Proper maintenance and timely rehabilitation of drilled water wells are crucial to controlling the cost of water production. **Prof. Dr. Christoph Treskatis**, associate professor RWTH Aachen University & TU University Darmstadt and **Päivi Puronpää-Schäfer**, MA, of cleanwells GbR explain proven ways to keep water wells flowing at optimum levels using prevention measures and rehabilitation methods.

Keeping up the flow

Most water wells decrease in yield over time. Once put into operation, wells begin to age; iron and manganese hydroxides start to develop around the pump and in the screen slots and gravel pack. Hydrochemical and microbiologically catalyzed reactions of mixing and precipitation form mineral crusts on these parts of the well, reducing the flow of water. Obvious signs, including higher drawdown at identical discharge capacity, lower pump performance, increasing power consumption, and higher production costs, indicate that the affected water well needs maintenance or, depending on the degree of incrustation, rehabilitation.

The ageing of water wells not only affects the cost of water production – new wells must be drilled on new sites to replace unmaintained wells – a preventable course of action that affects the environment. Consequently, the proper maintenance of water wells has become a high priority of water works, dependent on groundwater, in order to preserve the investment value of water resource infrastructure assets. In Germany, long-term empirical studies carried out by major water works prove that regular maintenance slows down well ageing significantly.

Why do wells age?

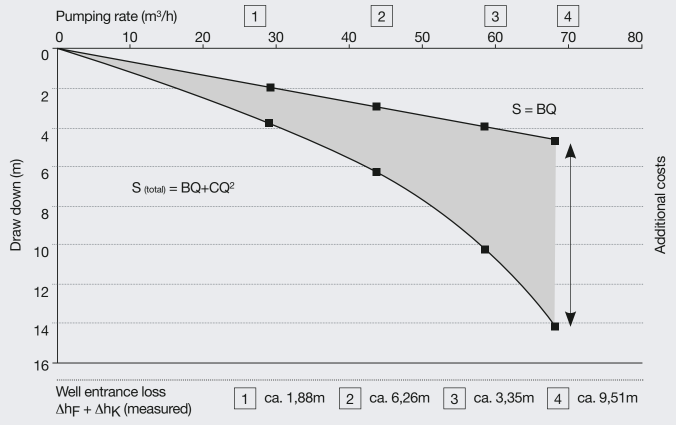
A fully screened well causes not only a change in the flow field, but also a vertical "short-circuit" for all hydrochemical zones. Most aquifers display a distinct redox zoning with the redox potential becoming sequentially more anoxic downwards. Redox is shorthand for oxidation reduction reaction. Camera inspections of well interiors show that the ageing process often starts to form at the top of the filter screen where most of the oxygen enters the well and mixes with dissolved iron and manganese leading to oxide precipitation. Mixing is accelerated by the turbulent flow conditions inside the well, i.e. whereas lower parts of a screen show a nearly homogeneous inflow; its upper meters provide the most water as per calculated flow models. These mineral incrustations gradually spread to deeper segments. Elevated content of iron oxides can reach a radius of up to four meters from the screen.

Mechanical, biological, and chemical factors also cause water wells to degrade. Screen, casing, pump, pipes, and sealings can deteriorate over time due to material ageing and corrosion. Mechanical clogging caused by dissolved and suspended particles of a size range between 0.0001 and nearly 10 millimeters transported by groundwater flow can decrease the well yield. Biomass accumulation accounts for the most common cause of ageing in injection wells. Ground movement, plant roots, and even vandalism can also affect wells.

