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Effective Water Well Rehabilitation Using a Combined Ultrasonic-Mechanical Method

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Abstract

The restoration of original boreholes is preferable to building new ones as the process is more cost-effective. However, traditional chemical or mechanical regeneration methods may cause soil contamination or destruction of the borehole equipment. Here, we report on a newly developed ultrasound device that has been designed to reduce the need for the heavy lifting equipment, such as cranes, that typically accompany commercially available equipment. The device is minimized in size and equipped with a PLC, allowing the unit to be controlled remotely using a laptop computer. We tested the prototype ultrasound device on a fifty-year-old borehole and used standard geophysical well-logging techniques to evaluate its regeneration efficiency. After regeneration the fundamental change was an increase in the intensity of the downward flow, the water no more flows across the borehole, but exclusively downward (Q=115,000 l/day) what was thirty-fold acceleration of the flow of water through the well. New tributaries to the well were activated, which also signaled cleaning of the formerly clogged gravel sheath. The specific yield derived after regeneration was 1.13-1.49 fold higher than the specific yield before regeneration. Borehole regeneration using ultrasound, while a less widely used method, offers adequate regeneration efficiency and is more environmentally friendly. Moreover, the presented prototype also offers reduced financial costs for regeneration compared to similar techniques that currently use heavy equipment and enables better mobility for harder-to-reach wells.

Keywords: Water well; Bore well; Ultrasonic mechanical method; Water yield

Highlights:

- Technology developed as easy to manipulate, cost-effective, and remote-controlled
- Piezoceramic generator is used to generate high-frequency ultrasound
- Effective and gentle regeneration of water wells
- A 50% increase in well yield was observed after regeneration

Introduction

Drilled water wells are important, widely-used, sources of water; however, as they age, their specific water yield may decline. This decrease in water yield, and consequently water level, in the well is usually the result of colmatation (clogging of originally porous media) of the gravel pack surrounding the filtering tube, causing it to become clogged with sand, bacterial biofilms or Iron (Fe) oxides from the well's steel casing [1-2]. Biological fouling is caused by microbial activity and their living processes [3]. The intensity of microbial action depends on conditions during the year and pumping regimes. There are also several kinds of bacteria supporting the growth of iron incrustations, for example *Gallionella* sp.

In line with increasing demands for sustainability and cost effectiveness, increasing efforts are being made to restore and/or regenerate such wells, rather than drill new ones.

Well regeneration is typically performed mechanically using brushes or high-pressure flows. While mechanical cleaning allows for the removal of incrustations on the inner side of the well casing and screens, accessibility to the pipe may be limited due to unevenness of the surface [4]. Moreover, the intensity of mechanical cleaning must be adapted to the well's condition to avoid destruction or full collapse of the well casing, which may have been weakened by age and corrosion; in such cases, gentle removal may not be enough to clean the well. Further, even after cleaning, colmatation of the gravel may still prevent any increase in the well's yield [5]. In contrast, chemical well regeneration methods, using reagents such as mineral or organic acids and hydroxides usually guarantee a significant improvement in yield as both the well casing and its backfill can be effectively treated. However, these methods have a number of technological limitations and can only be applied at selected locations and under certain conditions, *i.e.*, the well casing material must be resistant to the reagent used, water in the environment must be slow flowing to prevent migration of the reagent outside the well's body, and the composition of the local rock must not be such that chemical reactions result in the formation of harmful substances. Last, but not least, the application of chemical substances requires a demanding approval process.

In recent decades, a complex new cleaning method has been applied based on ultrasonic cleaning technology, originally used in the recovery of oil wells [6]. In short, ultrasound waves are directed through the media to be cleaned, causing strong molecular oscillations accompanied by an increase in temperature. At sites where the altering acoustic pressure has a negative value, miniature bubbles are formed (cavitation) and, due to the negative pressure, the bubbles gradually expand and rapidly shrink when polarity is opposed. The bubbles then collapse while forming a jet toward the surface. The resultant changes in temperature and pressure then disrupt the mechanical bond between the dirt and the object being cleaned [7]. The effectiveness of ultrasound treatment will depend on the frequency of oscillation, with lower frequencies (20-25 kHz) providing a greater erosive effect, preferable for large deposits.

