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# Purpose and Applicability

This guidance describes general methods for maintaining and redeveloping wells that contain groundwater and/or hydrocarbons termed, light non-aqueous phase liquid (LNAPL). Well maintenance and redevelopment is required to prevent loss of production capacity and to restore production capacity to original levels.

BP Remediation and Technology Team within Remediation Management prepared this guide which includes well performance investigation, identification of the causes of poor well performance, selection of the appropriate method for redevelopment, and establishing field procedures to restore and increase groundwater and/or LNAPL production capacity. Additionally, the mechanical development portion of this guidance should be used on the development of new wells to ensure that quality aquifer, LNAPL testing can be completed and quality groundwater samples can be collected. Correct development of new wells results in equilibrium of LNAPL occurring within days to a week rather than requiring 6 months to a few years.

## Responsibilities

In general on-site personnel are responsible for conducting the investigation activities to collect samples and data (flow rates, water levels, etc) to identify the cause, extent, and types of fouling at the wells. Results of the investigation should be reported and adhere to the remedy performance review practice and ultimately shared with the entire team. The team should ensure that operational field observation correspond to additional aspects of the site conceptual model including but not limited to hydrocarbon source distribution, natural zone source depletion, groundwater dissolved phase and geochemical data and groundwater elevation and gradient trends.

The project team will utilize these results to identify when it is appropriate to conduct redevelopment on specific wells. The results of the field investigation will be used to select the appropriate well redevelopment methodologies. Redevelopment Field Staff are responsible for overseeing well rehab contractors in the field or conducting well rehabilitation activities. Redevelopment Field Staff are responsible for contacting the well redevelopment project lead if there are any uncertainties about the procedures or any unusual observations in the field. Any field calculations carried out by the Redevelopment Field Staff should be reported to the Redevelopment project lead for QC before mixing chemicals. Typically these calculations and QC is completed as part of the project scope development, HITRA, and contracting rather than in the field. Changes in the scope should be reported. Redevelopment project lead has the responsibility to oversee and to ensure that the well redevelopment is performed in accordance with guidance and any chemical manufacturer’s guidelines.

## Health, Safety, and Environment

The health and safety issues associated with the well redevelopment are numerous and therefore the appropriate hazard review is needed. An Example hazard review has been developed and provided in Appendix A. The HITRA provided Identifies the tasks and specific hazards associated with each step of the redevelopment procedure and also provides the necessary methods to minimize health and safety concerns, namely worker exposure, spills, and chemical handling. All personnel that will be handling the well redevelopment chemicals will be required to review the MSDSs.

Previous well redevelopment activities have lead to H2S producing reactions and high concentrations of H2S at the well head and in the breathing zone. As such, the Lessons Leaned documents from well redevelopment activities are provided in Appendix B and the guide has been modified to incorporate these lessons.

## Guidance Organization

This guidance discusses the investigation and well redevelopment procedures in the following sections

1. Purpose and Applicability
2. Background Information
3. Investigation Procedures
4. Redevelopment Procedure Selection
5. Well Redevelopment Field Procedures
6. Materials List
7. Quality Assurance Quality Control
8. References

This guide also contains forms to organize data, facilitate pre-well redevelopment investigations, and to collect data in the field. The attached appendices are listed below.

Appendix A: Task Specific Health and Safety Plan

Appendix B: Well Redevelopment Lessons Leaned

Appendix C: O&M Field Forms for Investigation

Appendix D: Chemical Information and Material Safety Data Sheets

Appendix E Well Redevelopment Field Forms

# Background Information

## General Causes of Poor Well Performance

Within days or months of well installation and/or recovery operations, well screens, filter pack and adjacent formation may become clogged by physical blockage (silt and clay particle accumulation), mineral precipitation (scale), and/or biological fouling. These blockages can cause decreased groundwater and LNAPL production and well efficiency.

* **Physical Blockage:** Physical blockage is the plugging of filter pack and/or well screen by silt and clays, which are derived from formation, mud cake left on the borehole wall during drilling and within filter pack. These obstructions restrict (or minimize) inflow of groundwater and/or LNAPL into the well.
* **Mineral Accumulation:** Mineral accumulation is the chemical precipitation or incrustation that occurs within the well environment due to pumping, change in water chemistry and corrosion of casing. Most common accumulation include: carbonate based scale, sulfide based scale, and/or iron oxides. When mineral deposits form on the screen and/or filter pack, LNAPL/groundwater flow is restricted. Calcium and Magnesium carbonates are quite soluble in most acids, however Iron hydroxides are less soluble and will drop out of solution if the pH is above 3.
* **Biological Fouling:** Bio-fouling and related mineral precipitation occurs due to changes in oxygen levels and/or nutrient sources to available bacteria in the well. Bacteria growth produces organic slimes, biomass and/or mineral secretions on well screens and filter pack material. Biofouling does not typically occur in newly installed wells and therefore does not need to be a routine consideration for initial well development post installation. Three basic types of bacteria associated withwell fouling include:

1) Iron accumulating bacteria (e.g., gallionella) that collect soluble (ferrous) iron from water and produce slimy oxidized iron (ferric hydroxide) sheaths and deposit iron oxides. The combination of the ferric oxide sheaths, iron oxide deposits and bacteria is material is a dense slick substance that is typically found on the screen openings and can extend into the gravel pack.

2) Slime forming bacteria consist of multiple families of bacteria and secrete bio-films or exopolymer slime. Slime forming bacteria are primarily aerobic or facultative anaerobes (capable of existing in both aerobic and anaerobic environments) and are capable of proliferating on many types of nutrients and/or environmental conditions.