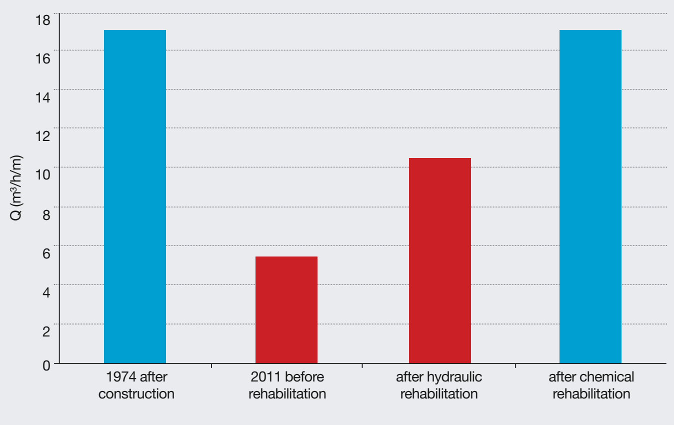
Mineral incrustations, however, are the principal cause of decreasing well yields. In Germany nearly 90 percent of investigated incrustation material consist of oxides, hydroxides, and oxihydroxides of iron and manganese. Specialized microorganisms such as *Gallionella ferruginea* and *Leptothrix ochracea* or discophorus, i.e. the so-called "iron bacteria,"thrive in mildly acidic groundwater environments depending on their nutrients Fe^{2+} and Mn^{2+} that flow past them. The outcome of this metabolism, Fe^{3+} and Mn^{4+} are insoluble and precipitate as iron and manganese oxides forming well incrustations.

These precipitates age in an irreversible sequence. The "fresh" iron oxides first dock on the surface of the gravel and slots of screen and are covered (laminated) by new precipitates. Microscopic, thin sections of iron-oxide samples reveal

Turbulent entrance losses and additional lifting capacity of a well pump in Well No. 4, Horgesgath, Rhine Valley (Treskatis 1999).



Results of a combined hydraulic-chemical well rehabilitation for Well No. 12 in Lower Saxony, Northern Germany.



structures that resemble annual rings. This shows that the precipitation is repeated continuously with the older layers acting as a starting point for the newer ones. In the case of the iron-oxide sequence, the first precipitates are usually ferri-hydrite, a phase of low crystallographic order and high surface area (150-400 m^2/g), which recrystallizes over time to the more stable phase goethite (∝-FeOOH, 20-80 m^2/g).

The re-crystallization process involves a decrease in surface area, solubility, and reactivity while thermodynamic stability and crystallite size increase. In time the sludgy ferrous fillings of pore spaces in combination with other particles develop into hard crystalline minerals. This transformation called Oswald ripening explains why older incrustations are harder to remove by chemical treatment.

Rising power costs

The flow of water from the aquifer through the water well should experience the least possible resistance. The natural ageing of wells, however, causes flow resistance to increase and drawdown to steepen exponentially. More electrical power is required to produce the same amount of water. The additional pumping cost due to natural ageing of the well can be calculated by multiplying the entrance loss by the operation time of the pump and the price of a kWh.

When pumping the example well at a capacity of 30 m^2/h more than 1.8 m of the total drawdown is due to natural well ageing. At a pumping rate of 40 m^2/h the entrance loss exceeds 3 m, whereas at 70 m^3/h more than 9.5 m of the total drawdown of 14.16 m can be documented as entrance loss. A running period of 10 years with a theoretical continuous production of 950,000 m^3 p.a. corresponding a life time of approximately 30 years total time in operation causes thus additional expenses for energy to compensate for entrance losses due to deficiency of construction depending on the well capacity of more than €10,200- (US$ 13,400-), i.e. every 5 m causes additional cost of €1,200- ($1,340-) per year due to the rising "wire-to-water-ratio."

The longer the interval between the commissioning and the maintenance measures, the more difficult and costly it becomes to restore the original well yield.

Working steps of well rehabilitation

A 10 percent decrease of the original well yield is generally considered as a sign to take action in order to find out the cause of the yield decline and to determine the method of well rehabilitation. Newer incrustations in the well are easier, faster, and less expensive to remove.

Well rehabilitation should follow the principle of separation, removal, and control, which means that the technical equipment in the well site plays a crucial role in the whole operation regarding cost and capacity. Principally the equipment in the market can be classified in three main categories based either on high water pressure, generation of pressure waves, or multi-chamber water circulation. In the ideal case, a strong separation capacity removes detached materials from the well and allows permanent control and monitoring of the operation.