Equipment specifically designed for the cleaning of water wells (Sonic Technologies GmbH, Germany) works on the principle of magnetostrictive generators that generate ultrasound with a frequency of 20 kHz. However, the lower-frequency ultrasound provided by such equipment may not be enough for certain borehole geometries or for heavily clogged boreholes. Furthermore, the higher pressure found in deep wells can increase resonance resistance, thereby reducing the ultrasound's effectiveness. Thus, the unit's power consumption must be increased, putting greater demands on the generator and the accessory ultrasound device, *i.e.*, increased demands on electrical power to be delivered and larger power lines and radiators required. The resulting size of the unit may then become an important issue, as heavy equipment will be needed to manipulate it, such as a crane for lowering the ultrasound generator into the well and a truck with a 20 kW electrical generator to power the ultrasound excitation source [8].

Here, we describe a newly developed well regeneration device based on ultrasound technology, designed as a mobile unit with minimal operating costs and operator requirements. The entire system comes as a relatively small unit, making it ideal for hydrogeological sites difficult to reach with heavy equipment, and can be completely controlled from an industrial PLC, which also allows for remote monitoring. Finally, a piezoceramic generator is used to generate high ultrasound frequencies, giving the unit increased efficiency even with lower generator power.

Materials and Methods

Development of the ultrasonic unit

The core of the whole system is the ultrasonic unit, consisting of an ultrasonic generator and the ultrasonic emitter, which is lowered into the well and generates the ultrasonic waves. Development of the ultrasonic generator and emitter was undertaken in cooperation with ECOSON s.r.o. (Slovakia), a commercial supplier of ultrasonic equipment, who designed and built the ultrasonic emitter and tuned the ultrasonic generator for this application. Tuning was required as the length of the cable (120 m) results in parasitic capacitance and inductance, requiring optimisation of the excitation current to eliminate any negative effects and ensure sufficient effective power for excitation of the ultrasound emitter. In addition, the company examined the effect of external medium pressure on the ultrasound power transmitted in the company's laboratory pressure chamber [9-10]. Subsequent experiments showed that external pressure reduced resonance resistance and decreased total power consumption, meaning that the output power of the ultrasound generator had to be controlled. These findings were then taken into consideration when designing the control unit prototype.

The ultrasonic emitter probe was designed around a piezoceramic element, which provides high performance even when using smaller, less efficient generators with a low power supply. One disadvantage of this arrangement, however, is an increase in sensitivity to excitation signal parameters, which can make the negative effect of using a long cable more pronounced (Figure 1).

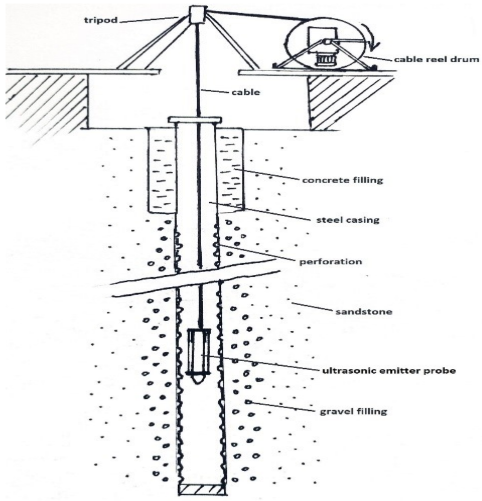

Figure 1: Ultrasonic emitter.

The original concept for the device was that it be mobile and self-sufficient; thus, a key element of the design was the cable reel drum, which contains all the necessary components for operation of the device within the drum itself. The drum is designed to hold a seven-core 12 mm cable (LAPP OLFLEX ROBUST 215 C 7 × 2.5 mm^2) for use in wells of ca. 100 m depth. Owing to the potential for parasitic inductance, the cable is wound in one layer, which is a determining factor for the final drum dimensions. The weight of the probe and cable together comes to around 25 kg, and it is assumed that the probe will be lowered at a velocity of 10m/min, which will influence engine and transmission performance. The complete drum drive assembly consists of a 370 W four-pole motor, a 1:3 direct gear and a second auxiliary worm gear.