3) Sulfate-reducing bacteria (SRB) that function in anaerobic conditions and are known for producing amorphous iron sulfide lead sulfide and other sulfide minerals. These sulfide deposits are readily soluble in acidic conditions. H2S can be rapidly formed by the inorganic chemical acidification of these mineral sulfides in the well. In the well bottom or sump (where water flow is restricted and organic material can accumulate), SRB are known to produce large amounts of H2S gas. The H2S gas often results in corrosion of steel surfaces and reformation of iron sulfide. In an oxygen rich environment, the iron sulfide can be oxidized to pure sulfur.

Hydrocarbon impacts represent a large substrate for aerobic, anaerobic and methanogenic microbes. The ubiquity of microbes and diversity of processes in the subsurface and hydrocarbon sources areas should not be underestimated when evaluating well rehabilitation. Improvements in quantifying the byproducts of methanogenesis and hydrocarbon volatilization through the vertical transport pathway has identified that these processes are a much larger contributor to overall degradation rates than what is represented by electron acceptors and byproducts in dissolved phase flux (Garg, 2017). Work completed on biodegradation of hydrocarbons related to the Bemidji Crude oil Research Site identifies that up to 90 percent of iron reduction can go undetected in analysis of groundwater samples (Ng et al, 2015). The majority of iron reduction goes from oxidized mineral form to reduced mineral form. The combined realization of the underestimated iron related processes with increase role of methanogenesis identifies that geochemistry of groundwater and dissolved electron acceptors alone do not provide accurate understanding of the microbial activity.

Overall any of the fouling processes described above are seldom isolated and are affected by differences in well construction, aquifer characteristics, type and extent of contamination, and product recovery methods. As such, multiple types of blockages can be found in the same well. It is important to determine which type(s) of blockage is affecting the well in order to select the most efficient development method. Section 3.0 discusses the investigation procedure to determine the cause(s).

### Hydrogen Sulfide

Hydrogen sulfide (H2S) is an explosive, corrosive and toxic substance that readily degasses from solution upon production. Hydrogen sulfide is frequently produced during the acidification portion of well rehabilitation. While sulfate reducing bacteria are known to produce H2S in anaerobic degradation of organic material in wastewater treatment plants, swamps, photosynthesis, anoxic ocean sediments and other environments. These microbes typically become inactive below pH 5. However, the subsurface microbial communities and even individual sulfate reducing bacteria can utilize both sulfate and ferric iron as electron acceptors. This occurs in sufficient proximity to generate complimentary byproducts of ferrous iron and sulfide which results in deposition of amorphous iron sulfide. Upon acidification of a well with iron sulfide within sediments occurring in the well casing, filter pack or adjacent formation, H2S can be produced rapidly through inorganic reaction.

It is important to recognize that sulfur, hydrogen and iron are all more abundant in the earth than carbon (ScienceNotes.org). This speaks to there is plenty of availability of these elements to generate H2S potential given the correct reducing environment. Literature (Johnson et al, 2006, Garg, 2017, Bekins, 201X and Ng et al, 2015) identifies natural biodegradation as a significant contributor to hydrocarbon source zone depletion. There is not a single biological or physical loss responsible for this rather multiple processes that express themselves through ebullition, vertical soil gas transport, changes in mineral composition from oxidized iron minerals to reduced iron sulfide, other reduced minerals as well as changes in geochemistry of groundwater. These processes result in the active microbial reduction zone not solely occurring at the LNAPL impact fringes or dissolved phase, rather throughout the source area and vertically above the source zone. Conceptual models need to account for the extent of biodegradation to properly understand where microbial processes can contribute to iron sulfide generation.

In addition projects focusing on geochemistry of groundwater alone may underestimate iron reduction magnitude even where little to no iron, sulfate or sulfide is detected in groundwater samples. Where sulfate reduction is occurring based on observed reduction in groundwater samples with down gradient distance, iron reduction should also be considered as likely occurring with the ultimate production of iron sulfides. Illustrations of aquifers portioned into discrete redox zones are inaccurate in portraying that iron reduction zones are separate from sulfate reduction zones. While thermodynamics in-fact favor a given electron acceptor for a given redox value, the redox zonation is on the pore scale rather than aquifer scale. This pore scale zonation allows for sulfate reduction and iron reduction to occur simultaneous and provides an improved conceptualization for the formation of these minerals. These processes are significant to well rehabilitation because precipitated minerals such as iron sulfides result in the risk of H2S production during acidification of well rehabilitation events.

Caser, Wyoming has ceased use of acid based redevelopment as a result of the consistent H2S production risk. This site exhibits sulfate concentration in the 100’s of mg/l. Sulfate reduction has long been identified as a dominant process at the site; however, the precipitation of sulfide minerals such as iron sulfides have been discussed less. Iron reduction occurring as part of MNA simultaneously which produces the reduced iron for the iron sulfide mineral. The resulting chemical rehabilitation process occurs more frequently and is surfactant based in order to avoid H2S risk. (consider providing reference to appendix procedure and chemical)

Wood River does not exhibit as high sulfate levels as Casper and utilized rehabilitation procedures that included acidification. Acidification resulted in H2S production during monitoring well rehabilitation (IRIS ref needed) as well as H2S production from an above ground tank that was being used for containing sediments produced and acid neutralization (IRIS Ref). The point is even low levels of sulfate concentrations can represent an H2S risk. Low concentrations of sulfate may simply require longer periods to produce sufficient amorphous iron-sulfides in the subsurface to result in an H2S production. Reducing conditions combined with sulfate reduction likely a risk of H2S production during acidification.

•Tetrakis(hydroxymethyl) phosphonium sulfate (THPS) is typically utilized as a biocide, but it can be used as a solvent to dissolve FeS solids

Indicators of microbial fouling ahead of decreased well production.

Langlier Index

Carbonate Index

Sulfate in groundwater

Sulfide mineral deposits – often these appear as black minerals within the soil column.

