

A more specific description of the content of the databases can be found in chapter 2.2.

Both databases are not exactly of the same integrity. The Berlin database was set up in 2006 and validated in WELLMA-1, whereas the French data were implemented principally during WELLMA-1 in 2008. Furthermore, both databases have their particular challenge for data homogeneity. The Berlin data are a combination of data of the former eastern and western parts of the city. Additionally, every waterworks has its own characteristics. Due to these variations in well management over space and time, not all information is available for each waterworks. On the other hand, the French data are heterogeneous, because they are located in different *Départements* and the waterworks have different owners but are contractually operated by *Veolia Eau*. For that reason, well management is differing from site to site.

In fact, the aim of data analysis is not a comparison of data quantity and quality of both databases. Nevertheless, the synergetic effects of the provided data of BWB and Veolia will be used. As a result, recommendations can be developed, if it could be useful to change strategies of data collection for one or another parameter in Berlin or France. The advantages and limitations of the different data sets will be discussed in Chapter 4to improve its practical use for well management in the context of well clogging.

2.2 Dataset Description

In the following chapters, the characteristics of the waterworks of Berlin and French wells will be described. In the *WELLMA*-database of Berlin 615 wells of nine different waterworks are available for statistical analysis. The waterworks have up to 7 wellfields comprising 6 to 59 wells (see Figure 1).

Table 1: Number of waterworks, wellfields and vertical filter wells of the BWB (1996-2006)

Waterworks	**number of wellfields**	**number of wells**
Beelitzhof	6	86
Friedrichshagen	5	173
Kaulsdorf	2	16
Kladow	2	14
Spandau	3	44
Stolpe	4	89
Tegel	7	120
Tiefwerder	4	55
Wuhlheide	1	18
Σ = 9	Σ = 34	Σ =615

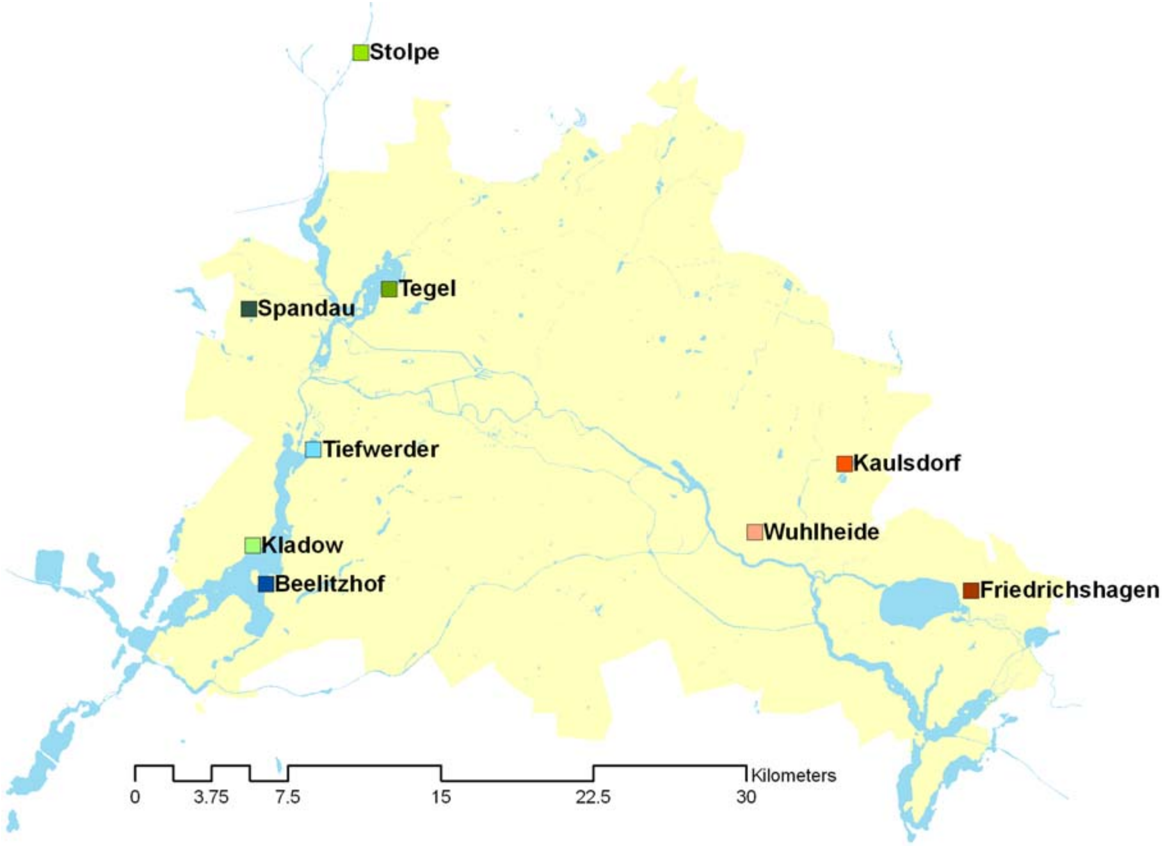

Figure 1: Map of the Berlin waterworks

All regarded datasets of the Berlin wells were validated by checking their ranges. If any irregularities were detected, they were compared with the original data sources (*BWB* database or the original well documents). All corrections and extensions in the database were documented as remarks in the database.

The WELLMA-database of France contains 47 wells originating from eleven different waterworks operated by Veolia Eau. Most of them are situated in the north of France, only the waterworks of *Saignonne* is located in southern France.

Table 2: Regarded well fields and number of vertical filter wells provided by *Veolia Eau*

waterworks	number of wells
Champ captant de Plaine	10
Lisieux de la bonde	2
Malicorne	1
Moulin de Douves	3
Mousseaux	1
Plaine Saint Denis	1
Quatres carreaux	2
Roissy	1
Saignonne	20
Val de Reuil	4
Verdun	2
$\Sigma = 11$	$\Sigma = 47$

Figure 2: Map of the French waterworks

Well Construction and Geological conditions

The basic table comprises all available information about the well construction and its geological conditions in **Berlin**. Selected characteristics are summarized in Table 3.

Table 3: Overview on the general characteristics of the Berlin wells

Type	Classes	Number of wells	Percentage of wells
Origin of water	groundwater	156	25 %
	river bank filtrate	415	68 %
	artificially recharged water	44	7 %
Aquifer type	confined	326	53 %
	unconfined	289	47 %
Total well depth [m]	< 40	342	56 %
	40-80	237	38 %
	> 80	36	6 %
Well age [y]	<10	94	15 %
	10-30	347	57 %
	>30	174	28 %
Number of filters	1	427	70 %
	2-3	161	26 %
	4-7	27	4 %
Filter material	Copper	37	6 %
	Steel	268	44 %
	Stainless Steel	184	30 %
	PVC	27	4 %
	Ceramics	97	16 %
	Other	2	< 1 %
Q tolerated [m³/h]	<100	338	55 %
	100-200	197	32 %
	>200	80	13 %
Distance to next surface water [m]	<100	251	40 %
	100-400	216	35 %
	>400	148	24 %

Referring to the information of the database two thirds of all wells abstract a high fraction of riverbank-filtrate due to their close distance to surface waters like the rivers Havel and Spree or the lakes *Tegel, Wannsee* or *Müggelsee*. Additionally, some wells are supplied by water from recharge basins. The classification in the database is based on an approximation of the origin of the abstracted water. This was arranged in cooperation with *Heidi Dlubek* from *BWB*. The reason for distinguishing the water sources is that a mixture of ground and surface water in the aquifer leads to higher variations in water quality like for example higher oxygen contents (SCHMOLKE 2006). The mixture of water with different oxygen content can accelerate clogging processes (KUNZ 2006).

A similar approach is the classification into confined or unconfined conditions of the aquifer. The information results from the geological cross sections of well construction. The classification was carried out in the context of database creation. The same applies to the data describing the distance to the next surface water. It was started during database creation and was completed in the recent analysis. *BWB* provided a digital map of groundwater levels and Berlin surface waters, which were imported into a GIS-project. This information was used to measure the approximate distance to next surface waters.

The summary of the wells ages shows that most wells exceed an age of 10 years. Therefore, the detection of ageing processes in the data sets seems to be probable.

In contrast to Berlin, the **French** data derive from different waterworks all over France what accounts for some heterogeneity in the data (see Table 4).

Table 4: Overview on the general well characteristics of the French wells

Type	Classes	Number of Wells	Percentage of wells
Aquifer type	confined	9	20 %
	unconfined	35	80 %
Aquifer texture	gravel to sand	20	46 %
	sand	12	27 %
	chalk and limestone	8	18 %
	clay and limestone	4	9 %
Total well depth [m]	< 40	29	66 %
	40-80	5	11 %
	> 80	5	11 %
Well age [y]	<10	21	48 %
	10-30	19	43 %
	>30	4	9 %
Q tolerated [m³/h]	<100	17	39 %
	100-200	17	39 %
	>200	7	16 %

Comparing Table 3 and Table 4 about well construction parameters, it is obvious that the type of the French waterworks is different from the ones in Berlin. The regarded French well fields consist mainly of only one or two wells. Due to the spatial spreading of the selected sites, they have by far more different site conditions like e.g. loose and solid rock. Some information like filter materials cannot be provided because it was not included in all well documents and could not be delivered easily by Veolia Eau.

Hydrochemical data

The hydrochemical data are stored in the tables *laboratory data*. The analysis of the selected standard parameters of the **Berlin** wells is based on different sampling strategies in the decade between 1996 and 2006. In the years between 1996 and 2002, the aim was to sample all single wells every four years with an analysis of the standard parameters (in situ- parameters, main ions). For the in situ-parameters, redox potential and oxygen content were often not included. In 2001, the German Drinking Water Ordinance was amended. Due to its amendment and some crew changes at *BWB,* the aim from 2003 on was to sample every single well once a year. The monitoring covered all standard parameters including redox potential and oxygen content. For practical reasons it was not possible to sample and analyse around 800 Berlin wells per year so that the sampling interval actually is around 1.5 years (statement of *A. Deffke, BWB-WV*). The chemical data contain 7511 sampling dates for the 615 vertical filter wells.

For the **French wells**, hydrochemical data from 1996 to 2006 were imported from datasets of a central database of Veolia. It comprises chemical data for 39 of the 47 wells. There are no data for seven wells of *Champ Captant de Plaine* and one well of *Verdun*. As the sampling campaigns are generally focussed on one or two selected parameters like e.g. iron and nitrate contents (statement of *M. Alary*), no sampling campaign contains parallel measurements of all parameters.

Well performance

In **Berlin** well performance is measured about every three months. The interval varies slightly between the single waterworks. The main parameters are dynamic water levels both in the well and in the observation well in the gravel pack to calculate the entrance resistance of the filter screen Δh. Additionally, current discharge and operating hours are recorded. There is no measurement of the static water level.

Therefore, it is not possible to calculate drawdown s and consequently specific capacity *Qs* by these measurements. The available performance parameter that can be calculated with the dataset is *Δh* of the filter screen.

In general, all well performance data are recorded in a database by *BWB* starting after the 01.01.1996. The start date and the amount of values per well vary. A summarized overview of the first and last records in the *WELLMA*-database is given in Table 5:

Table 5: First and last date of well performance tests of the Berlin database

Waterworks	Wellfield	First Date	Last Date
Beelitzhof	Großes Fenster	01.1998	02.2007
	Lieper Bucht, Lindwerder, Wannsee, Wiesenleitung	02.1999	03.2007
	Rehwiese	06.2002	02.2007
Friedrichshagen	B, C, D, E, F	10.1997	04.2007
Kaulsdorf	Nord, Süd	10.1998	06.2007
Kladow	Breitehorn, Kladow	03.1997	04.2007
Spandau	Kuhlake, Nord, Süd	07.1996	03.2007
Stolpe	Birkenwerder	07.2002	04.2007
	Borgsdorf	02.1998	04.2007
	Nord	10.1997	12.2006
	Süd	01.1998	12.2006
Tegel	Baumwerder, Hohenzollernkanal, Ost, Saatwinkel, Tegelort-Nord, Tegelort-Süd, West	05.1998	10.2006
Tiefwerder	Nord	04.1998	05.2007
	Rupenhorn	01.1996	05.2007
	Schildhorn, Süd	01.1998	01.2007

In Table 6 the number, first and last date of well performance test of the **French** wells is summarized. Waterworks having only one performance test are not included (*Mousseaux, Malicorne, Verdun* and eleven wells of *Saignonne*).

Table 6: Number, first and last date of well performance measurements included in the French database

Waterworks	Well-ID	Num-ber	First Date	Last Date
Champ captant de Plaine	PC-PLAIN1: P1, P2, P3, P4,-P5	2	10.1961	08.1996
	PC-PLAIN2: P6. P7, P8, P9,-P10	4	01.1969	04.2006
Lisieux de la bonde	PC-F1BOND-D01	3	06.2000	03.2006
	PC-F1BOND-D02	3	07.1994	05.2002
Moulin de Douves	PC-DOUVE1-001	54	01.1989	03.2003
	PC-DOUVE3-001	55	06.1971	09.2006
	PC-DOUVE4-001	56	11.1971	03.2003
Plaine Saint Denis	PC-SPARNA-001	2	04.1977	07.2006
Quatres carreaux	PC-F1QCAR: D01-D02	3-4	11.1964	06.2006
Roissy	PC-ROISSY-001	71	01.1978	11.2008
Saignonne	PC-SAIGNONN: 301, 302, 307, 316, 319	3-5	06.1985	05.2005
	PC-SAIGNONN-303	7	05.1985	07.2007
	PC-SAIGNONN: 304, 305	3-4	11.1985	05.2005
	PC-SAIGNONN-318	3	01.1986	05.2005
Val de Reuil	PC-PRESF1-M01, M02, M03	2	01.1993	10.2003
	PC-PRESF4-M04	39	12.1992	07.2003

The French well performance data include either the static and dynamic water level or already the calculated drawdown, so it is possible to calculate the specific capacity *Qs*. The frequently sampled wells at *Moulin de Douves*, *Roissy* and *Val de Reuil* can be used to test the development of *Qs* over time.

An extensive data source of the French data is the table about initial pumping tests. Most of them are recorded with several steps of pumping rate. They vary between three to eight documented discharge rates (Table 7). It includes again the information of drawdown and discharge.

Table 7: French waterworks with initial pumping tests including (4-8 steps)

Waterworks	Well-ID	number of pump steps	Initial Operation Date
Lisieux de la bonde	PC-F1BOND-D01	5	21.06.2000
	PC-F1BOND-D02	5	30.07.1994
Malicorne	PC-FMALIC-D01	5	16.08.2004
Moulin de Douves	PC-DOUVE3-001	8	16.06.1971
	PC-DOUVE4-001	6	01.11.1971
Mousseaux	PC-MOUSSO-EB	4	28.04.2006
Plaine Saint Denis	PC-SPARNA-001	3	07.04.1977
Quatres carreaux	PC-F1QCAR-D01	4	30.05.2002
	PC-F2QCAR-D02	4	04.06.2002
Roissy	PC-ROISSY-001	6	01.01.1978
Saignonne	PC-SAIGNONN-301	3	20.06.1985
	PC-SAIGNONN-302	3	14.05.1985
	PC-SAIGNONN-303	3	14.05.1985
	PC-SAIGNONN-304	3	21.11.1985
	PC-SAIGNONN-305	3	20.11.1985
	PC-SAIGNONN-306	3	19.06.1985
	PC-SAIGNONN-316	3	10.05.1985
	PC-SAIGNONN-318	3	17.01.1986
	PC-SAIGNONN-319	3	18.05.1985
Val de Reuil	PC-PRESF1-M01	4	25.01.1993
	PC-PRESF2-M02	4	05.11.1992
	PC-PRESF3-M03	4	19.10.1992
	PC-PRESF4-M04	5	10.12.1992

Well Maintenance

Maintenance activities in **Berlin** are documented by pumping tests. Usually after the first pumping test, the decision is made if a pump exchange or a rehabilitation is necessary. In case of rehabilitation, a second pump testing afterwards is executed. The obtained parameters of such pump tests are the static and dynamic water levels for both in the well and in the observation well in the gravel pack, and current discharge Q. Furthermore, the used rehabilitation techniques are given. This enables the calculation of the specific capacity *Qs* before and after the rehabilitation to quantify the efficiency of the maintenance activity. These pumping tests concerning maintenance are executed on average every 6 years. But, not all maintenance activities are documented with two pumping tests before and after rehabilitation. For 614 wells there are data of 2219 pumping tests available. 602 of them include a pair-wise pumping test before and after a rehabilitation.

In the **French** database, well maintenance data with pumping tests related to rehabilitation activities are available for only 12 of the 47 wells.

Pumping tests before and after rehabilitation are available for the waterworks *Champ captant de Plaine* and *Val de Reuil*.

Table 8: Number of pumping tests in the context of rehabilitation activities

Waterworks	Well-ID	number of pumping tests
Champ captant de Plaine	PC-PLAIN2-P7	2
	PC-PLAIN2-P8	2
	PC-PLAIN2-P9	2
	PC-PLAIN2-P10	2
Lisieux de la bonde	PC-F1BOND-D02	2
Moulin de Douves	PC-DOUVE3-001	1
Plaine Saint Denis	PC-SPARNA-001	1
Quatres carreaux	PC-F1QCAR-D01	1
	PC-F2QCAR-D02	1
Val de Reuil	PC-PRESF1-M01	2
	PC-PRESF2-M02	3
	PC-PRESF3-M03	3

The more qualitative information about well rehabilitation activities are connected to TV camera inspections of the well, which is commented in the following section.

TV camera inspections

For the **Berlin** data in the context of detecting clogging parameters, the last camera inspection of every well was integrated in the database (June 2008). The BWB database includes a short verbal methodical description of the well condition concerning the filter screen, casing, riser and pump. The description was transformed to a numeric code what represents an information about *no clogging* (0), *light clogging* (1), *medium clogging* (2) and *intense clogging* (3). This information is a static but a definite indicator for clogging.

For the **French** wells, the observation results of camera inspections are described as well. However, their verbal description is not systematic. So it cannot be transformed to an ordinal scale of clogging intensity. The information was saved, but it cannot be used for an automated data analysis in the sense of statistics.

Pump Switchings

In addition to the above described parameters, the **Berlin** database includes information on pump switchings for all former western waterworks and the waterworks in *Stolpe*. Please note, that the wells are generally older than the start of this recording. The time spans, with available data are listed in Table 9:

Table 9: Available data of waterworks with information on pump switching

Waterworks	First date	Last date
Beelitzhof	01.01.2002	31.12.2006
Kladow	01.01.2001	31.12.2006
Spandau	01.01.1995	31.12.2006
Stolpe	01.02.2004	31.12.2006
Tegel	01.06.1999	31.12.2006

The documentation includes daily information if the pump was switched on and/or off. These data provide the absolute frequency of switchings per well. A well that is switched more often is supposed to age sooner (SCHMOLKE 2006).

H_2O_2-Treatments

Furthermore, there is a table with information about the preventive H_2O_2-treatments in the **Berlin** wells, which were carried out since 1997:

Table 10: First and last date of preventive H_2O_2-treatments

Waterworks	Wellfield	First Date	Last Date
Beelitzhof	Großes Fenster, LindwerderWannsee, Wiesenleitung	01.1997	12.2006
	Lieper Bucht	02.1997	09.2002
Friedrichshagen	B, C, E, F	03.1996	12.2006
	D	03.1996	09.1997
Kaulsdorf	Nord	01.2003	09.2006
	Süd	01.2003	07.2005
Spandau	Nord, Süd	01.1997	12.2006
Stolpe	Borgsdorf	01.2003	11.2006
	Nord, Süd	01.1998	12.2006
Tegel	Baumwerder	02.1997	12.2001
	Hohenzollernkanal, Ost, Saatwinkel, Tegelort-Nord, Tegelort-Süd, West	01.1997	12.2006
Tiefwerder	Nord	01.1997	04.2003
	Süd	01.1997	12.2000
Wuhlheide	Ost	02.1997	12.2001

It documents the wells with regular H_2O_2-treatments and the used concentration of H_2O_2. Due to economical reasons, there have been several modifications in treatment intervals. For example, between 1997 and 2002, some wells were treated twice a month by H_2O_2. In 2002 *BWB* reduced the frequency to six times per year (see *chapter 3.8 Preventive treatment with* H_2O_2 of the report *Field investigations*). Furthermore, the number of treated wells was reduced.

2.3 Data Selection

An agreement of the technical committee in the beginning of the data analysis was to include as much wells as possible for the identification of clogging processes instead of having the focus on a reduced number of wells having an extensive amount of data. However, for the analysis, data need to be comparable. Therefore, some defined selection criteria needed to be applied to the data. First, it had to be decided which parameters are relevant for the analysis of well clogging.

Well Construction and Geological Conditions

The different conditions in the wells are characterized by well construction parameters and geology. Therefore, for the investigation of clogging processes well age, depth, filter characteristics, origin of water and aquifer conditions (confined or unconfined) are regarded. After data completion these information is available for all wells in the database. Therefore, there is no need for selection criteria.

Hydrochemical Data

Referring to the main processes of well clogging in **Berlin** (BARTEZKO 2006) the following hydrochemical parameters are of main interest:

- oxygen (O2)
- iron (Fe), manganese (Mn),
- redox potential (Eh) and pH

For further hydrochemical characterisation of the abstracted water it is useful to account for standard parameters like hydrogen carbonate (HCO3), sodium (Na), calcium (Ca), magnesia (Mg), potassium (K), chloride (Cl), sulphate (SO4), nitrate (NO3) and dissolved organic carbon (DOC).

In the second step, it is important to have always a minimum of analyses of the selected parameters for each well to be sure that the data are representative for the well's water chemistry. Therefore, it was necessary to decide what amount of samples is representative for the data analysis. For the chemical data the minimal criteria is set to at least three samples for all selected parameters. Many wells have only two samplings in the decade between 1996 and 2006. This applies especially to the parameters redox potential, oxygen content and dissolved organic carbon. Because changes in oxygen content and redox capacity are of main interest for the investigation of clogging processes these parameters are the limiting parameters for the data analysis. To fulfil the criteria of three samplings for the selected hydro chemical parameters, the laboratory data of 2007 were additionally integrated into the database (April 2008). Based on this selection criteria, 387 of the 615 wells were chosen for analysis of the hydrochemical data.

For the **French** wells, chemical data and well maintenance are less representative than for the Berlin wells. The effort to apply some selection criteria leads to the conclusion that there are no parallel samplings. So, the hydrochemical information is not connected for a characterization of the chemical condition.

Well performance

The table on well performance of the **Berlin** data includes quarterly measurements of productivity. As explained previously the measurements do not include the static water level to calculate *Qs.* Nevertheless, the values can be used to analyse changes in entrance resistance of the filter screens (Δh). The practical problem of measuring the parameters in the well and its gauge is that the piezometer in the gravel pack may lead to wrong data due to failures in construction. Therefore the reliability of this parameter is often discussed in the context well performance (STEUßLOFF & STEINBRECHER 2006). In the BWB database, the two water levels are available in 14727 cases, but the data seem to have a high error ratio. Therefore, the consideration of Δh is not emphasized.

Well performance data additionally include the number of operating hours. The validation of the data showed that in some wells the daily time of operation exceeds 24h. These discrepancies are presumably caused by the fact, that operation hours in some waterworks are measured indirectly like e.g. electricity consumption.

Finally, there is the information of total discharge. These values need to be regarded carefully, as the values given by the flow meters can be wrong due to clogging in it. In some cases, the values are recalculated by different parameters. A retrospective correction of operating hours and total discharge is quite complicated. The irregularities of datasets can be mitigated by the high frequency of measurements, which consolidates the representativeness of the data.

In most cases, the **French** data are not as extensive as the Berlin well data. However, the French data contain more detailed information on well performance data to evaluate the relevance of pumping test including several steps of pumping rate. Therefore, the analysis of the French data is focussed on checking the relevance of *Qs* for the estimation of well performance.

The initial pumping tests containing three to four steps in pumping rates are a valuable basis for the evaluation of well performance. Furthermore, it can be tested if a more regular recording of Q*s* by measuring the static and dynamic water level is an improvement for assessing the well performance. The selection of wells with the initial pumping test data can be seen in Table 7 (page 10). Selected wells with a high amount of measurements of *Qs* will be used for the temporal analysis of *Qs* development in wells. Referring to Table 6, these will be wells from *Moulin de Douces*, *Roissy* and *Val de Reuil*.

Well Maintenance

Next, there is the information about maintenance activities. To have an idea how the productivity of the well changed over time there is the need for at least one pumping tests to calculate and compare Qs with the value at initial operation. In the **Berlin** database, 556 wells have at least one pumping test after the initial operation test. Another important information on well maintenance is the calculation of rehabilitation intervals. The aim for *BWB* is to rehabilitate a well every 5 years. To be able to calculate the rehabilitation intervals only wells with at least two rehabilitations can be considered. These criteria apply to 416 wells in the database.

Rehabilitation data from **France** are difficult to compare, because there are only a few pumping tests and some verbal description of the maintenance activities available. Therefore, the dataset cannot fulfil the criteria for a statistical analysis.

Pump Switchings

Some additional information for the **Berlin** wells is the frequency of pump switchings. The strategy of BWB is that the number of pump switchings is defined in relation to the condition of the well: Old wells with high clogging affinity are switched as little as possible to prevent them from further clogging. They are mentioned as *permanently operating wells* (*Dauerläufer)*. New wells can be switched more often due to their better performance. They are called *short time operating wells* (*Kurzläufer)* (SCHMOLKE 2006). The statistical analysis will test if pump switching can be used as an indirect indicator for well ageing. Data about pump switchings are available for a total of 406 wells but not for the full decade (see Table 9). Therefore, they need to be indexed in relation to the documented time span of pump switchings. We chose mean switchings per month.

H2O2 Treatments

Furthermore, H_2O_2 treatments are included in the database of the **Berlin** wells. They can be used as an indicator for clogging susceptibility, because only wells susceptible to clogging are treated preventively by H_2O_2 (DVGW 1970). The necessity for H_2O_2-treatments is defined by:

- the presence of iron and manganese bacteria,
- the presence of dissolved iron or manganese (e. g. >0,2 mg/L of Fe^{2+}),
- redox potential exceeding 20 mV
- pH around 7
- an increase of natural flow velocity due to water abstraction

(DVGW 1970, DVGW 2001).

In general, these conditions are present in the Berlin waterworks and lead to preventive H_2O_2 treatments (see Field investigations report, chapter 3.7.1). As already mentioned, the treatment with H_2O_2 started in 1997. In 2002, the intervals were reduced from twice a month to once every two months. Therefore, the frequency of H_2O_2 treatments cannot be taken as a measure for clogging intensity because it is mainly influenced by economical decisions. However, it can be investigated if there are some characteristically differences in the datasets of wells with or without some H_2O_2-treatment. In the last 10 years, up to 380 wells were treated with H_2O_2. Because H_2O_2 treatments started mainly a long time after well construction, the number of treatments has to be related to absolute time span of treatments.

TV camera inspections

The information of camera inspections will be used to have qualitative information of well condition referring to clogging processes of the **Berlin** wells. Because the data are only from the last inspection, there is no possibility to analyse a time series of clogging intensity. For some data analysis wells with medium to intense clogging are classified as wells what tend to clogging whereas wells with no clogging or light clogging characteristics are classified as no-clogging wells.

For the **French** wells, the digitized information of TV camera inspections is not systematic. Therefore, the classification in *clogging* and *no clogging* wells is not assured. Furthermore, due to the variety of different sites in France, the reason for performance loss is not only iron induced clogging. In some cases, clogging is probably related to calcification or physical clogging.

2.4 Statistical Methods

Statistics offer many different methods for descriptive and multivariate analysis of data. There are, however, certain requirements to the data that act as prerequisites. As mentioned in the previous sections the data are of different types comprising nominal, ordinal and metric data. Furthermore, they have a different variability in space and time. Therefore, the used methods have to be quite robust to analyse the different datasets.

The data analysis is done with the statistical software packages R and SPSS.

Boxplots

For a description of the datasets, mainly boxplots are used in order to give a compact overview of the value distributions. Whereas the box comprises the inner 50% of the respective values (from 25% to 75%), the whiskers contain the range of the values (100%). Every box is divided by a black bar representing the median. The median divides the values in two halves with the equal amount of data – therefore it is called the 50% percentile (Figure 3).

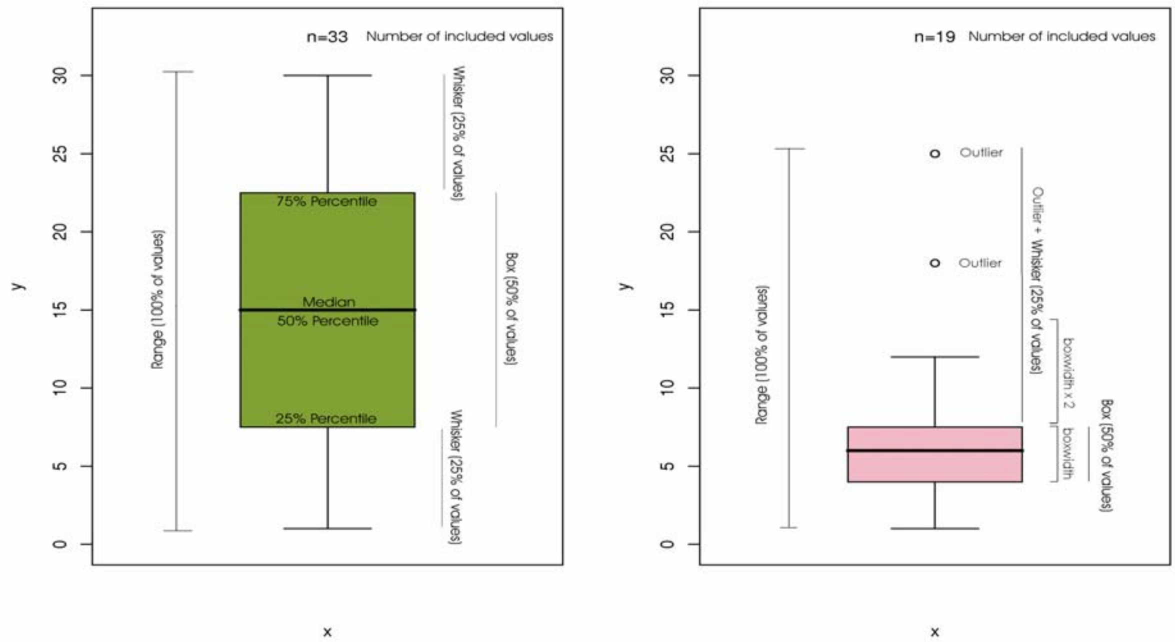

Figure 3: Description of boxplots

Narrow boxes and whiskers indicate a low variation of the data whereas extended boxes and whiskers signalize a higher variation. If the position of the median is in the centre of the range, the values tend to be normally distributed. If it deviates from the centre, the distribution of values tend to be left or right skewed. Value distributions of hydrochemical data tend to be right skewed, because they have mainly a high amount of low concentrations and a lower amount of data with high concentrations. To have a more detailed view about outliers that widen the range, in some cases another boxplot design is chosen. In these cases, the range is not indicated by the whiskers but additionally by dots what identifies the amount of outliers. Values are defined as outliers when they exceed the double box width. Examples are given in Figure 3.

Welch's T-test

The Welch's T-Test is applied to test for significant deviations in the means of two value distributions for clogged and non-clogged wells. The null hypothesis implies that two population means are equal. So the yielded probability value (p-value) needs to be smaller than 0.05 to give evidence to reject the null hypothesis, meaning that the two population means are significantly unequal.

Linear regression

Linear regression describes the relationship between one or more independent variables and one dependent variable. It is modelled by a linear least squares function. This function is a linear combination of one or more model parameters, called regression coefficients, what have an explanatory character for the dependent variable. A linear regression equation with one independent variable (X) and one dependent variable (Y) represents a straight line.

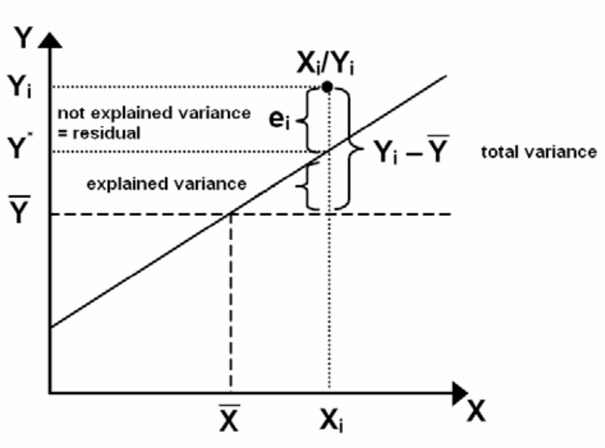

Figure 4: Example for a simple linear regression model with the explained and unexplained variance of single observations and its mean (BROSIUS 1998)

A multiple linear regression model follows the same principal, but it considers several dimensions, which cannot be displayed in two dimensions anymore.

The first objective of regression analysis is to receive the best fit of the data by adjusting the parameters of the model. The best fit is obtained when the sum of squared residuals, is minimized

Multiple linear regression has the aims to describe the correlation between one dependent and several independent variables and to quantify how much of the variability of the dependent variable is predictable by the independent variables.

If the correlation is satisfying the regression model allows a prediction of the dependent variable by the independent ones (DORMANN & KÜHN 2008).

Whereas Pearson's correlation coefficient R is a measure for the quality of correlation between variables, R^2 is the coefficient of determination and describes the quality of a regression model. R^2 is calculated by dividing the explained variance (regression sum of squares) by the total variance (total sum of squares) and indicates the quality of the fit of the regression function.

It ranges between >0 and <1 and indicates the amount of explained variance in the data. A regression with $R^2 = 0.6$ explains 60 % of the variance in the original dataset (DORMANN & KÜHN 2008).

The multiple linear regression is executed by the *forward method*. One after another, the variables with the highest partial correlation coefficient are included in the regression equation. In this method, the first selected parameter has the highest partial correlation to the dependent variable followed by the next one. This operation is repeated until the available independent variables have no significant explanatory influence on the variance of the clogging index. Adding a new independent variable to the regression model leads to an increase in R^2 and so to an improvement of the model.

To avoid that an increase of correlation to the dependent variable is mainly achieved by adding new variables, an adjusted R^2 is calculated. The *adjusted* R^2 is decreasing with the amount of added variables (BROSIUS 1998).

By these parameters, the multiple linear regression model quantifies the cumulative correlation between the measured independent variables and the dependent variable of clogging. Furthermore, it can be seen in how far the independent variables can predict the dependent one. So the regression model is used to evaluate detected relationships.

Chapter 3 Data Analysis and Results

The first step of the data analysis was to summarize the characteristics of the data and to see differences and similarities in the different locations of the respective waterworks (chapter 5.1).

The second step of the data analysis was to define parameters that can be used to identify clogging by the listed hypotheses (chapter 5.2). Subsequently their quantitative relevance for clogging was analysed.

Because the French data are not extensive enough and not sufficiently validated yet the analysis is mainly based on the Berlin data. The French data are exclusively taken into account for the evaluation of specific capacity *Qs*.

3.1 Descriptive Data Analysis

For a first, descriptive data analysis, the available data were grouped by waterworks to obtain an overview of the ranges and variations of the parameters.

Well construction

The **Berlin** data offer an extensive dataset of 615 wells, which currently have an age between 2 and 55 years (Figure 5). The histogram of well age reveals that well construction activities are not carried out constantly in the same quantity. For example, 17 years ago in 1991 nearly 50 wells were newly constructed in consequence of the German reunification in 1989. Therefore, in the following years no more wells were built. This is an obvious example how political, operational or economical reasons influence well management and thus the data variability.