The device also includes an INVT good drive 10 frequency converter, used to regulate the speed of the electric motors. In this case, the frequency and voltage are changed simultaneously; once the nominal voltage values are reached then only the frequency need be adjusted. Controlling the speed of an AC motor with a converter allows for smooth or abrupt changes in speed and direct control of the output torque of the drive system. Additionally, a converter allows for controlled starting and stopping of the drive system, significantly reducing mechanical current and torque shocks when applied with high inertia. Finally, the converter provides significant energy savings, especially in applications where speed control replaces the need for throttling valves or spillways.

As all the equipment had to be fitted within the rotating cable drum, the control system was based on a control system implemented using an industrial Tecomat PLC personal computer with a Wi-Fi connection, which meant the device could be operated from any location via a laptop or mobile phone. The PLC controllers are fully developed and manufactured in the Czech Republic by Teco a.s. and comply with all international standards. For our needs, the Tecomat CP-1005 PLC control module proved to be most suitable. The module is equipped with six multi-purpose inputs, each of which can be used as analog or binary, one fast input that can be used as a counter input, six relay outputs, two analog outputs and a CIB bus. It also includes a backup CMOS RAM for data, tables, etc., a flash memory for the program, an SD memory card slot for data storage, an RTC circuit, an Ethernet interface (built-in web server), two serial communication lines for communicating with peripherals and a TCL2 system interface for connecting additional modules if needed [11-12].

During tuning of the ultrasound generator-emitter system, it was found necessary to control the emitter power depending on immersion depth to prevent fluctuations in the ultrasound power supply caused by increasing hydrostatic pressure. To achieve this, the control system was equipped with a C-EM-0401M electric meter connected directly to the ClB bus, allowing for fast and accurate measurement of the power supply current. The electric meter allows for the measurement of phase voltages, currents, active and reactive power, power factor, frequency and harmonic distortion in the low-voltage 230/400 V AC network and within the range of nominal currents (Figure 2).

Figure 2: Left: Lowering the ultrasonic emitter into the borehole; Middle: The device in process with an operator using a laptop to control the system; Right: The probe after re-emerging from the borehole.

Borehole geology and lithology

Geologically, the area of the borehole (KVH-6) lies at the junction of two geological units, sedimentary rocks of the upper cretaceous forming the Elbe sandstone Mtns., and the substrate of the Lusatian Mtns. The drill borehole passes through the cretaceous sandstone formation, comprising alternating layers of argillaceous, dusty and clayey sandstones with layers of relatively pure fine to medium-grained sandstone. The primary source of groundwater in the area is through rainfall infiltration, with runoff occurring through drainage into streams and springs or catchment objects. The catchment is drained by the River Chřibská Kamenice and several unnamed tributaries [13]. The well was chosen for testing the ultrasonic device as it was not possible to regenerate it chemically due to the high probability of hydraulic communication with other wells in the area.

Well parameters

The borehole, which was installed in 1971, has a diameter of 530 mm and is 83 m deep. The entire borehole is lined with a 355 mm diameter steel casing, perforated in sections of 6.2–21.3 m and 26.3–72.6 m. Down to 5 m, the well annulus between the borehole wall and the casing is sealed with cement, while the rest of the hole is filled with gravel. Prior to well regeneration, a complete diagnostic inspection of the well borehole was performed with a video camera, along with logging and pumping measurements. The well casing showed advanced corrosion with heavy surface encrustations, which made it impossible to recognize the perforation holes. Growths on the casing caused it to narrow in several places by 1-2 cm. Drawdown tests revealed a yield of Q=0.63 L/s. Owing to its age, it was assumed that there would be significant colmatation of the casing along the entire length of the well.

Well rehabilitation process

The regeneration process, including tests of well efficiency, was performed over a 13-day period. As a first step, drawdown tests were performed and water samples taken for chemical and bacterial analysis. Next, the ultrasonic probe was lowered to a depth of 60 m and, after a regeneration period of 5 min, the probe was lifted in 0.5 m increments (*i.e.*, the active length of the ultrasonic emitter), with a 5 min regenerate period between each increment. Next, the borehole was purged using the air-lift technique and well-logging and drawdown tests performed over subsequent days. Following the ultrasonic regeneration, this pipe was cleaned mechanically with steel brushes, after which the well was air-lifted again to remove any residual sediment. After this, the regeneration process was repeated once more and, finally, drawdown tests, well-logging and a final visualization of the borehole were performed [14].

