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IN SITU REHABILITATION OF AGING PUBLIC WATER SUPPLY WELLS

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Abstract: The main causes of well aging and consequently performance decline are incrustation from mineral scaling, biofilm development, and microbial fouling. The presented research was conducted with the aim of examination and comparison of advantages and disadvantages of different *in situ* rehabilitation methods for improving well yield and water quality. Mechanical approaches which include wire brushing, jetting, and surging physically remove deposits and clogs, while chemical techniques utilize acid dissolution, oxidizing and reducing agents, and chelating compounds. Chemical techniques effectively treat iron, manganese, and calcium scales. The novel biological treatments, including enzyme-based biofilm removal and bacteriophage applications, offer a promising approach to selective and sustainable prevention of fouling. As a result, the mechanisms, advantages, and limitations of each method along with safety and regulatory considerations for their use in potable water systems are analyzed. The paper emphasizes the need for well-adapted, integrated approaches to maintain long-term functionality and protect and safe public health.
Key words: Well rehabilitation, incrustation, biofilm, water supply wells

INTRODUCTION

Over time the accumulation of mineral and biological deposits in public water supply wells leads to performance and yield decline, the process commonly known as well ageing or incrustation. Fouling usually includes the formation of ochre deposits, from iron and manganese oxides, calcium carbonate scaling, and development of biofilms due to iron bacteria and other microorganisms.
Such deposits narrow screen openings, clog adjacent aquifer pore spaces, and restrict water inflow, leading to reduced yield, impaired water quality, and increased operational costs. The primary contributors to well fouling are iron and manganese oxides, which precipitate as reddish-brown or black crusts on well infrastructure. Calcium carbonate scaling, formed from the precipitation of carbonate-rich groundwater minerals, creating hard, calcareous deposits. The slime produced by microbial communities includes a gelatinous extracellular material that can trap metals and other particles. These components often co-occur, creating complex and persistent incrustations that resist removal. In response, water utilities employ a combination of *in situ* rehabilitation techniques that restore well performance without necessitating complete reconstruction. Such methods must be evidently effective, safe for drinking water systems, and ideally supported by field validation or peer-reviewed literature.
We reviewed techniques alongside new developments aimed at improving well rehabilitation methods. It discusses their mechanisms of action, field applications, benefits, and limitations. The objective of conducted review is to offer a technically sound reference for utility engineers and hydrogeologists involved in maintaining the longevity and efficiency of public water supply infrastructure.

MATERIAL AND METHODS

To review the advantages and disadvantages of available regeneration methods, presented research encompassed comprehensive synthesis of established field practices, scientific research, industry manuals, and technical reports related to the *in situ* rehabilitation of aging water supply wells. The review includes both conventional techniques and innovative technologies, evaluated considering practical applicability, safety, and regulatory compliance. Standard operating procedures were drawn from established guidelines published by organizations such as Penn State Extension [1], the American Water Works Association (AWWA) [7], and industry publications like the Water Well Journal [2]. These were complemented by peer-reviewed studies focused on removing mineral deposits, such as carbonate scale and iron or manganese oxides [4,5], as well as research on the use of chemical agents like oxidants and chelating compounds for cleaning wells [3,5,7]. In addition, recent advances in biological treatment methods, including enzyme-based cleaning and bacteriophage applications, were considered for their potential in controlling biofilms [6]. Safety and regulatory aspects were reviewed using drinking water standards such as NSF/ANSI Standard 60, which sets the criteria for allowable treatment chemicals in potable water systems.

Methodological Approach

The three main well regeneration categories, which represent the principal approaches to well rehabilitation: mechanical, chemical, and biological (innovative) techniques are differentiated. Mechanical *in situ* techniques consider physical breaking up and removing mineral and biological buildup inside the well, through direct agitation, brushing, jetting, or hydraulic impulses. Chemical methods comprise the use of acids, oxidants, reducing agents, and chelants to dissolve or dislodge incrustation and sanitize biofouled surfaces. Innovative biological strategies, including enzymatic treatments and bacteriophage applications, represent a growing area of interest for selective and environmentally compatible biofilm control.

The distinguished categories were critically assessed considering their mechanism of action and primary fouling targets (e.g., carbonate scaling, iron oxide coatings, or biofilms). The results of laboratory studies and field-scale implementations indicated the effectiveness of applied methods. The consideration of operational safety and compatibility with potable water standards was also analyzed, along with attention to infrastructure integrity and potential impacts on well components. The review also accounted for regulatory and environmental aspects, to determine the feasibility of each approach within public water supply systems. Special emphasis was placed on practical field guidelines and multi-method rehabilitation sequences commonly used by utilities. This structured, multidisciplinary approach provides a solid basis for understanding how *in situ* well rehabilitation techniques function individually and in combination, and under what conditions each method is most appropriate.