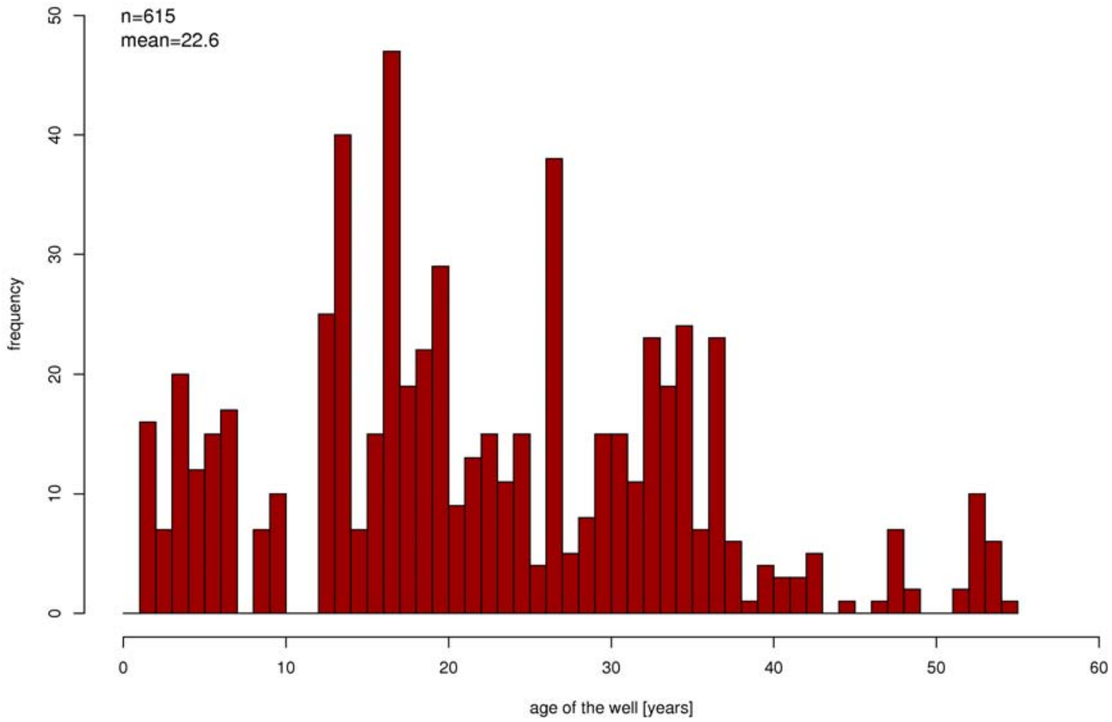

Figure 5: Well Construction characteristics of the Berlin waterworks

An even more impressive example on data heterogeneity is an overview of the most characteristic well construction parameters of the Berlin waterworks (Figure 6).

The same summarizing overview has been drawn for the **French** wells (Figure 7) as far as data were available.

By comparison of Figure 6 and Figure 7 it can be stated that well construction of the **French** waterworks has similar ranges than the **Berlin** ones. But the amount of data is less representative for the different well construction data. Well age for the French wells is mainly defined by the first operation date, because some of the wells are from the 1930s but put in operation in 1985. So it can be assumed that they were replaces in 1985. The database for the French wells shows that all of them have only one filter screen, therefore it is not included in the overview plot. The distance to the next surface water is not available for the French wells.

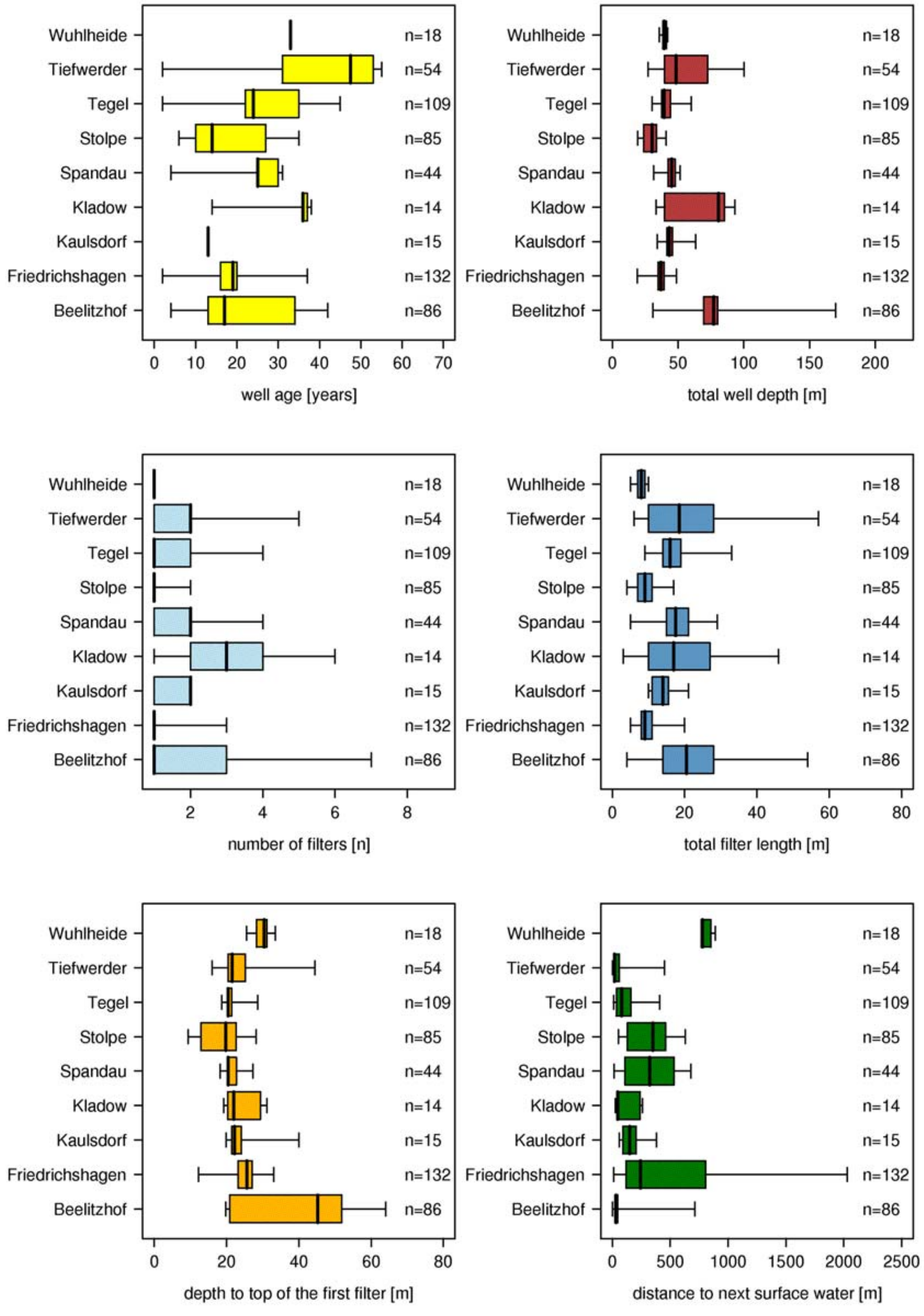

Figure 6: Overview on the available well construction characteristics in the Berlin waterworks

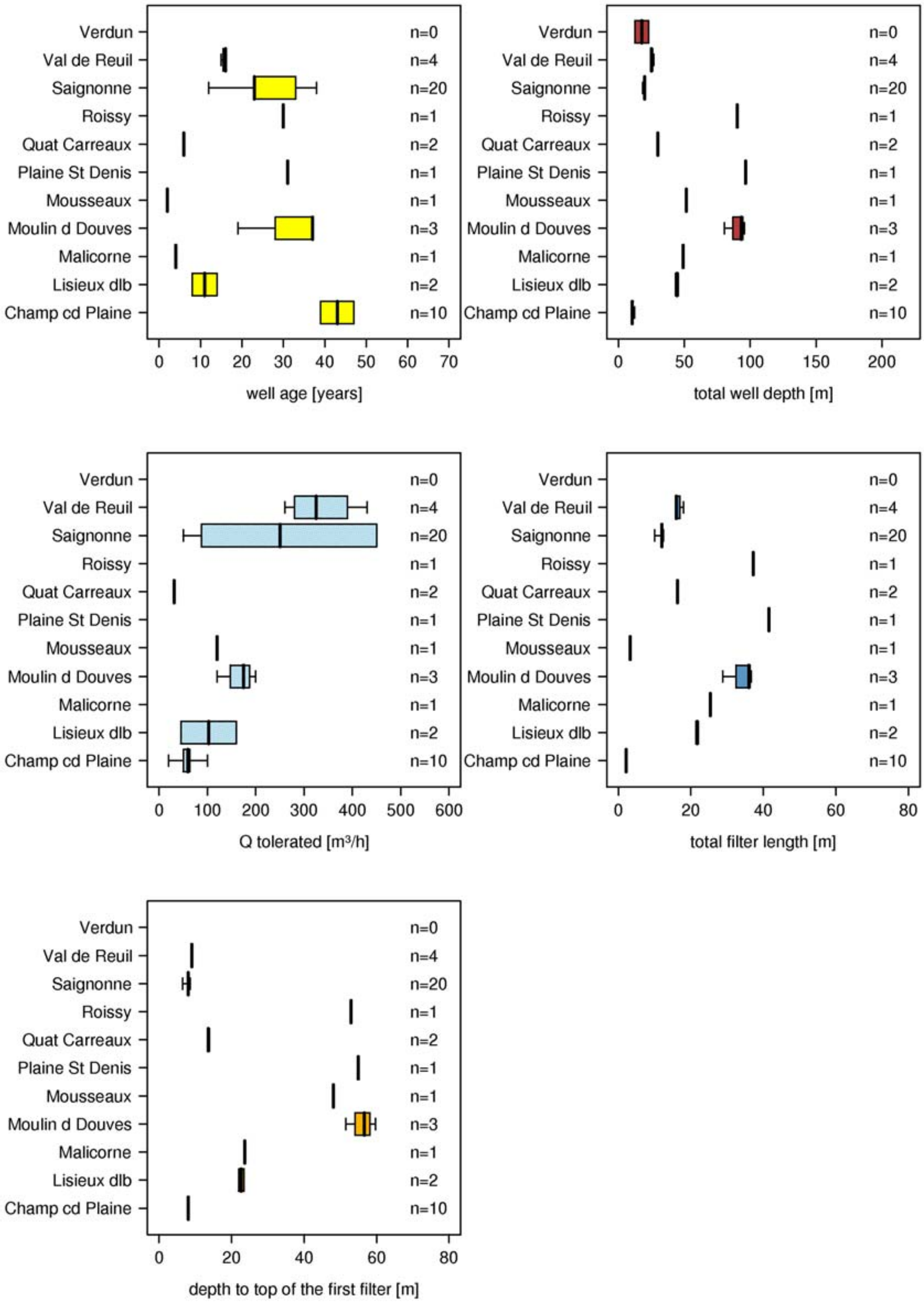

Figure 7: Overview on the available well construction characteristics in the French waterworks

Hydrochemistry

The next step of the data analysis is to assess the range of chemical conditions in the well water and how they can be linked to clogging conditions.

Therefore, the available measurements of the 378 Berlin wells with at least three measurements per parameter were plotted in boxplots.

The iron concentrations of all selected waterworks show that in general all wells contain more than 0.2 mg/L dissolved iron (Figure 3). This is supposed to be the minimal value for well clogging conditions (DVGW 1970). The ideal living conditions for iron bacteria are characterized by concentrations between 0.2 and 25 mg/L (HOUBEN & TRESKATIS 2007). The iron content in the selected Berlin wells ranges between 0.02 and 7.1 mg/L. Only 14 measurements have values below 0.2 mg/L iron (Figure 8).

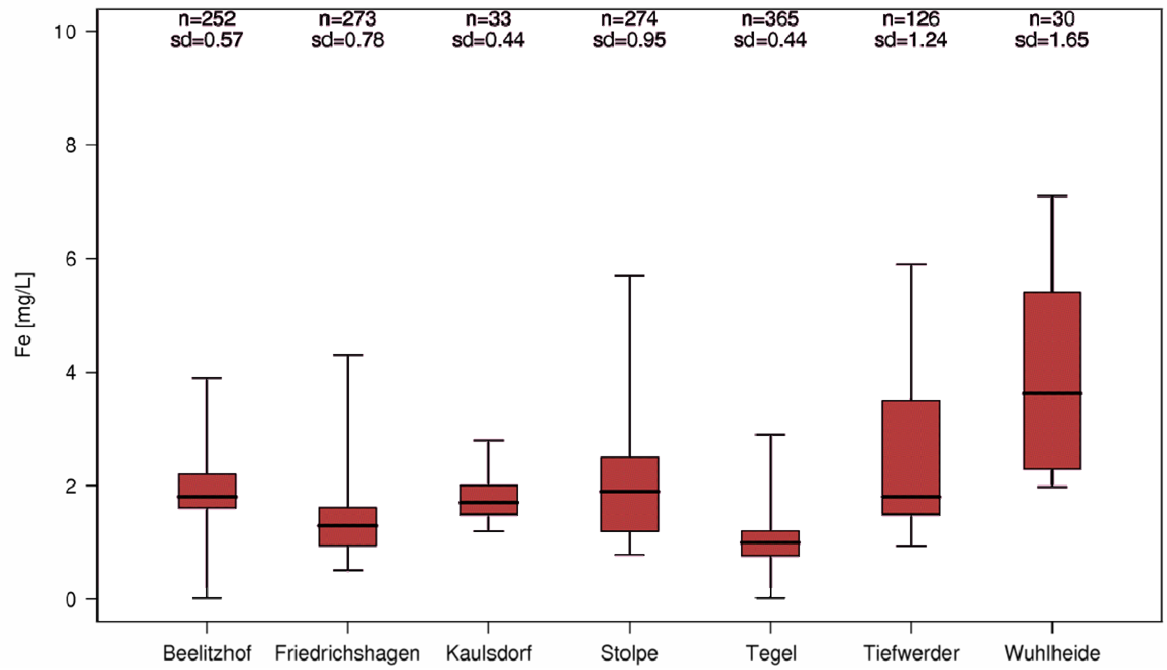

Figure 8: Boxplot with range and median of Fe-concentrations in the Berlin waterworks

Furthermore, manganese concentrations (Figure 9) show that every well contains dissolved manganese what can also be oxidized by the iron-bacteria (BARTEZKO 2006).

The concentration of iron and manganese is influenced by the respective oxygen content and its redox potential (see Figure 10 and Figure 12).

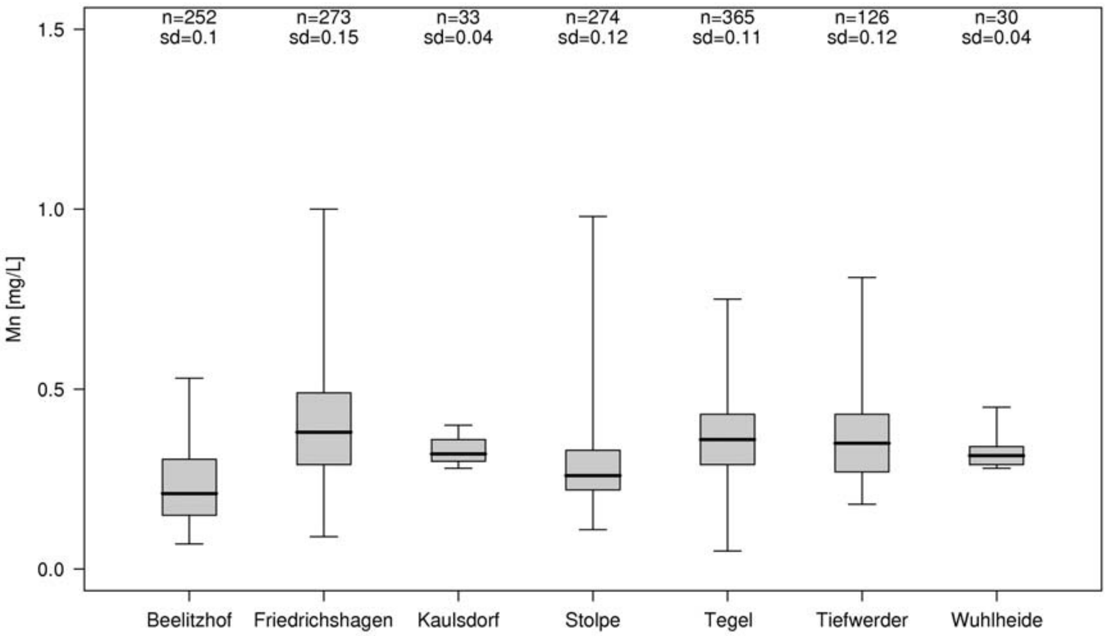

Figure 9: Boxplot with range and median of Mn-concentrations in the Berlin waterworks

Iron bacteria prefer 0.1 to 1 mg/L dissolved oxygen in the water. Around 95% of all oxygen measurements lie within this optimal range (Figure 10). Additionally it can be stated that the waterworks *Kaulsdorf* and *Wuhlheide* what are mainly abstracting groundwater do not have lower oxygen contents compared to the remaining waterworks which are mainly abstracting riverbank-filtrate.

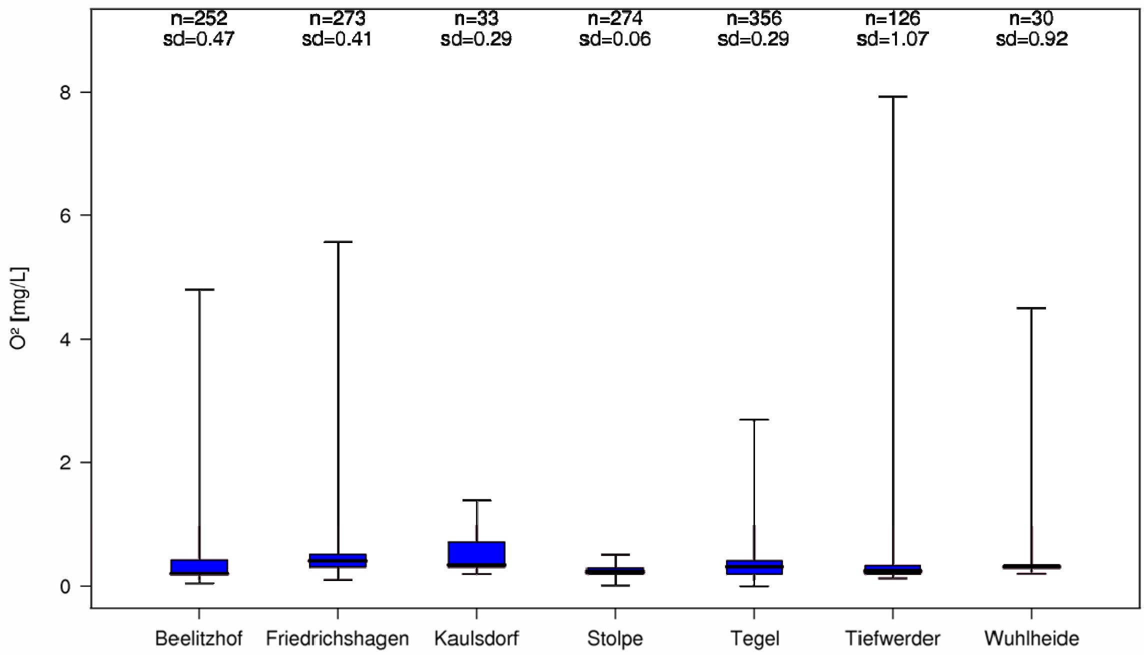

Figure 10: Boxplot with range and median of oxygen content in wells of the Berlin waterworks

Because measuring the oxygen content often has inaccuracies, nitrate-nitrogen concentrations are used as an additional indicator for the presence of oxidative conditions (Figure 11). Only around 25% of measurements of nitrate-nitrogen are above the detection limit of 0.05 mg/L. Looking for oxygen and nitrate contents in the database leads to the conclusion that in all wells occasionally slightly oxic conditions and nitrate compounds are present. These are preferred living conditions for iron bacteria because oxygen and nutrients are available (BARTEZKO 2006).

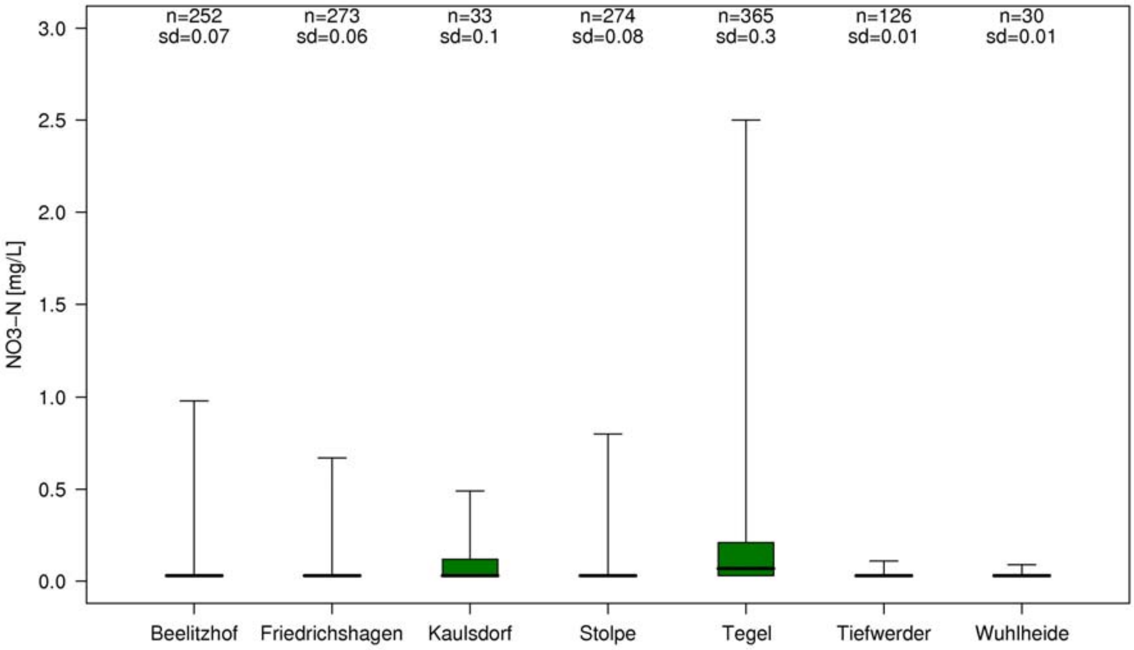

Figure 11: Boxplot with range and median of NO3-N-concentration in the Berlin waterworks

Investigations of the ideal conditions of redox potentials for iron bacteria come to different results. Whereas HANERT and DRISCOLL specify it at 200 to 300 mV, HÄSSELBARTH & LÜDEMANN come up with a range between -30 to 20 mV (HOUBEN & TRESKATIS 2007). Measurements of redox potential in the Berlin wells are mainly between 150 and 200 mV (Figure 12). Actually, they are not reflecting optimal conditions for iron bacteria. Additionally the redox potential is in the range of iron and manganese reduction (HÖLTING 1989), what argues against iron and manganese oxidisation processes in the Berlin wells. Contrary, KREMS stated that clogging occurs in wells as soon as the redox potential is positive (KREMS 1972). This applies to most Berlin wells.

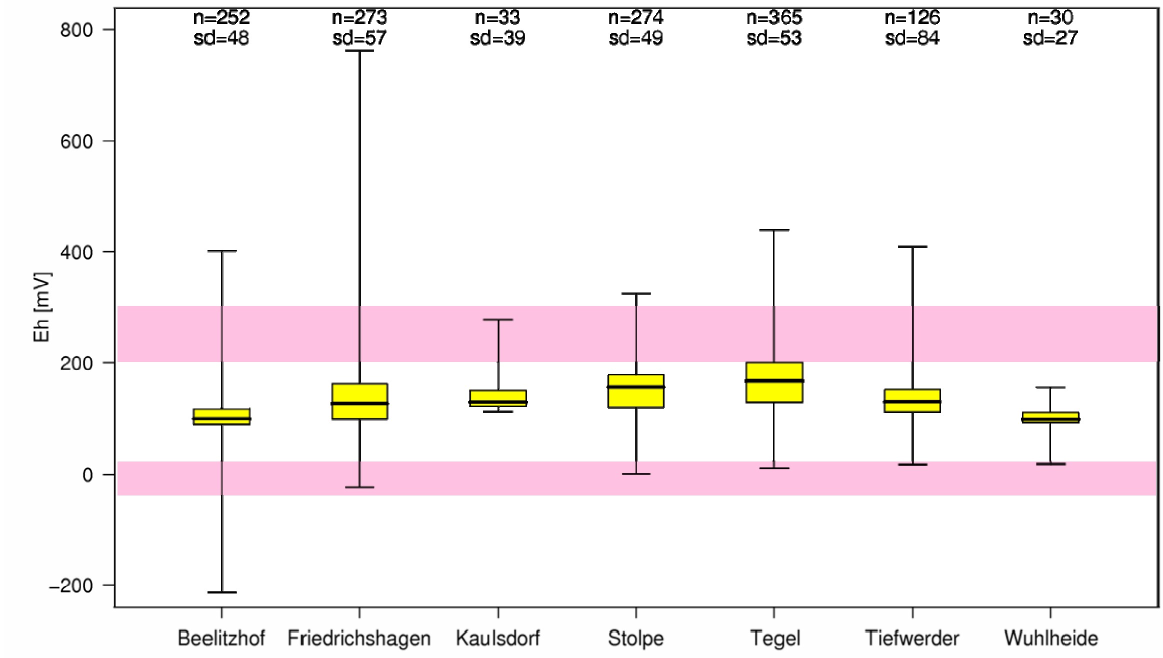

Figure 12: Boxplot with range and median of redox potential in the Berlin waterworks

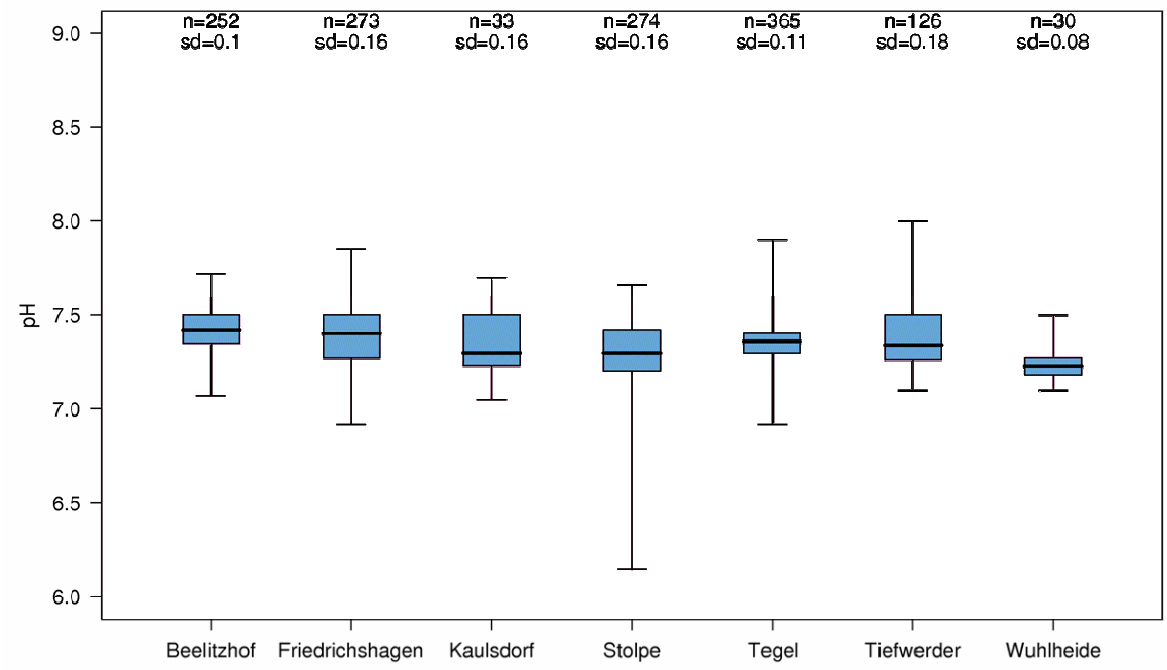

Figure 13: Boxplot with range and median of pH in the Berlin waterworks

Concerning the pH, the optimal living conditions for iron bacteria lie between pH 6 and 7.6. In most wells, a pH around 7.4 is measured (Figure 13). Finally, in every waterworks an amount of 2 to 11 mg/L DOC is available.

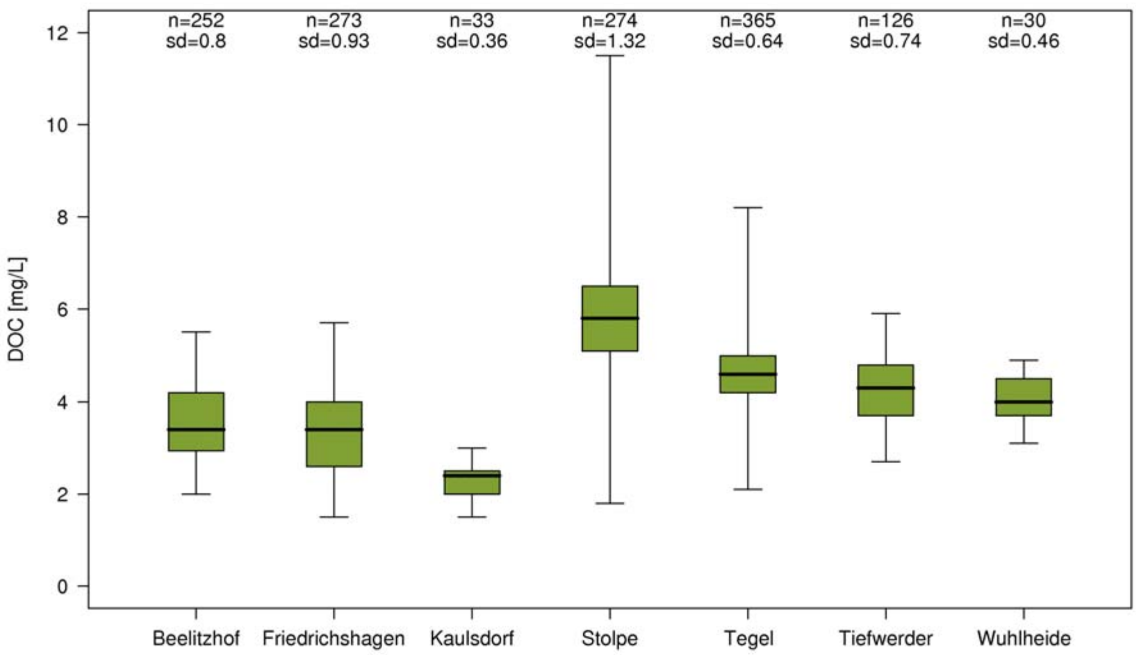

Figure 14: Boxplot with range and median of DOC-concentrations in the Berlin waterworks

Another quite compact description of hydro chemical characteristics in the different wells can be provided in a Piper diagram (Figure 15). The included data base on the median of the concentrations in each well (calcium, magnesia, sodium, potassium, chloride and sulphate).

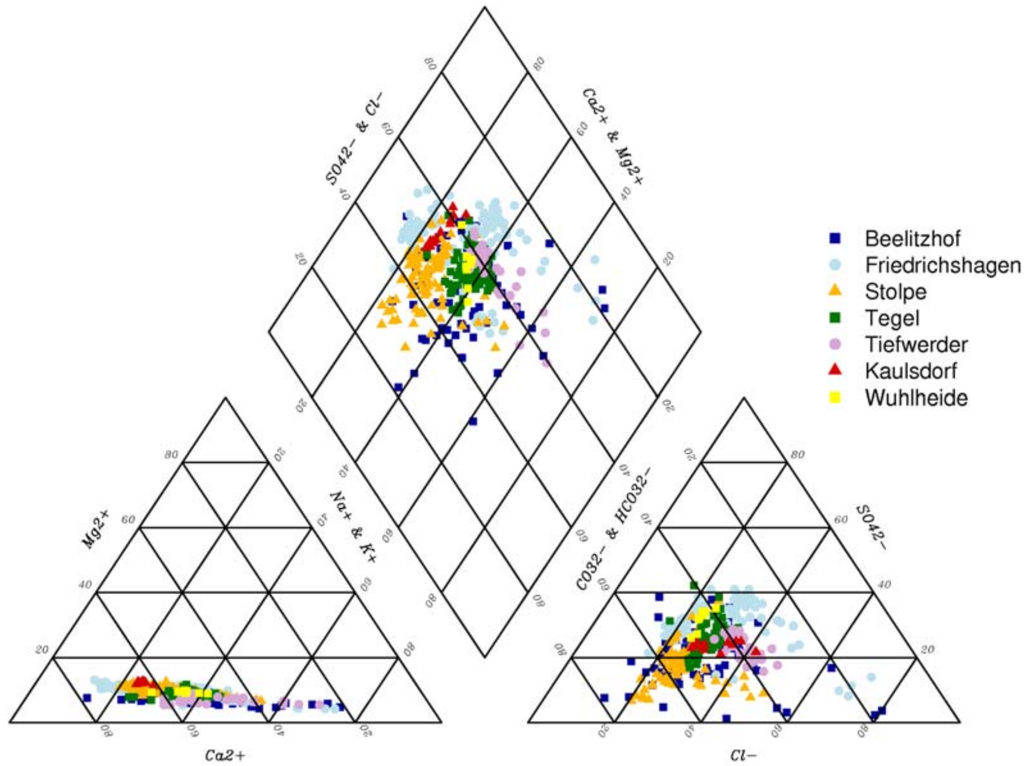

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Figure 15: Piper Diagram of all hydrochemical data per well in Berlin (medians)

It can be seen that some waterworks like e.g. *Beelitzhof* and *Friedrichshagen* have a relatively high variation in water chemistry from well to well. This can be caused by different origins of water like for example a high fraction of riverbank-filtrate or water abstraction out of different aquifers. Clogging processes are often a consequence of mixing water qualities (VAN BEEK 1995).

The **French** wells reveal slightly different hydrochemical conditions. Iron contents are generally very low (Figure 16). Only *Malicorne, Quatres carreaux* and *Val de Reuil* reveal iron contents, which are equivalent to the lower iron contents in Berlin wells like *Tegel* or *Friedrichshagen*.