Evaluation of regeneration process effectiveness

A commercial company, SG GEOTECHNIKA, a.s. (Czech Republic), was hired to assess the method's effectiveness, using a suite of standard geophysical well-logging techniques. The techniques applied included:

- Drawndown tests.
- Video inspection with a remote camera.
- Sensitive thermometry.
- Resistometry, using 'labelled liquid dilution'.
- Resistometry, using 'constant labelled liquid pumping'.
- Gamma logging.
- Gamma-gamma density modification logging.
- Cavernometry.
- Neutron-neutron logging.
- Measurement of physical and chemical water properties: pH, Redox potential, percentage of dissolved oxygen, conductivity.
- Molecular-genetic analysis overall microbial recovery and detection of selected microorganisms.

Methodology of evaluation of microbial settlement

Samples were filtered using a 0.22 µm filter followed by extraction of DNA (by means of FastDNA SPIN Kit for Soil). A specific marker for bacterial 16S rDNA which corresponds with bacterial recovery was observed by means of quantitative polymerase reaction (qPCR). Also, the sulfate-reducing (markers apsA and dsrA), iron-reducing (Geobacter-Geo and Shewanella-Sw), iron-oxidizing (Gallionella-Gall), and denitrifying bacteria (markers nirK and nirS) were monitored. Analysis was performed using LightCycler 480 System (Roche). The Cq value is the number of cycles that are required to overcome the detection limit. The interpretation of qPCR is based on indirect proportion; the lower the Cq value the higher the amount of specific DNA. Relative quantity refers to comparing of Cq of the sample to Cq of the reference sample. Number 1 refers to the same quantity; number 2 refers to twice the quantity, etc [15]. A reference was a sample of water from the borehole before the regeneration.

Results and Discussion

Video monitoring

Video monitoring of the condition of the borehole casing before, during and after regeneration (Figure 3) revealed a perforation in the casing structure previously invisible due to sediment coverage. On the other hand, a section of approx. 15-20 m of the casing still supported “veils” of bacteria, indicating that the ultrasonic method had not completely eliminated them. It is likely, however, that the cell walls of the bacteria had been disrupted by the ultrasonic treatment, thereby killing the bacteria, though this was not confirmed during monitoring. However, clumps of bacterial metabolites in the downhole equipment indicated that at least some of the bacteria had been removed from the walls under the intense ultrasonic effect. While the original bacterial growths, or incrustations, on the borehole wall were not particularly large before regeneration, it was clear that the largest of these had been removed.

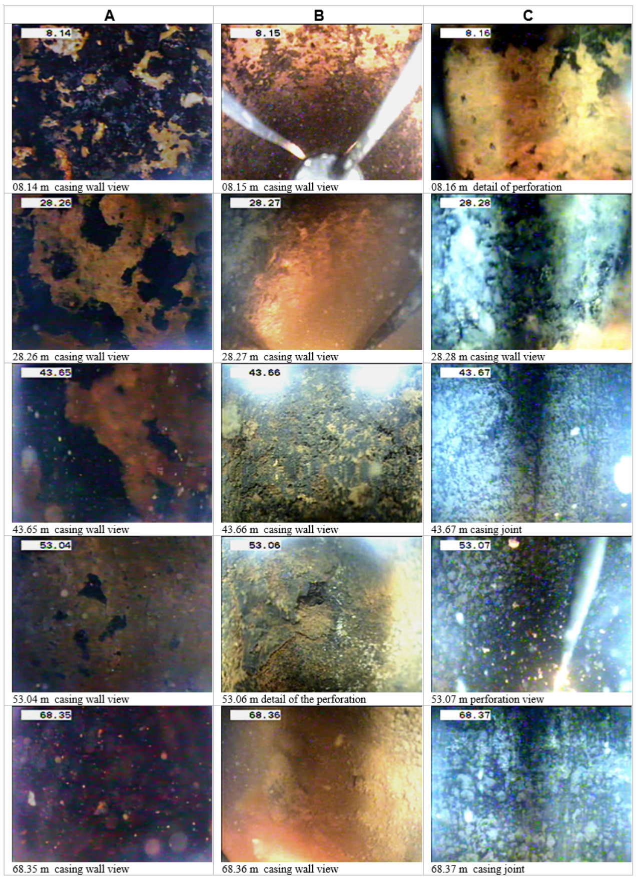

Figure 3: Comparison of borehole equipment technical condition A) before regeneration, B) after the regeneration first step, and C) after the second regeneration step.