RESULTS AND DISCUSSION

This section presents a comprehensive overview of *in situ* rehabilitation techniques used in public water supply wells, organized into mentioned categories: mechanical methods, chemical treatments and innovative biological approaches. In addition to these categories, regulatory constraints are also considered, since these are public supply wells. The evaluation of each method considers its working principle, effectiveness in the field, strengths, and potential constraints.

Mechanical Rehabilitation Techniques

Mechanical methods are often the first line of defense in well rehabilitation and remain the most widely known and commonly applied regeneration approach. In considers mechanical action and physical disturbance of mineral and biological deposits without introducing chemical agents. These techniques are long-established and widely field-tested and form the foundation of most well maintenance programs.

One of the most commonly applied mechanical cleaning methods involves the use of wire or nylon brushes attached to drill rods, which are lowered into the well to physically scrub the casing and screen surfaces. This approach is very effective in physically removing formed rust, mineral scale, and biofilm from wells with uniform diameters. To enhance the efficiency of debris removal, brushing is often combined with swabbing or simultaneous pumping, which facilitates the extraction of dislodged material from the wellbore [1,2]. Another widely used physical method is high-pressure jetting, where water is injected through specialized nozzles onto the well screen and adjacent formation. This technique effectively dislodges mineral deposits and hardened biofilms by hydraulic flushing. When applied at carefully regulated pressures, jetting can clean well components without compromising the integrity of the gravel pack or casing infrastructure [1]. Another widely used in situ method is surging, which creates turbulent water movement inside the well. This is typically done by repeatedly reversing the flow using a surge block or by quickly turning the pump on and off. The resulting agitation helps to dislodge mineral particles, bacterial slimes, and sediment from the screen and casing surfaces. To remove the mobilized debris, air-lift pumping is often employed. This method introduces compressed air into the well to lift water and suspended solids to the surface. Surging and air-lift pumping are frequently used together, offering a cost-effective means of mechanical cleaning and improving the distribution and penetration of subsequently applied chemical treatments [1]. In cases of severe clogging or significantly reduced well yield, energy-based methods such as hydrofracturing and impulse treatments may be required. For example, liquid carbon dioxide can be injected into the well, where it rapidly expands and creates a series of pressure pulses or micro-explosions. These impulses generate mechanical disruption within the clogged formation while simultaneously forming carbonic acid through CO_2 dissolution, which enhances the chemical breakdown of carbonate scale. Compared to conventional brushing or jetting, these methods can reach deeper into the aquifer matrix and are typically employed when shallower in-well techniques prove insufficient.

Mechanical rehabilitation methods offer several advantages in the context of well maintenance. They eliminate the risk of chemical contamination, making them particularly suitable for drinking water wells. Most techniques are compatible with a wide range of well designs and can be safely repeated as part of routine maintenance. These methods are especially effective in physically removing thick biofilms, rust deposits, and debris from clogged screens.

The limitations of mechanical approaches are that they are generally ineffective at fully dissolving hardened mineral scale and do not prevent bacterial recolonization, which can occur shortly after treatment. Their action is confined to surfaces that are directly accessible, leaving deeper zones of the formation untreated. Additionally, improper application may lead to mechanical damage, highlighting the importance of operator experience and equipment control during implementation.