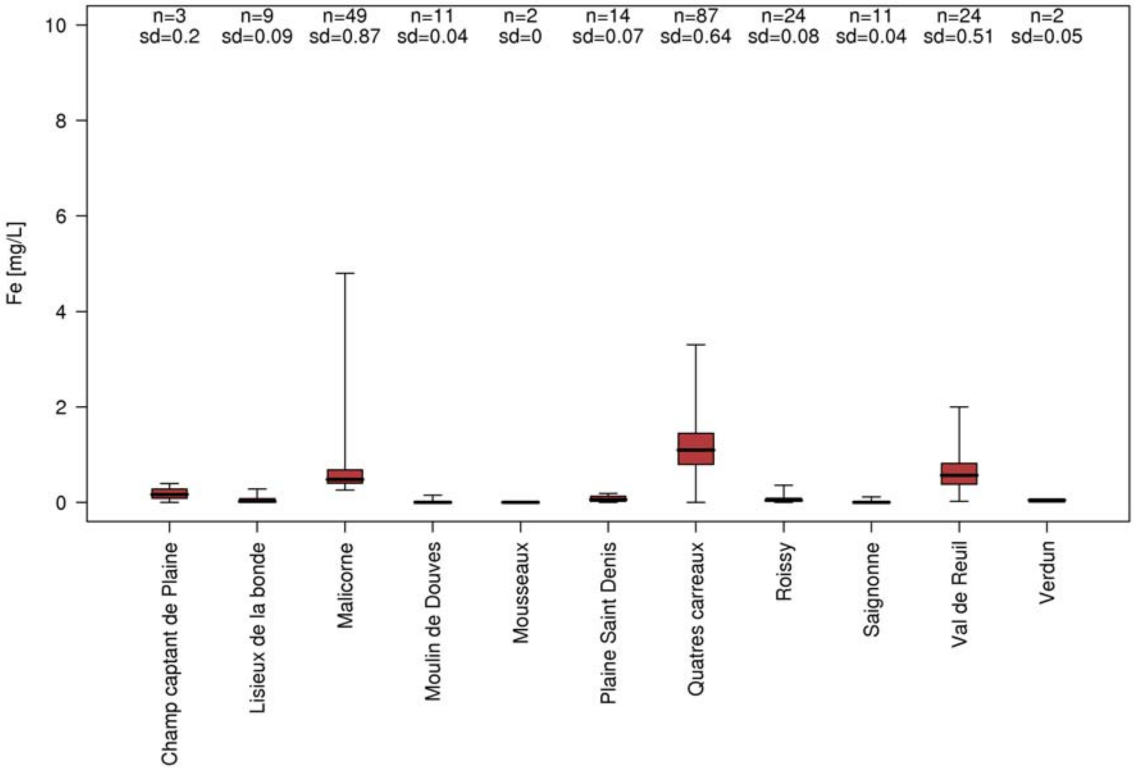

Figure 16: Boxplot with range and median of Fe-concentrations in the French waterworks

Similarly, manganese contents in the French wells are mainly around the detection limit of 0.02 mg/L. In comparison, the Berlin manganese contents are ten times higher with concentrations between 0.2 and 0.5 mg/L (Figure 17).

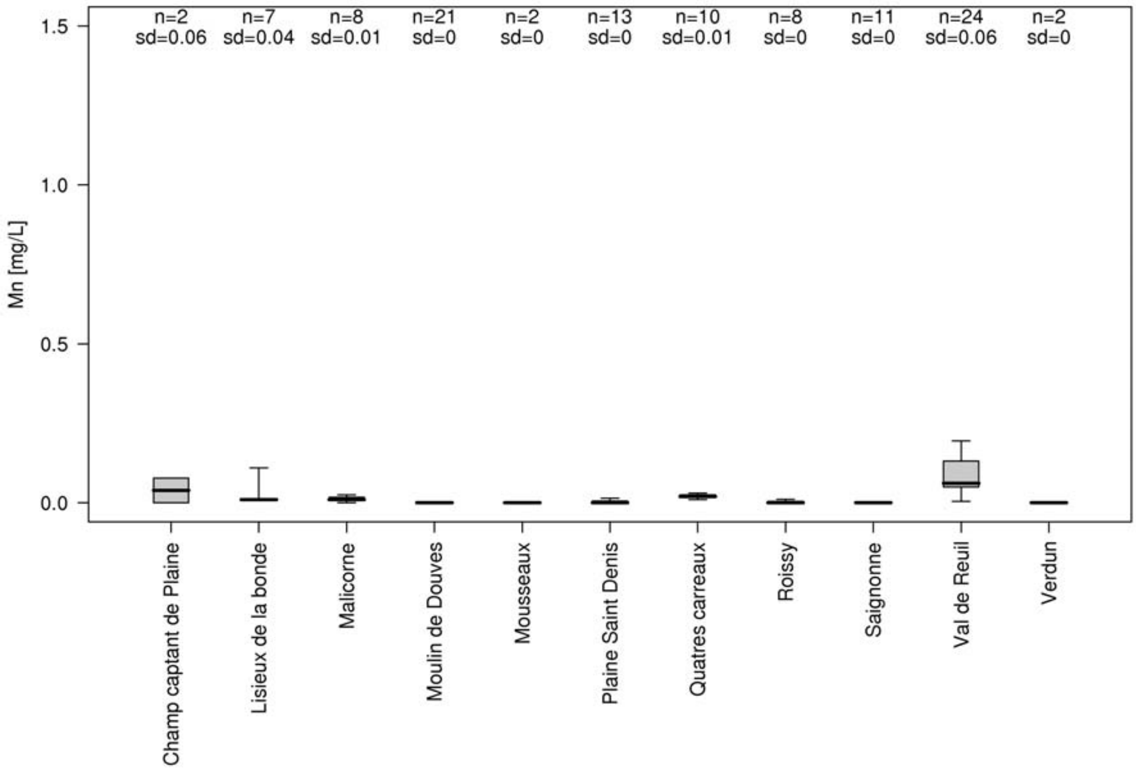

Figure 17: Boxplot with range and median of Mn-concentrations in the French waterworks

In contrast, oxygen contents in most French waterworks are significantly higher ranging between 1 and 8 mg/L (Figure 18). Especially *Champ captant de Plaine, Lisieux de la bonde* and *Saignonne* have oxygen contents above 3 mg/L. As already mentioned, oxygen measurements are not very reliable and the boxplots are based only on 2 to 6 measurements. There are no data for *Mousseaux* and *Verdun*. In general, it can be stated that the oxygen contents of the French wells are above the preferred living conditions for iron bacteria. The conditions seem to be more appropriate to chemical clogging processes.

Furthermore nitrate-nitrogen concentrations in *Champ captant de Plaine, Lisieux de la bonde, Mousseaux* and *Saignonne* and *Verdun* are between 1 and 4 mg/L what is mainly above the values in Berlin (Figure 19). In most waterworks, the nitrate contents reflect the distribution of oxygen values. In general, the nitrate concentrations have more variance due to the different site conditions.

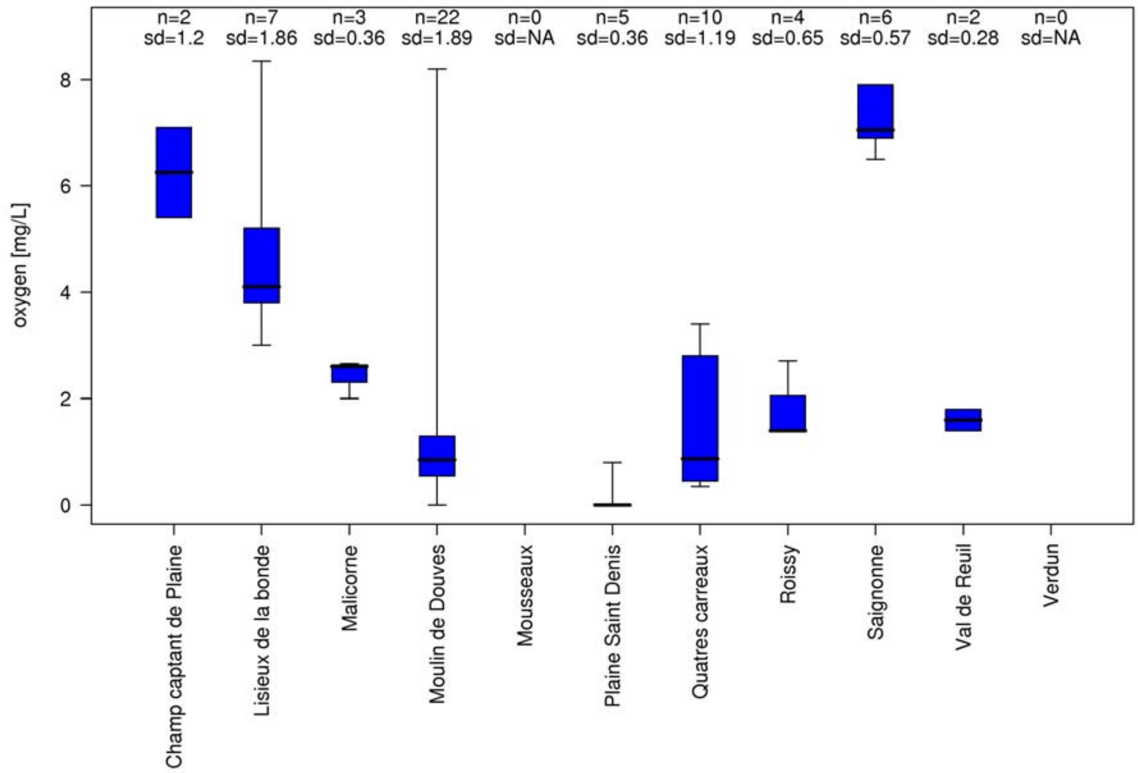

Figure 18: Boxplot with range and median of oxygen-contents in the French waterworks

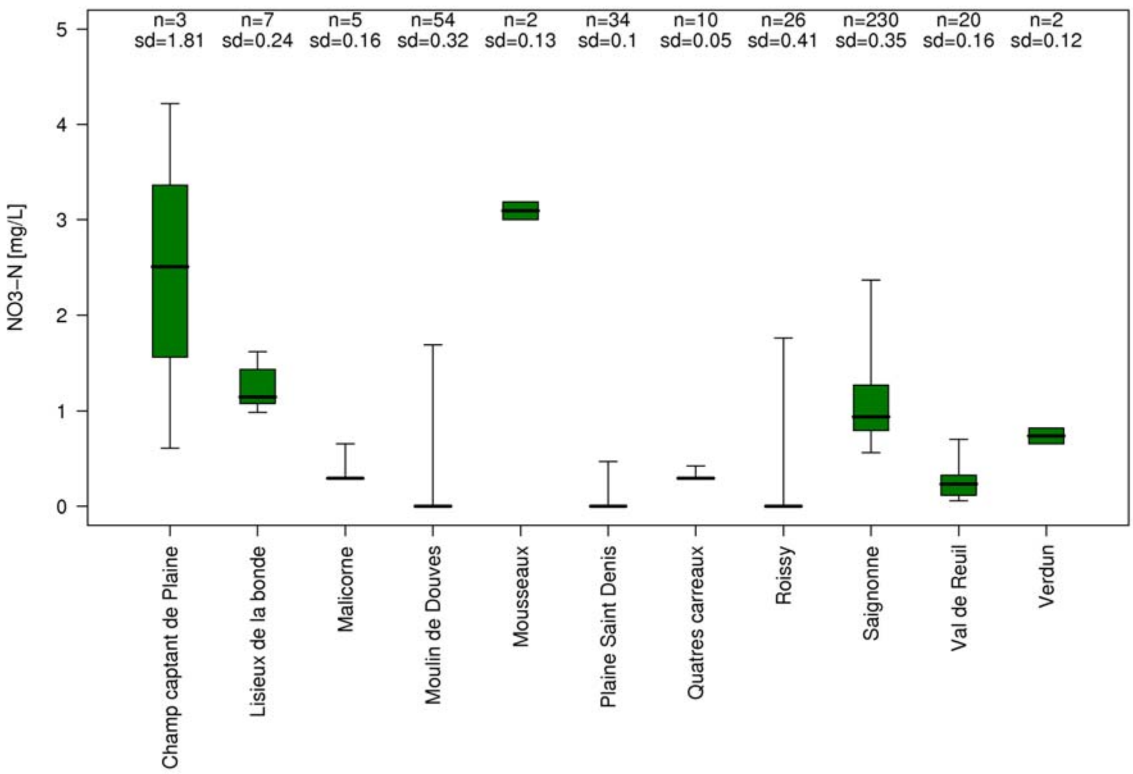

Figure 19: Boxplot with range and median of nitrate-nitrogen-contents in the French waterworks

Finally, the differences of the French sites can be characterized by higher calcium concentrations (Figure 20). Whereas in Berlin the calcium values vary around 100 and 120 mg/L, the French waterworks often have concentrations around 140 mg/L. This is most probably due to the presence of calciferous aquifers in France. Only *Mousseaux, Saignonne* and *Verdun* reflect the Berlin conditions.

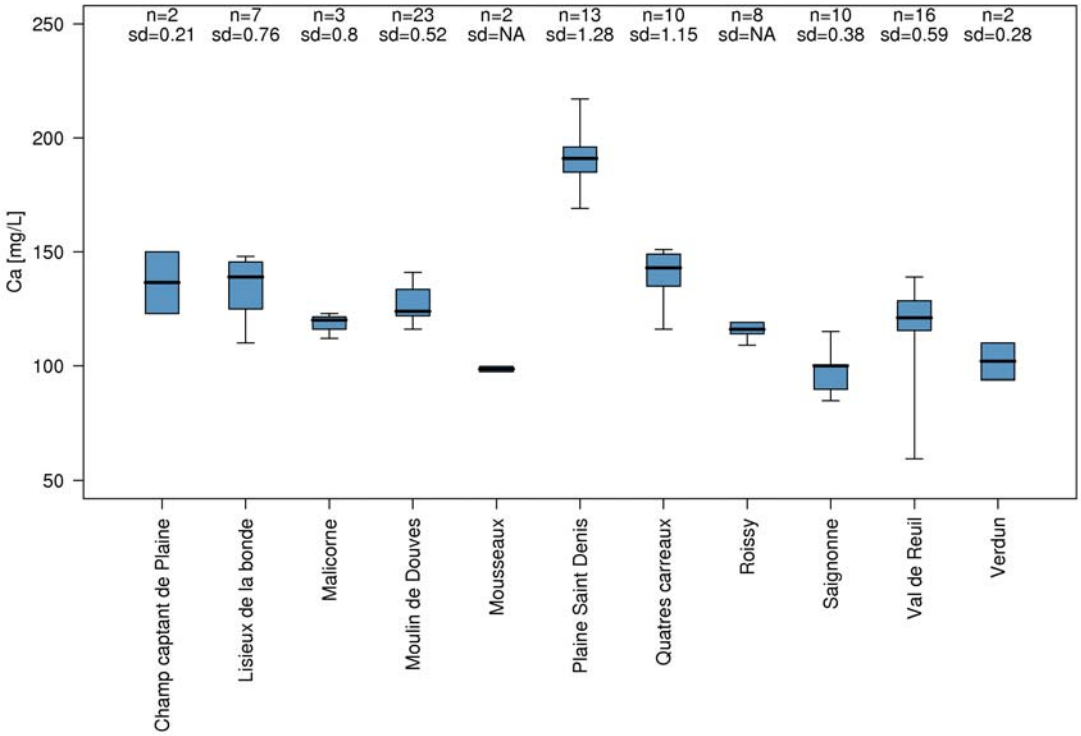

Figure 20: Boxplot with range and median of calcium contents in the French waterworks

Summarizing the characteristics of hydrochemistry in the **Berlin** wells all relevant parameters aside from the redox potential show optimal living conditions for iron bacteria that may contribute to well clogging. The redox potential shows that Berlin wells are mainly in the range of iron and manganese reduction. The availability of oxygen can lead to oxidization of iron and manganese ions. Looking at the Piper diagram it can be stated that water chemistry is varying in every well depending on the origin of water.

In **France,** iron and manganese are minor but oxygen and nitrate as well as calcium reveal higher contents than in Berlin. Therefore, it seems that in France the conditions for biological clogging are worse. Reddish encrustations might be a result from chemical clogging due to the oxidizing conditions, while white encrustations seem to be based on higher calcium concentrations of the French aquifers leading to sintering. However, a classified distinction of clogging intensity in an ordinal scale could not be done for the French wells. Therefore, a detailed descriptive analysis of the well conditions was carried out separately. Please refer to Appendix B for more details on the **French** wells.

Well performance

In most cases, well performance is evaluated by the specific capacity *Qs*. For each individual well, the decrease of well performance can be identified by plotting *Qs* versus the respective selected period (SCHMOLKE 2006, STEUßLOFF & STEINBRECHER 2006). One of the most probable reasons for a decrease in performance is clogging. Therefore, *Qs* is a relevant parameter for the identification of clogging and is regarded in more detail.

The actual hydraulic conditions in the well can be controlled by looking at the *Q/s-diagram*. It confirms if the aquifer conditions are confined or unconfined. Usually, this decision is based on the geological information obtained during drilling. However, as the geological classification can lead to wrong estimations, it might be not conform to the real hydraulic conditions. Therefore, the availability of *Q/s-diagrams* of initial pumping tests provides the advantage for a definite differentiation of confined and unconfined aquifers. The relation of *Q* and *s* in confined aquifers is linear, whereas in unconfined aquifers it is not linear (THOLEN 2005, STEUßLOFF & STEINBRECHER 2006). In the following figures, two examples of the French sites are presented. The initial pumping test of the well PC-PRESF4-M04 in *Val de Reuil* reveals a nonlinear *Q/s-curve*, so it is unconfined (Figure 21).

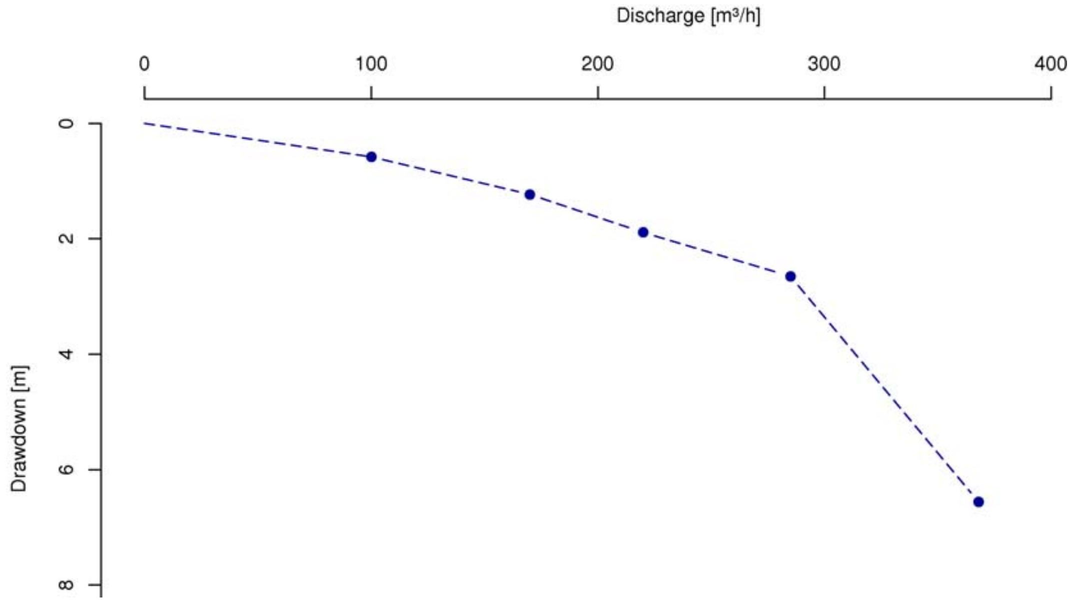

Figure 21: Q/s-diagram of the initial step pumping test at well PC-PRESF4-M04, Val de Reuil

The second example of a well at *Moulin de Douves* shows a linear relation of *Q* and *s*, so it is a confined aquifer (Figure 22).

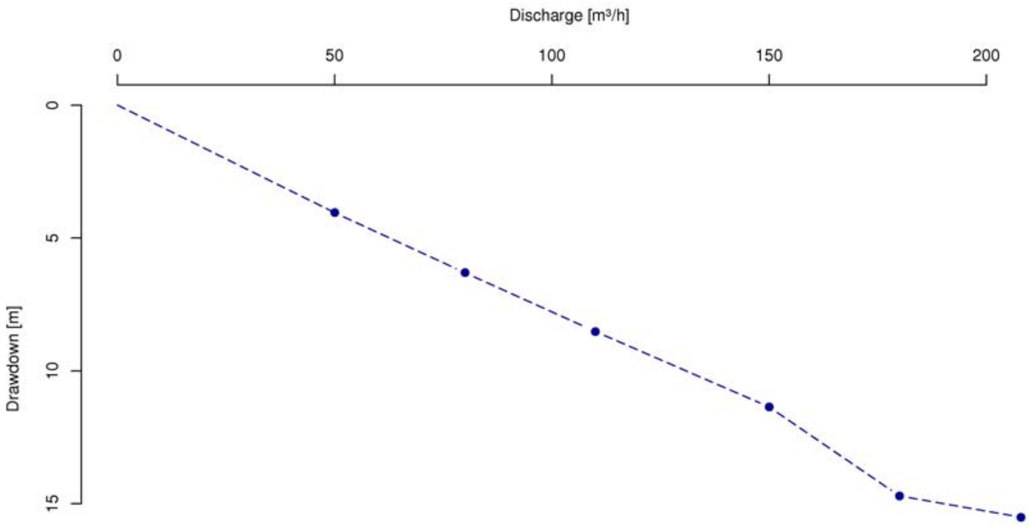

Figure 22: Q/s-diagram of the initial step pumping test at well PC-DOUVE04-001, Moulin de Douves

For an analysis regarding spatial and temporal changes, it is necessary to have an index of the *Qs* changes over the respective time period.

A typical example for the development of *Qs* over time is given in Figure 23. A well usually has its best specific capacity directly after it was set in operation (blue dot). In the example *Qs* decreases over time (green dots) but regular rehabilitations lead to *Qs*-increase for the short term (red dots). The ideal situation for assessing the well performance depending on rehabilitation efforts is such a so-called sawtooth-diagram, named after the shape of the curve.

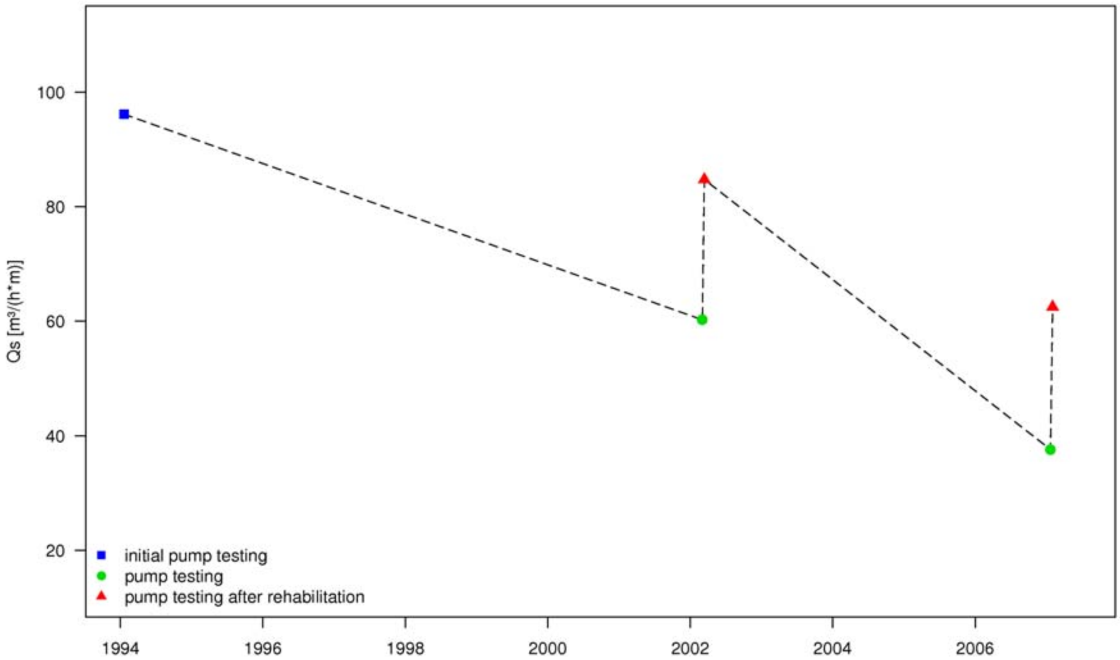

Figure 23: Lineplot of Specific capacity Qs over time of the Berlin well STOborg14

For the comparison of decrease in *Qs*, the best way is to compare *Qs*-values in percent of the initial *Qs*. Regarding the theoretical background, for wells with unconfined aquifers and consequently non-linear *Q/s*-diagrams, it has to be considered that *Qs*-values are only an approximation of the actual well performance. However, it is the only possibility for a quantification of well performance.

Actually, there remain two possibilities to receive comparable *Qs*-numbers for wells. The first one is to execute pumping tests at a fixed pumping rate. This is practised in the Netherlands. Therefore in the Dutch statistical analysis of well data Qs could be used as a relatively reliable clogging indicator (RAAT 2008)

At BWB, for reasons of water management, it is not possible to use fixed delivery rates at all wells due to differences in well construction (Information of *E. Höhndorf*, *BWB*). Qs values are derived only from the assessment of maintenance activities with pumping tests before and after rehabilitation (see chapter 2.2).

By plotting *Qs* and calculating its percentage of decrease for the Berlin wells it turned out that in 98 wells *Qs* seem to increase over time. One reason can be a real increase of well performance due to cleaning of the gravel pack by high pumping rates (SCHMOLKE 2006, NILLERT et al. 2008). A more probable reason is that the performance is not tested at fixed delivery rates.

In **Berlin**, regular control of well performance is done by quarterly measurement of the filter entrance resistance Δh. However, the calculated difference of water levels between inner and outer piezometer reveals a range of negative values up to 14 m difference. This range is not plausible. Therefore, it was attempted to validate the dataset, but it was only possible to find corrections for most of the negative values. A complete validation of the data for every well was too elaborative in the context of *WELLMA-1*. Therefore, Δh was not considered in the further analysis.

The advantage about the **French** data is that they have more extensive datasets of discharge *Q* and drawdown *s* as the following two examples for highly resolved *Qs* data will show:

The first example is the *Qs*-curve related to time for well F4 in the waterworks at *Val de Reuil* (Figure 24). In the upper half, a lineplot of high frequent *Qs* values is presented. In the lower half, the particular delivery rates are added. By comparison of the two lines, the influence of changing delivery rates to *Qs* is quite obvious.

A similar example is presented by the *Qs*-curve versus time of the well in the waterworks of *Roissy*. In general, *Qs* decreases dependent on decreasing delivery rates (Figure 25). In the time between 1982 and 2002, the delivery rate was nearly constant at around 100 m³/h. During this period, the decrease in *Qs* seems to represent the real *Qs* decrease. The abrupt loss in performance in 2002 has to be a result of a significant change in delivery rate.

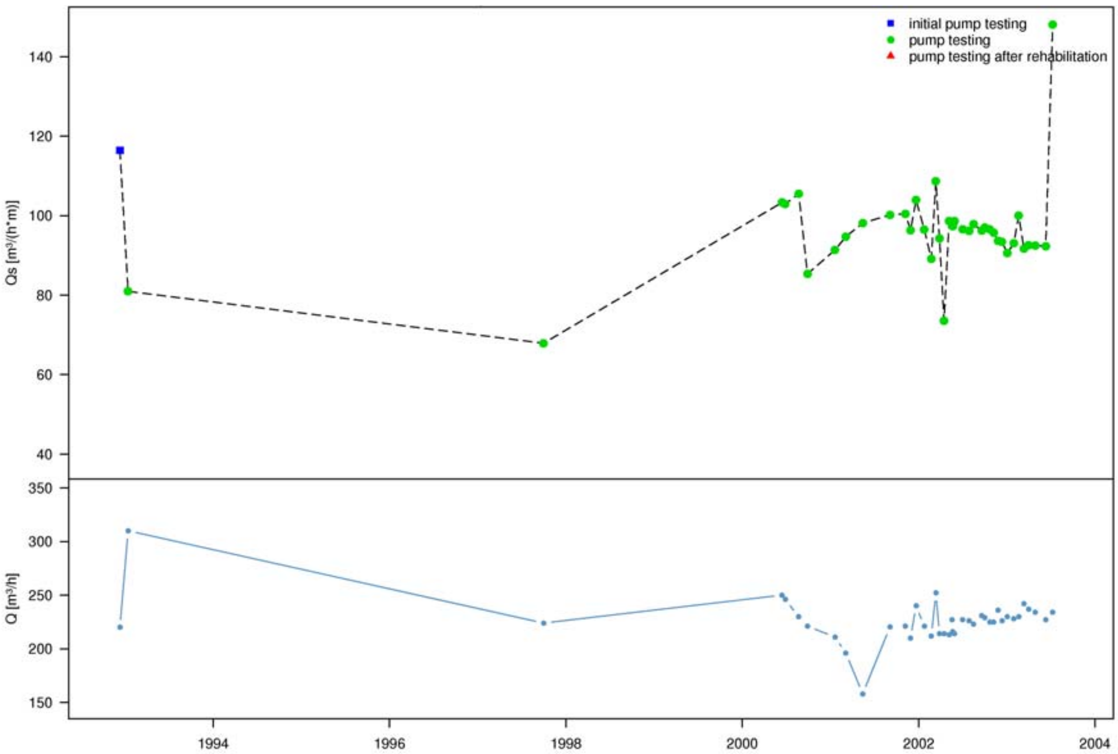

Figure 24: Comparison of specific capacity Qs and delivery rate Q at PC-PRESF4-M04 (upper line: Qs, lower line: delivery rate)

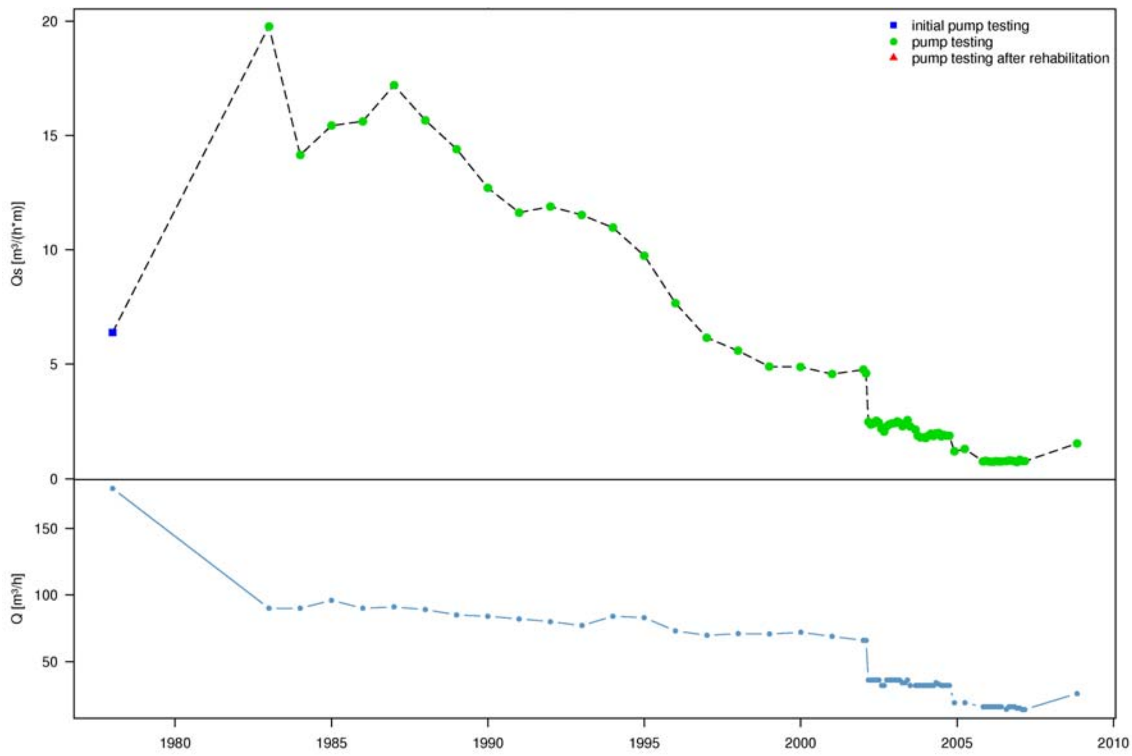

Figure 25: Comparison of specific capacity Qs and delivery rates Q at PC-ROISSY-001

Therefore, Qs is highlighted to be a source of great errors. If only Q/s numbers based on different pumping rates and no step test drawdown data are availablel, t is not possible to quantify changes over time in well performance correctly (UMBLE 1999, THOLEN 2005).

Nevertheless, because most water companies are currently using *Qs* as a measure for well performance, the informative value of *Qs* for the identification of clogging is investigated in chapter 3.2.

The more practical possibility for an evaluation of *Qs* is a diagram of the initial step pumping test, where any discharge rate *Q* can be related to its drawdown *s*. A comparison of the current pump testing results with the *Q/s-diagram* reveals if well performance is stable, in- or decreasing. In most cases, the **French** data offer initial pumping tests including 3 to 5 steps of pumping rate (Table 7). This offers the possibility to check the relation of *Q* and *s*.

Well maintenance

In **Berlin,** the rehabilitation intervals are related to decrease in *Qs*. Monitoring and maintenance intervals are derived mainly from practical experience over years of operation. Furthermore, they refer to the Technical Rule of the DVGW (DVGW 2001). The data analysis confirms the *BWB* strategy that most wells are rehabilitated after 6 years. However, the rehabilitation intervals in general vary between 1 and 16 years (Figure 26).

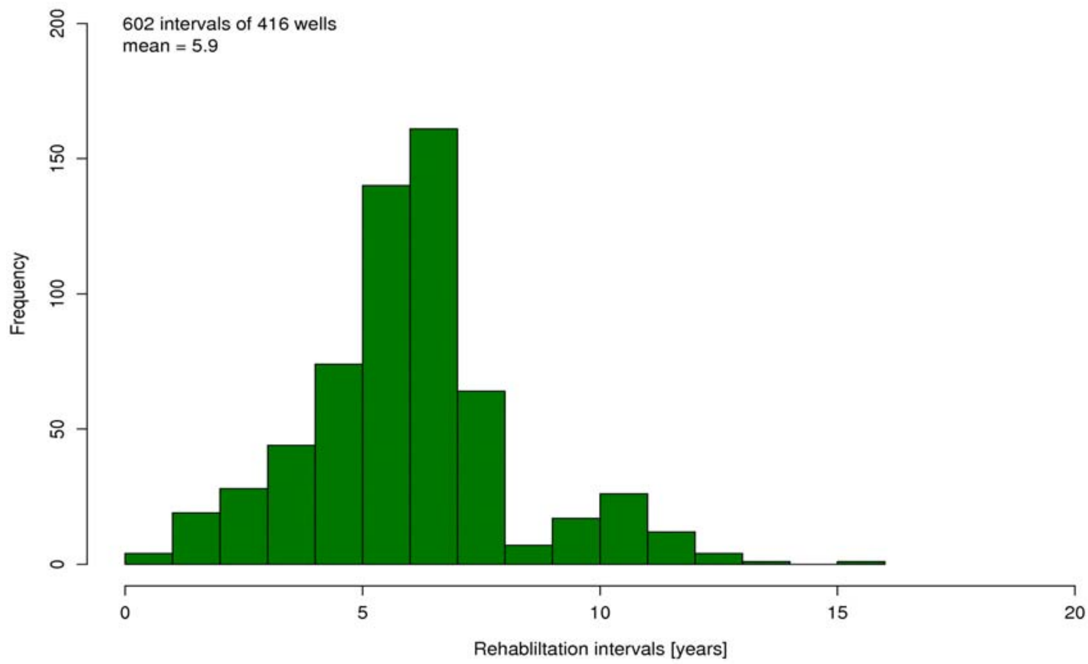

Figure 26: Histogram of rehabilitation intervals for the Berlin wells

The term rehabilitation refers to the application of either hydro pulse or shock blasting or a combination of both. The choice, which method is applied depends on well construction characteristics, intensity of ageing and practical experience.

As stated in the previous chapter, for the **French** wells data availability was not good enough to include the data into further statistical data analysis.

TV camera inspections

As described in chapter 2.2 (page 11), the results of TV inspections were related to one of four classes of clogging intensities.