Well logging

Well logging to assess hydrogeological conditions before and after regeneration (Figure 4; three graphs on left) revealed significant changes in the circulation of well groundwater during and after regeneration.

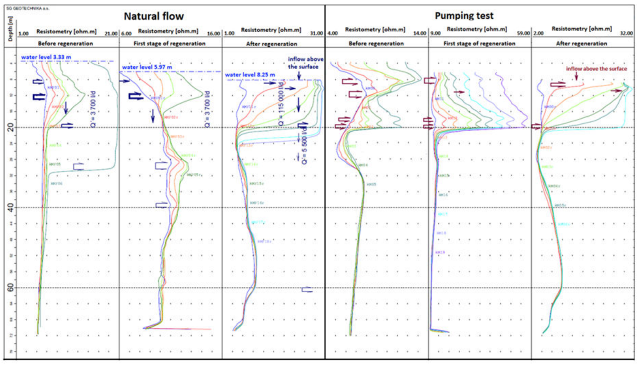

Figure 4: Hydrodynamic conditions in the well before and after ultrasonic regeneration.

There was also a decrease in water level and, while this may partly be related to pumping from a relatively close well within the borehole’s hydraulic range, it clearly indicated an increase in the well casing’s (and probably also the gravel layer) permeability. Prior to regeneration, the water level was recorded at 3.33 m below the surface, with water flowing into the well across the borehole at a rate of up to 1.6 m/day at depths of 7.9-9.5 m and 11.0-12.5 m. Part of the water flowing at 11.0-12.5 m did not flow across the borehole but rather flowed downward through the borehole, with a discharge rate of Q=3700 l/day. The flowing water then left the inner space of the well at a depth of 17.8-20.2 m. No flow was observed below 20.2 m throughout the five-hour observation period. Three weeks later, a second series of resistometry measurements were taken, and these revealed slow flow below 20.2 m. Water was recorded flowing slowly (in the order of tens of litres per day) down to a depth of 30.0–30.5 m, where it then left the well, with just a very small amount, ranging from tenths of a litre to a few litres per day, continued on downward and left the definitively well at a depth of 59.2 m (Figure 5).

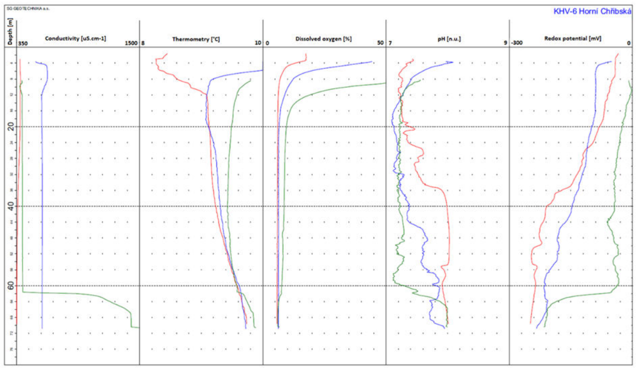

Figure 5: Physical-chemical water properties during regeneration. Red line=before regeneration, blue line=after the first regeneration stage, green line=after the second regeneration stage.

After the first stage of regeneration, the water level had risen to 5.97 m, with water flowing in at the same depths as before regeneration though the inflow at 11.0–12.5 m was more pronounced flow than that at 7.9–9.5 m. While flow rate across the well had increased to 2.2 m/day, downward flow was as at a similar intensity as before regeneration at Q'=3700 l/day. The permeable position at 29–30.5 m was more pronounced, with signs of dilution already visible during the first hours of monitoring, and a weak inflow was also recorded at 39–40 m.