Chemical Rehabilitation Techniques

Chemical rehabilitation techniques are used to dissolve incrustation, destroy biofilms, and neutralize contaminants that cannot be removed mechanically. To ensure these methods are highly effective and safe, it's essential to carefully formulate the treatment, apply the right dose, and thoroughly flush the system afterward. Treatments considering acid application are widely used in well rehabilitation to dissolve mineral incrustations and improve hydraulic performance. Hydrochloric acid (HCl), typically applied at concentrations between 5% and 15%, is the most commonly used agent for dissolving calcium carbonate scale and iron oxide crusts [4]. Sulfamic and acetic acid can be useful alternatives, depending on site-specific conditions and infrastructure compatibility. These treatments significantly lower the pH (< 2), causing rapid dissolution of scale and, in some cases, indirectly reducing biofilm presence by disrupting the mineral substrate in which microbial communities reside. Optimal results are achieved when acid contact time is maintained for 24 to 48 hours, often accompanied by intermittent surging to improve acid distribution and mobilize loosened material. Field experience indicates that adequate acid treatments often lead to significant improvements in well yield and specific capacity [1,4,5]. Oxidizing biocides are commonly employed to disinfect wells and control biofilm-related clogging. Strong oxidative potential of sodium hypochlorite (NaOCl), hydrogen peroxide (H_2O_2), and chlorine dioxide (ClO_2) is frequently used due to their aggressiveness and efficacy [1]. High-dose chlorination, often known as shock treatment, considers the use of chlorine concentrations in dose from 500 to 2,000 mg/L. It is particularly effective in eliminating iron bacteria and disrupting microbial films. Hydrogen peroxide not only serves as a disinfectant but also generates oxygen gas bubbles that promote mechanical agitation and physical detachment of biofilms from well surfaces. Chlorine dioxide is valued for its stability across a wider pH range and for producing fewer disinfection byproducts compared to traditional chlorination methods, making it suitable for sensitive applications where water quality preservation is critical. Reducing agents and chelating compounds play an important role in the chemical rehabilitation of wells affected by iron and manganese oxide fouling. Sodium dithionite ($Na_2S_2O_4$) is a potent reductant that converts insoluble ferric (Fe^{3+}) and manganese (Mn^{4+}) oxides into their soluble ferrous (Fe^{2+}) and manganous (Mn^{2+}) forms, facilitating their removal through subsequent pumping [5]. Chelating agents such as ethylenediaminetetraacetic acid (EDTA) and polyphosphates are employed to bind dissolved metal ions, thereby preventing their reprecipitation within the well structure. These substances are often mixed with acids, surfactants, or dispersing agents in special cleaning solutions made to work better in real-world conditions [2,5]. Chemical treatments offer significant advantages over purely mechanical methods, particularly in their ability to dissolve mineral deposits and microbial films that cannot be eliminated by physical agitation. Acidic formulations act rapidly to dissolve carbonate and iron oxide scale, oxidizing agents sanitize the well environment and degrade biofilms, while reducing agents effectively solubilize otherwise persistent metal oxides. These mechanisms, when properly applied, can result in significant improvements in well performance and water quality.

However, chemical treatments also present operational challenges and safety considerations. Acids, while effective, can corrode metal well components if not carefully managed. Oxidizing agents may lead to the formation of disinfection byproducts, especially in the presence of organic matter, while reducing agents require strict pH control to remain effective. Additionally, thorough post-treatment flushing is critical to remove residual chemicals and avoid contamination of the potable water supply.

Innovative Biological Approaches

As the water sector moves toward more sustainable practices, interest is growing in biological methods for rehabilitating public water supply wells. These methods are being explored as alternatives to conventional chemical treatments, especially because they may offer safer and more targeted ways to manage biofouling.

Biological approaches typically aim at microorganisms that form biofilms, using either enzymes or bacteriophages. Enzymes like dispersin B and certain glycosidases can break down the extracellular matrix that holds biofilms together. These compounds are generally considered as non-toxic, are effective in neutral pH conditions, and don't pose risks to well structures or water quality. In lab settings, combining enzymatic treatment with mechanical surging has led to more than 90% biofilm reduction (result under controlled conditions).

Another line of research involves bacteriophages, viruses that infect and destroy specific bacteria. This method is promising for controlling prevalent iron-related biofouling caused by bacteria such as *Gallionella* and *Leptothrix*. Once inside the system, bacteriophages multiply within their target bacteria and eventually cause them to rupture, which helps reduce microbial buildup. While still in the early stages of development, initial field examinations have shown a decrease in bacteria counts and reduced clogging potential. However, questions remain about regulatory approval, long-term effects, and the specificity of these viruses to their intended bacterial hosts.

Biological treatments have shown several advantages. They are highly selective, leaving non-target organisms unaffected and avoiding chemical residues that could harm groundwater. Their environmental profile makes them well-suited for sensitive aquifers or protected zones. Used alongside mechanical or chemical methods, they may also become a useful part of broader, integrated strategies for maintaining wells clean over the long period.

Figure 1 provides an overview of *in situ* rehabilitation techniques currently being explored for aging public water supply wells.