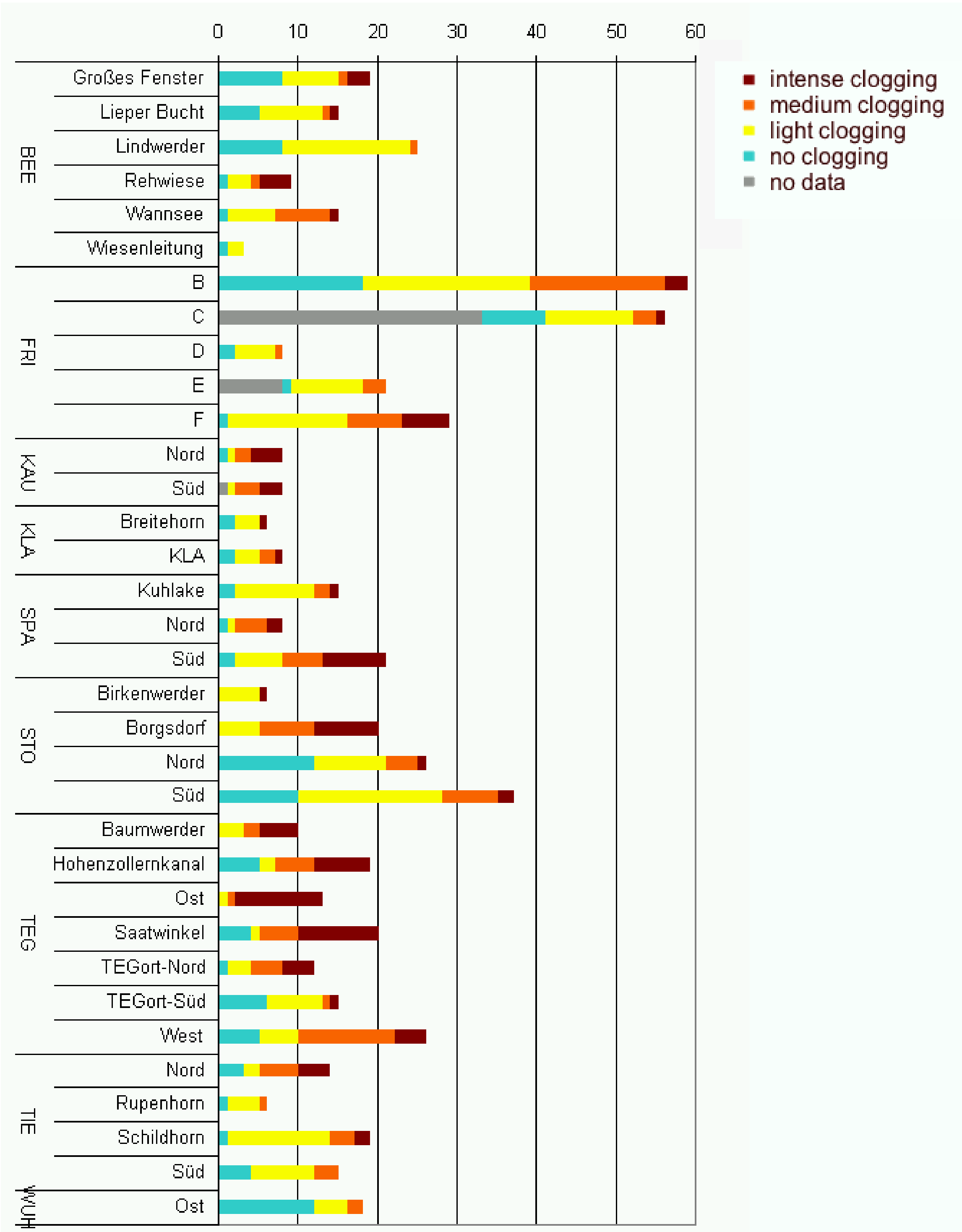

Figure 27: Frequency and classification of clogging in the Berlin Well fields related to TV camera inspections

Figure 27 gives an overview on this classification observed at the last TV camera inspections in the **Berlin** well fields. It reveals that wells in every well field are affected by clogging. But there are some interesting differences in clogging intensity in the particular well fields.

For example, *Tegel Ost*, *Saatwinkel* and *Hohenzollernkanal* show intensive clogging in most wells. The waterworks in *Tegel* are characterized by mixing of different origins of water from bank-filtrate, artificial recharge water and groundwater. Whereas the well fields *Beelitzhof Lindwerder* and *Stolpe Nord* and *Stolpe Süd* show no or light clogging in the TV camera inspection, though they abstract definitely high fractions of riverbank-filtrate. In contrast, the wells of *Wuhlheide* have nearly no clogging compared to the ones of *Kaulsdorf* with a lot of intense clogging of the wells although both waterworks are mainly abstracting groundwater.

Here too, **French** data could not be regarded, because a similar classification was not possible.

The impression that clogging occurs by coincidence can be found more often than any general dependencies. It is supported by various authors, which state that the variance in the particular observations is an effect of different interactions between all influencing factors (VAN BEEK 1995, RUBBERT & TRESKATIS 2008).

Hence, the statistical analysis can only provide some general trends what can be found in most wells. The irregularities need to be investigated in more detail after the identification of the most relevant clogging parameters. The investigation and explanation of irregularities in the data are the Task of *WELLMA-2*.

3.2 Identification of a clogging Indicator

The first step for the statistical analysis of the available well data was to identify an indicator that gives reliable information on the clogging status of a well. This value can then be related to other well characteristics and hydrochemical parameters in order to evaluate which may influence the clogging status.

- There is general consent within the well operating "scene", that well ageing can be identified by a decreasing *Qs* value. Different authors postulate that more than 10% of Q*s* reduction are an indication for the initiation of clogging processes (DVGW 2001, STEUßLOFF & STEINBRECHER 2006, RUBBERT & TRESKATIS 2008).
- Furthermore, it is current state of practice at *BWB,* that wells, which tend to clog, are treated by H_2O_2 (information by *L. SCHMOLKE, BWB*). Therefore, it can be concluded that wells without clogging tendency have no H_2O_2 treatment.
- Additionally, the database includes information about the observations of TV camera inspections in an ordinal scale of the clogging tendency. The advantage of this parameter is that it is a clear evidence for clogging or no clogging.

Therefore, the following three hypotheses for the indication of clogging **for *BWB* wells** are tested with regard to the available independent variables of well construction and geology, hydrochemistry, well performance and maintenance:

- Clogged wells can be identified by TV camera inspections.
- Clogged wells have a decreasing specific capacity *Qs* of more than 10% compared to their initial specific capacity (DVGW 2001).
- Clogged wells are treated preventively by H_2O_2.

The first hypothesis seems self-evident, but actually, camera inspections are only able to observe clogging on the filter screen or the well casing but not in the gravel pack. In the latter case, the camera inspection would not be an adequate means to identify clogging.

For the three parameters *Qs*, H_2O_2 treatment and TV camera inspections the following criteria are set for the data analysis. The cases of doubt in the transition zone representing light and medium clogging are excluded to receive a definite identification of factors related to *clogging* and *no clogging*.

An observed index for clogging is the **TV camera inspection**, which is saved in an ordinal scale in the *BWB* well database. For the approach to identify a parameter, only the wells with *intense clogging* (3) and *no clogging (*0) were included. Therefore, the final dataset consists of 89 wells, 52 of them with intense clogging and 37 of them without clogging indication.

For every well, the mean **reduction of *Qs*** compared to its initial *Qs* is calculated. Because for every well the *Qs*-change is related to a different period of time, the percentage of *Qs* reduction is divided by the respective amount of time between the initial *Qs* and the last pump testing. The resulting index is the *mean Qs reduction per year* for each well. For the classification if a well shows a notable decrease in *Qs*, a yearly reduction of 2 percent is chosen. This is corresponding to 10% of *Qs* reduction in five years, which suits the mean rehabilitation interval of around six years. Wells without *Qs* reduction are classified as wells without clogging. The resulting dataset includes 61 wells with a notable yearly *Qs* reduction whereas 35 wells do not show a *Qs* reduction.

A similar index is created for the H_2O_2 treatments. The dataset includes wells with or without regular H_2O_2 treatments. Because treatment intervals were changed over time and are not of the same duration for every well, only wells with a calculated index of 0.5 and more treatments per month are regarded. This index corresponds to the current treatment interval of at least one time every two months for clogged wells. Several wells have never been treated by H_2O_2, so they have an index of zero. On that base, 209 wells can be considered for the analysis. 160 of them are regularly treated by H_2O_2 - in average once every two months - and 49 have no treatments at all. The remaining wells do not meet these conditions.

In order to identify the most reliable clogging indicator their relation to well characteristics and hydrochemical parameters that are expected to be clogging-related were investigated. The aim was to identify the value that shows the most significant differences in clogging related well characteristics and hydrochemical parameters. This would then be used for further statistical investigations. The considered clogging-related well characteristics and hydrochemical parameters are:

- Well age, total well depth, total filter length, number of filters, top of the first filter, distance to next surface water
- E_H, pH, O_2, Fe, Mn, NO3-N, DOC
- mean rehabilitation interval of the well
- operating hours per month, mean discharge (sum of total discharge / sum of total operating hours)

Looking at the relation between *no* and *intense clogging* identified by TV camera inspections the following results can be stated:

The probability of clogging increases with decreasing distance to the next surface water (Figure 28). This confirms the experiences of *BWB*, that wells abstracting a high share of bank-filtrate tend to be more affected by clogging processes (SCHMOLKE 2006). 75 % of the wells showing an intense clogging are located in a distance less than 250 m from the next surface water. Certainly, there are deviations as can be seen especially from the three indicated outliers. However, the mean of the two value distributions can be stated as being statistically highly significant (please see also Table 11 on page 42).

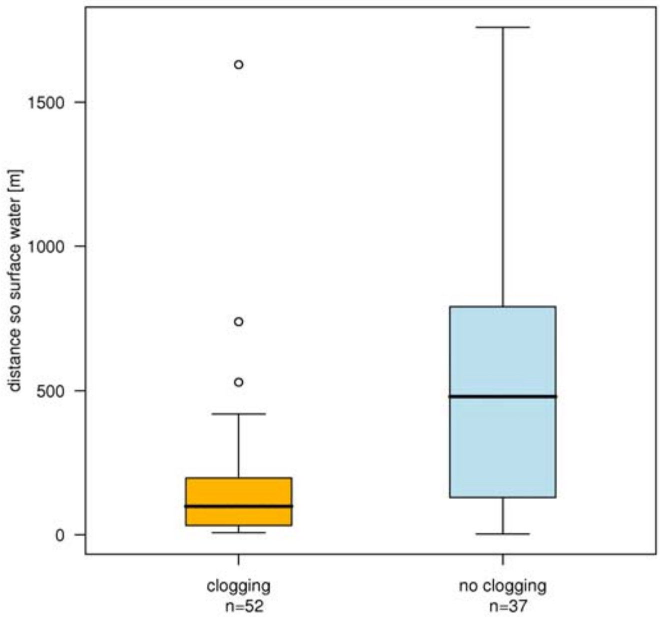

Figure 28: Distance to next surface water of Berlin wells related to clogging

A similar trend can be identified for iron concentrations in clogged wells (Figure 29 Wells with an intense clogging have a mean content of 1.33 mg/L iron which is significantly lower than in wells without clogging indication (mean 1.99 mg/L). An explanation for the lower iron contents could be oxidation processes, which result in iron incrustations. The iron oxides precipitate in the well and are responsible for clogging. Therefore, the mean content of dissolved iron is lower in clogged wells than in wells, which do not clog – assuming that in general the original content of dissolved iron is similar in the Berlin water resources.

In contrast, manganese shows higher contents in the clogged wells (Figure 30). Obviously, slightly oxic conditions lead not to an oxidation of manganese ions. Therefore, in the Berlin wells grey manganese precipitations are found less frequent than the brown and reddish iron precipitations. In *non-clogged* wells, the manganese contents are generally lower. This might be a hint that *clogged* wells originally show a higher iron and manganese load. Whereas the iron contents decrease due to oxidation, the manganese content does not change. Definitely, manganese reacts chemically more inert compared to iron and nitrate (see below).

However, the basic load can only be identified by transects up and downstream of the wells.

Furthermore it needs to be considered, that hydro-chemical parameters are not measured depth oriented but in mixed water. Therefore, the reduction zones cannot be identified clearly leading to conflicts in interpretation.

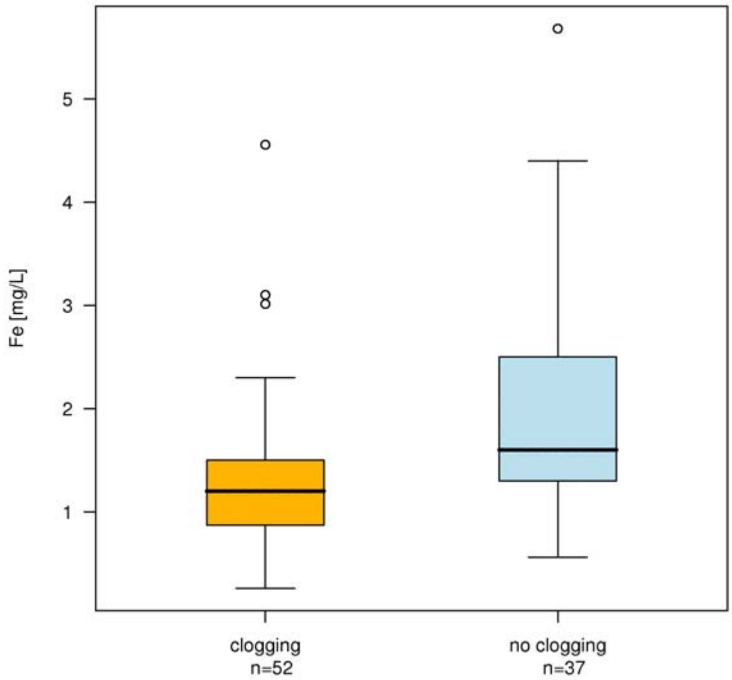

Figure 29: Median iron concentrations in Berlin wells related to clogging

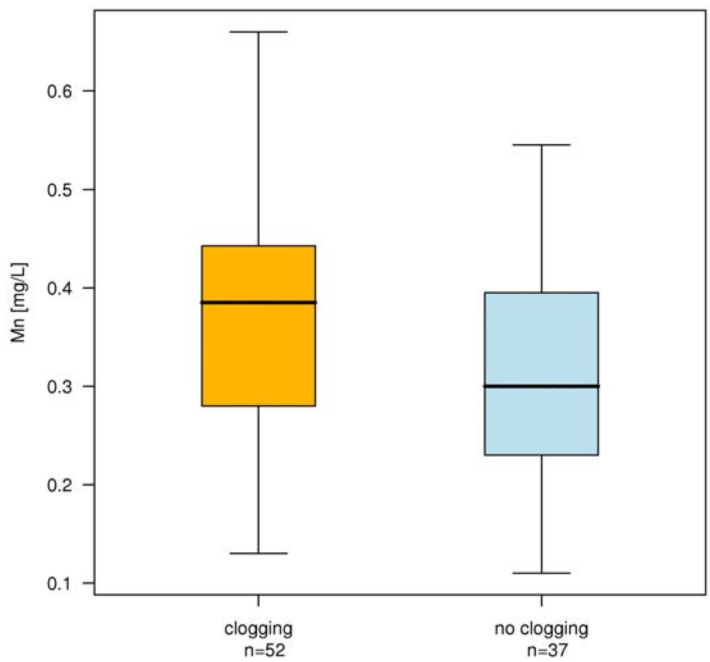

Figure 30: Median manganese concentrations in Berlin wells related to clogging

Appropriate to the lower content of dissolved iron, the Berlin wells with clogging show slightly higher concentrations of nitrate (Figure 31), which is an indicator for a higher redox status. Nitrogen compounds might promote the living conditions for iron related bacteria due to their nutrient properties.

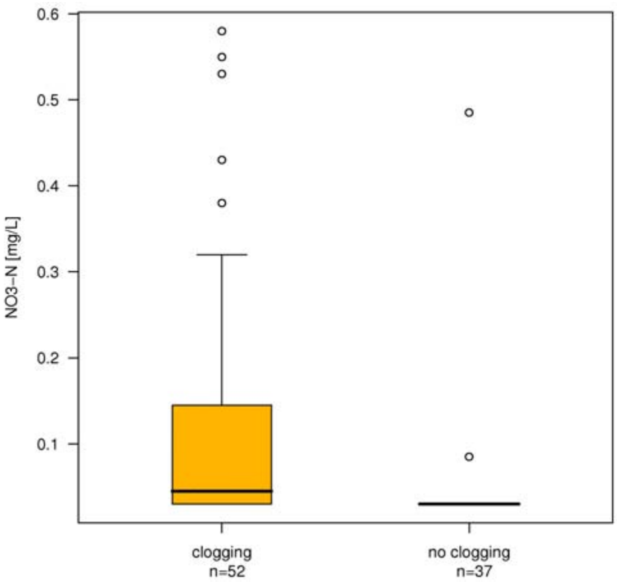

Figure 31: Median nitrate-N concentrations in Berlin wells related to clogging

Additionally a strong relation between the total operating hours and the clogging status can be detected (Figure 32). Whereas the mean for clogged wells is 338 hours per month the mean of operating hours in non-clogged wells is at 242 operating hours per month (see also Table 11).

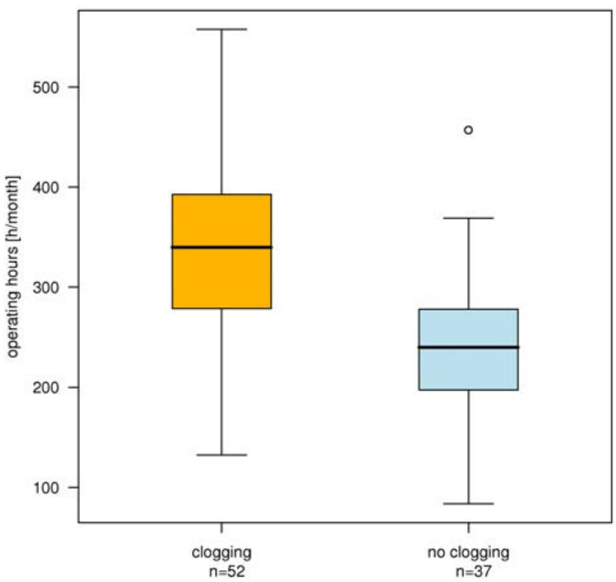

Figure 32: Operation hours per month of Berlin wells related to clogging

A similar connection can be stated for the total mean discharge. The *clogged* wells have a mean of 119 m³/h, the *non-clogged* wells of only 82m³/h. Both, operating hours and total mean discharge correspond well with the current knowledge about clogging processes, stating that well ageing increases with operating hours and discharge (DVGW 2001, RUBBERT & TRESKATIS 2008). A higher discharge enables higher loads of iron, manganese, nitrate, oxygen and organic nutrients, which supports living conditions for iron bacteria.

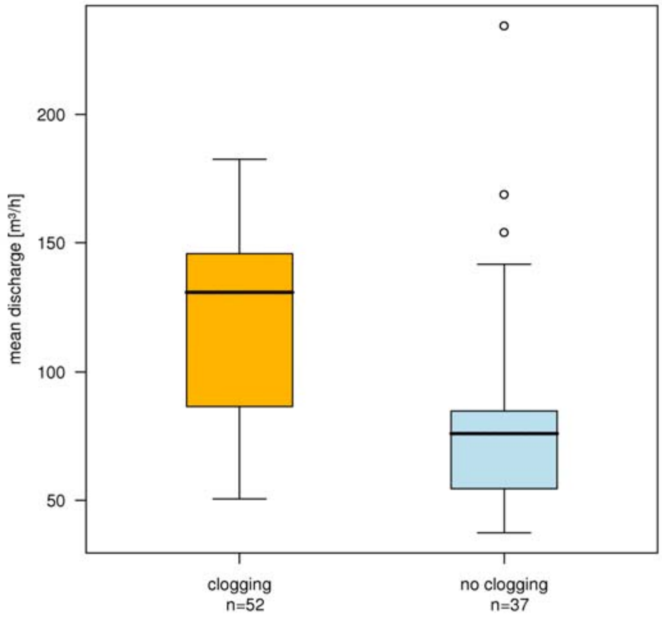

Figure 33: Total mean discharge of the Berlin wells related to clogging

Table 11: Results of Welch Two sample test for clogging and no clogging indicated by TV camera inspection

Parameter	p-value	Mean clogging	Mean no clogging	t	df
Well age [a]	0.259	27.78	25.73	1.14	75
Total well depth [m]	0.436	43.4	40.7	0.78	71
Total Filter length [m]	*0.027	17.1	12.6	2.25	69
Number of filters [n]	**0.009	0.10	0.68	2.66	86
Top of the first filter [m]	0.073	21.6	24.2	-1.82	70
Distance to next surface water [m]	***0.000	168	583	-4.63	49
Eh [mV]	0.198	157	148	1.30	84
pH	**0.005	7.38	7.32	2.84	68
O2 [mg/L]	0.834	0.34	0.34	-0.21	64
Fe [mg/L]	**0.002	1.33	1.99	-3.11	58
Mn [mg/L]	*0.013	0.37	0.31	2.54	73
NO3-N [mg/L]	**0.002	0.12	0.04	3.20	81
DOC [mg/L]	0.415	4.45	4.18	0.82	49
Mean reha interval [a]	0.441	6.22	6.00	0.77	87
Operating hours per month [h/m]	***0.000	58	133	5.06	86
Mean total discharge [m³/h]	***0.000	21	54	4.41	71

*marginal significant, **significant , *** highly significant

Finally, it can be stated that TV camera inspections seem to be an adequate means to identify relevant clogging parameters. Nine of the 16 tested parameters have a significant difference of their means, whereas distance to next surface water, operating hours and mean total discharge are highly significant (Table 11).

The remaining seven parameters show no significant differences in their mean. The only parameter having no difference though theoretically it is a relevant clogging parameter is oxygen content. However, this might be due to general measuring inaccuracy for oxygen contents. Furthermore, an interpretation of the value distributions presented in the boxplots suits well to the knowledge about clogging processes.

The second hypothesis that a decreasing specific capacity *Qs* is an indicator for clogging was tested in the same way. The results of the *Welch Two sample test* reveal only five significant deviations in the mean for the two groups of wells with and without *Qs* reduction (Table 12). Certainly, the mean rehabilitation interval is significant because well rehabilitations are executed consequently due to noticeable *Qs* reductions. Therefore only well age, depth of the first filter, manganese content and operating hours support a logical relation to well clogging. So, the relation to clogging is not as strong as for the TV camera inspections.

Table 12: Results of Welch Two sample test for Qs reduction and no Qs reduction

Parameter	p-value	Qs reduction per year	no Qs reduction per year	t	df
Well age [a]	***0.000	21.1	26.6	-3.81	76
Total well depth [m]	0.328	41.6	38.7	0.98	92
Total Filter length [m]	0.451	12.8	13.9	-0.76	85
Number of filters [n]	0.609	1.24	1.31	-0.51	70
Top of the first filter [m]	*0.017	25.8	26.7	2.44	83
Distance to next surface water [m]	0.123	339	216	1.55	89
Eh [mV]	0.667	139	142	-0.43	78
pH	0.972	7.37	7.37	-0.03	60
O2 [mg/L]	0.070	0.347	0.304	1.83	91
Fe [mg/L]	0.996	1.61	1.61	0.01	53
Mn [mg/L]	**0.001	0.32	0.42	-3.34	61
NO3-N [mg/L]	0.073	0.04	0.07	-1.85	37
DOC [mg/L]	0.064	4.02	4.55	-1.90	75
Mean reha interval [a]	**0.007	5.7	6.5	-2.77	72
Operating hours per month [h/m]	***0.000	352	259	4.02	68
Mean total discharge [m³/h]	0.361	93	101	-0.92	66

*marginal significant, **significant , *** highly significant

To rank third the hypothesis that wells with H_2O_2-treatments tend to clog this parameter will also be compared with the available dataset. Like for the TV camera inspections there are eleven significant deviations from the particular means for wells with or without H_2O_2 treatment (Table 13):

Table 13: Results of Welch Two sample test for H_2O_2 and no H_2O_2 treatment

Parameter	p-value	H_2O_2	no H_2O_2	t	df
Well age [a]	**0.001	25	32	-3.86	60
Total well depth [m]	*0.019	306	261	-4.50	78
Total Filter length [m]	**0.002	12	18	-3.21	56
Number of filters [n]	**0.013	1.4	1.9	-2.57	60
Top of the first filter [m]	*0.014	22.3	26.6	-2.54	53
Distance to next surface water [m]	***0.000	423	196	4.35	153
Eh [mV]	***0.000	150	128	4.43	96
pH	0.927	7.37	7.37	-0.09	74
O2 [mg/L]	0.570	0.36	0.34	0.57	61
Fe [mg/L]	***0.000	1.43	2.32	-5.25	64
Mn [mg/L]	*0.046	0.35	0.3	2.03	83
NO3-N [mg/L]	***0.000	0.07	0.04	3.70	188
DOC [mg/L]	0.367	4.14	4.36	-0.91	70
Mean reha interval [a]	0.310	6.4	6.7	-1.02	66
Operating hours per month [h/m]	*0.019	306	261	2.40	78
Mean total discharge [m³/h]	0.819	97	95	0.23	77

*marginal significant, **significant , *** highly significant

The T-test comes up with the result, that wells what are younger and closer to surface water are not treated by H_2O_2. However, the problem about H_2O_2-treatment as a clogging indicator is that it certainly interferes with clogging processes. Furthermore, it is mainly controlled by economical and operational decisions. Therefore, it is not an appropriate indicator for clogging affinity.

In general, there remain inconsistencies by combining the identified parameters with the theoretical background.

The first step of the analysis yields, that TV camera inspections are an adequate and robust measure to identify the characteristic parameters of wells, which tend to clog.

Pump Switchings

Additionally, the parameter pump switchings – which is only available for a selection of waterworks - was set in relation to the chosen clogging index *TV camera inspections*.

The experience of *BWB that* a higher frequency of pump switchings promotes clogging processes, can be confirmed. However, this might also be due to the fact, that, the results of TV camera inspections are used anyway to decide which wells should be switched less to slow down the clogging processes.

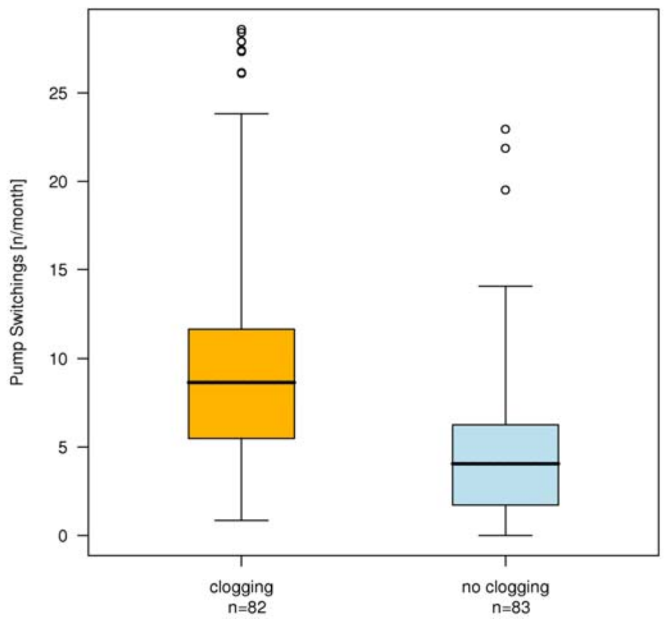

Figure 34: Pump switchings of the Berlin wells in related to clogging

3.3 Parameters related to clogging

After having identified TV-camera inspections as a reliable clogging indicator with the data subsets of highly *clogged* and *non-clogged* wells, in the next step the question dealt with is if it is possible to identify conditions which are typically for clogging in all comparable samples. However, it has to be considered that the database information includes only the latest status of clogging. Therefore, the information has no temporal resolution.

To check the link between clogging related parameters and the degree of clogging, the parameters were plotted against the four stages *no clogging* (0), *light clogging* (1), *medium clogging* (2) and *intense clogging* (3) (see chapter 2.2).

To have a comparable dataset the following investigations are made by a selection of 367 wells that include all relevant parameters for well construction, hydrochemical data, and well performance. Data of the waterworks in *Kladow* and *Spandau* are not included because they have not enough comparable datasets for hydrochemistry.

Well Construction

First, the hypothesis that well clogging is related to well age and construction parameters was checked.

Looking at Figure 35, the degree of clogging shows a dependency on well age as reported from other sites (SCHMOLKE 2006, RUBBERT & TRESKATIS 2008). Older wells have more residues of clogging because they cannot be totally cleaned anymore. This is the reason why TV camera inspections come up with the result of increasing clogging with age.

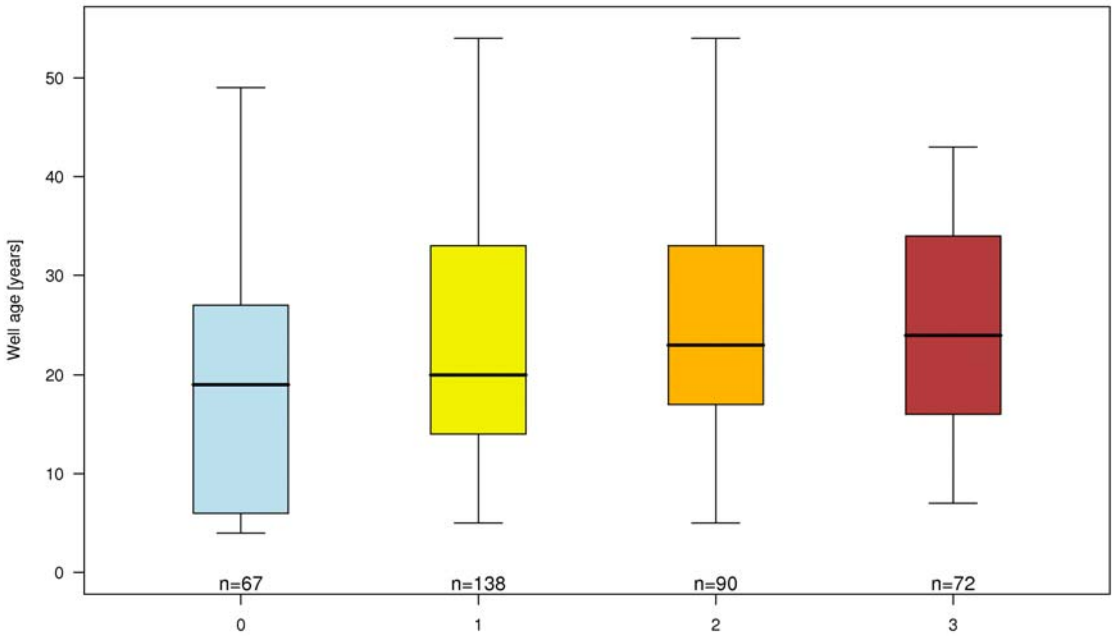

Figure 35: Well age of Berlin wells compared to clogging tendency (0 = no clogging, 3 = intense clogging)

Light trends corresponding to clogging intensity can be seen as well by plotting the depth of top of the first filter (Figure 36). The data confirm the trend, that filters, which are closer to the surface tend to clog to a greater extent, which itself might be linked to higher oxygen contents closer to the groundwater surface (Hölting 1989).

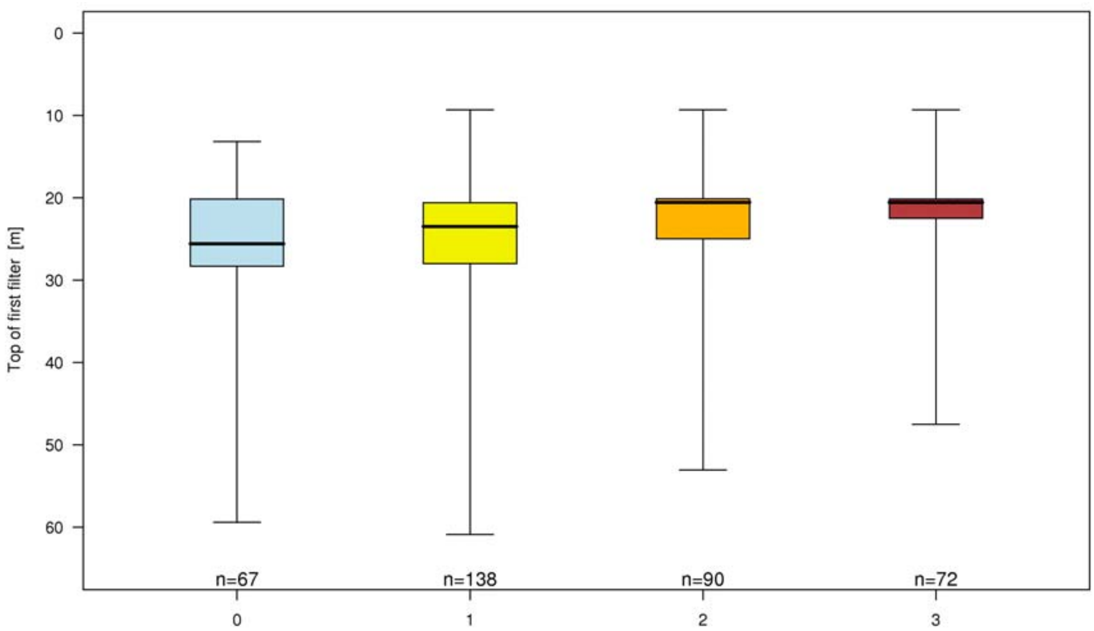

Figure 36: Top of the first filter of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

An increasing number of filters and therefore an increasing filter length has a light influence to clogging. But it seems to be of less importance than the position of the filter beneath the surface.

According to practical experience in Berlin, wells that abstract a higher amount of bank-filtrate tend to clog more easily (SCHMOLKE 2006). However, neither the distance to surface water nor the classification of the origin of water reflects this trend clearly (see graphs in Appendix A). Probably the approximated classifications are too inaccurate (see chapter 2.2), but the detailed groundwater hydraulics could not be considered. Furthermore, not for all wells the source of water could be clearly determined and modifications in water management can result in changes with time.

The parameters well depth, number of filters, total filter length, distance to next surface water and $Q_{tolerated}$ show a weak or no connection to clogging intensity. The respective figures are given in the appendix clearly (see graphs in Appendix A).

In general, there seems to be a relation between well age and filter characteristics and clogging status. Therefore, some more detailed analysis for the waterworks and its well galleries were executed. To reduce complexity in the figures, the four stages of clogging were summarized to two stages. The wells of the classes *0* and *1* are marked as *non-clogged wells* whereas *2* and *3* are marked as *clogged wells*.