After the second regeneration phase, the water level had risen to 8.2 m. Hence the inflow, now at 7.9–9.5 m, was partially above the water level, at which point the video camera clearly showed water spraying into the well through perforation holes at 7.9 m (Figure 3) [16]. There was also a distinct increase in the intensity of downward flow, with water no longer flowing across the borehole but instead flowing exclusively downward at Q'=115,000 l/day, resulting in a thirty-fold acceleration in the flow of water through the well. Of this flowing water, 95 % left the well through permeable positions at 17.8–20.2 m, and the remaining 5 % (5,500 l/day) continued downward. Temperature curve dynamics indicated that part of this water left the well at 39–40 m, and the rest at 59.5–61.5 m (Figure 6).

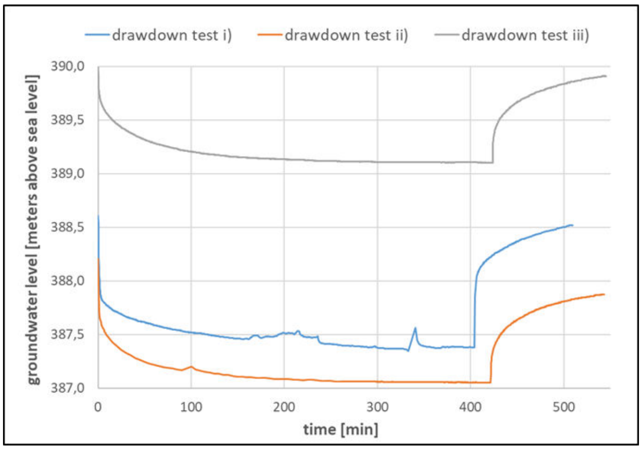

Figure 6: Groundwater level at the KHV-6 well during pumping tests: i) Drawdown before regeneration; ii) Drawdown after treatment with ultrasound; iii) Drawdown after treatment with a combination of mechanical and ultrasound methods.

Drawdown tests

Drawdown tests were used to verify the water inflows reported above, as well as their relative yields (Figure 5; three graphs on right). Before regeneration, water was pumped at a flow rate of Q=0.63 l/s, after which the level dropped by dS=0.22 m and stabilized. While inflows were recorded at 7.9-9.5 m, 11.0-12.5 m, 17.8-18.8 m and 19.8-20.2 m, none were recorded in the middle part of the lower half of the borehole during pumping.

After the first stage of regeneration, the water pumping capacity had risen to Q=0.71 l/s, after which the level dropped by dS=0.21 m and stabilized. Inflows once again appeared at the same depths as before regeneration, but inflows at 17.8–18.8 m and 19.8–20.2 m were stronger (Figure 4).

After the second regeneration stage, water was pumped at a capacity of Q=0.63 l/s, *i.e.*, the same as before regeneration, but the level then dropped to dS=0.49 m and stabilized. Though the water level had dropped by 49 cm, water continued to flow down the pipe. At this point, water was only flowing into the pump from the affluent at 7.9–9.5 m. Part of the water from this affluent continued down the borehole, most of it leaving at the permeable position at 19.8-20.2 m. While this might be considered an 'hydraulic short circuit', this was not due to a difference in water levels in our case, but rather to the high volume of water flowing in at 7.9-9.5 m and 11 m (115,000 l/d=1.33 l/s), of which roughly 50% was then pumped out, the remaining half continuing to flow down the well (Figure 4).

Nevertheless, the thorough hydrodynamic change in the drawdown regime was also due to using another borehole in the area nearby at the same time.

Physical-chemical properties

Monitoring of the physic-chemical properties during the water well regeneration can be useful for understanding of groundwater flow or to distinguish underground water with a longer residence time from surface water seepages and last but not least a zonality of physical-chemical parameters may localize the inflows. Additionally, specific physical-chemical conditions (pH, ORP, T, dissolved oxygen) may give to rise of incrustations which are formed for example by iron oxides and hydroxides, sulfur-enriched iron oxides, manganese oxides, calcium and magnesium carbonates and aluminum hydroxides. For example, the iron hydroxides are formed from iron oxidation in anoxic water to the ferrous ions which are changed to ferric ions these are then hydrolyzed into insoluble iron hydroxides. The release of carbon dioxide affects the bicarbonate balance by precipitating calcium carbonate. Chemical fouling also includes electrochemical corrosion of iron and steel parts of the well.