Iron

Do we need to eliminate the bacteria with well development or do we need to remove the deposits and slimes that inhibit well production. Wood River has undergone well rehabilitation events with improved microbial monitoring via adenosine triphosphate concentrations and BART kit sampling.

Discuss High TOC content

Indicators of Fe Sulfides

## General Methods to Improve Well Performance

Once the cause(s) of the deteriorating well performance is known, one or more maintenance or rehabilitation techniques can be used to restore the well performance and protect it from further deterioration. Several development methods can be applied to the well before and after performance declines. When needed, these techniques should be used in phased approaches to restore the well’s performance.

* **Physical Redevelopment:** Physical methods involve the use of hydro-mechanical tools including surge blocks, jetting tools, or pumps that force water in and out of the well screen and sand/gravel pack to remove fine‑grained sediments and incrustations and to enhance the effectiveness of chemical treatment and disperse chemicals within the well bore. Surge blocks followed by sediment removal methods sand bailing/air lifting and pumping should be the initial methodology. Alternate tools would be used where these are understood to not be completely effective. This sediment removal helps reduce risk of H2S generation from sulfide minerals bacteria (SRB) that may exist within the sump sediments.
* **Chemical Redevelopment Methods for Physical Blockage:** Chemical methods to remove physical blockages include the use detergents (such as polyphosphates) to disperse clays and silts around well screens and sand/gravel packs. These methods are typically used following well construction to break down filter pack bridges, remove fines and flush the fine-grained filter cake on the borehole wall left behind as a result of drilling with mud rotary or hollow stem auger rigs. Chemical development for physical blockage should be viewed as a secondary and more aggressive approach to physical redevelopment.
* **Chemical Redevelopment for Mineral Accumulation:** Chemical methods for mineral accumulation involve the use of acid-based solutions to lower the pH of well water and dissolve mineral incrustations in the sand/gravel pack and well screen. Mechanical agitation is required to agitate chemicals introduced into the well to break apart well incrustations and force fresh acids into areas where they have become diluted.
* **Chemical Redevelopment for Bio-film Removal:** Redevelopment methods for removal of bio-films involve the use of acid-based polymers that act as biocides and also disperse incrustations and slime layers. Bio-slimes must be penetrated and dispersed to expose bacteria to biocides and keep ionic precipitates dissolved in solution. Mechanical agitation is required to correctly introduce the chemicals into the well, break apart well incrustations, and force fresh acids into areas where they have become diluted.
* **Surfactant based methods:** Redevelopment with acids consistently exhibits a risk of H2S production, while the risk can be minimized via sediment removal in well casing and dispersant use to breakup less recalcitrant deposits within the filter pack, sulfide minerals can still remain in the filterpack and formation. Upon acidification H2S is produced. Sites exhibiting either relatively low scale with biofouling or sufficient H2S production with acids even following best practices to minimize sulfide deposits and sediment in the casing may consider use of surfactant only chemical redevelopment. Efficacy for this relies on a more frequent usage, which maintains a low bio community through surfactant application.

The five abovementioned methods are general redevelopment methods. The specifics on each well redevelopment method (i.e. chemical type, chemical dosage, mechanical method) are dependent on the well of concern. Flow rates, contaminants, LNAPL types, fluid levels, geology, well construction, well materials and compliance monitoring can all affect the specifics chosen for well redevelopment. In general, if a well is exhibiting biofouling and physical blockage, then a phase approach would be completed. The first phase could be directed at the physical blockage and the second phase would be directed at the biofouling (i.e., chemical redevelopment to remove biofouling). Similarly for mineral accumulation and physical blockage, redevelopment could be first directed at the mineral accumulation followed by directing it towards the physical blockage. The goal in the program design is directing each phase appropriately and conducting multiple iterations for severely affected wells. Biofilms or mineral encrustation may initially inhibit access to particles causing physical blockage. Alternating between chemical and physical techniques may be needed. Initial steps may remove one of these components (e.g., mineral encrustation) partially allowing better contact with the chemical to treat biofouling, which then further allows for additional mineral encrustation removal. Finally, after the physical blockage is removed, then new pathways would be available to better dispersant acids and biocides to further reduce the biofouling within the well.

# Investigation Procedures

The performance of most wells will decrease over time without some form of maintenance. Monitoring of groundwater and/or LNAPL production rates can be used to detect well performance deterioration. Prior to any well redevelopment efforts, a well performance investigation should be conducted to determine the causes of poor performance. Because of the various differences between water supply wells and remediation monitoring/recovery wells this investigations need to occur to understand the source of the problem and the potential risks that may be encountered during well redevelopment. This section discusses the procedure for field based and office based investigations.

## Field Investigation with Maintenance Activities

Field investigation activities for well redevelopment should be conducted in conjunction with routine O&M activities. Field noted observations during maintenance activities can provide valuable insight to the cause of poor well performance with minimal additional costs to the project. As such, the following procedure is recommended for investigation during O&M activities:

1. Note fluid levels, pump inlet depths, and operational problems with pump operation during routine operational checks.
2. Note any biofouling, sediment build up, or scale in basket strainers when cleaned during ops checks.
   1. Remove basket strainer from manifold.
   2. Inspect contents in basket strainer for sludge, slime and sediments.
   3. Note quantity, color, texture, and odors. Take pictures if possible. Notes should be recorded on a Well Maintenance Form – for example see Appendix C.
   4. If this is a re-occurring problem at the well, note the frequency of strainer cleaning. The frequency of required strainer cleaning provides valuable information on the magnitude of the problem at the well.
3. Any time the down-hole equipment is removed from the well (ex. foot valve maintenance) following steps are recommended.
   1. Remove down-hole equipment.
   2. Use interface probe or tape measure to note the location (from TOC or pump inlet) of any scale of fouling on pump components.
   3. Collect samples of scale or fouling for analysis, if possible. Put samples on ice for preservation and bring back to the office at the end of the day. The Project Manager will decide if sample analysis by a laboratory is necessary after visual observation.
   4. Measure the total depth of the well and compare to the total depth to the boring log. Note measured total depth.
      1. Determine if there are sediments at the bottom of the well.
      2. Remove sediments from the bottom of the well (if practical) and collect a sediment sample.
      3. Put samples on ice for preservation and bring back to the office at the end of the day. The Project Manager will decide if sample analysis by a laboratory is necessary after visual observation.
   5. Note any colors, textures and odors from the sediments. Notes should be made on the utilized O&M Field forms with the measured depths. – See Appendix C.
4. If scale or biofouling is determined to be an issue at the recovery well, collect an LNAPL sample and send to laboratory for analytical testing. The sample should be analyzed for sulfur content. Based on a previous lesson’s learned, wells with sulfur concentrations greater than 1.5% may have H2S issues from sulfate reducing bacteria. The Lesson’s Learned document is provided in Appendix B.

Appendix C contains field forms that can be used to collect information for well redevelopment during O&M activities. If a well is suspected of being physically block or fouled but no definitive evidence is available, then slug testing the well with three different slugs of sizes that induce drawdown values that vary by a factor of four will provide evidence if the well is efficient (Butler, 1998) Additionally, a step drawdown test will provide a more definitive understanding of well efficiency.

## Desktop Investigation

To be efficient and cost effective, several desktop reviews can be conducted prior to or concurrently with field activities. The desktop review is based on readily available historically collected field data. This review should be conducted and any results should be confirmed with current field observations prior to selecting a redevelopment method or chemical.

1. Well performance data should be collected on a routine basis for O&M, monitoring and compliance purposes. Flow rates, volumes, oil/water ratios are all valuable when evaluating pump performance. These parameters should be monitored to determine when redevelopment is necessary at each well.
2. Pump operational history should be considered when evaluating well performance. A poorly operating pump may be the cause of low volume recovery.
3. Changes in fluid levels at recovery wells and nearby monitoring wells should be noted as the fluid levels may affect the pumping capacity of the recovery wells.
4. Changes in types of LNAPL in the recovery wells and nearby monitoring wells should be noted as historically high sulfur containing LNAPL may provide additional sulfur source for H2S generation.

## Video Logging

Video logging a well can provide valuable information regarding the well screen. This technique uses a dual-view camera to provide both a downhole view and a detailed, 360 degree continuous scan of well sidewalls. A side view allows a well video logging operator to examine the formation walls, casings, screen, gravel pack, infiltration, encrustations, deterioration, perforation blockage or other physical damage within the well. A video log will allow the operated to determine the type, extent and location of fouling within the well. While this is the most effective method to diagnose a well, video logging may not be a viable option for all wells. Wells that contain high concentrations of hydrocarbons or LNAPLs are considered hazardous locations. Wells that contain LNAPL are considered a Class 1, Division I Class C & D hazardous area according API guidance. This requires all electrically powered equipment that is placed down the well to be intrinsically safe or rated for use in hazardous locations and no camera has been identified to be certified for use in wells that contain LNAPL.

## 

# Redevelopment Procedure Selection

## Mechanical Development Options

Chemicals added to a well must be agitated to effectively remove clay particles, bio-film accumulations, and incrustations. Pumping, airlifting or bailing is required following the completion of these steps to remove particles and fluids introduced into the well during redevelopment. Mechanical methods should be applied on a defined schedule (before well performance declines) once the rate of clogging, incrustation or bio-fouling is known. The various mechanical methods are listed below with recommended application requirements.

**Bailing:**  Bailing involves the repetitive raising and lowering of a bailer which creates weak negative and positive pressures above and below the bailer as it is being moved. Bailers are most effective for removing silt, sand, and bio-solids from the bottom of a well or well sump. Effluent is typically discharged to a drum or tank. This procedure requires that any pump and associated piping be removed from the well.

**Swabbing:** Swabbing involves raising and lowering a long shaft with single or double surge blocks to create strong negative and positive pressures on either side of the tool. It is an effective method for agitating the filter pack and the formation to displace fines and bio-solids from sand/gravel pack and the well bore. Surge blocks must be used in conjunction with bailers for removing silt, sand, and bio-solids from the bottom of a well or well sump. This procedure requires that any pump and associated piping be removed from the well.

**Scrubbing**: Scrubbing involves raising and lowering a long shaft with single or multiple all purpose brushes to scrub, agitate, and surge the well simultaneously. The brushes should be chosen based on compatibility with the well construction material (i.e., stainless steel versus PVC). Scrubbing is used in conjunction with surging, bailing, and pumping. This procedure requires that any pump and associated piping be removed from the well.

**Air Surging:** Air surging involves the use of a pressurized air line and a discharge pipe to create strong positive pressures to surge water and remove it from the well casing. It is an effective method for agitating the filter pack and the formation to displace fines and bio-solids from sand/gravel pack and the well bore. Silt, sand, and bio-solids are readily lifted from the well bore with groundwater and discharged to a tank or drum.

Several application options are possible. One option is to dedicate an air line and discharge pipe at each well so the well can be periodically developed or flushed by connecting the air line and discharge line at the well head. For this option, the pump equipment can be left in the well. Another option is to hang the air-lifting tool from a pump rig and raise and lower it to develop any specific length of the well screen. For this case, any pump and equipment must be removed from the well.

**Jetting:** Development by jetting involves pressure spraying water within the well screen using a drop pipe connected to a high pressure pump. High-velocity water is forced through the screen openings to scour the screen and sand/gravel pack. Penetration depth is dependent on well construction and the water pressure. High pressure jetting in conjunction with air-lifting to remove fines from the well has proven to be an effective development technique. It is also an effective method for agitating the filter pack and the formation to displace fines and bio-solids from sand/gravel pack and the well bore.