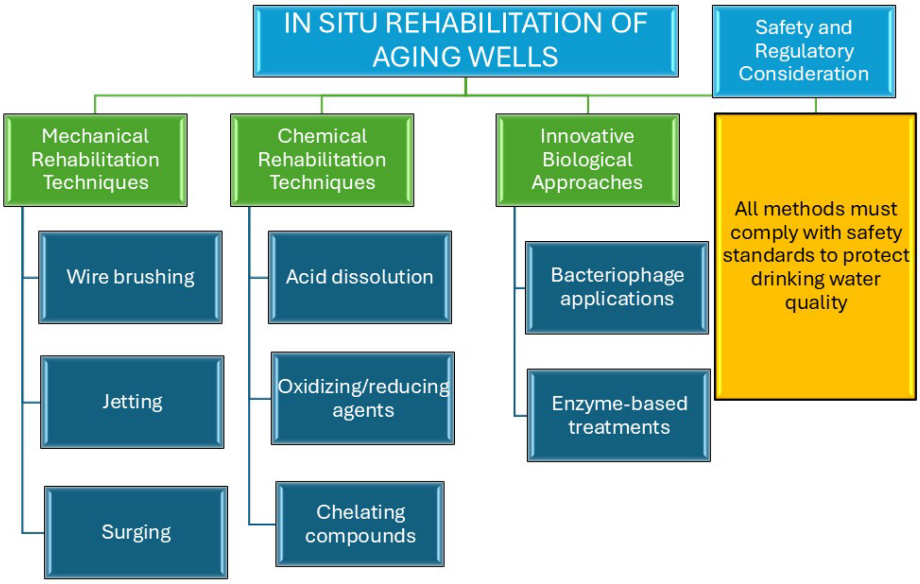

Fig. 1. *Overview of In Situ Rehabilitation Techniques for Aging Public Water Supply Wells*

It should be emphasized that innovative biological approaches are still in the research and development phase, and their widespread implementation depends on several factors. Their effectiveness is highly dependent on the composition of the microbial community and site-specific well conditions. In addition, regulatory acceptance remains limited, with few approved protocols for use in potable water systems. Standardized application procedures and long-term performance data are still not available, emphasizing the need for further examination and validation before routine field deployment can be recommended.

Safety and Regulatory Considerations

All *in situ* rehabilitation treatments must comply with strict and rigorous drinking water safety standards to protect both public health and environmental quality. For example, in the United States, chemicals introduced into potable water systems are required to meet the allowable levels and purity requirements for drinking water treatment chemicals defined in NSF/ANSI Standard 60, developed by the National Sanitation Foundation (NSF) and the American National Standards Institute (ANSI) [1,8]. While Serbia does not formally adopt this standard, it provides a widely recognized international criterion for chemical safety. In practice, all treated wells should be thoroughly flushed until water quality stabilizes and key parameters, including, among others, pH, turbidity, residual disinfectants, and concentrations of dissolved metals, return to values compliant with national drinking water regulations. Chemical safety during application is a critical point. Acids and oxidants must be handled using appropriate personal protective equipment, and their application must be carefully controlled to prevent operator exposure or corrosion of well infrastructure. Wastewater generated during rehabilitation contains elevated concentrations of metals, residual disinfectants, or other reactive compounds. New biological agents like enzymes or bacteriophages need careful review by public health authorities. To be considered for use in public water systems, they must be shown to be safe, effective, and not persistent in the treated water. Successful and safe implementation of well rehabilitation strategies requires not only technically sound methods but also skilled personnel, environmental risk management, and regulatory alignment to ensure that the well can be returned to service without adverse impact.

CONCLUSION

In situ rehabilitation of aging public water supply wells is a well-established but still continuously advancing field that brings together years of field experience and modern scientific progress. As wells age, they are increasingly susceptible to hydraulic inefficiency and water quality degradation caused by mineral incrustation, biofouling, and physical clogging of the well screen and surrounding aquifer matrix. Effective restoration of well performance requires the strategic application of multiple techniques, each selected based on the specific fouling mechanisms present. Mechanical interventions remain essential for mobilizing and removing deposits from accessible well surfaces. Their effectiveness is often enhanced when combined with chemical treatments, which provide deeper penetration and dissolution of carbonate scales, iron oxides, and biofilm matrices that are otherwise resistant to physical removal. Chemical strategies, including acidification, oxidizing and reducing agents, and chelating compounds, are widely validated and remain central to most rehabilitation programs. Biological methods, particularly enzymatic treatments and phage application are gaining interest as environmentally sustainable alternatives for selective biofilm control. Although still in the research, these approaches offer promising synergies with conventional treatments and may shape the future of well maintenance. Throughout all stages of rehabilitation, adherence to safety protocols and regulatory standards is critical. Chemicals must meet drinking water criteria, and all treatment residuals must be properly neutralized and disposed of in compliance with environmental protection laws. Routine monitoring, preventive maintenance, and timely intervention further reduce the frequency and severity of well degradation. A multidisciplinary and adaptive approach remains essential for ensuring the long-term sustainability of public water supply infrastructure.

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