There were no significant changes recorded in physical-chemical water properties until the second regeneration step, after which dissolved oxygen levels near the surface increased, while levels lower in the well decreased rapidly from origin 5–6% to 9-10% (green line, Figure 6). This was primarily due to the water level dropping to 8.2 m, meaning that the first inlet tributary was now above the water level. Consequently, water sprayed from the perforations onto the surface of the water, absorbed oxygen from the air as it did so. This fast-flowing water had elevated oxygen levels over pre-regeneration levels and oxygen content decreased slightly with depth from 10% to 8 % at 60 meters and on down to the original value of 5–6% at 62 m (Figure 6). It is at this point that the flowing water definitively leaves the borehole area; below this level, water remained in the well and did not circulate.

Our results showed a direct relationship between oxygen content and redox values, with redox potential decreasing from zero to significantly negative values before regeneration, but levels remaining close to zero down to 62 m (the last point at which flowing water leaves the borehole) after regeneration, presumably as the water is now flowing faster down the borehole. At 62 m, there is an interface at which values decrease sharply until near the bottom of the well, when they approach the values from before regeneration (Figure 7). Similarly, there was no significant change in pH (pH=7.2) up to 60 m depth; however, values increased significantly to pH 8.0 over the 60–63 m section (Figure 6), presumably due to reactivation of water flow following regeneration.

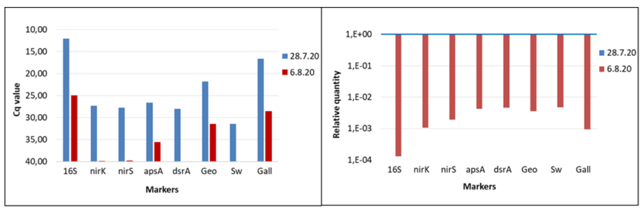

Figure 7: Bacterial recovery of water from well KHV-6, sampling before (blue) and after (red) regeneration (Cq values on the left, relative quantity on the right).

Temperature curves before and during regeneration remained similar aside from some seasonal fluctuations, observable to a depth of

12 m (Figure 6). After regeneration, however, there were two changes. First, the temperature gradient was much reduced down to a depth of 61.5 m due to the faster flow of water down the well (Figure 6). In the 12-40 m section, water temperatures remained relatively constant, but rose slowly between 40 and 61.5 m. The temperature gradient was somewhat higher around this point as part of the water leaves the well at 39–40 m and, consequently, the downward flow of water is somewhat reduced. Secondly, the flowing water leaves the well at a depth of 61.5 m; consequently, there is a sudden increase in temperature at 61.5-62 m (Figure 7).

We observed no significant zoning in water conductivity before regeneration; however, while conductivity values remained relatively constant and similar to those before regeneration (approx. 360 µS/cm) down to 61.5 m after regeneration, values rose sharply to almost 1500 µS/cm at 61.5–62 m, and remained at this level to the bottom of the borehole (Figure 7). During regeneration, it is likely that impurities were released into the water, where they became partially dissolved, and increasing conductivity. Rapid water flow between the surface and 62 m, however, ensured that the water with dissolved substances was flushed away. In the section from 61.5 m to the bottom, however, there was no longer any water circulation, and the impurities were able to build up, increasing local conductivity.

Evaluation of the drawdown tests

The effect of regeneration was assessed based on the drawdown tests results i) before regeneration, ii) after regeneration using ultrasound, iii) after regeneration using ultrasound and mechanical brush. A seven hour taking drawdown test was performed before regeneration with drawdown capacity of 1.72 $L.s^{-1}$. After regeneration, two further seven hour tests were performed with drawdown capacities of 1.83 and 1.87 $L.s^{-1}$ (Figure 6).