Several applications are possible. One option is to hang the air-lifting and jetting tool from a pump rig and raise and lower it to develop specific lengths of the well screen. For this case, the pump equipment must be removed from the well. Another option is to use a permanent drop tube through which high pressure water and chemicals are introduced into the borehole without removing the pump.

**Pumping:** During pumping, a purging pump is used to clear the wells of water and sediments to provide further cleaning and to allow recharge to occur. Pumping also is used to remove any chemicals or fluids added to the well during the rehabilitation process. Pump specification for any pump used in conjunction with LNAPL or groundwater with high dissolved-phase concentrations of petroleum hydrocarbons should be discussed with and approved by the project manager.

### Mechanical Development Selection

The mechanical development method should be chosen based on the type and extent of the well blockages and the age/integrity of the well screen. Several mechanical methods can be used in combination during well redevelopment.

* y

### The Importance of Mechanical Well Cleaning and Sediment Bailing

The previous SOP masked the importance of preliminary mechanical development prior to chemical addition. This step was hidden in the LNAPL removal step and could easily be missed if there was no LNAPL contained in the well.

Preliminary brushing/swabbing/surging is an effective method for displacing fines, dislodging incrusted minerals, and scrapping off bio-solids. When conducted correctly, mechanical developments can

* Reduce the overall mass of mineral incrustations and biofouling to be treated, which
  + Reduces the amount of chemicals needed to redevelop the well,
  + Reduces chemical costs,
  + Reduces time for well development, and
  + Reduces waste at the end of development activities;
* Opens up portions of the screen and allows chemicals to penetrate into the formation

This step also creates sediments of dislodged mineral encrustation or biofilm, which can settle to the bottom of the well. The presence of sediments in the well can decrease the effectiveness of both chemical and mechanical well redevelopment. Sediments effectively plug the bottom of the well and prevent mechanical development (surge, brush, swab, etc.) and chemical penetration. Large volumes of sediment can also create low oxygen environments where anerobic bacteria can thrive. As such sediments found within the well need to be removed from the well prior to chemical addition.

## Chemical Selection Options

As with any cleaning operation, proper selection of chemicals and its application is important. Careful consideration must be given to the selection and use of chemicals as well as its application because of the possible uniqueness of the contaminants and the well.

Each well should be evaluated for chemical selections; factors that can influence chemical selection include: cause of poor well performance, presence of well sump, geology, LNAPL presence and type, sulfur content of LNAPL, and well depth. This section summarizes the types of chemicals that can be used for well redevelopment:

### Acids

Acids are primarily used for mineral removal during well cleaning. Minerals can be accumulated in the well from chemical precipitates (eg: calcium carbonate, magnesium carbonate, gypsum), iron oxide accumulation from corrosion of the well structure or oxidation of aquifer iron. **Acids promoted dissolution of most minerals when the pH drops below 7.0; however, the pH should be maintained at 3.0 or below during well redevelopment. At pH conditions above 4.0, the precipitates will fall out of solution, considerable amounts of minerals will remain in the well, and development methods will not be effective.** When acids are added to a well and allowed to site overnight or for an extended period, the pH should remain below 4 SU throughout this period. If upon return the pH rose above 4, then the fluids within the well should be extracted, neutralized and acid reapplied.

The properties of commonly used redevelopment acids for water supply wells were analyzed for use in remediation wells. Table 1 summarizes the pros, cons, and resulting usage recommendations with each of the five acids. The chemical properties of each of these acids can be found in Appendix D.

| **Table 1 – Pros, Cons, and Recommendations for Well Redevelopment Acids** | | | |
| --- | --- | --- | --- |
|  | **Pros** | **Cons** | **Usage Recommendations** |
| Sulfamic Acid | * No hazardous acid fumes * Relatively strong acid, quick reaction time * Effective against carbonate scale and sulfate scale * Moderately affective against Fe/Mn Oxides. * Only moderately corrosive to metals and skin * Available in solid form – easy handling and transport * Shipped in dry form for safe handling | * Not effective against biofilm * Additional sulfates can be produced from the hydrolysis of Sulfamic acid. This can created H2S gas from SRB. Additional sulfate ions in the well may slow down reactions with gypsum scale. * Hydrolysis of sulfamic acid could cause reprecipitation of calcium sulfate further out into the gravel pack or formation. | * Use in wells with carbonate scale problems. * Only for wells that have low sulfur concentrations. * Recommend using an acid based biocide in addition to sulfamic acid. * Use caution in wells that contain unscreened sumps. Sumps can create a low oxygen zones and promote SRB activity. * Not to be used in wells where Sulfate Reducing Bacteria is the primary concern. * H2S mitigation measures should be included in the work plan in the event that H2S is formed by SRB. |
| Phosphoric Acid | * No hazardous acid fumes * Relatively strong acid * Slow reaction – which can add additional safety to redevelopment activities * Effective against carbonate scale, sulfate scale, and Fe/Mn oxides * Only slightly corrosive to metals and moderately corrosive to skin * Easily purchased in food grade quality. * Can cause chelation and improve cleanup of metal surfaces and increase iron dissolution and removal. * Shipped in dry form for safe handling | * This tribasic acid makes this a very slow reaction – may require additional time line for well redevelopment activities. * May be a stimulus for bacterial growth – not effective against biofilm. | * Can be used in wells with carbonate, sulfate, and oxide problems. * Can be used in wells with high sulfur concentrations. * Recommend using an acid based biocide in addition to phosphoric acid to deter bacterial growth. * Additional time for well redevelopment may be required due to slow reaction times. |
| Hydrochloric Acid | * Relatively strong acid, quick reaction time * Effective against carbonate scale and sulfate scale and Fe/MN oxides * No net increase in common ions contained in the reaction. – limits reprecipitation during cleaning * Low volume of acid required to dissolved scale. | * High corrosion rates against stainless steel and carbon steel. * Severely corrosive to skin * Limited access to food grade or NSF certified Products. * Upon mixing with oxidizing chemicals, toxic chlorine gas may be produced. * Concentrated hydrochloric acid could form acid mist. | * Hydrochloric acid is highly reactive acid, and it is **not** recommended for use in redevelopment activities in wells with LNAPL or groundwater contaminants. |
| Glycolic Acid | * No hazardous acid fumes * Slow reaction times * Only slightly corrosive to metal and skin | * Weak acid - not effective against scale, oxides or biofilm * High volume of acid needed to dissolve scale * The solubility of some of the by-products formed with calcium is limited an often results in plugging of the formation. * This acid provides an additional carbon source to the formation and can results in additional bacterial growth. – Additional care must be taken to ensure complete removal from the well. | * Because this acid is not effective, it is **not** recommended for use in redevelopment activities in wells with LNAPL or groundwater contaminants. |
| Citric Acid | * Only slightly corrosive to metal and skin * No hazardous acid fumes * Acid is available in solid form – easy handling. | * Weak acid - not effective against scale, oxides or biofilm * High volume of acid needed to dissolve scale * This acid provides an additional carbon source to the formation and can results in additional bacterial growth. – Additional care must be taken to ensure complete removal from the well. | * Because this acid is not effective, it is **not** recommended for use in redevelopment activities in wells with LNAPL or groundwater contaminants. |