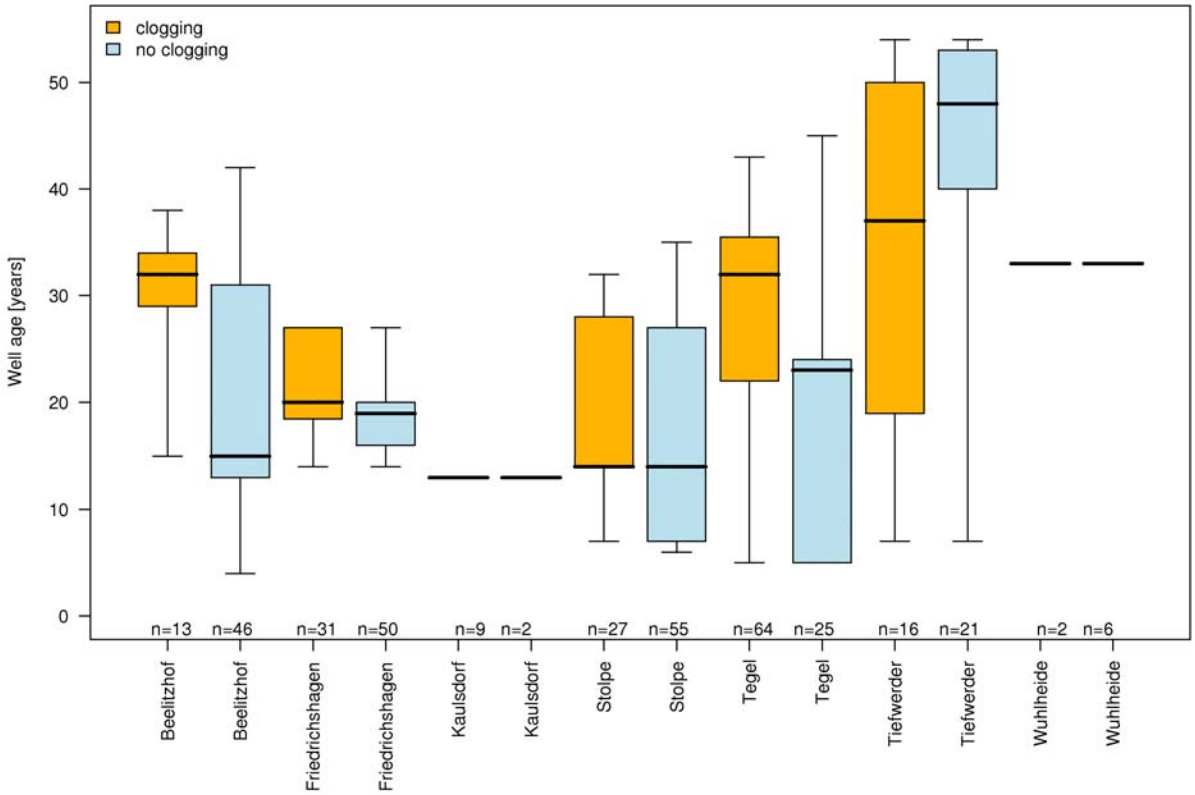

Figure 37: Well age in the Berlin waterworks compared to clogging behaviour

By analysing the clogging behaviour on the scale of waterworks it can be stated, that not always the older wells tend to clog (Figure 37). For the major waterworks of Beelitzhof, Friedrichshagen and Tegel clogged wells are clearly older than non-clogged wells. The waterworks Stolpe seems to follow that trend. But for the waterworks Tiefwerder the opposite trend can be observed. Tiefwerder has less clogging affinity. This might be due to a specific feature of these wells as most of them are filtered with copper screens. BWB made the experience that copper filters show less clogging (statement by E. Höhndorf, BWB). For Kaulsdorf and Wuhlheide all wells have the same construction year, therefore no differentiation between age and clogging can be observed. Nevertheless, some of them tend to clog whereas the others do not.

A similar result can be stated for a more detailed view of the depth of top edge of the first filter (Figure 38). For the waterworks *Beelitzhof, Kaulsdorf, Stolpe, Tiefwerder* and *Wuhlheide* wells with filters near to the surface are more affected by clogging. The trend can only be seen in waterworks where filter depth varies significantly. *Friedrichshagen* and *Tegel* show no differentiation because they are mainly filtered in the same depth.

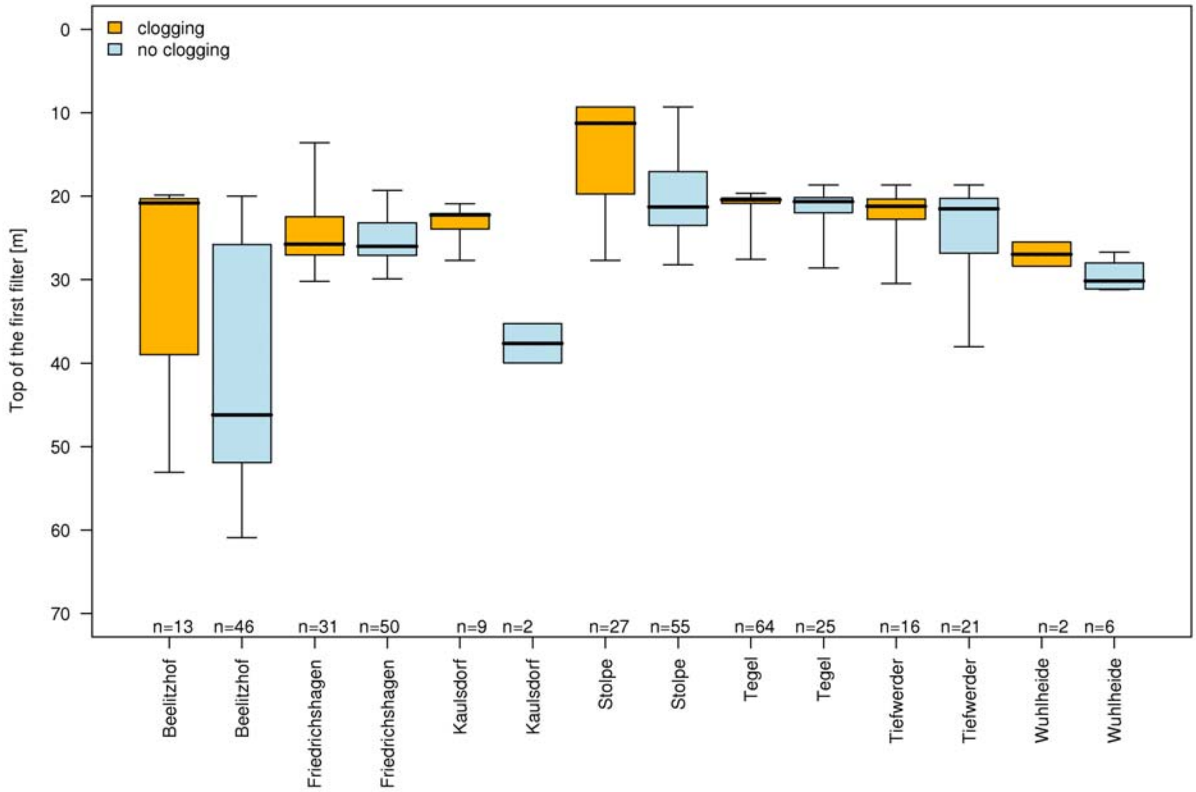

Figure 38: Top of the first filter in the Berlin waterworks compared to clogging behaviour

More detailed analysis by comparing well field by well field or finally well by well leads to an increase of variability in the clogging pattern related to well construction parameters.

It can be stated that there is a general trend for clogging with well age and in near surface filtered wells. However, an evaluation of this relation in more detail also shows an increase of exceptions.

Hydrochemical Data

For the comparison of hydro-chemical data with clogging affinity, the parameters redox potential, pH, oxygen, iron, manganese and dissolved organic carbon were considered. Figures for parameters not shown here are given in the Appendix A.

Looking at the data reveals again that increasing clogging intensity comes along with decreasing dissolved iron concentrations and increasing manganese and nitrate-nirogen concentrations (Figure 39, Figure 40). The detected trend can be confirmed for all stages of clogging although the concentrations differ only slightly. This clarifies that only a light variation of well conditions is critical for *clogging* or *no clogging.* Furthermore, it is an explanation for the small-scale variations from well to well.

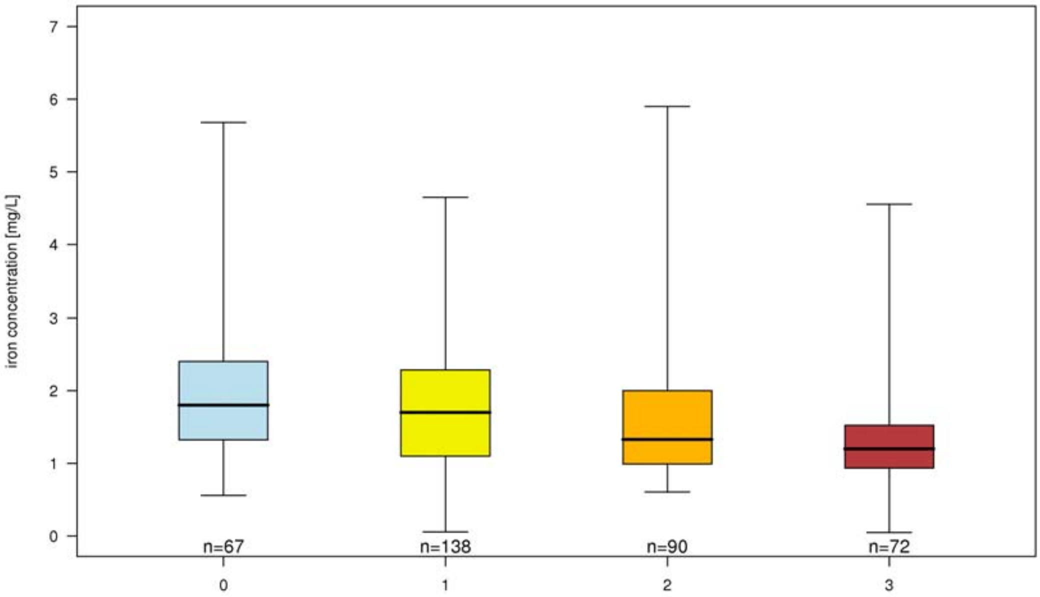

Figure 39: Iron concentrations of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

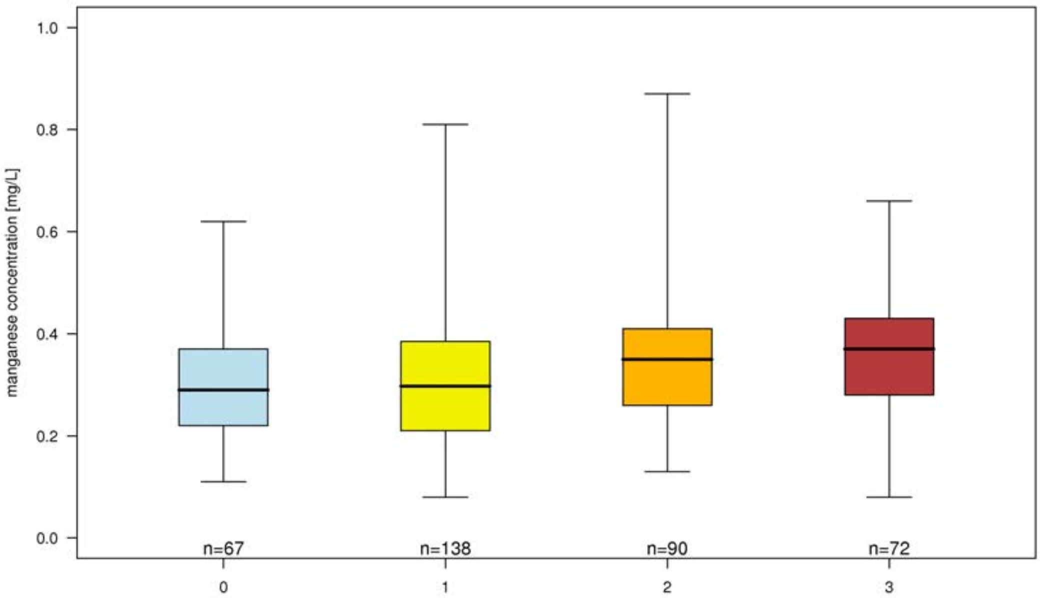

Figure 40: Manganese concentrations of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

The trend of observing lower iron concentrations in clogged wells is checked in more detail for the different waterworks of Berlin (Figure 41). Like for the well construction parameters, the hydrochemistry reveals again an increased variability. Nevertheless, in most waterworks at least half of the iron concentrations in clogged wells have lower iron concentrations. Only in *Wuhlheide* it is completely the opposite. The two wells that tend to clog have a significant higher iron concentration than the non-clogged wells. Well construction data show that all wells in the gallery have the same age and construction.

This is a typical case that cannot be explained by general trends for clogging but shows the individuality of wells. On the spatial scale of waterworks, the variability in data is increasing and the relation cannot be explained by statistics anymore.

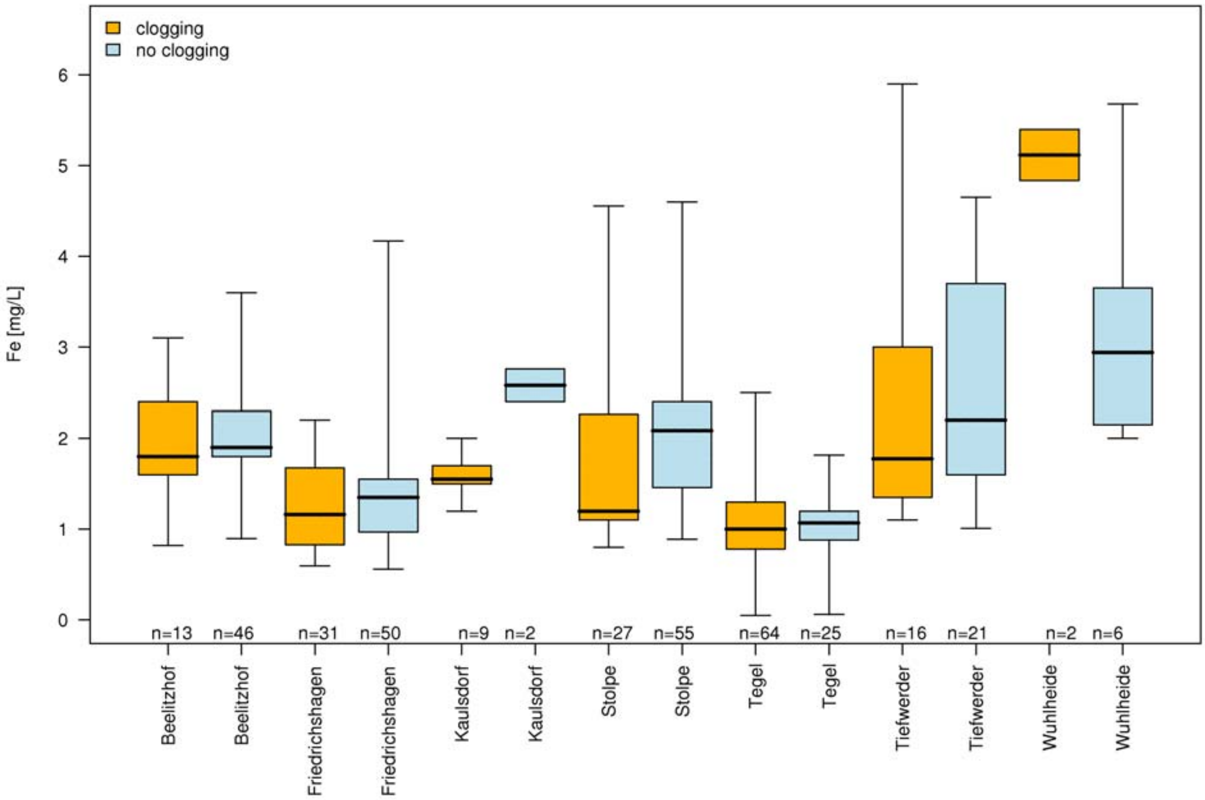

Figure 41: Iron concentrations in the Berlin waterworks compared to clogging behaviour

Well Performance

Finally, trends in well performance parameters were investigated for all four stages of clogging.

An increase in mean monthly operating hours and mean discharge can be related to increasing clogging (Figure 42, Figure 43). This trend can be generally confirmed in a more detailed view of all waterworks (Figure 44). More operating hours seem to enhance well clogging with exception of the waterworks Kaulsdorf and Wuhlheide. However, this can be due to the fact that these wells are usually operated in a nearly constant mode. An interesting observation is that Beelitzhof has less clogging affinity though it has a high range of operating hours, what indicates a high variety in hydraulic conditions.

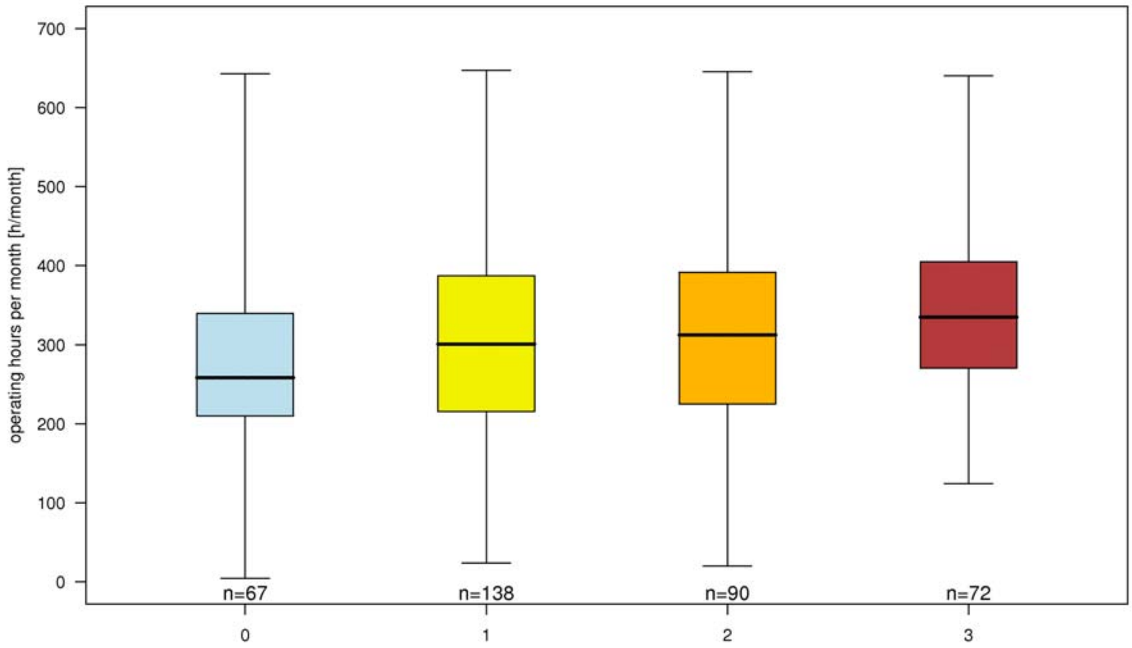

Figure 42: Operating hours of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

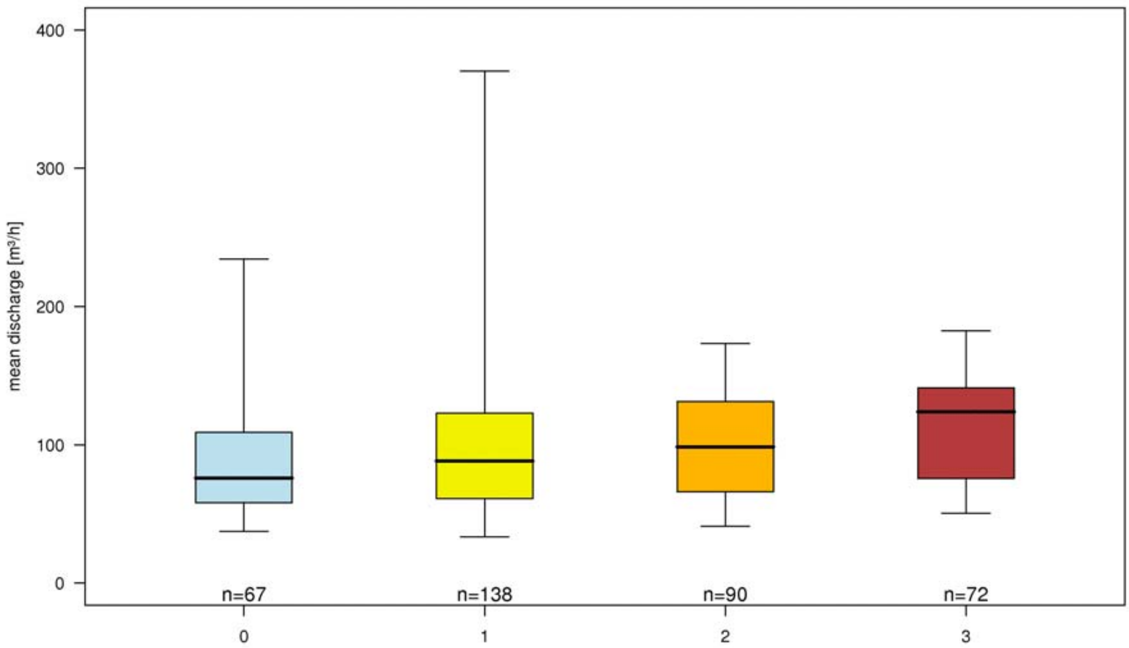

Figure 43: Mean discharge of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

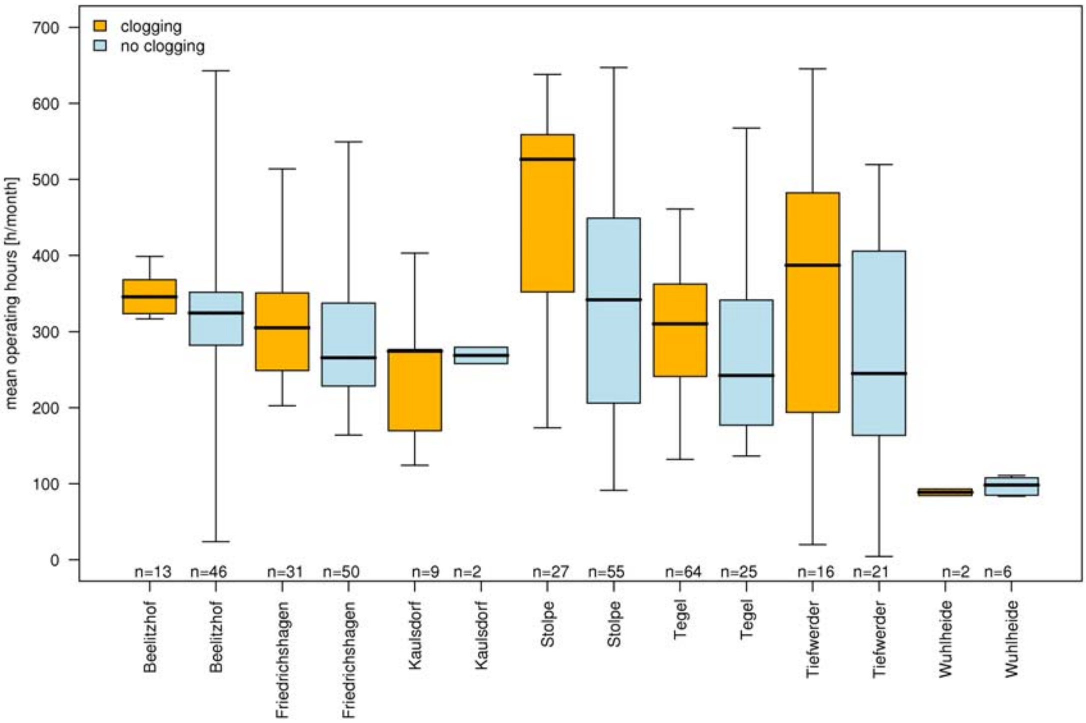

Figure 44: Operating hours per month in the Berlin waterworks compared to clogging behaviour

3.4 Evaluation of parameters related to clogging

For an evaluation of the clogging related parameters, a multiple linear regression model is used. By this method, the cumulative correlation between the independent variables and the identified clogging indicator *TV camera inspections* is quantified. The regression is applied although a bivariate correlation of all the selected variables did not lead to satisfying results. The advantage of the multiple linear regression is, that it can be used to analyze how far the independent variables can predict clogging, and respectively which of the independent variables of the previously investigated parameters explains the highest proportion of the dependent variable *clogging.*

Ten of the investigated variables are included in the regression, because the bivariate statistics indicated a relation to clogging. The selected well construction variables are

- well age (age),
- number of filters (NrF),
- top of the first filter (TFF),
- total filter length (TFL) and
- distance to next surface water (Dist)

Concerning the hydrochemical parameters

- the iron- (Fe),
- manganese- (Mn) and
- nitrate (NO3-N) concentrations

seem to be most representative for well clogging processes.

For well performance, the parameters

- mean monthly operating hours (OPH) and
- the mean discharge (meanQ)

are chosen.

In the resulting model, first the top of the first filter is added, followed by mean discharge, iron content, well age, operating hours and manganese concentrations (Table 14).

R^2 shows the strength in the relation between the independent parameters of well construction, hydrochemistry, well performance and the dependent variable clogging. Finally, the model reveals that only a very small amount of the variance of clogging can be explained by the independent variables. This can be seen in the R^2 and adjusted R^2 value of only about 20% (step 6 in Table 15).

This really weak relationship shows that only a fifth of the variance of clogging can be explained by the independent variables, although all of them contribute a small amount.

Table 14: Steps of entered variables in the regression model

	Variable 1	**Variable 2**	**Variable 3**	**Variable 4**	**Variable 5**	**Variable 6**
Step 1	TFF					
Step 2	TFF	meanQ				
Step 3	TFF	meanQ	Fe			
Step 4	TFF	meanQ	Fe	age		
Step 5	TFF	meanQ	Fe	age	OPH	
Step 6	TFF	meanQ	Fe	age	OPH	Mn
	Dependent Variable: **Clogging** indicated by TV camera inspections					

Table 15. Summary of the regression model

Step	R	R^2	Adjusted R^2	Standard error of the estimate
1	0.273	0.075	0.072	0.967
2	0.377	0.142	0.137	0.933
3	0.400	0.160	0.153	0.924
4	0.431	0.186	0.177	0.911
5	0.450	0.203	0.191	0.903
6	0.466	0.217	0.204	0.896

In the coefficient statistics, all entered variables are already tested for their linear relationship. For all introduced independent variables the significances is smaller than 0.05, meaning that the relationship to clogging is not by coincidence (Table 16).

Table 16: Analysis of Variance (ANOVA) of the Regression model

Model		Sum of Squares	df	Mean	F	Significance
1	Regression	27.542	1	27.542	29.440	,000(1)
	Residual	341.466	365	0.936		
	Total	369.008	366			
2	Regression	52.450	2	26.225	30.155	,000(2)
	Residual	316.558	364	0.870		
	Total	369.008	366			
3	Regression	58.946	3	19.649	23.003	,000(3)
	Residual	310.063	363	0.854		
	Total	369.008	366			
4	Regression	68.658	4	17.164	20.688	,000(4)
	Residual	300.350	362	0.830		
	Total	369.008	366			
5	Regression	74.724	5	14.945	18.333	,000(5)
	Residual	294.284	361	0.815		
	Total	369.008	366			
6	Regression	80.126	6	13.354	16.642	,000(6)
	Residual	288.882	360	0.802		
	Total	369.008	366			

For a comparison of the partial regression coefficients, the standardized Beta-coefficients need to be considered (Table 17). There it can be seen how the explanatory content varies slightly by adding a new variable.

Finally, the mean discharge (meanQ) has the highest explanatory content followed by depth of the first filter (TFF). To see if the model suits the theory, the coefficients need to be checked for plausibility. That can be easily done by checking if the relationship is positive or negative. The coefficients for mean discharge, well age, operating hours and manganese are correlated positively with increasing clogging. Decreasing depth of the top of first filter (TFF) and decreasing iron content is correlated negatively with increasing clogging. It can be concluded that the model bears the theoretical background because all relations are reflected as theoretically expected.

Collinearity, that is correlations between one or more of the independent variables, are tested by the Tolerance T and Variance Inflation Factor VIF. Values should be higher than 0.1 for the Tolerance and under 10 for VIF. This is given for the data set looked at (see Table 17). The independent variables are not collinear (BROSIUS 1998).

Finally, it is tested if the residuals are varying by coincidence and have a normal distribution. Both tests are can be confirmed.

Table 17: Coefficients of the regression model and collinearity

Model		Unstandardized coefficients		Coefficients	T	Significane	Collinearity Statistics	
		B	Standard Error	Beta			T	VIF
1	(constant)	2.168	0.141					
	TFF	-0.029	0.005	-0.273	15.404	0.000	1.000	1.000
2	(constant)	1.725	0.159		-5.426	0.000		
	TFF	-0.037	0.005	-0.350	10.858	0.000	0.920	1.087
	meanQ	0.006	0.001	0.271	-6.909	0.000	0.920	1.087
3	(constant)	1.947	0.177		5.352	0.000		
	TFF	-0.034	0.005	-0.318	11.012	0.000	0.875	1.143
	meanQ	0.006	0.001	0.246	-6.187	0.000	0.893	1.120
	Fe	-0.143	0.052	-0.137	4.839	0.000	0.939	1.065
4	(constant)	1.622	0.199		-2.758	0.006		
	TFF	-0.030	0.005	-0.283	8.169	0.000	0.840	1.191
	meanQ	0.006	0.001	0.230	-5.463	0.000	0.885	1.130
	Fe	-0.179	0.052	-0.171	4.573	0.000	0.901	1.110
	age	0.014	0.004	0.168	-3.425	0.001	0.936	1.069
5	(constant)	1.126	0.268		3.421	0.001		
	TFF	-0.027	0.006	-0.251	4.207	0.000	0.798	1.252
	meanQ	0.005	0.001	0.229	-4.768	0.000	0.885	1.130
	Fe	-0.165	0.052	-0.158	4.586	0.000	0.893	1.120
	age	0.017	0.004	0.197	-3.181	0.002	0.891	1.122
	OPH	0.001	0.000	0.136	3.966	0.000	0.890	1.124
6	(constant)	0.736	0.305		2.728	0.007		
	TFF	-0.021	0.006	-0.203	2.409	0.017	0.710	1.408
	meanQ	0.005	0.001	0.217	-3.671	0.000	0.876	1.141
	Fe	-0.194	0.053	-0.186	4.346	0.000	0.852	1.174
	age	0.016	0.004	0.194	-3.687	0.000	0.890	1.123
	OPH	0.001	0.000	0.142	3.929	0.000	0.888	1.126
	Mn	1.034	0.399	0.131	2.877	0.004	0.859	1.164

The regression model reveals that only around 20 % of the variance in clogging can be explained by the introduced variables depth of the filter, mean discharge, iron, well age, operation hours and manganese. All of them are obviously related to clogging and seem to be plausible in the context of clogging processes (see chapter 3.3).

However, 80% of this variance is still unknown. Obviously, the indication for clogging suffers from multivariate interaction of processes that can hardly be represented with the available data. In addition, the used clogging indicator – observations of TV-camera inspections – is not very detailed at the moment. These can be some reasons why the relationship between clogging and the selected parameters is only 20%. It will be discussed in more detail in the conclusions and recommendations.

Chapter 4 Conclusions and Recommendations

4.1 Summary

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

(1) Identification of a reliable clogging indicator,

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

(3) Conclusions for grouping wells for further investigations.

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

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

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

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

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

4.2 Conclusions

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

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

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

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

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

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

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

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

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

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

4.3 Recommendations for

Well monitoring, diagnosis and operation

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

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

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

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

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

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

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

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

Data analysis and field investigations in WellMa2

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

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

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

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

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

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

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

At the moment, the classified TV-camera inspections yield only static information from the last inspection date. For further investigations, **the time series of all available TV-camera inspections** should be implemented in the database to see if it is possible to use the clogging rate to differentiate the wells. The current analysis showed that it is preferable to focus on a small but defined dataset with reduced data variability. Therefore, it seems to be useful to include only wells with extensive information of camera inspections. Subsequently the strength of any identified trend can be rechecked with a more extensive dataset as it was done during our analyses.