The first step of a state-of-the-art well rehabilitation is the separation process, i.e. the physical and chemical parting of interconnected deposits from the well casing, screen slots, grain, and pores of the gravel pack in addition to the adjacent geology and aquifer. A thorough removal of the loosened incrustations is a prerequisite for an economical and successful chemical treatment. The emptier the pores and the cleaner the grains of the gravel pack are, the deeper chemical agents can penetrate and dissolve the rest of the incrustations, which could not be reached by the force of the preceding treatments.

The choice of the chemical agent should be based on a geochemical and/or mineralogical analysis of the well incrustations. Iron and manganese oxides are dissolved with pH-neutral reducers, which have a 50 times higher dissolving capacity of iron (III) than hydrochloric acid at a pH-value of 1.0 in the equal molar concentration as per stoichiometry. Carbonate incrustations require an inorganic, pH-dependant substance.

The process control during chemical rehabil-itation plays a crucial role in the sustainability of the maintenance measure. If iron oxides are not dissolved as thoroughly as possible during the treatments and the surface area of the remaining oxide incrustations is larger than before the rehabilitation, it provides an increased settling ground for iron bacteria. Due to the catalytic efficiency of the oxides the oxidization of the iron increases, i.e. the well rehabilitation acts as a catalyst causing a faster accumulation of incrustations than previously.

Control is also an instrument that helps the well owner to evaluate the performance of the executing company by providing for quality standards. It starts before the rehabilitation process begins with the documentation of the actual well data, and does not end even after the completed rehabilitation as the sustainability of the maintenance measure must be kept in view.

The intervals between well rehabilitations can only be defined individually for each well on the basis of systematic evaluation of monitoring data and tracking the yield during the production. Several factors influence the time frame of rehabilitation cycles, i.e. hydrochemistry of

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raw water, total abstraction volume, mode of operation (e.g. on/off switching rhythm, distance of dynamic water level to top of screen), constructional state (e.g. annular seals and casing joints), and thoroughness and efficiency of preceding rehabilitations.

The original specific yield of a vertical well in Lower Saxony in Northern Germany had dropped from the original QE = 17 m³/h/m in 1974 to 5.4 m³/h/m accompanied by an increase of drawdown from 15.25 m by one meter. The well no. 12 with a total depth of 39 m and a drilling diameter of 850 mm was built with a wooden screen of 18 m length and 300 mm diameter. Based on the well construction and operation data, the geochemistry of the groundwater and the analysis of the well incrustations, the well owner decided to carry out the rehabilitation with multi-chamber equipment in combination with a pH-neutral reducer of Fe3+ and Mn 4+. A geophysical survey to document the efficiency of the different working steps was conducted prior and after the rehabilitation in addition to a CCTV inspection and a pump test. The mechanical precleaning, the hydraulic rehabilitation of the gravel pack and the removal of the incrustations increased the specific yield up to QE = 17.1 m³/h/m. The original well yield was exceeded due to the chemical rehabilitation in combination with desanding.

Preventive measures

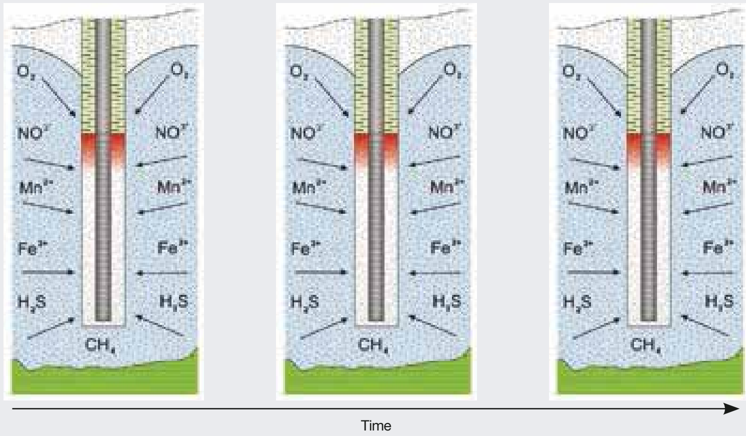
Water wells are a major investment for municipalities and private well owners, so they should bring the maximum return for the longest possible period of time. This target can only be achieved by constructing wells according to the long-term capacity of the aquifers. Locating an appropriate well site, which includes geological and hydrochemical investigations, can prevent wells from ageing early. For example, areas with high pH values and concentrations of chemical constituents that promote rapid development of incrustations, should be avoided. Hydrochemical conditions, including several aquifers that cause mixing of different waters in the well, also cause untimely ageing due to mineral oversaturation.