### Acid-Based Dispersant Polymers

Modern chemistry uses acid-based dispersant polymers to control solids during chemical cleaning and to provide dissolution of the biological portion of the blockage. Acid-based polymer dispersants block the attraction of positive and negative forces, which account for the formation of salts, crystals, granules and other mineral masses.

As the surfaces of chemical entities (such as ions, molecules, crystals, etc) become coated with a negative charge, the repulsion of similar charges results in maintaining these products in solution or suspending them in the cleaning liquid. This reaction prevents reprecipitation and agglomeration of particles toward large sizes which would otherwise settle at the bottom of the well.

During the acid cleaning reactions, these mineral masses can slow down the chemical activity. Thus, acid-based dispersant polymers can increases the activity of the acid cleaner by impeding re-precipitation of mineral solids and improving the removal of dissolved and suspended products during pump-out.

### Polyphosphates Dispersants

Polyphosphates are primarily used as silt and clay dispersants during well development. These products are mostly granular products and depend on acidifying the solution to loosen or break down silt and clay from the gravel pack. These are effective in loosening the physical blockage but have minimal effect on removal. Phosphates are known to simulate bacterial growth. Interactions of phoshphates with calcium can create insoluable salts that can remain in the well and cause bacterial problems over extended periods of time. As such, polyphosphates (if necessary) should be used after chemical treatment for biofouling. An example of a polyphosphate is Johnson’s Screen’s NuWell220.

## Chemical Selection Example

Based on the typical causes of fouling at a active refinery with hydrocarbons in the shallow aquifer, the following table has been created to summarize the chemicals used in well redevelopment. Johnson’s NuWell Series chemicals were selected for redevelopment activities, but similar chemicals from other vendors may be acceptable for use. Additional details on the chemicals are provided in the paragraphs that follow.

**Table 2 – Recommended Redevelopment Chemical Usage**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Well Plugging Scenario1 | | Mechanical Development and Sediment Bailing | Acid2 | | NuWell 310  (Dispersant Polymer) | NuWell 220  (Polyphosphate Detergent) |
| NuWell 110  (Sulfamic Acid) | NuWell 120  (Phosphoric Acid) |
| Biofouling | Iron Reducing Bacteria | X3 | Optional |  | X4 |  |
| SRB | X3 | Not Recommended6 | Optional | X4 |  |
| Unknown Bacteria Type | X3 |  | Optional | X4 |  |
| Mineral Scale | Carbonate Scale | X3 | X |  | Optional4 |  |
| Sulfate Scale (gypsum) | X3 | Not Recommended6 | X | Optional4 |  |
| Metal Oxides | X3 | X |  | Optional4 |  |
| Unknown scale | X3 |  | X | Optional4 |  |
| Physical Blockage (silts/clays) | | X3 |  |  |  | X5 |
| Additional Considerations | Sulfur Containing LNAPL in Well | X3 | Not Recommended6 | X | X |  |
| Well Contains Sump | Highly Recommended3,7 |  |  | X |  |
| Area Contains SRB | X3 | Not Recommended6 | X | X |  |
| 1. X = Recommended Chemical, 2. Only 1 acid should be used per well per redevelopment activity. 3. Mechanical development and sediment bailing should be used for all chemical redevelopment activities 4. NuWell 310 can be used in conjunction with acids to provide maximum dispersion of dissolved solids. 5. NuWell 220 is not compatible with redevelopment acids or dispersant polymer. As such, acids and polymer need to be removed from the well prior to adding NuWell 220 to avoid adverse reactions. Additionally, it is recommended to treat wells for biofoulng prior to using NuWell 220 as phosphates can enhance biological growth. 6. Caution is advised with Sulfamic Acid. Combinations of sulfamic acid, sulfate ions, and SRB can cause H2S forming reactions 7. Mechanical development and sediment bailing is highly recommended for wells that contain sumps. Sediments in well sumps can create low-oxygen zones where anaerobic bacteria thrive. | | | | | | |

NuWell 110 is a dry granular sulfamic acid that removes mineral and carbonate scaling. NuWell 110 can be introduced into the well in granular form or can be pumped into the well as a liquid. The manufacture recommends dissolving the granular acid in water and pumping the acid into the well. This acid is used to remove carbonate scale, iron deposits and moderate biological growth. Because additional sulfates can be produced from the hydrolysis of sulfamic acid, caution is advised for wells that contain LNAPL and sulfur concentrations > 1.5%. The use of sulfamic acid is can cause H2S gas from Sulfate Reducing Bacteria.