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

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

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

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Appendix A

Boxplots

Well construction

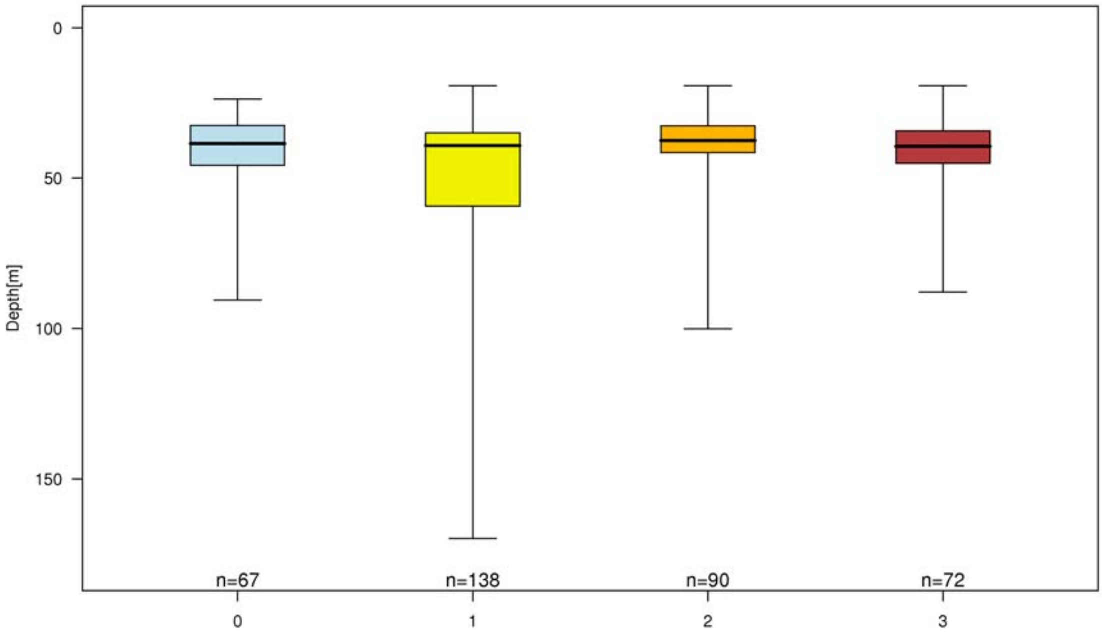

Figure 45: Depth of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

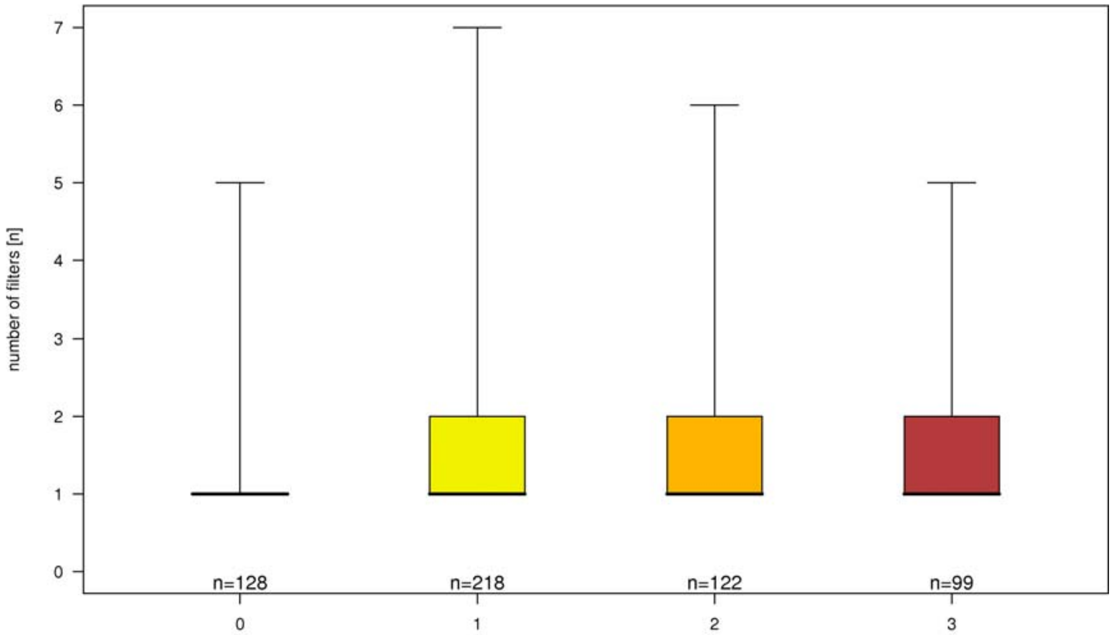

Figure 46: Number of filters of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

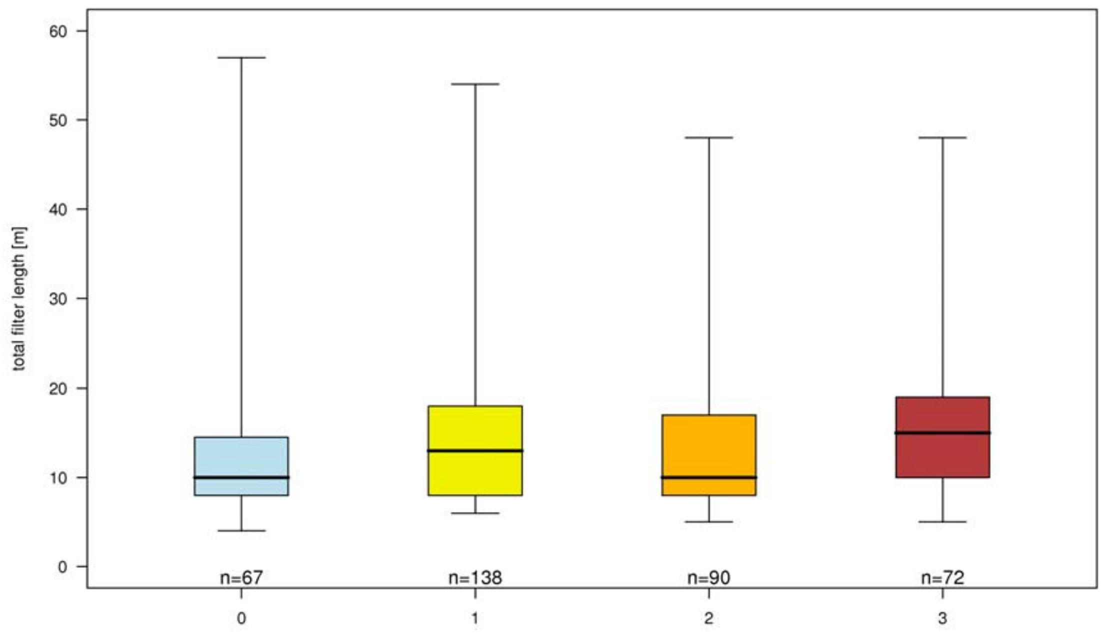

Figure 47: Total filter length of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

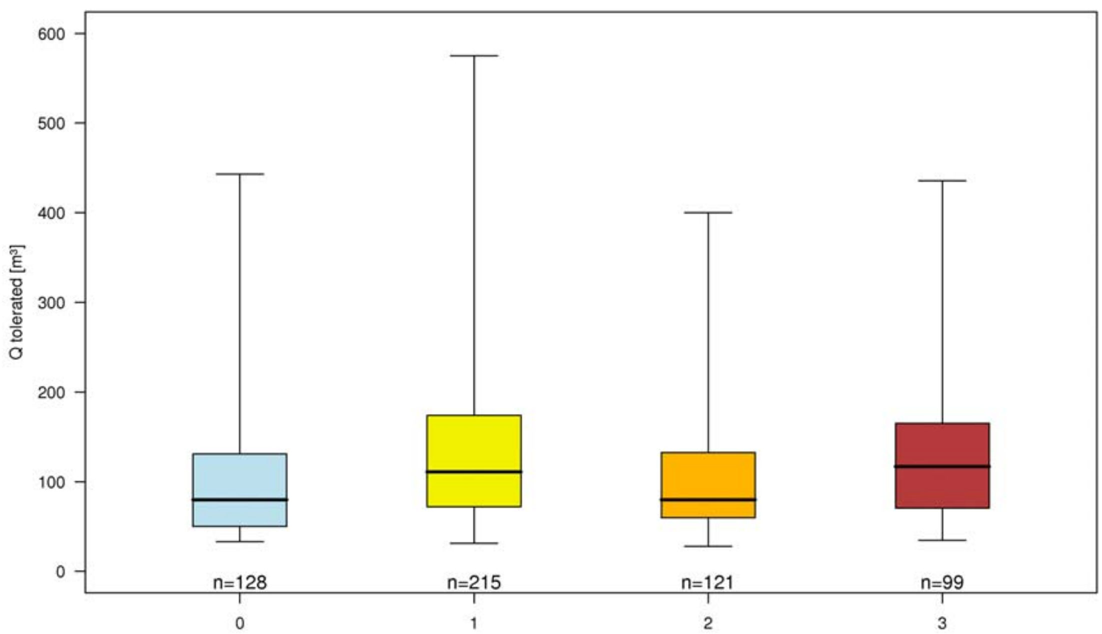

Figure 48: Q tolerated of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

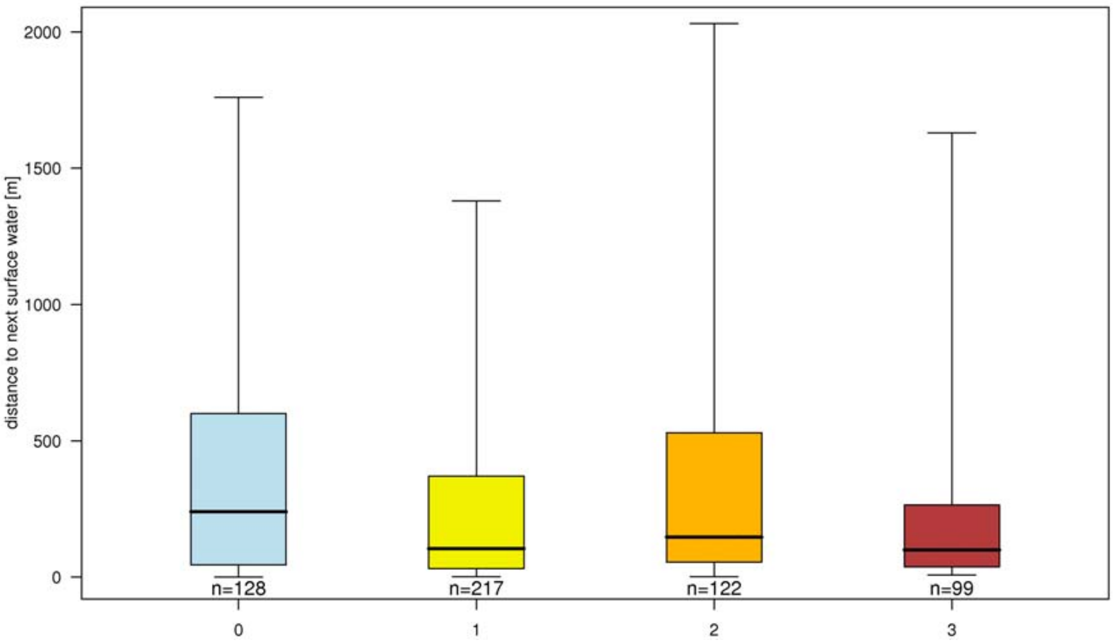

Figure 49: Distance to the next surface water of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

Hydrochemical data

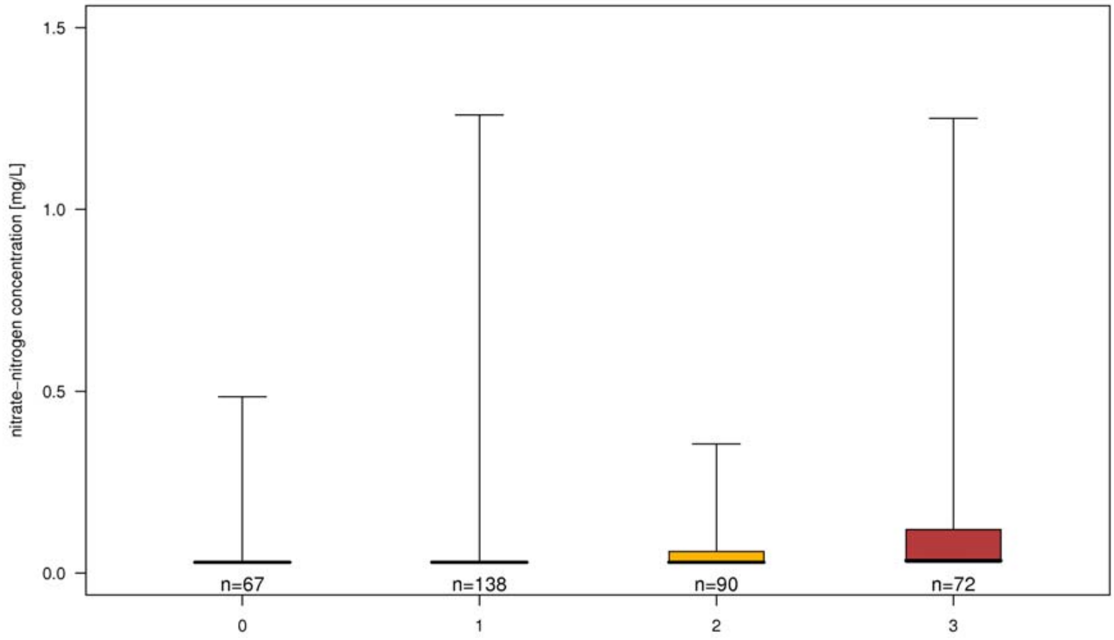

Figure 50: Nitrate-nitrogen concentrations of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

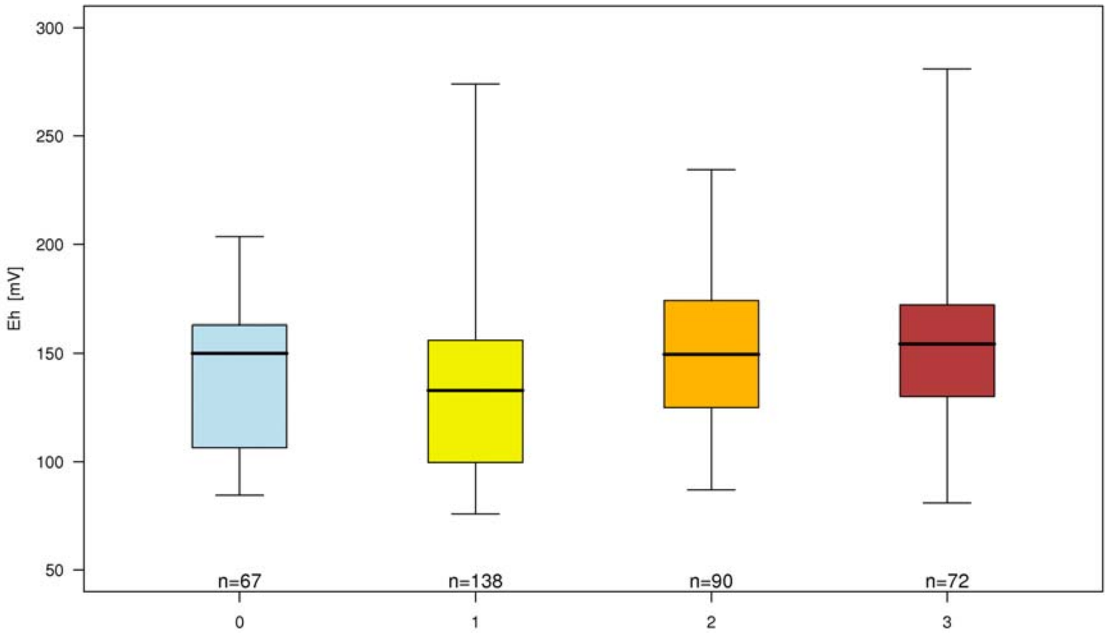

Figure 51: Redox potentials of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

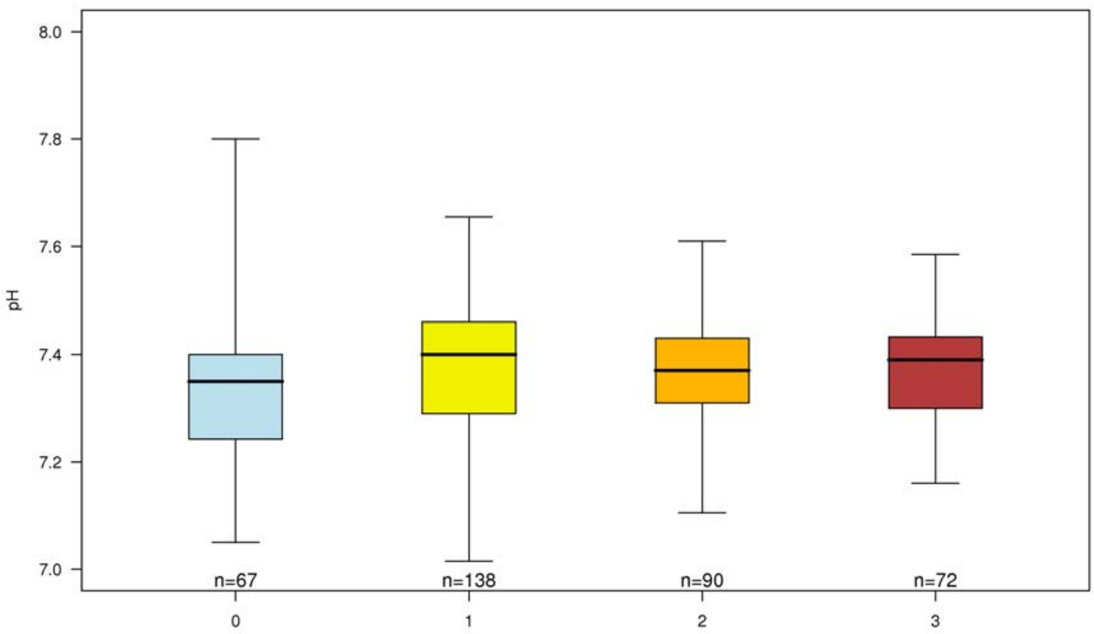

Figure 52: pH of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

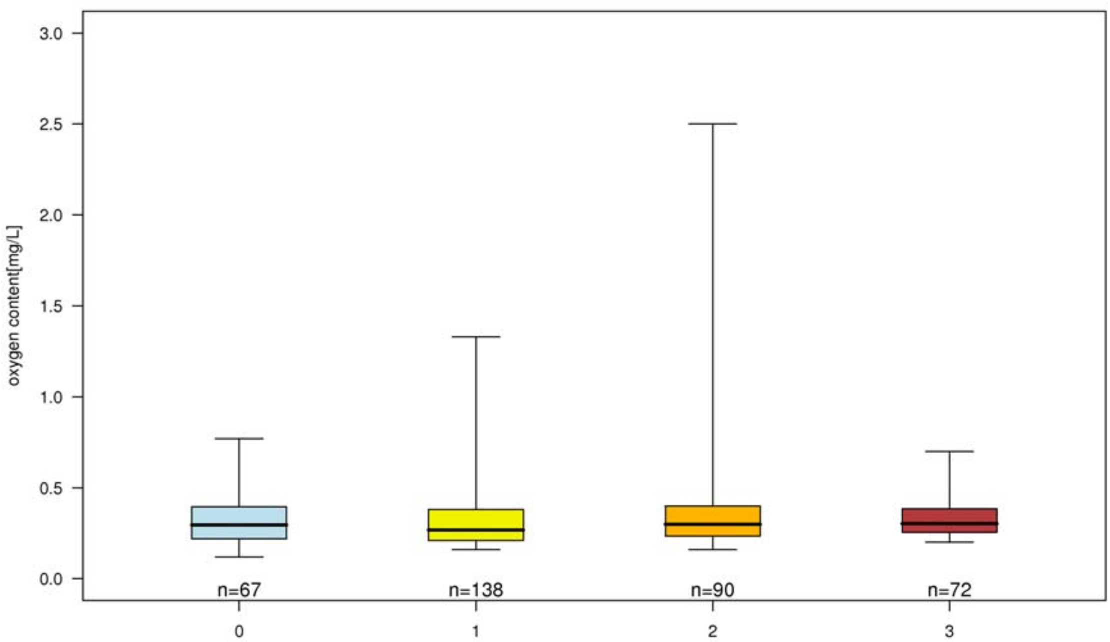

Figure 53: Oxygen contents of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

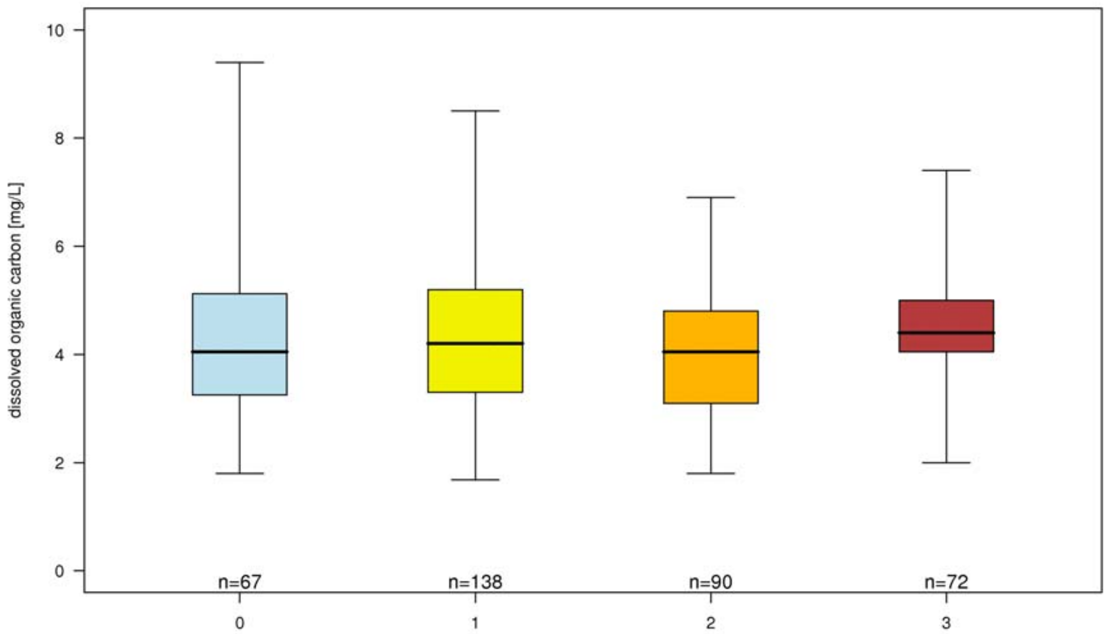

Figure 54: Dissolved organic carbon concentrations of Berlin wells compared to clogging tendency (0 = no clogging; 3 = intense clogging)

Appendix B
Descriptive analysis of French well data

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List of figures and tables

Chapter 1 Objective and Strategy

Part of WP 1, task 1.2 of the WellMa1 project was the use of French well data for statistical analyses. Aim was to identify similarities and differences between all considered well sites and to assess principle relations to the geological and hydrological site conditions. Basis for such a data assessment is a well planned monitoring and documentation of all necessary well data. It should include:

1. Well construction including geology and the origin of the water
    - Material of the screen
    - Filter sections: number, length, depth
    - Diameter: borehole and screen
    - Coordinates: easting, northing, ground level elevation (masl)
    - Year of construction
    - Maximum allowable discharge rate/ well yield (according to the well performance test)
    - Classification of the aquifer (stratigraphy)
    - Lithology: Grain size/ soil texture of the aquifer material
    - Aquifer-type: unconfined/ confined
    - Source of the raw water (groundwater/ bank filtrate/ artificial recharge)
    - Distance to river (or lake) bank / recharge basin
2. Chemical Parameters
    - Time series of selected parameters on water contents and conditions (Ca, Cl, electrical conductivity, DOC, Eh, Fe, HCO3, K, Mg, Mn, Na, NO3-N, NH4-N, O2, pH, SO4, Temp)
3. Performance
    - Rated power of the pump (if so: modifications, with date)
    - Total discharge
    - Total operating hours
    - Drawdown in the well and in the observation well in the gravel pack (calculation of Δh)
    - Maintenance with special regard to rehabilitations
    - Pumping tests: Well performance test before and after rehabilitation
    - Rehabilitation methods and maintenance activities (e.g. shock blasting, brushing, pump changes etc.)
    - Date and observations of camera inspections

As far as possible, time series should be taken starting immediately after the start of operation and continuing with measurements in fixed intervals to allow a comparison and assessment of the development of the well condition.

Challenges for the WellMa project were the heterogeneity of the available data and the fact that all reports and diagnosis summaries were in French language. With the help of Marc Alary of the technical direction of Veolia Eau (Paris) and Marie-Claire Dron, a French trainee going through the data files (KWB), all available valuable information could be extracted to the database and a review document in English. These two sources are the basis for this report.

However, because the database was not set up prior to the project start, as it was done for the Berlin wells, there was not enough time to really validate the data or to fill gaps. So, there were not enough data available to be really representative for the single geological and hydrological conditions, which should be analysed. Therefore, no statistical analysis could be performed, but all available data were summarized and the sites compared beneath each other and with the Berlin conditions.

During the ongoing project, the database should be further filled and validated to use it to verify the investigated trends and interactions between well characteristics and ageing processes.

Chapter 2 Descriptive analysis of French data

Major difference compared to the dataset of Berlin is the presence of different geological background conditions. Therefore, the French data provide the opportunity to consider for example

- Consolidated rocks, especially fissured limestone, versus quaternary sediments with alternating silt, sand or gravel layers
- Processes in carbonate aquifers
- A variety of well designs and according diameters, screen materials et.

Altogether nine sites could be evaluated, in which

- Chateau Thierry and Saignonne represent alluvial sedimentary aquifers
- Moulin de Douves, Roissy and Saint Denis represent deeper (and hence older) sedimentary aquifers
- Lisieux, Mousseaux, Val-de-Reuil and Verdun represent fissured limestone or other chalk aquifers of different ages and depths

Because of the quite good availability of well performance data, focus of this descriptive data analysis lies on the assessment of the development of the specific capacity Qs with operation time against the background of different geological pre-settings and hence the detection of related ageing types and processes.

Basic data to calculate Qs are step tests or short pumping tests containing at least the discharge rate Q and final drawdown (at stable condition) s, which is the difference between static water level and dynamic water level in quasi-stationary state.

Either water levels or drawdown values were available for nearly all of the sites. *(14 gaps, limited to Ile de France, Roissy, well F2 and Normandie, Val de Reuil, wells F1 and F3)*.

Please note that the data are only partially validated. This applies to master as well as to operational data, as for the most sites the files we received included secondary data (e.g. reports of previous diagnoses, written by SADE or by BRGM), but not always original data material from the time of measurement. Because of the heterogeneity of available data, the assessment was made firstly site-by-site.

2.1 Châteu-Thierry

2.1.1 Site description

The well field is situated in the northeast of France in the town of Château-Thierry (Dept. Aisne (02)). The database exposes the characteristics of ten vertical (P1 to P10) and two horizontal (C1 and C2) filter wells. This report considers only the vertical filter wells.

The well field is composed of two different galleries, one in the North, named “Plaine I” (PI), consisting of wells P1 to P5, built in 1961, and the other one in 800 meters distance in the South of the area, named “Plaine II” (PII) with the wells P6 to P10, built in 1969.

Altogether the wells supply a volume of xxx m³ per year.

2.1.2 Hydrogeological background

The aquifer exploited consists of unconfined layers of sand and gravel, deposited by the nearby river La Marne (Alluvial). It is a rather shallow and thin aquifer, starting at 3 m below surface, being only about 5 m thick. With depths of 7.7 to 9.3m below surface, the wells seem to be fully penetrating wells (*wells, which extend through the whole saturated depth of an aquifer and are constructed in such a manner that water is permitted to enter the well over the whole length of the filter section* [definition after http://webworld.unesco.org/water/ihp/db/glossary/glu/DE/GF0525DE.HTM]).

As the well field is situated near the river "La Marne", river bank filtration processes are most probable.

2.1.3 The wells

The two well galleries were built separately and underwent different evolutions since their construction. Therefore, the amount of data is quite unequal between PI and PII. Because the performance of PII decreased more rapidly, more data and investigations are provided. To draw up the database, the following files were available:

- « Evaluation des ressources en eau souterraine de l'arrondissement de Château-Thierry » ("Assessment of the groundwater resources of the urban district of Château Thierry") **- BRGM* 1986**
- Compte rendu de prospection géophysique-BRGM-1990 (Report of the geophysical prospecting) **- BRGM-1990**
- « Diagnostic des champs captant de Château-Thierry (Aisne)- Forages de Plaine I et II » ("Diagnosis of the catchment area in Château Thierry (Aisne) – Wells of PI and PII") **Syndicat des eaux de Château-Thierry** (Water trade union of Château-Thierry) **1996**
- « Réhabilitation des puits colmatés de plaine II » ("Rehabilitation of PII clogged wells") **Syndicat des eaux de Château-Thierry 1997**
- "Diagnostic du champ captant de Château-Thierry suite à une perte de production des ouvrages de plaine II et des puits C1 et C2 » ("Diagnosis of the catchment area in Château Thierry, after a production loss of PII, C1 and C2") Service « Etudes et diagnostics » - ("Studies and diagnosis") - **Sade Forages d'eau LILLE-2006**

Master data

Geographic, geological and technical information, including a standardized well cross section were taken mainly from the 2006 report by SADE, containing a review of original data and well history.

With the available data it was possible to fill all requested columns for well construction and general characteristics of the wells (e.g. coordinates, aquifer description, year of construction, depths etc.)

According to these documents, field PI was constructed in 1961 and started operation in October 1961. Field PII was constructed and started to operate in 1969.

For both fields, well constructions are the same: Casings are made of eternit and start at 3m below ground surface. Screen sections start at 5.90m below surface and have a length of 1,90m. Well diameter is 600 mm.

Only the maximum tolerated discharge rate varies considerably, lying between 59 and 83 m³ per hour for PI, with highest value at F2, and 20 to 100 m³ per hour for PII, with lowest value at F7 and highest at F10.

Hydrochemical data

Some data from water sampling and chemical analyses carried out in 2001 were available for wells P2, P6 and P10. However, as there are only 3 wells and one sampling campaign available, only a short assessment can be given.

The chemical composition of the raw water indicates oxic conditions, which corresponds to the hydrogeological characteristics (very shallow wells near the river). Electric conductivity lies between 700 and 800 µS/cm. Iron contents vary from well to well, lying between 0 and 0.4 mg/l.

A comparison of the wells or the two galleries is not possible. For further assessment, more data would be necessary.

Operating data and maintenance history

All available performance data were included in the database and, as far as the data sets were complete, taken to plot Q-s-curves and development of specific capacity with time in operation. For this site, the files included 56 data sets with 4 to 7 measurements for each well. Figure 1 gives an example of the resulting Qs-plots:

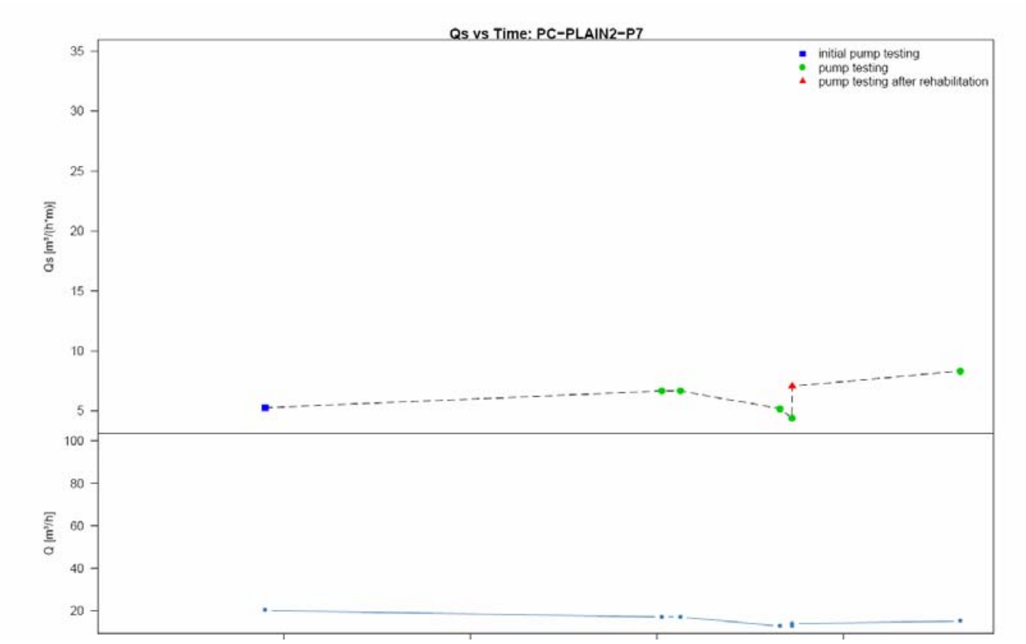


Figure 1: Example of a Qs-curve (upper part) containing the initial capacity (blue square) and available pumping test results (green dots). If rehabilitation data is included, measurements are marked with a red triangle. The lower part contains the corresponding discharge rates to assess the Qs changes (non-linear, because aquifer is unconfined).

To really assess the Qs changes it is necessary (1) to include the Q-s-curve from a step-test (e.g. from the initial step test for the well), (2) the information, if the aquifer is confined or unconfined and (3) to consider possible changes within the aquifer (e.g. general decrease of static water level). Here the first limitation is the availability of data. For this site, no water level data were provided. All data were secondary data taken from other diagnosis reports.

However, the 2006 document shows that the static water level varies. This of course distorts the informative value of any Qs-curve. As done in the 2006 diagnosis, recommendation is to plot Q-s-curves for each well. The steeper the curve becomes with time in operation, the higher is the loss in performance (see Figure 2):

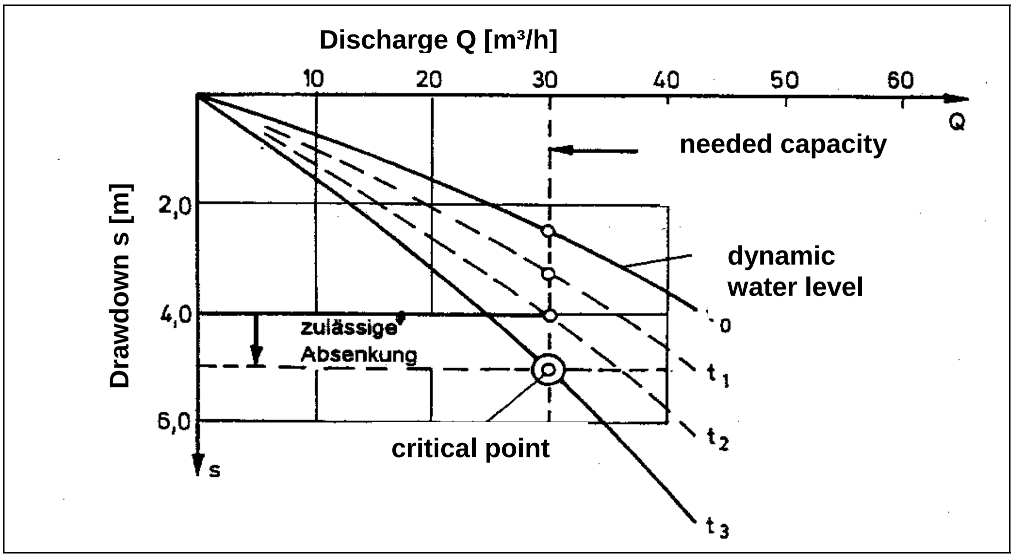


Figure 2: Example of a Q-s-curve for an unconfined aquifer, derived from step pumping tests. t_0 represents the initial capacity, t_{1-3} come from well monitoring [after DVGW W111, 1997]

Maintenance history is documented within the 2006 diagnosis report containing information on TV inspections, chemical and microbiological investigations, pumping tests with calculations of decreases in the specific capacities and applied rehabilitation. P4 to P10 were rehabilitated in 1991, P4 to P6 only mechanical, P7 to P10 additionally chemically treated.

Assessment of well condition

The 2006 diagnosis summarizes a good knowledge. Well ageing processes were identified as being mainly biologically induced iron oxidation with highest impact on the wells P8, 9 and 10. These wells show negative redox potential, high iron concentrations and the presence of iron-related bacteria (IRB).

P10 (PII) was identified as the well with highest initial discharge, but also highest rate of loss in performance. Furthermore, it is the well with the shortest distance to river La Marne.

P6 was the well with the second highest discharge, staying at a good level of performance, which is also displayed by the fact, that it did not need to be rehabilitated as often as the other wells of the gallery. It is also the well with highest distance to the adjacent river.

These data support the following theses:

(1) As soon as conditions are favourable for iron-related bacteria, biologically induced iron oxidation is the most relevant and dominating ageing process. Favourable conditions are presence of iron, low redox potential (KREMS 1972: Study on well ageing in Berlin), presence of oxygen and nutrient supply. While e.g. P6 obviously contains no iron and has no need to be rehabilitated, P10 with low iron content exhibits iron deposits. P2 on the other hand shows high iron content and presumably no need for rehabilitation, as the iron is not incorporated into iron deposits.

(2) For riverbank filtration-influenced sites, the distance to the surface water influences the rate of loss of performance. This is most presumably due to chemical clogging because of mixing of oxygen-rich and iron-containing waters.

2.2 Lisieux

2.2.1 Site description

The data available to us include altogether six wells, located in three different well fields, which supply the town of Lisieux in the north-west of France (Dept. Calvados (14)). The well fields are operated separate from each other with the three waterworks Quatre Sonnettes, Malicorne and Quatre carreaux (see Figure 3).

Well F1 in Quatre Sonnettes was the first well, constructed in 1957. It was followed by wells F1 and F2 of Quatre carreaux, built in 1964. Malicorne (F1) was set in operation in 1972. The last two wells were added in 1994, at Quatre Sonnettes (F2) and Quatre carreaux (F3).

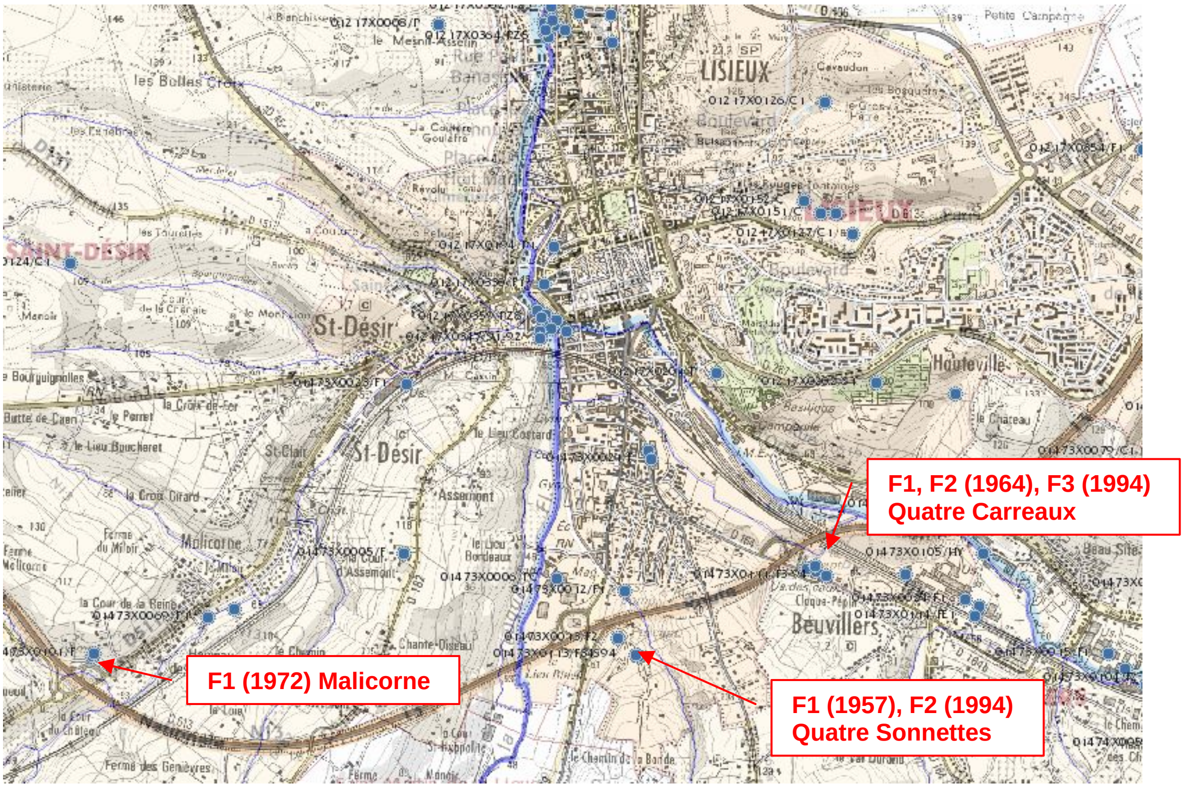


Figure 3: Map of the well fields of Lisieux [from http://infoterre.brgm.fr]

2.2.2 Hydrogeological background

All files contain cross sections including geological logs. The exploited aquifer is a limestone with alternating layers with shares of gravel, sand or clay. It is overlain by a thin layer of quaternary argillaceous silt.