Well design influences the development of incrustations. Careful dimensioning of well components, especially of the gravel pack and the screen slots, is another way to extend the life span of a well. The gravel pack must be as fine as possible to retain sand from the aquifer, but at the same time coarse enough to allow desanding and to minimize head losses. The general aim is to minimize turbulent flow, which can enhance incrustation buildup through degassing and mixing.

Whereas wire-wound screens are easy to rehabilitate due to their high entrance area and geometry of the rods, resin-bound gravel packs attached to the screen have proven to be very difficult to rehabilitate. In recent years, approximately 250 water wells have been constructed in Germany using glass pearls instead of traditional gravel with remarkable advantages during operation and maintenance resulting in long-term cost efficiency.

Well operation practices have significant potential to minimize ageing processes. Excessive pumping should be avoided at all

Vertical redox zonation in an aquifer and the effect of a pumping well (Houben, Merten & Treskatis 1999)



Results of step-down pump test calculated turbulent entrance loss and additional pumping requirement at Well No. 4 in Horgesgath, Rhine Valley (Treskatis 1999).

Pumping rate Q		Total drawdowns	Additional drawdown Δs	Sw / Q	BQ	CQ²	s (calculated)
[m³/h]	[m³/s]	[m]	D s [m]	[s*m-2]	[m]	[m]	[m]
30	0.0083	3.88	3.88	465.79	1.99	1.69	3.68
45	0.0125	6.35	2.47	508.00	3.00	3.81	6.81
60	0.0167	10.26	3.91	615.48	4.00	6.78	10.78
70	0.0194	14.16	3.9	729.90	4.66	9.18	13.81

Key: B = hydraulic resistance (s/m²), C = entrance loss (s²/m⁵).

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costs because this will induce turbulence, mixing, oxygen input, and carbon dioxide degassing. One crucial aspect to prevent in well operation is to let the drawdown reach the screened interval, which leads to extremely accelerated incrustation buildup. If mechanical clogging by particles is the main cause of yield decline, changes in flow rate and flow direction, e.g. by repeatedly switching the pump on and off, can facilitate the breakup of particle bridges and the entrainment of plugging material.

During well commissioning methods of monitoring and measuring should be implemented to secure a continuous and reliable operation and to help identify problems that may emerge. A systematic data collection of hydraulics, water chemistry, and structural integrity is a prerequisite for preventive well maintenance instead of relying on “action by reaction” maintenance strategies.

Summary

The majority of drilled water wells age and accumulate mineral incrustations from natural causes. It is a global phenomenon that cannot be entirely prevented; however, it can be slowed down by timely countermeasures over the whole life cycle in order to reduce its cost. In Germany, approximately 25,000 wells are used for public water supply and ageing affects the majority of wells. The DVGW provides a set of technical standards that helps the water industry, engineering consulting firms, and rehabilitation companies to perform maintenance on these wells, according to the latest scientific findings.

Both preventive maintenance and regular rehabilitation play an increasingly significant role in controlling water production costs. Longer intervals between well commissioning and maintenance lead to more costly and difficult efforts to restore to the original well yields. State-of-the-art maintenance measures can keep existing wells running and even lengthen their lifespan. Consequently, fewer new wells require drilling, thereby saving costs in regards to construction and the environment.

Authors’ Note

Prof. habil. Dr. Christoph Treskatis, is the co-author of Water Well Rehabilitation and Reconstruction, *published in 2003 by McGraw-Hill in New York, USA, and in Germany (2001) and Poland (2007). The second edition was published in 2012. He is an associate professor at RWTH Aachen University and TU University Darmstadt in Germany.*

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