NuWell 120 is a liquid food-grade phosphoric mineral acid that can effectively remove common mineral deposits found in well, filter beds and water system equipment. This acid is less corrosive than hydrochloric acid and does not emit harmful vapors. This tribasic acid makes this a very slow reaction with the mineral scale in the well and may require additional chemicals and reaction times. Also, adding phosphates into the formation may result in additional bacterial growth. NuWell 120 should be used with NuWell 310 to prevent bacterial growth.

NuWell 310 is a liquid acid-based polymer that breaks down bio-film, disperses mineral salts, and holds dispersed material in suspension. NuWell 310 is used in place of polyphosphates to disperse clay and silt size particles from filter pack materials by lowering the surface tensions that hold the particles together. NuWell 310 is utilized in conjunction with other NuWell acids to block the attraction of positive and negative forces and provide maximum dispersion of dissolved solids. The use of a polymeric dispersant increases penetration of acid into the formation and enables the acid to function more effectively. The polymeric dispersant also helps prevent the reformation of mineral agglomeration once they have been dissolved by the acid reaction (Powers, 2007).

NuWell 220 is a dispersant polymer that is designed to remove mud, clay, and fine sands that have filled in the gravel pack and bore hole. As designed for removing blockage from outside of the well screen, NuWell220 should be used after chemical development for mineral scale and/or biofouling and after all of the treatment chemicals and sediments have been removed from the well. NuWell 220 is not compatible with the NuWell acids or NuWell 310.

Additional information on these products is provided in Appendix D. This information includes manufacture information, usage instructions, and Material Safety Data Sheets (MSDSs) of these products. Chemical properties and manufacturer’s instructions should be reviewed before utilizing these chemicals for redevelopment.

# Redevelopment Procedures

Well redevelopment is a standard practice for water supply wells and most methods can be applied to remediation wells; however, the presence of contaminants, likely lower pumping rates, and varied water quality at remediation sites can affect redevelopment methods. Manufacturer-recommended chemical application guidelines should be reviewed and utilized with these differences in mind.

Depending on the cause of plugging/scaling/fouling different chemicals and or methods may be selected for the well of concern. As such, chemicals should be selected based on the well characteristics and the procedures outlined in this section should be reviewed and modified (if necessary) prior to conducting field activities. **Any utilized procedure should include an interactive process between the field staff and project/task manger**.

Section 5.1 discusses the procedure for redevelopment with acids and/or acid-based dispersant polymers. Because the acid-based dispersant polymers helps hold dissolved salts in solution, it is recommended to use the acid and the acid-based dispersant polymer together.

Section 5.2 discuses the procedure for redevelopment with polyphosphate dispersants. Because polyphosphates are not compatible with acids or acid based polymer and they designed to remove blockages from outside of the well screen, NuWell220 should be used after chemical development for mineral scale and/or biofouling and after all of the treatment chemicals and sediments have been removed from the well. As such, the chemicals used in procedure described in Section 5.1 should be utilized with the chemicals in section 5.2.

## Acid and Acid-Based Dispersant Polymer Treatment

1. **Permission to Work**: Obtain the necessary permission from active facility operations personnel for the affected unit. Based on use of acids, advanced planning and notification of operations will be required.
2. **Refinery Work Permits:**  Obtain the necessary work permits from the Unit Operator, including Hot Work and Safe Work, from the affected Unit. If a vacuum truck is needed to remove LNAPL a vacuum truck permit will also be needed.
3. **Well Preparation:**  If necessary, disconnect groundwater and LNAPL discharge piping and electrical components per existing BP standard operating procedures and health/safety requirements (e.g. Lockout/Tagout). If required, remove pump and piping from well. When removing a pump from a well, special care should be taken when handling the fiberglass line. Inspect the fiberglass line for signs of damage to reduce the risk of a hand injury.
4. **Well Measurements**: Measure static water level, LNAPL level, and total depth, and collect a water sample with a bailer for pH measurement. Record data on the Well Redevelopment Form.
5. **Water Use:** Any water that enters the well from maintenance or redevelopment activities **must** be of potable quality. This includes but is not limited to water mixed with redevelopment chemicals and water used for jetting. Prior to conducting the field activity a potable water source on the refinery needs to be identified or potable water should be transported for use.
6. **LNAPL Removal/Purging:** Prior to chemical addition, LNAPL should be removed from the casing using a vacuum truck or other appropriate method. In higher LNAPL producing wells this may not be feasible and well redevelopment procedures should try to minimize smearing of LNAPL within the well filter pack.
7. **Well Agitation and Sediment Bailing (Preliminary):** To facilitate the rehabilitation process, preliminary brushing and swabbing should be performed to agitate well water and remove any loose incrustations on the well casing prior to chemical addition. After well agitation, well measurements (Step 4) should be re-recorded and any sediments at the bottom of the well need to be removed via bailer. Sediments left at the bottom of the well can cause increased bioactivity and unfavorable reactions to occur during acid development.
8. **Well Volume and Chemical Dosage Calculation:** Calculate the volume of water in the borehole to include the water within the sand/gravel pack and the screened area of the well (typical porosity of the sand/gravel pack is assumed to be 30 to 40 percent). Use this volume of the water in the borehole as the treatment volume for chemical dosage and purge volume calculations. Calculate chemical dosage according to the manufacturer’s instructions.

The chemical quantity calculations should be documented on the Well Redevelopment Forms provided in Appendix E. All chemicals should be handled in accordance with the Task Specific health and safety plan provided in Appendix A.