The drawdown tests were performed in the same way however the real process was not completely the same, thus the resulting curves were devoted to three parts: beginning, middle, end part with every part evaluated separately. The curves were fitted with theoretic theis-type model and model derivated from theis-type the Cooper-Jacob, by means these the hydraulic transmissivity was derived (Table 1). The beginning part is characterized by the fastest drop in the level of ground water and represents the nearest zone surrounding the well. Transmissivity of the beginning part was as 2.65-3.48 folds higher after regeneration by means theis method. The Cooper-Jacob was not evaluated due to enormous drop of ground water level. The middle part of theoretical curve represents more remote surrounds. After regeneration the transmissivity according the theis method was 1.66-1.68 fold higher and according the Cooper-Jacob method the transmissivity was 1.56-1.88 fold higher than before regeneration. The end of the drawdown test is characterized by the stabile level of ground water. In the end part the transmissivity was 1.04-1.49 fold higher than before regeneration is according the theis method and 1.09-1.53 fold higher according the Cooper-Jacob method. Finally, before and after regeneration the specific yield of the well was calculated. The specific yield was 1.13-1.49 fold higher after regeneration. The end part provided the most relevant results when transmissivity and specific was about 10% higher after first regeneration step and about 50% higher after second regeneration step including mechanical purging.

Method	Part of the curve	Parameter	i) before regeneration (drawdown 1.72 l/s)	ii) after first regeneration (drawdown 1.83 l/s)	iii) after second part of regeneration (drawdown 1.87l/s)	ratio i)/ii)	ratio i)/iii)
Theis	Beginning	Transmissivity (m^2/s)	4.62E-04	-	1.39E-03	-	3
	Middle	Transmissivity (m^2/s)	7.13E-04	1.50E-03	1.02E-03	2.1	1.43
	End	Transmissivity (m^2/s)	1.16E-03	1.21E-03	1.68E-03	1.04	1.45
Cooper-Jacobs	Beginning	Transmissivity (m^2/s)	4.53E-04	-	1.58E-03	-	3.48
	Middle	Transmissivity (m^2/s)	6.36E-04	1.15E-03	1.19E-03	1.81	1.88
	End	Transmissivity (m^2/s)	1.22E-03	1.33E-03	1.87E-03	1.09	1.53
Stabile flow	End	Drawdown (l/s)	1.72	1.83	1.87		
	End	Groundwater level (m)	1.23	1.16	0.9		
	End	Specific yield (l/s/m)	1.4	1.58	2.08	1.13	1.49

Table 1: Evaluation of drawdown tests by means theoretic model Theis-type and Cooper-Jacob.

Evaluation of microbial settlement

Cq values before regeneration demonstrate high settlement of all monitored bacterial groups. After regeneration, a significant decrease in all bacterial colonies occurred. The relative quantity graph shows that the decrease was by two or four orders of magnitude. Some of the bacterial markers even completely disappeared. Regeneration possessed a strong antimicrobial effect despite persistent bacterial "veils" on borehole walls detected by camera survey at end of activities.

Conclusions

Borehole regeneration with ultrasound had a significant impact on well hydrogeological parameters, with major changes in the water flow regime observable after previously clogged permeable positions were re-opened, leading to observable changes in water physical-chemical properties and their zonation and a 50% increase in well yield. Ultrasound, unlike conventional mechanical regeneration methods, had an effect on the space outside the equipment, with oscillation of the gravel resulting in the release of particles and subsequent opening of clogged pore spaces. By combining ultrasound with a mechanical brush, the internal surface of the borehole was largely cleaned, and the effect was higher than that when using the ultrasound only. Contrary to expectations, it was not possible to completely remove all bacterial colonies using ultrasound, though partial elimination was achieved.

The great advantage of the ultrasonic regeneration method is its universal applicability. For example, chemical regeneration is limited in wells where groundwater flow could contaminate other water sources, while mechanical regeneration, and especially the hydraulic shock method, is limited by the strength of the well equipment, particularly when made of hardened plywood or in wells where the steel casing is weakened due to corrosion. We suggest that a combination of the ultrasonic method with another method that affects the internal space of the well is optimal. The choice of complementary method depends on the construction material and current state of the well equipment, this could involve a combination of ultrasonics with airlift or mechanical brushes, the choice of method being carefully selected based on the parameters and technical condition of the specific well.

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Data Availability

All relevant data has been included in the manuscript.

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