All wells catch the same aquifer. Total well depths and water level vary with the altitude of the well sites. The water table lies at approximately 40 mNN and is unconfined.

2.2.3 The wells

Most presumably influenced by their ages, the wells feature different constructions. Although they all access consolidated rock, they are cased. The older wells have steel screens and no gravel pack; wells F2 in Quatre Sonnettes and F3 in Quatre Carreaux (both 1994) are made of stainless steel and backfilled with a gravel pack.

MALICORNE (1 well)

Available was one report:

- « Forage de Malicorne à Saint-Désir pour l'AEP de la ville de Lisieux (14) – Rapport d'étude diagnostic »
  ("Well of Malicorne in Saint-Désir for drinking water supply of Lisieux – Diagnosis Report")
  Générale des Eaux, August 2004

Master data

The well is 49 m deep. Casing and screen are made of sheet steel and have a diameter of 550 mm. The well is designed with a gravel pack and has a maximum tolerated discharge of 70m³/h, calculated from the aquifer test by Générale des eaux in 2004.

Hydrochemical data

The lab data at hand are quite unremarkable except of the comparatively high variation in the iron content, lying between 0.3 and 4.8 mg/L with a mean value at 0.73 mg/L.

Compared to the other two well fields of this site, this well has medium mean iron concentration and oxygen content.

Operating data and maintenance history

In 2004, the well showed frequent deterioration in water quality, which was traced back to both, precipitated iron hydroxides and calcium carbonate and additionally sand intake in the lower part of the well (see below).

It remains unclear if there have been any maintenance measures.

Assessment of well condition

Because of its capacity decrease, the well was examined in 2002. The investigation revealed the presence of iron hydroxides as well as calcium carbonate deposits and additionally evidence for sand intake (accumulation of fine material at the bottom of the well).

However, the diagnosis report contains data of only one performance test. As neither the initial performance nor any time series are available, the well cannot be further assessed.

CHAMP CAPTANT DE LA BONDE - QUATRE SONNETTES (2 wells)

The available files for this site include:

- « Alimentation en eau potable –Station de la Bonde-Diagnostic et réhabilitation du forage d'exploitation F2 » ("Drinking water supply- Station "La Bonde"- Diagnosis and rehabilitation of F2") **ANTEA-October 2002**
- « Alimentation en eau potable-Champ captant de la Bonde -Vérification des conditions d'exploitation du forage F1- Appréhension des perspectives d'exploitation du champ captant (forages F1 et F2) » "Drinking water supply- Catchment area of « La Bonde » - Check of F1 working conditions - Apprehension of working perspectives of the field (F1 and F2)") **ANTEA-December 2002**
- « Investigations sur le forage F1 de la Bonde à Lisieux (14)- Compte Rendu » ("Investigations on F1 – Report") **SADE-March 2006**

These reports are an extensive source of information, gathering operational data, TV inspections, performance assessments and recommendations for future operation and maintenance. The following can be summarized:

Master data

All necessary information about well design and construction could be drawn from the available cross sections.

F1 and F2 have a distinct difference - the latter one is build with a gravel pack, leading to a smaller inner diameter and a lower maximum discharge rate.

Noticeably, already the static water level seems to be beyond the top of the screen, which is not favourable in terms of preventing oxygen entry.

Hydrochemical data

The hydrochemical data reveal no distinctive features. The raw water of Quatre Sonnettes contains medium oxygen, low iron and manganese and medium calcium and bicarbonate concentrations.

However, compared to the other two well fields of this site, the oxygen content is the highest and iron concentration is the lowest in this well field.

Operating data and maintenance history

As the overall capacity of the aquifer is limited, which is expressed by decreasing water level with time of operation, the wells are operated intermittent to allow recovery. Exact specifications are given in the above named reports.

From the above named data, several step pumping test data could be extracted to track the specific capacity development.

Well F1 kept performance and has not been rehabilitated. Also, drawdown is quite low.

Well F2, although much younger, lost half of its performance until 2002 and was rehabilitated. Measures included brushing and acidification. As Qs could be increased to more than the initial capacity, the rehabilitation was successful. However, performance and well condition should be further monitored, e.g. to assess the sustainability of the rehabilitation.

Assessment of well condition

As stated above, both wells were subject of diagnoses. These state

for F1: carbonate deposits within the casing and deposits made of carbonates and iron hydroxides along the screen with a clear evidence for iron-related bacteria at a depth of 38 m below ground surface [TV inspection, SADE 2006]

for F2: iron hydroxide deposits together with carbonate precipitates within the casing and biofilm development at the depth of pump intake.

As well F2 has been constructed with gravel pack filling the annular space, it is most probable, that the clogging extends to the gravel pack.

QUATRE CARREAUX (3 wells)

This well field consists of two wells (F1 + F2) built in 1964 and one well (F3) added in 1994. Available to draw our conclusions were:

- "Alimentation en eau potable-Champ captant des Quatre Carreaux- Vérification des conditions d'exploitation des forages F1 et F2-Appréhension des perspectives d'exploitation du champ captant" ("Drinking water supply in the catchment area « Quatre Carreaux » -Checking of exploitation conditions of F1 and F2 – Apprehension of running perspectives") **ANTEA - December 2002**
- « Investigation des les forages F1 et F2 des Quatre Carreaux à Lisieux (14) » ("Investigations on F1 and F2 from the field « Quatre Carreaux » in Lisieux") **SADE- July 2006**

The 2006 SADE report mentions, that well F3 is not operated anymore due to quality deterioration. Therefore, only wells F1 and F2 are further assessed.

Master data

Wells F1 and F2 were originally built with a steel casing and screen with 580 mm diameter and no gravel pack. In contrast to F2, F1 has two screen sections and blind casing between 21.80m and 25.20m depth. The pump intake is in the lower part of the upper filter section. Both wells were refurnished with PVC inliners (F1: 400 mm, F2: 500 mm).

Well F3 has a stainless steel wire-wound screen with 340 mm diameter and is backfilled with gravel. It has one screen section. However, directly at the pump intake, there is a short intersection with a blind casing, which reflects the state of the art of 1994 compared to 1964.

Hydrochemical data

The data extracted from the database show slightly higher calcium concentrations compared to the other French sites, but unremarkable oxygen, manganese and nitrate contents. On the other hand, the iron content has the highest mean value and the second highest range of variation. However, this might be due to a special sampling campaign, focussing on iron concentrations and redox conditions.

So, the 2006 SADE report contains valuable information about a flowmeter measurement with parallel chemical sampling. There, the depth with the highest redox potential correlates with low dissolved and high total iron. Furthermore, it is located at depth of pump intake. Well F2 has at the same time a much lower redox potential and is more affected by a loss in performance.

For the WellMa investigations, more details should be evaluated to see how these measurements correlate with the Berlin short-term monitoring to try confirming chemical clogging by the precipitation of iron hydroxides.

Operating data and maintenance history

F1 is the highest yielding well of this well field with twice the discharge than F2 and F3. Due to the different chemical compositions and the interaction during simultaneous operation, SADE recommends alternating operation.

Both wells, F1 and F2, were rehabilitated in 2005. The rehabilitation itself was successful in increasing the performance, but not as sustainable as expected (see Figure 4):

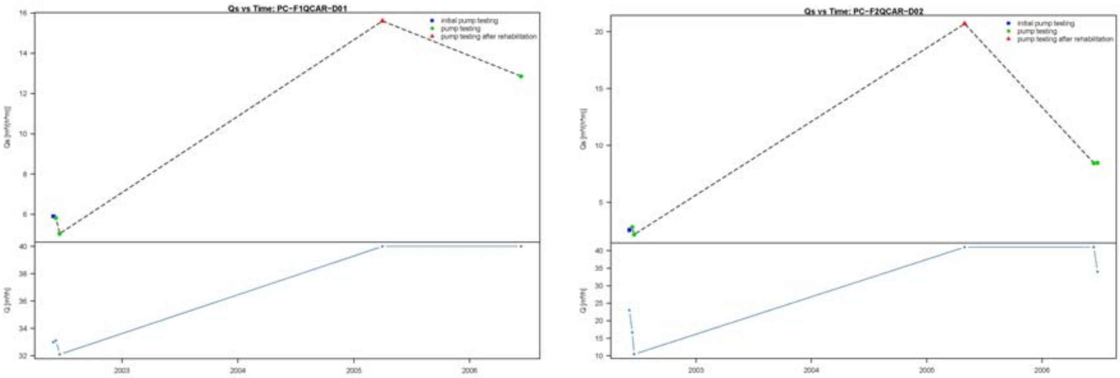


Figure 4: Capacity development in A) F1 and B) F2

For both wells, capacity could be raised with the rehabilitation, but in 2006, for the same discharge rate, drawdown was higher again. Between the rehabilitation in 2005 and the pumping test in 2006 F1 lost 20% and F2 60% of its capacity.

Assessment of well condition

Although the two investigated wells are constructed in the same manner, they are affected by well ageing processes in a different extent. This is most probable due to their chemical characteristics.

Unfortunately, we do not have further information about any TV inspection and on the rehabilitation carried out in 2005. Also, the reports do not contain specific information on the causes of the “colmatage”, only some introducing words about the presence of iron. Here, further details would need to be discussed with the technical staff.

SUMMARY (all wells of Lisieux)

Clogging processes observed during TV inspections include carbonate deposition, iron hydroxide precipitation and biofouling at the same time. Hence, the different processes within the geological context can be further investigated.

In general, from the examination of the six (five) wells, it is remarkably, that the wells with gravel pack are to a greater extent affected by ageing processes. At the same time, rehabilitation is less sustainable in these wells. This finding should be further assessed because it reflects the role of the gravel pack for clogging processes.

2.3 Moulin de Douves

2.3.1 Site description

The well site consists of originally four wells supplying the town Torcy in the north of France (Dept. Seine-et-Marne (77)). They lay near the river “La Marne”

Well F1 was built in 1963, F2 in 1966, and both F3 and F4 in 1971. The well F2 is abandoned since 1994 because of a failure of construction. The wells have a distance of 150m between F1 and F3 and 100m between F3 and F4.

Altogether, the three wells supply 550 m³ per hour and respectively about 2 million m³ per year.

2.3.2 Hydrogeological background

The wells lay in the alluvial valley of the river “La Marne”. The aquifer exploited consists of layers of tertiary sands and clays, overlain by lime, marl and sand. It starts at a depth of approximately 60 m below the surface.

The static water table varies between 5 and 10m below ground.

Because of the close distance to the river “La Marne”, river bank filtration processes are possible for the upper layers of sediments.

However, as the wells exploit deeper sandy layers, which are confined, a possible mixture of river bank filtrate and deeper groundwater needs to be further assessed, e.g. by depth-oriented sampling.

2.3.3 The wells

The provided data are an extensive basis for the assessment of the wells. Available for all wells are records and documents from the year of construction, investigations about the extent of protection areas (1983 and 1999), a general study of the catchment (1999) and reports of different maintenance measures including TV inspections (1996, 2006), pumping tests (2003, 2006), geophysical logs (2006) and a rehabilitation of well F3 (2006).

Master data

All three wells are constructed with steel screens (coated, slot-bridge openings) with a diameter of 300 mm, backfilled with gravel. F1 has three screen sections, F3 and F4 have four.

Remarkably, as could be seen from the 2006 TV inspection, in well F4 the upper screen sections are made from the steel screens, but the last filter section is a stainless steel wire-wound Johnson screen. From the pictures, it is not clear, if the diameter is reduced. However, as during the 1996 TV inspection a partial “collapse” was noted, this wells was obviously equipped with an inliner. But, the use of different steel types connected to each other might promote corrosion processes due to the electric potential between the different noble metals.

Hydrochemical data

All wells have a high load of calcium and bicarbonate. Iron content is low. Oxygen concentration is highest in well F4 and decreases towards well F1. Furthermore, it displays the highest range of variation looking at all sites we got data from.

However, the report by BOIRE (1999) states, that iron (and fluorine) is of geological origin and is reduced, because the aquifer is sealed by impermeable clay and marl sediment layers against oxygen intake.

So, the high variation in oxygen remains unexplained. Other sampling campaigns focussed on nitrates and are therefore not relevant for this assessment.

Operating data and maintenance history

All wells in operation have a good documentation status regarding their physico-chemical parameters and their performance. The data available to us show yearly sampling campaigns and three to four evaluations of drawdown each year. Because the aquifer is confined and furthermore the measures were taken with constant discharge rates for a couple of years, they can be used to quantify the performance development.

According to the data (Figure 5), well F1 has decreased in performance from around 8 m³/h*m to around 6 m³/h*m, but with a reduction of the discharge rate from 170 m³/h to now only 40 m³/h.

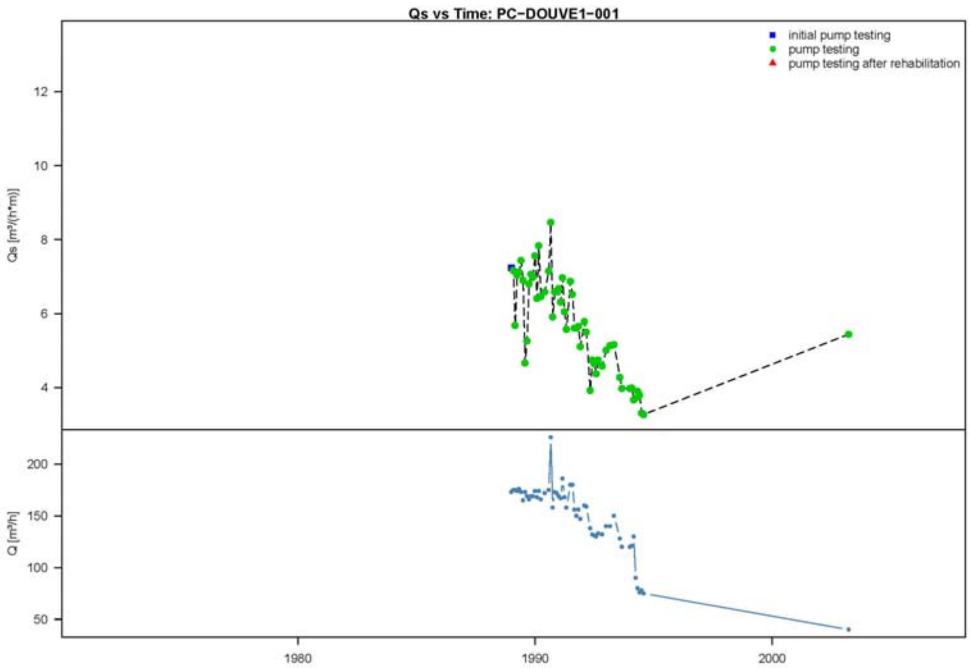


Figure 5: Qs curve (upper part) and respective discharge Q (lower part) for well Moulin de Douves, F1

As there are no actual diagnosis reports, it cannot be assessed if this reduction is due to economic reasons or a general decrease in aquifer capacity.

Wells F3 and F4 have been rehabilitated once each.

Assessment of well condition

The available data on the well condition can be summarized as follows:

F1 showed in the 2003 inspection corrosion in the upper part and sand intake at the bottom. There are no data on rehabilitation or reconstruction measures. Technical details need to be discussed with the staff on site for further evaluation.

F3 was diagnosed prior to its rehabilitation in 2006. The report states the presence of corrosion and colmation for the casing (and the rising main?), but a good condition for the screen sections. Obviously, corrosion is biologically induced leading to the precipitation of iron hydroxide and sulphate reaction products. However, sulphate-reducing bacteria could not be detected. Ochre samples were analysed revealing the presence of iron hydroxides as well as carbonates.

The rehabilitation measure included hydraulic pulse (pump between packers) and the treatment with polyphosphate but could improve the performance of the well only slightly.

F4 was advised to be rehabilitated in 1996 (brushing, intensive pumping, acidification with Herli), but no data were available to us stating any rehabilitation success or sustainability.

In 2006, it was diagnosed too, revealing the presence of ferrous deposits in the casing and not specified brown and white deposits in the upper and middle screen section. This well seems to be partly reconstructed. In 2003, a stainless steel wire wound screen was inserted to stabilize the bottom part of the screen. However, this was not clearly documented and could be concluded only from the 2006 TV inspection pictures.

However, the report also states that iron-related or sulphur-reducing bacteria are not present. Therefore, the decrease in capacity is claimed to be due to physical clogging. This is supported by the observed corrosion, sand intake and reconstruction with an inliner.

Remarkably, the corrosion processes leading to a deposition of ferrous sulphates, seems to be biologically induced, but the related bacteria could not be observed in large number. Also, in both wells F3 and F4, different types of clogging were monitored. To investigate more detailed processes, alternative sampling methods and depth-oriented sampling should be discussed.

2.4 Mousseaux

2.4.1 Site description

For this site in the north-west of France (Ile de France), there is one well “Le puits des Mousseaux” built in 1959 and supplying the approximately 4.000 inhabitants of Jouars-Pontchartrain (Dept. Yvelines (78)).

2.4.2 Hydrogeological background

The well exploits the deeper one of two aquifers. It consists of a fissured tertiary chalk starting presumably at about 21 metres depth.

The aquifer is confined by clay layers at the basis of the upper aquifer. The static water level lies at 45.30 m below ground surface, which eqals the top of the intake area.

2.4.3 The well

Available to us were four data sources:

- Official form summarizing technical data **« Générale des Eaux », 1979**
- "Définition des paramètres de protection du puits 218.2X.0059 (Yvelines)" ("Definition of the protection parameters of the well 218.2X.0059 (Yvelines)") **P.Andre, Hydrogeologist-1983**
- Essais de puits sur les communes de Jouars-Pontchartrain et Villiers-Saint-Fréderic Report on the wells of Jouars-Pontchartrain and Villiers-Saint-Fréderic **SADE, 2006**
- « Résultat des essais de puits par palier sur le forage dit « des Mousseaux » »("Results of the step pumping tests on the well called « Les Mousseaux »") **Veolia Eau, April 2006**

containing a cross section of the well, a geological classification of the aquifer, a short summary of a TV inspection (2006) and data of one stepwise pumping test.

Master data

According to that data the well is 51 m deep. The upper part down to 45.30 m below ground surface has a protective casing made of concrete serving two functions - (1) to stabilize the borehole and (2) to seal of the upper aquifer. The area of intake is an open borehole with no screen. The well has 2 metres diameter.

Hydrochemical data

The raw water contains no iron or manganese. Nitrate is quite high, while carbonates are in medium range.

Operating data and maintenance history

The maximum tolerated discharge rate was at 120m³/h. This is the yield of the well after construction. Pump tests were carried out in 1983 and 2006 showing a decrease in the discharge for a more or less constant drawdown (otherwise the pump would run dry). In 1983, about 40m³/h could be extracted. Current operation reaches 24m³/h reflecting the decrease in (1) well performance due to blocked fissures and (2) most probably in the overall aquifer yield due to decreased static water levels, seasonal effects and/ or overexploitation. This assessment is supported by a reported decrease of the static water level from initially 45.30m to 47.30m.

Assessment of well condition

As stated in the 2006 reports by SADE and Veolia Eau, further investigations are needed to clarify the exact causes of the high decrease in the performance of the well. A TV inspection is recommended to assess if the fissures are blocked or open.

2.5 Roissy

2.5.1 Site description

The well field was originally composed of two wells supplying the town of Roissy-En-France (Dept. Val d'Oise (95)) in the east of Paris. F1 was built in 1901 and is now abandoned due to a failure of construction. F2 was built in 1978 to increase the overall capacity of water supply.

2.5.2 Hydrogeological background

The aquifer exploited is the second aquifer on site (first aquifer: 20 to 35m below ground surface). It consists of tertiary sands and clays (Ypresian), overlain by lime, marl and sands and is the same as in Moulin de Douves.

According to the geological expertise it is semi-confined and lies between 62 and 90m below ground surface. However, the data of the initial pumping test reveal a linear relation between discharge and drawdown, so the aquifer seems to be clearly confined (see Figure 6):

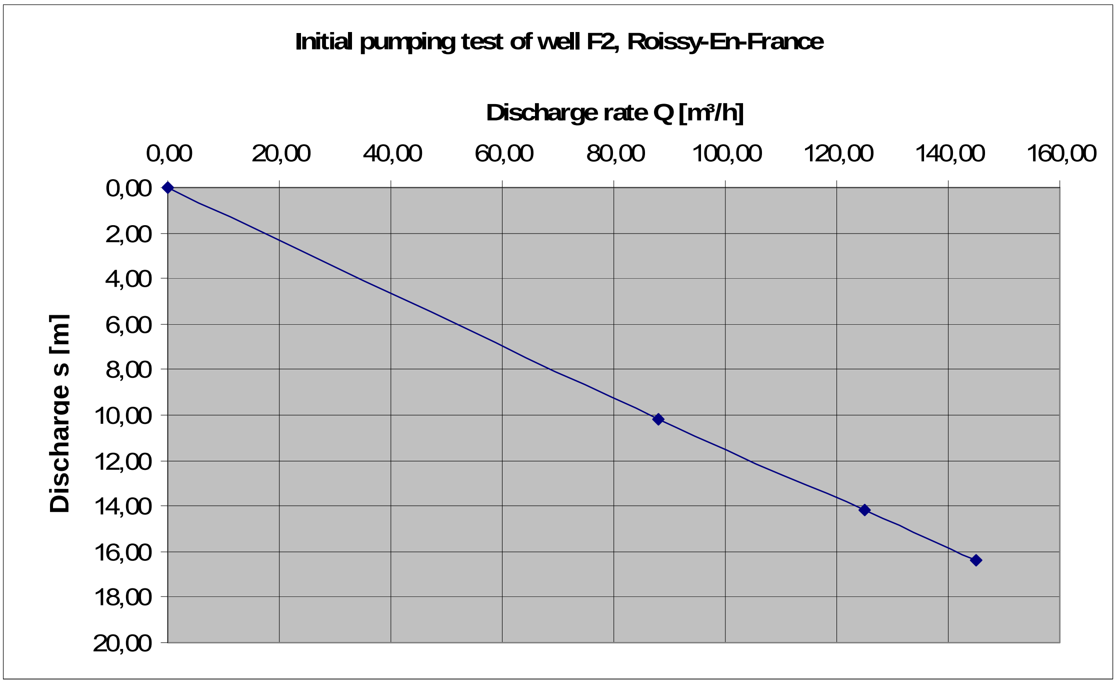


Figure 6: Initial pumping test of well F2 Roissy-En-France [Data from SADE 1978]

2.5.3 The well

There are much data available in the files given to us, which are:

- "Renforcement de l'alimentation en eau potable de la commune de Roissy-En-France" ("Strengthening of water supply in the town of Roissy-En-France")
  B.R.G.M. - 1977
- Initial report just after construction
  SADE - 1978
- Bill of the rehabilitation operations
  Archambault Conseil - 2003
- « Diagnostic du forage F2-154 5X 85-Commune de Roissy en France(95) » (« Diagnosis of F2-Town of Roissy-En-France »)
  Archambault Conseil - 2003
- On CD-Rom: Chemical data, pumping test data (Excel Files), and a slide-show with a summary
  Veolia Eau, 2007

So we were able to draw all necessary information to fill the database.

Master data

The well is 87m deep and has a steel screen (slot-bridges) with 600mm diameter and 33m length in one screen section. The screen section is backfilled with a gravel pack.

The following scheme (Figure 7) summarizes well construction features and master data:

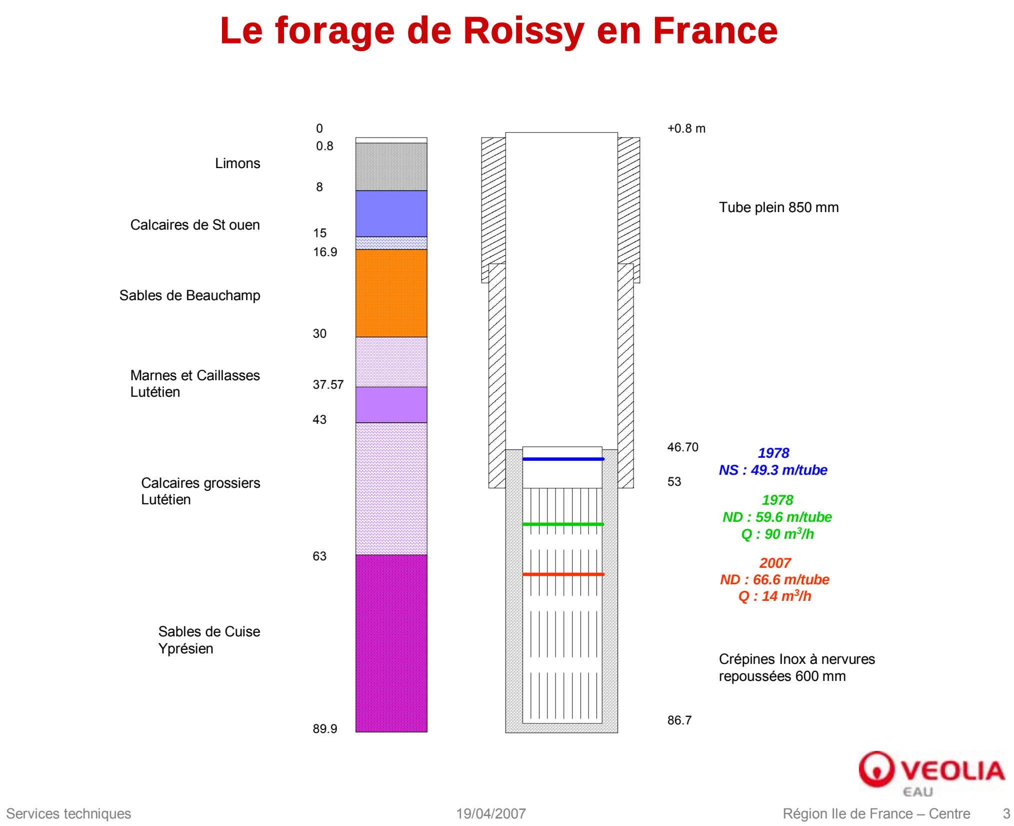


Figure 7: Scheme of well F2 of Roissy-En-France [from the PowerPoint presentation on CD]

Hydrochemical data

Data are available for the time period 1998 to 2006. They show low iron and manganese concentration, medium oxygen and calcium contents.

Operating data and maintenance history

The data available to us show a quite good historic record of water levels and development of discharge.

As the respective Figure 8 and Figure 9 show, the capacity of the well has decreased very much. At the same time the discharge rate had to be reduced more and more. In the end, since around 1989, parts of the filter section ran dry.

A rehabilitation was recommended in 2003 after a TV inspection.

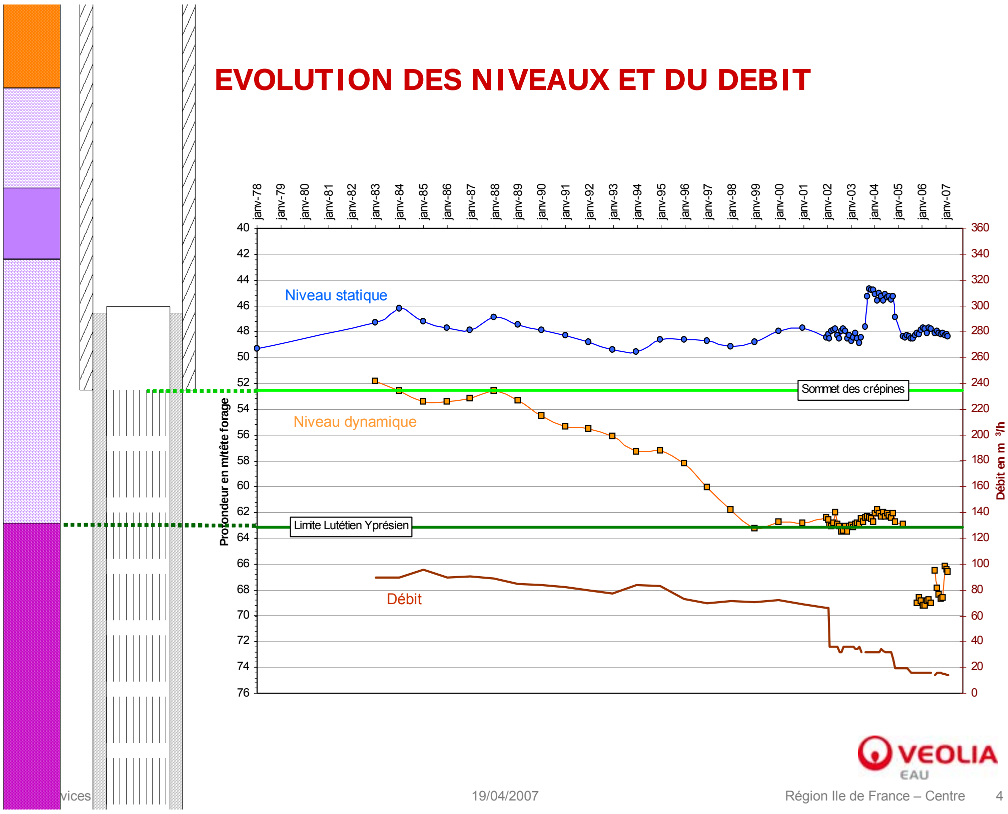


Figure 8: Performance data of well F2 Roissy-En-France [from the PowerPoint presentation on CD]

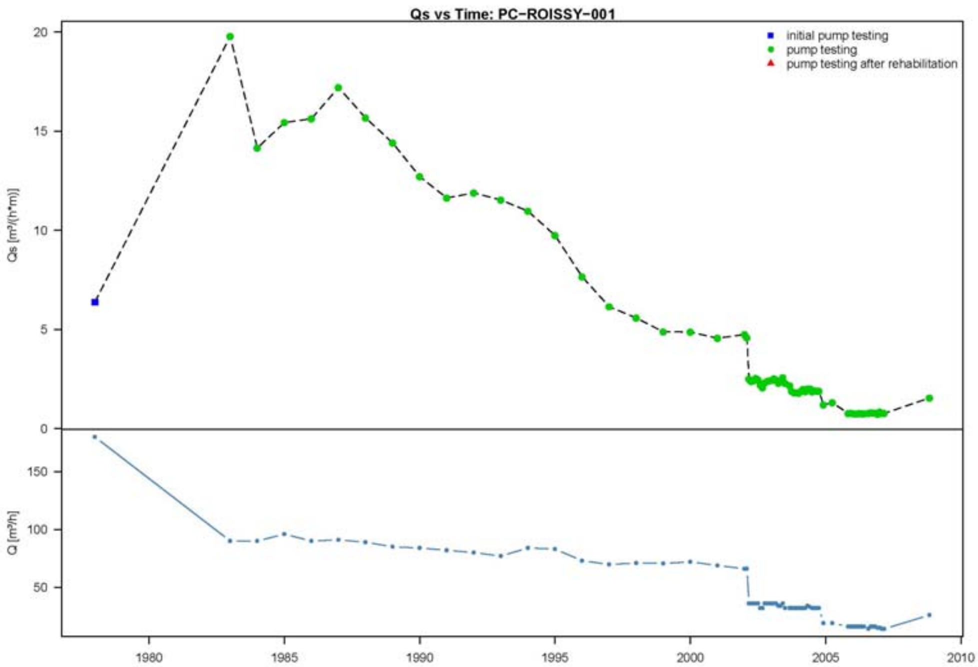


Figure 9: Development of specific capacity Qs with time in operation [KWB 2008]

Assessment of well condition

According to the diagnosis of 2003, preparing a rehabilitation measure because of the bad capacity of the well, clogging products could be observed between 59 and 65m below ground surface. This is in good correlation with the depth of the dynamic water level. Hence, clogging occurs in that part of the screen, which is exposed to air.

The report claims iron-related bacteria responsible for the deposition of iron hydroxides. Furthermore, below 68m the screen opening were found to be blocked by hardened incrustations, which are described as being presumably bacteriological or carbonate sintering induced deposits.

Remarkably, filter sections showing deposits alternate with clean sections and the type of precipitates seems to change with depth. Here again, a depth-oriented sampling is strongly recommended.

2.6 Saint Denis

2.6.1 Site description

The site includes one well "Forage dit du Sparnacien" supplying the town Saint-Denis in the North of Paris (Dept. Saint-Denis (93)). It was taken in operation in 1977 and replaced a well from 1936, which was abandoned because of sand intake.

The total annual supply was at 590.000 m³ per year in 2000.

2.6.2 Hydrogeological background

The aquifer exploited is the same as in Moulin de Douves and Roissy, namely tertiary sand and clay layers (Ypresian), starting at approximately 60m below ground surface. The ground water table seems to vary. The aquifer is confined (see Figure 10).

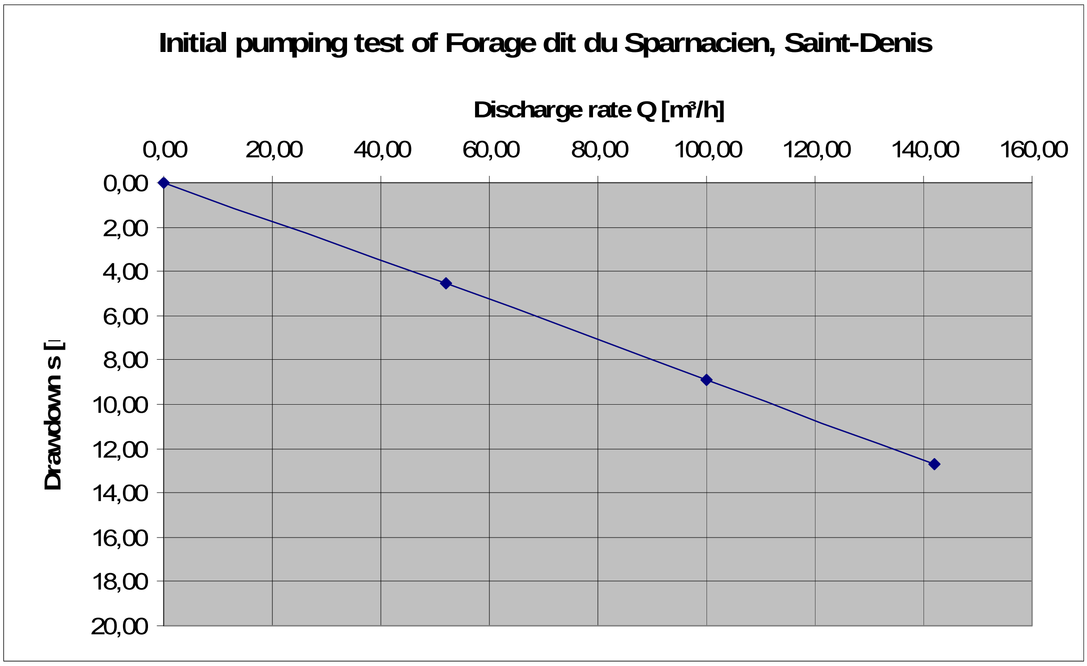


Figure 10: Initial pumping test of well „Forage au Sparnacien", Saint-Denis [Data from SADE 2001]

2.6.3 The wells

With the files sent to us:

- « Diagnostic du forage sparnacien »
  (Diagnosis of the well)
  Sade –April 2001
- « Forage de la Plaine Saint Denis sparnacien-Diagnostic »
  (Diagnosis of the well)
  Hydro-invest- 2006
- « Forage de la plaine Saint-Denis sparnacien-Essais de décolmatage »
  ("Well in Saint Denis field, sparnacian- Rehabilitation report")
  Hydro-Invest- 2006

we had a good documentation enabling us to fill the required columns of the database. Included were data of the initial pumping test carried out in April 1977 as well as several following step tests, summary forms of diagnosis reports, technical documentation of the design and construction, TV inspections (2001), lab data etc.

Master data

The official forms of SADE from 2001 contain most relevant information. The well is 96.70m deep. The casing starts at 54.50m below ground surface. The screen has its top at 63.50m and bottom at 95.50m. Both are made of steel (screen with slot-bridge openings) and have a diameter of 300mm. The borehole diameter at depth of casing and screen is at 500mm. There exists a gravel pack. The screen is subdivided into three sections by short blind casing intervals (1m length each, at 74.50 and 83.50m).

The discharge had to be reduced in 1999 from 90m³/h to 70m³/h. With a discharge rate higher then 90m³/h the raw water contained sand.

Hydrochemical data

The data available to us show no remarkable loads of oxygen or nitrogen. Iron and manganese are also low.

Compared to the other French sites, carbonate concentration (reflected by the calcium content), was the highest of all sites.

Also, the electric conductivity is quite high.

Operating data and maintenance history

Measurements of the static water level once a year show for the time period 1996 to 2000 increasing static water levels, but at the same time decreasing dynamic water levels. Both, discharge rate decreased and drawdown increased, which reflects a severe loss of performance (see Figure 11):

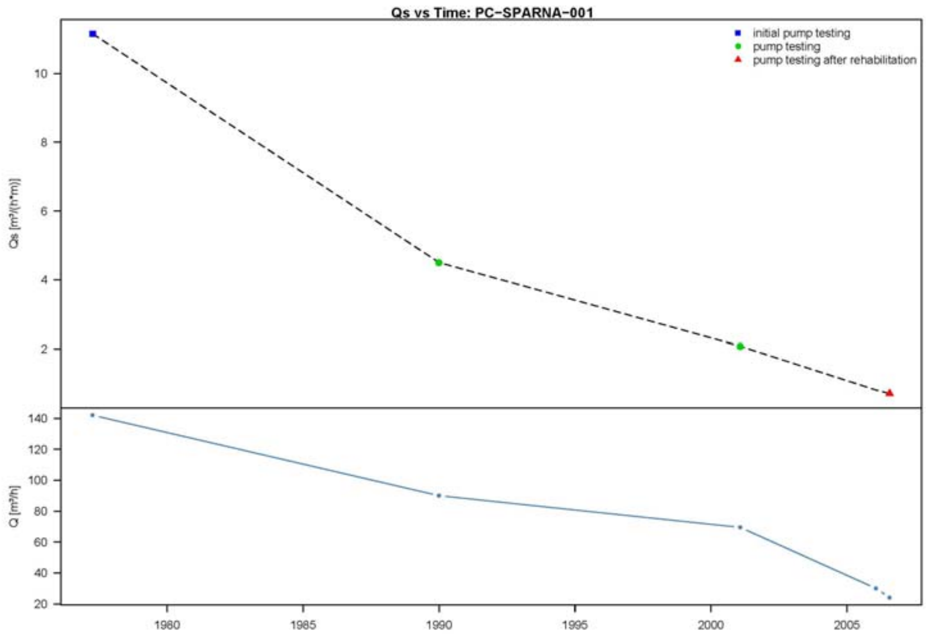


Figure 11: Development of specific capacity and discharge rate with time in operation. Please note: The connection between two points was interpolated by the software and does not display the real slope of changes. [KWB 2008]

According to the 2001 TV inspection, the well exposed firstly carbonate deposits and with increasing depth less carbonates but more iron hydroxide deposits in the protective casing (15 to 54m below ground surface). Casing and screen were clean and screen openings not blocked. However, at the bottom there were sand and clay accumulations.

The two 2006 reports state the condition before (Diagnostic) and after (essais de decolmatage) rehabilitation.

Assessment of well condition

As observed during the 2006 investigations, in the upper part the well shows corrosion. Because of the evidence for the presence of sulphate-reducing bacteria it seems to be biologically induced.

A gamma-log revealed the presence of clay within the gravel pack in the lower part of the well at 75m below ground surface (second of the three screen sections) and in addition the presence of a clay layer within the aquifer below 89m depth.

According to it and the heavy loss in performance (Figure 11), the well seems to be totally blocked by deposits in the gravel pack or even within the aquifer. However, the detailed depths and positions could not be clarified.

The rehabilitation with polyphosphates aimed at the removal of the clay agglomerates, but was not successful as can be seen on the further decrease of specific capacity. The following trial with hydraulic pulse (pump between packers) was partly successful, increasing the performance by 25%. However, only the combination of both techniques showed this effect. Hydraulic pulse (pump between packers) alone did cause an even worse performance.

The report recommended a repetition of the combined treatment. However, as the problem seems to be due to the aquifer geology, it might not be sustainable. In that case, our recommendation would follow the 2001 conclusion (SADE) to think about to shorten the well by cutting of the bottom part being affected by the clay sediments of the aquifer.

2.7 La Saignonne

2.7.1 Site description

The well field is situated in the South of France in the Provence-Alpes-Côte d'Azur, Dept. Vaucluse (84). It supplies the towns Avignon and Morières.

The well field originally included 27 wells, built in different stages (Figure 12):

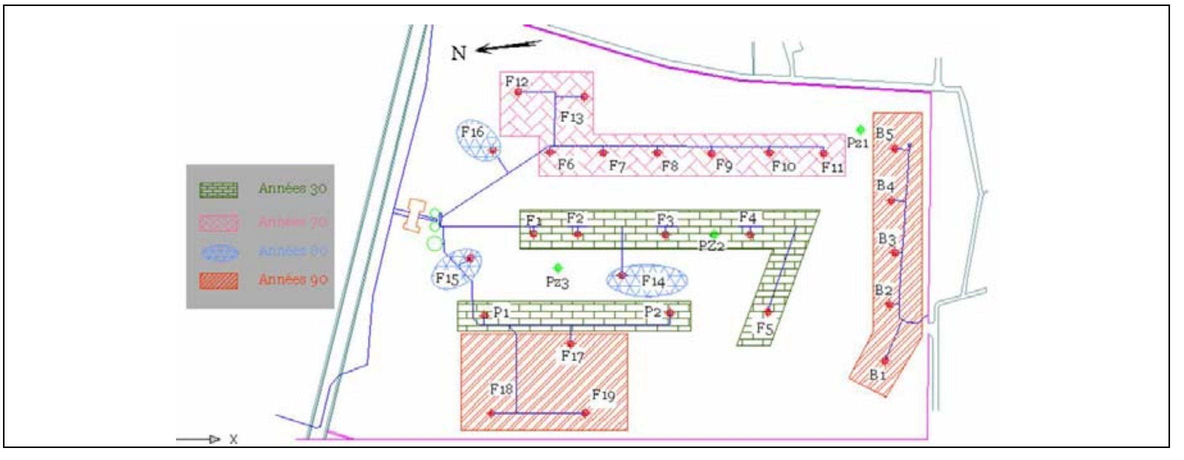


Figure 12: Map of the Saignonne wells [Source: Internship report 2005, on CD]

The wells F1 to F19 are abstraction wells, while the wells B1 to B5 were constructed to form a hydraulic barrier to protect the other wells against pollution. The wells P1, P2 and P3 are injection wells for aquifer recharge. P3 has been abandoned and is now used as an piezometer.

The abstraction wells are sorted to three galleries (Figure 13):

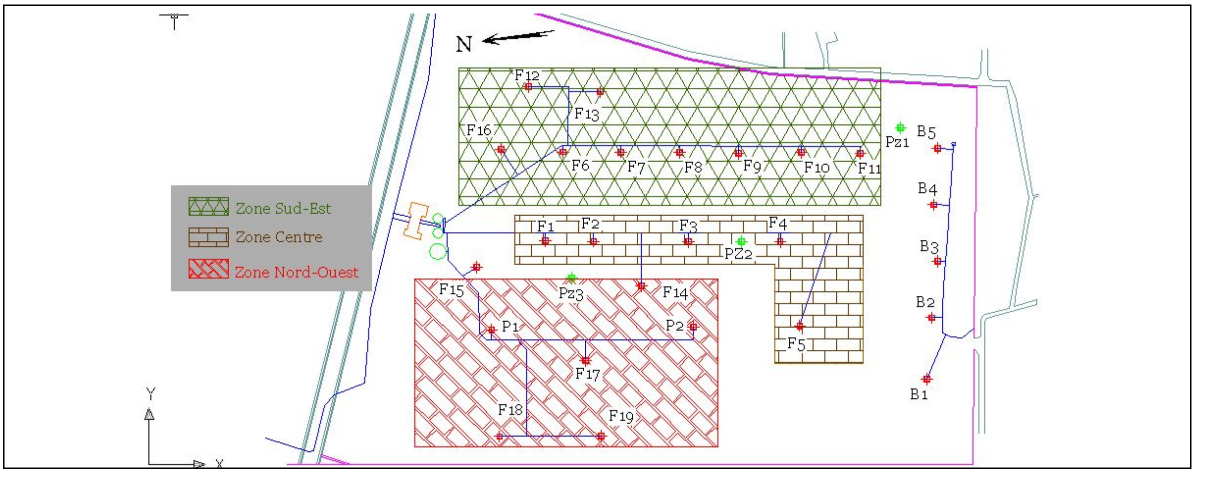


Figure 13: Assignment of the operation wells to zones [Source: Internship report 2005, on CD]

2.7.2 Hydrogeological background

The aquifer is composed of layers of gravel, rock and fine sand in an alluvium complex, covered by a thin layer of silt. It is a rather shallow aquifer, beginning at about three metres underground. Static water level is unconfined and lies at 5 m underground.

The alluvial sediments are about 15 to 20 m thick and follow on top of a till, covering cretaceous limestone.

With depths of 20 m, the wells seem to be fully penetrating wells.

The well field is supposed to be supplied by the surrounding river “La Durance» (depending on the global water static level and the location of the well).

2.7.3 The wells

To draw up the database, a CD from an internship in 2005 was provided, containing the following information:

- « Dessins » (“Drawings”) including technical and geological scanned schemas
- « Dossier Forages » (“Well file”) including pumping tests data and general information
- « Dossier Word » (“Word file”) including an abstract and a report of the internship
- « Informations Complémentaires » (“Further information”) displaying general files on pumping tests and protection areas
- « Photos » including photos of the site (no TV-Inspection)
- « Présentation Power Point » slide show of the internship
- «Résumés» gathering abstracts of reports from 1972 (BRGM), 1974 (University of Provence) 1986 (BRGM), 1987 (Jacques Mudry), and comments on the report of BURGEAP (2004)

According to the data, 17 of the abstraction wells are still in operation. F4 has been abandoned and F6 is (was in 2005?) out of operation.

However, as primary data were not available, our database bears some gaps.

Master data

Due to the different times of construction, the general design of the wells varies, but follows technical development.

The oldest wells are made of asbestos and have diameters of 30 mm; the newest wells are made of stainless steel and have diameters of 700 (1980er) or 800 (1996er) mm.

With screen lengths of 10 to 12 m, the abstraction rate lies at about 15 m^3/h per meter filter length, which is quite high. On the other hand, well diameters are at about 700 mm or 800 mm, which is, compared to German wells, also quite high.

Hydrochemical data

There are only a few values available for the oxygen content. They range between 6.1 and 7.9 (years 1998/ 1999), which corresponds to the low distance between top of the aquifer and ground surface. Iron or manganese is not contained according to the data we received. Calcium is at about 100 mg/L and HCO_3 between 208 and 280 mg/L. Different resumes state the presence of calcium carbonate deposits.

Operating data and maintenance history

Pump capacities lay between 50 and 450m³/h. For most of the wells, the average discharge is at 150 m³/ h (see also Figure 14).

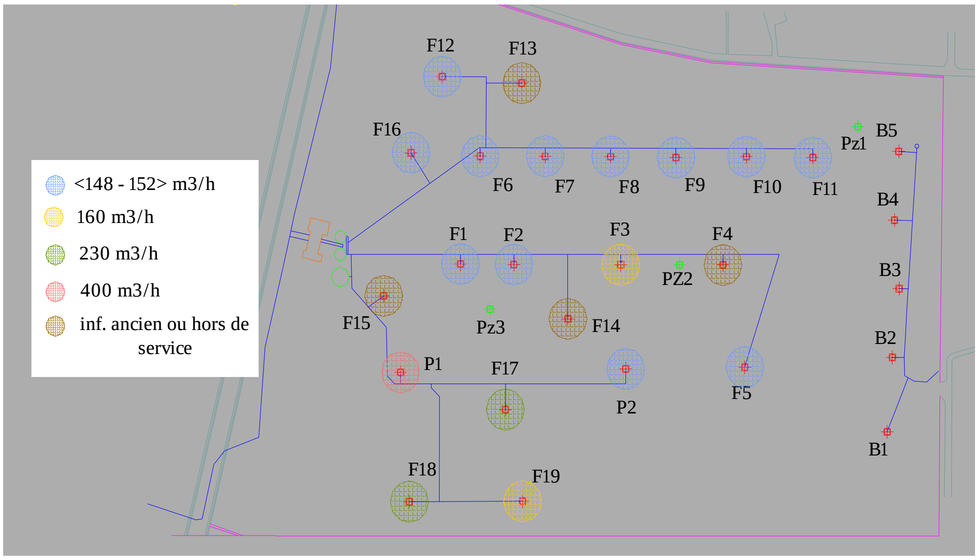


Figure 14: Discharge rates of the operation wells [Source: Présentation Power Point, Internship report 2005, on CD]

Various pumping tests have been performed starting in 1985. The data were included to draw Qs-curves.

Considering well maintenance, TV inspections of some of the wells, carried out in 1986 by BRGM, and 2003 by SONDALP are mentioned. However, pictures or reports were not available to us. Also, there are no data on any rehabilitation measure.

Assessment of well condition

The Internship report contains an assessment of the well condition made in 2003 by BURGEAP. It states acceptable well conditions for the central wells, a slight performance decrease for the northwestern wells and a notable decrease for the wells in the southeast. The following table summarizes the well condition and groups the wells according to their condition:

Table B-1: Well condition summary [from Rapport stage, 2005, on CD]

Wells	Qs (m³/h*m)	well condition
F15, F16, F17, (B1)	> 450	wells in excellent condition
P1, F19, (B3, B4, B5)	250 à 450	wells in good condition, 1 m drawdown at maximum discharge
F1, F3, F8, F14, (B2)	125 à 250	wells in good condition, but should be monitored, drawdown at 2,5 m
P2, F5, F7, F11, F18	50 à 125	well condition ok, but increasing loss in performance since last maintenance
F2, F9, F10, F12, F13	< 50	well performance affected, TV inspection revealed presence of deposits (mentioned to be carbonate deposits)

On the other hand, for some of the wells the Qs plots derived from the data available to us show partly contrary results. This accounts especially for wells F1 and F2, where we state a good condition for well F2 and a loss in performance for well F1.

However, some technical details of the wells remain unclear on the basis of the data available to us and need to be sorted out together with the technical staff.

Remarkably (noticed in the cross sections for the oldest wells, but also in the technical schemes within the power point presentation and stated in the internship report), the pump intake seems to be located at filter depth and not above the screen or in a casing intersection, as it would nowadays be state of the art.

Accordingly, the report claims three facts responsible for the well conditions, which can be supported from our point of view:

(1) The most affected wells are the ones situated between the river and the less affected wells. They might act as kind of a “filter” protecting the other wells.

(2) The pumps are too deep and should be in a full screen section.

(3) The abstraction rate is too high, obviously leading to colmation and/ or sand intake.

Although compared to most other French sites, calcium and hydrogen carbonate contents are rather low, calcium carbonate deposits are mentioned. Because the aquifer is underlain by limestone, the presence of carbonate sintering is reasonable.

Further assessment should include calculation of chemical balances of input- and output-concentrations, e.g. for Ca, HCO_3, O_2/ NO_3 and Fe, to investigate the occurrence of precipitation processes reducing initially high loads (input) to the measured low values (output).

2.8 Val de Reuil

2.8.1 Site description

To supply the town of Val de Reuil west of Paris, altogether four wells were constructed in 1992 and 1993 to supply a total volume of 900m³ per hour.

The wells are sorted from F1 to F4 in a gallery from west to east, with a distance of about 50m towards each other.

2.8.2 Hydrogeological background

Water supply comes from the second aquifer, starting at 8 to 10m below ground surface, consisting of fissured limestone.

It is covered by a layer of sands and clays topped by alluvial sands (first aquifer). Groundwater table is currently at 5m below surface, but decreased from being at 1m below ground when the wells were constructed.

The figures drawn from the initial step pumping tests (see Figure 15), show that the aquifer is unconfined.

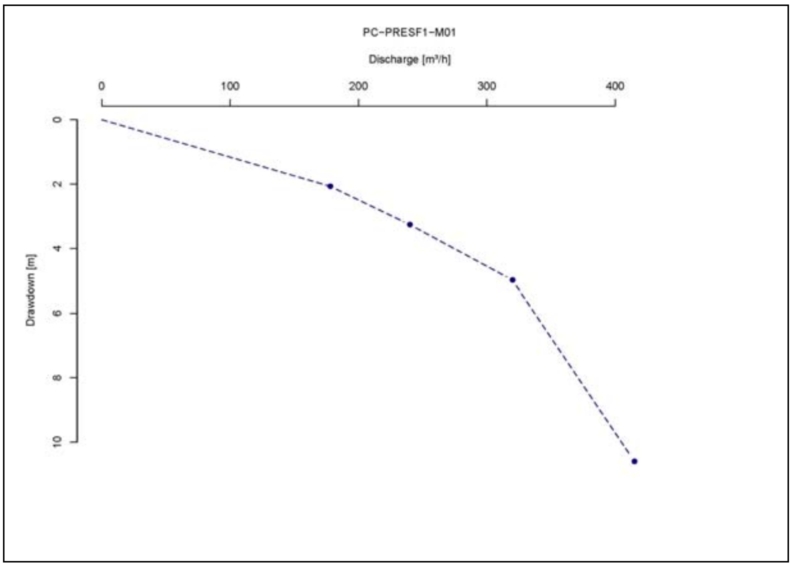


Figure 15: Example-plot of discharge Q against drawdown s, well F1, Val de Reuil (KWB 2008 with data from SADE]

2.8.3 The wells

As the documentation for these wells is very good, all necessary information could be drawn from the provided reports:

- « Inspection télévisée-Champ captant Val de Reuil » (« TV-Inspection – Catchment area of Val de Reuil”) - **Géo-Hydro-Investigation-2002**
- PDF papers on TV-Inspection carried out **Geo-Hydro-Investigation - 1998 to 2007**
- « Nouvelles propriétés hydrauliques des puits F1, F2, et F3 du champ captant des « Hauts Prés » après l’opération de génération de Septembre 2003 » (“New hydrological properties of F1, F2, F3 from the catchment area: « Les Hauts Prés »”) - **Générale des Eaux- October 2003**
- « Gestion optimale de la ressource en eau du champ captant de Val de Reuil- F1-F2-F3-F4 » (“Optimal management of water resource of the filed of Val de Reuil –F1 F2 F3 F4”) **SADE-1997**
- « Etude hydrogéologique et environnementale de la ressource en eau des Hauts Prés » (“Hydrogeological and environmental study of water resource of « Les Hauts Prés”) **Générale des Eaux- 2004**
- “Investigations de Juin et Octobre 2004 sur le champ captant de Val de Reuil » (“Investigations of June and October 2004 on the catchment area of Val de Reuil”) **SADE-2004**
- « Investigations complémentaires sur le champ captant de Val de Reuil » (“Complementary investigations on the catchment area of Val de Reuil”) **SADE-2004**

- « Etude diagnostic du champ captant de Val de Reuil - Diagraphie et prospection géophysique »
  (“Diagnosis of the catchment area of Val de Reuil –geophysical prospecting”) **SADE-2004**

Master data

F1, F2 and F4 are constructed in the same manner, being 24m deep, having a steel casing and screen with 1000mm diameter, backfilled with gravel. They are currently equipped with 260m³/h pumps.

F3 is 26m deep and has a 1000mm steel casing and screen, backfilled with gravel, too.

Hydrochemical data

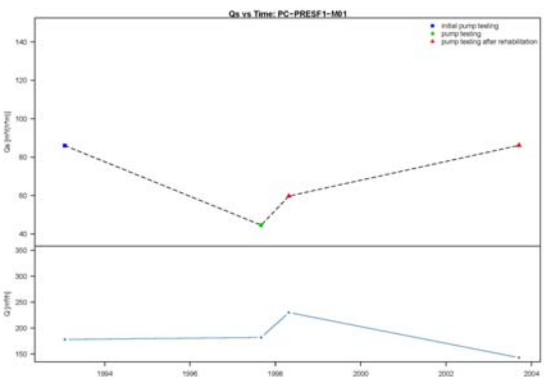
Compared to the other sites, iron and manganese concentrations are high with iron contents between 0.57 and 0.76mg/L and manganese between 0.05. and 0.16mg/L. Oxygen, nitrogen and calcium content are in medium ranges.

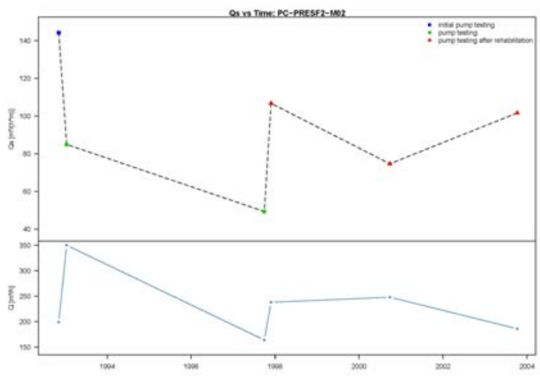
The file of SADE from June 2004 contains depth-oriented profiles for the presence of SRB and IRB, Mn, Fe, Oxygen, conductivity, turbidity and redox potential.

Operating data and maintenance history

All documents reveal the general ageing potential for wells F1, F2 and F3, while F4 is unaffected by clogging. All wells have a good documented maintenance history showing different progression. Measures included brushing, acidification with HCL and hydromechanical rehabilitation with compressed air. Data were available for the years 1997, 1998, 2000 and 2003. They showed that the rehabilitations itself were quite successful, but not in all wells sustainable. In addition, due to a general overexploitation, marked by progressively decreasing static water levels, the discharge had to be reduced.

However, further assessment needs a discussion of further details with the technical staff. The following figures display the development of the well performance with time:





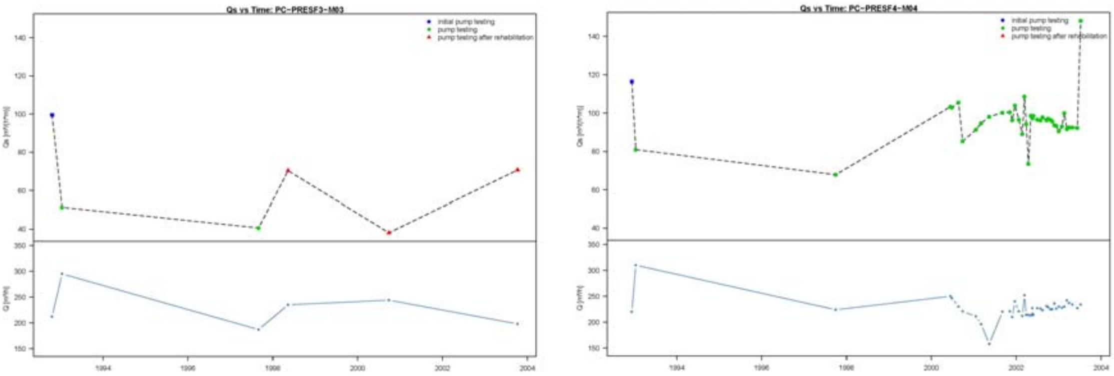


Figure 16: Development of Qs (upper part) with time in operation for the wells of Val-de-Reuil and related changes in discharge rates (lower part) [KWB 2008]

Assessment of well condition

The pumping test data (1993, 1997) show that the performance of the wells started to decrease right with the beginning of their operation.

All TV inspections (1997, 2002, 2004) show the presence of reddish deposits and clogged screen openings in the wells F1 (8.60 to 11.50m below ground surface), F2 (8.90 to 16m) and F3 (9.40 to 16.50m). F4 is free of deposits.

The 2002 report details the presence of mineralogical and biologically formed iron hydroxides. Furthermore, it reports the occurrence of carbonate precipitates at the bottom of wells F1, F2 and F3 as well as at the pumps of wells F1 and F2.

The data show quite a good correlation with the hypothesis drawn from the Berlin data that the biologically induced precipitation of iron hydroxides is accompanied by a lower iron concentration. The comparison of chemical analyses from 1993 (start of operation) and 1997 (SADE 1997) shows decreased iron concentrations for the wells F1, F2 and F3, which are also the ones with the presence of iron-related bacteria and the observation of reddish deposits during TV inspections.

The main question to be discussed is why F4 is different. SADE 2004 states two possibilities: an influence of the close distance to a railway of well F4 and the absent connection between the upper and the exploited aquifer. The latter is shown by flowmeter measurements. The absence of sulphate-reducing bacteria supports this interpretation further. In addition, this well seems to be (1) separated from the other three wells by a geological anomaly and (2) influenced by the nearby railway leading to e.g. high ammonium concentration, which may for example influence the bacteria community.

The investigations of interactions between micro organisms and hydrochemical conditions during the WellMa-project could contribute to a final assessment.

2.9 Verdun

2.9.1 Site description

Verdun, in the north-east of France (Dept. Meuse (55)), is supplied by two wells PN1 and PN2. According to what we could find out from Infoterre (BRGM), well PN1 (`01358X0149/F`) has been constructed in 1957 and PN2 (well `01358X0168/F`) in 1969.

2.9.2 Hydrogeological background

According to infoterre, the first well exploit a shallow alluvial aquifer consisting of sand and gravel, reaching from 2.20m to 10.00 m below ground surface. The underlying basis is a lime. On top is a silt and clay layer. Well PN2 exploits the sand as wells as the second aquifer, which is the fissured limestone. Looking at the pumping step test curves shows that both aquifers are unconfined.

2.9.3 The wells

Some data needed to be researched at Infoterre. Together with the available files:

- Données techniques lors de l'utilisation en secours de PN1 et PN2 (1994-2000) **Generale des Eaux - Archive**
- "Essais de pompage longue durée (72 heures)-Puits PN2-Avril 2007- Après régénération mécanique" (Long-time pumping test (72 hours) - Well PN2- April 2007-After mechanical rehabilitation) **CEO VERDUN Herli France –April 2007**
- Paper on PN2 rehabilitation, **CEO VERDUN January 2007** (handwritten date)
- General data in a report with no source mentioned
- "Rapport d'analyse" ("Analysis Report")- **CAE 2007**

the most important information could be drawn. However, there remain some gaps.

Master data

Well PN1 is 10.4 metres deep and has a maximum discharge of 390m³/h. Casing and screen are made from ceramics with a diameter of 500mm. The screen section starts at 7.50m below surface. The screen is backfilled with an artificial gravel pack starting at 6.00m.

Well PN 2 is 23 metres deep and discharges 200m³/h. Casing and screen are made of steel and have a diameter of 600mm in the beginning and 400mm further on. There are two screen sections, the upper from 4.00 to 10.50 in the first aquifer (alluvial sands) and the second from 12.00 to 22.50m below surface. Both are backfilled with an artificial gravel pack, separated by a one-metre thick layer of cement and clay.

Hydrochemical data

There was only one analysis available to us, containing not all parameters. However, the raw water seems to be quite unremarkable. With regard to the presence of calcium carbonates, this site has a rather low calcium concentration, comparable to La Saignonne and Mousseaux.

Operating data and maintenance history

An assessment of the wells was made in 2007. According to the files sent to us, well PN1 was in good condition, but well PN2 showed the need to be rehabilitated due to the presence of corrosion deposits (iron oxides) and carbonate precipitates.

The specific capacity of well PN1 (at 216m³/h) was at 104m³/h per metre drawdown. Well PN2 could be increased from 28 to 36m³/h per metre drawdown. However, as we do not have further data, we cannot access, if that is a good result or if it could have been better.

Assessment of well condition

For this site, the comparison of the both wells is quite interesting and correlates to the state of the art. The major difference lies in the fact that well PN1 exploits only the upper aquifer while PN2 is screened over both aquifers. Most probably this enables mixing processes to occur, leading to the observed corrosion and sintering processes.

A recommendation would be again to perform a depth-oriented measurement. In addition, flowmeter measurements could clarify, if both aquifers contribute to the discharge. If not, the weaker one could be sealed off.

Chapter 3 Conclusions

3.1 Relations between geology and ageing processes

Because wells always interact with the aquifer they are situated in, the hydrological and geochemical background is most important. These given conditions determine the well ageing potential, because they deliver the starting material for all occurring processes and reactions, be they chemically or microbiologically induced or of physical nature. Therefore, certain ageing types are linked to special geological pre-sets, e.g. carbonate sintering needs a limestone aquifer as source for the precipitating carbonates.

Here, the French data sets deliver a good starting point to assess such relationships. In the first instance, the interpretations support the hypothesis that the redox potential is a limiting factor determining the ageing type and that ageing occurs, where waters with different chemical composition and hence different redox potentials, mix. Secondly, they emphasize the role of oxygen as a limiting factor, both for biological and chemical iron clogging. Low oxygen seems to be either favourable for or pointing to biologically induced iron oxidation while high oxygen contents seem to enhance chemical clogging. The latter could be observed in the shallow aquifers of Chateau-Thierry and Saignonne. And thirdly, the role of a confining layer for preventing mixing of oxygen-rich upper water with the exploited second aquifer could be set in relation to well design showing that it is most important to properly seal off any surface water

For the consolidated rock aquifers counts a stronger dependence to the overall water availability within the catchment area. Wells in these aquifers are more vulnerable to a general decrease in discharge rates, not linked to well deterioration itself but to the aquifer loss.

The wells of Lisieux presented additionally the opportunity to compare wells without and with artificial gravel packs, both in consolidated rock aquifers. Here it was obvious that the gravel pack makes a well more vulnerable to clogging processes.

What could be observed mainly from the interpretations of TV inspections was the occurrence of different ageing types in one well. In any case, there seemed to be a depth-oriented distribution with biologically induced clogging (biofouling - iron-related bacteria) or corrosion (biocorrosion - sulphate-reducing bacteria) rather on top, followed by a zone with carbonate precipitates. Physical clogging occurred at the bottom or was restricted to sediment layers with smaller grain sizes than the main aquifer sediment type. Therefore, further investigations should include taking depth profiles for chemical contents such as oxygen, iron and/ or calcium and the redox potential (as done e.g. in Lisieux and Val-de-Reuil) to allow firstly input-output mass-balance calculations and secondly the calculation of mixing reactions.

3.2 Assessment of well performance data

As stated before, the quantitative monitoring is most useful if Q-s-curves of step pump tests are included. Compared to the sheer assessment of the specific capacity Qs during time of operation such data allow a relative assessment of any decrease or increase compared to the initial state. Without step test-Q-s-curves, this would only be possible for confined wells or for pumping tests with either the same discharge or a constant drawdown. Any changes in the discharge rate have to be included for assessment.

Most important is the initial pumping test performed at the starting point of well operation. However, because practical experience shows quite often differences in the calculated capacity, the initial capacity right at the start and after a few weeks of operation (due to well development effects during initial operation, e.g. increased packing density within the gravel pack or slight de-sanding of the adjacent aquifer etc.), it is recommended to repeat a step-pumping test after three to six months of operation.

The derived Q-s-curves have to be evaluated for each well individually by calculating firstly the initial specific capacity Qs and secondly the aquifer loss B and well loss C from the specific drawdown s/Q.

The graphical representation shows the well characteristics as relation between discharge rate Q and drawdown s. Plotting the initial curve and any actual curves in one diagram allows the comparison and assessment of the well performance. In general, steeper curves show a well deterioration.

What could be learned from the French data is firstly, that measurements should be automated as far as possible to prevent sheer reading errors during manual dip-meter measurements. Secondly, the monitoring interval or at least the time between two records, which are incorporated into graphical representations needs to be based on practical experience and cannot be generalized for all well sites.

Uncertainties come from interactions between adjacent wells or variations of the overall static water level. Hence, a very dense measuring interval might only increase the variability leading to wrong interpretations of changes in drawdown. On the other hand, the interval needs to be small enough to ensure an early detection of any well deterioration. Therefore, a dense interval together with a stepwise assessment of the measurements is recommended. The steps are

- evaluation of the overall static water level,
- calculation of drawdown,
- verification of discharge rate (especially for unconfined aquifers),
- conclusion of a trend line

The slope of this trend line then indicates the well condition with increased or constant values indicating a good condition and a decreasing trend line showing a general deterioration and the need for further assessment.

In addition, any technical and/ or economical decision, e.g. to change pump size or discharge rate, and maintenance operations needs to be recorded, too.

Chapter 4 Summary

With regard to the results of the statistical analysis of the Berlin well data, the French data basically seem to follow the general trends relating well ageing processes to parameters such as iron and oxygen concentrations, mean discharge, operation hours etc. However, for more detailed assessments and multivariate linear regressions, the data need to be completed and validated first.

To assess the wells further and to draw conclusions about potential interactions, recommendations for monitoring and diagnosis are in general the same as for Berlin or any other site.

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

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

The sampling and/ or monitoring interval depends on the rate of ageing and cannot be given in general but has to be decided for each well individually.

Altogether, these monitoring methods do also present first diagnosis of ageing types and extents necessary to plan any rehabilitation measure or adaptations of operation.

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

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

As all of the French well sites represent unique features, the selection of sites for the field investigations needs to be discussed with the technical directions. The following table summarizes the present state of our knowledge:

Table B-2: Basic features represented by the nine well sites with data available to us [KWB 2008]

Well site	Number of wells	Aquifer type	Features
Chateau-Thierry	10	shallow, sands, unconfined	• Redox conditions • Distance to nearby surface water
Lisieux	5 (6)	limestone, unconfined	• Consolidated aquifer with different well designs (with and without gravel)
Moulin de Douves	3 (4)	deep, sands, confined	• Deep aquifer • All ageing types
Mousseaux	1	deep, limestone, confined	• Aquifer type • Heavy decrease in well performance • But: Quite different well design
Roissy	1 (2)	same as Moulin de Douves	• Good documentation • All ageing types • Heavy decrease in well performance • But: only one well
Saint Denis	1	same as Moulin de Douves	• Presence of physical clogging • Heavy decrease • But: only one well
Saignonne	17 (22)	shallow, sands, unconfined	• One well field with quite different wells regarding age, design etc. • Presence of physical clogging • Presence of carbonate deposits
Val de Reuil	4	two aquifers, shallow, limestone, confined	• Good documentation • Presence of IRB • Depth-oriented sampling in 2004
Verdun	2	shallow, limestone, confined	• Chemically induced corrosion • Presence of carbonate deposits

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