It’s important to note that the main purpose of acid addition is to lower the pH of the fluid within the well screen in order to dissolve the incrusted minerals; the acid reaction is only effective when the pH is lower than 3. If the pH rises above 3.0, more acid can be added. This low pH is required to keep the dissolved minerals in solution. NuWell manufacturers have evaluated the average acid requirement of the well based on the static water level and well diameter. The static water level is calculated from the depth to water and the total measured depth of the well.

It is recommended that 1.5 to 2 times the static well volume used in the calculation to provide additional penetration into the surrounding formation. The acids will need to be mixed in the water to get the acid into solution. Both NuWell Acids and NuWell 310 are denser than water will sink to the bottom of the water container without proper mixing.

1. **Chemical Dosage Calculation QAQC**: All field calculations should be verified with the well redevelopment task manager.
2. **Chemical Mixing:** Mix the chemicals per the manufacturer specifications and QCed dosage calculations. Dumping chemicals into the well without proper dilution will not provide adequate penetration into the filter pack and formation.
3. **Injection Piping and Chemical Delivery:** If LNAPL is floating on the water table, use a flush-threaded 2-inch tremie pipe in the well to deliver the chemical solution. The acid solution should be added to the well via tremie pipe closest to the blockage point. Adding the chemicals near the blockages provides additional hydraulic pressure and helps penetrate the screen blockage. If the location of the blockage is unknown, the chemical should be added uniformly throughout the well screen, starting at the bottom of the screen and slowly moving upwards. Because the acids are denser than water, the acids will sink to the bottom of the well if left un-agitated. LNAPL can also be removed from the well using a vacuum truck prior to and during the chemical delivery.
4. **Chemical Agitation, pH Monitoring, and Sediment Bailing:** After the pipe/hose is removed, an appropriate diameter swab/brush (depending on casing size) is placed into the well and agitated to mix the chemicals for a 15 to 20 minute period. Agitation will ensure contract between the acid solution and the screen blockage, force the acid into the plugged area and enhance the effectiveness of the cleaning. After well agitation, well measurements (Step 4) should be re-recorded and any sediments at the bottom of the well need to be removed. Sediments left at the bottom of the well can cause increased bioactivity and unfavorable reactions to occur.
5. **Acid Addition, Agitation, pH Monitoring, and Sediment Bailing (Repeat):** After the sediments are removed, the pH of the well should be re-measured to ensure that the enough acid was added to for effective cleaning (pH<3). If the pH is above 3, additional acids should be added to the well (per manufacturer’s instructions) to reduce the pH. Chemical dosage calculations, QC, injections, agitation, pH monitoring and sediment bailing (steps 8 though 12) should be repeated until the pH is below 3. Well measurements, chemical dosages, and any sediment removal should be recorded in the field notes.
6. **Periodic Agitation:** Periodic agitation is recommended every 2 to 3 hours during each work day over the treatment period or as practical. The project manager shall give specific instruction concerning practical intervals for agitation and chemical addition. Contact time for the chemicals in the well is recommended to be 36 to 48 hours. Agitate the well periodically with a surge block or air line. Monitor the pH periodically and add an amount equal to 20 percent of the original NuWell-110 volume if the pH rises above 3.0. Steps 12 and 13 should be repeated for periodic agitation. Well measurements, chemical dosages, and any sediment removal should be recorded in the field notes.
7. **Water Slug Addition:** A slug of water equal to one borehole volume should be placed into the well to force the acid material into the formation at the end of the first day, if practical.
8. **Chemical and Water Removal:** If necessary, reinstall the pump in the well or use an appropriate pump for a monitoring well. Pump water from the well into a waste tank compatible with the chemicals. Extract approximately 3 to 4 borehole volumes to remove presence of residual chemicals to within 0.5 units of the original pH. Bail any silt and/or sediment to clean well to original total depth.
9. **Decontamination and Development Water Disposal:** Regardless of the development method employed, any liquid or solid materials from each well must be neutralized to a pH of 6 or 7 before discharging to the wastewater treatment system unless authorized by the project manager. If neutralization is required, soda ash (NA2CO3) will be added to a vented tank containing the development water. The soda ash should be placed in the tank prior to filling. Soda ash releases carbon dioxide during acid neutralization, so some frothing or reactivity will take place. Allow for adequate ventilation of the storage tank, mixing tank, or wellhead during neutralization activity. The mixing ratios for pounds of soda ash required per pound of acid used to clean a well are provided on the Well Redevelopment Field Forms provided in Appendix E.

Additionally, all materials and equipment placed into the well in conjunction with development must be free of any acid residuals prior to transfer to a new well location. Decontamination procedures should be consistent with those described in the health and safety plan and be consistent with BP procedures. Spill containment and clean-up supplies should be readily available. Storage of unused materials shall be kept dry and in resealed containers supplied by the manufacturer.

## Polyphosphate Dispersant Treatment

Polyphosphate treatment (NuWell220) should be used after chemical development for mineral scale and/or biofouling and after all of the treatment chemicals and sediments have been removed from the well.

1. **Acid and Acid Polymer Well Redevelopment:** if necessary, redevelopment wells following the procedure outlined in section 5.1.
2. **Well Preparation:**  If necessary, disconnect groundwater and LNAPL discharge piping and electrical components per existing BP and operating procedures and health/safety requirements (e.g. Lockout/Tagout). If required, remove pump and piping from well. When removing a pump from a well, special care should be taken when handling the fiberglass line. Inspect the fiberglass line for signs of damage to reduce the possibility of a hand injury.
3. **Well Measurements**: Measure static water level, LNAPL level, and total depth, and collect a water sample with a bailer for pH measurement. Record data on the Well Redevelopment Form.
4. **Water Usage:** Any water that enters the well from maintenance or redevelopment activities **must** be of potable quality. This includes but is not limited to water mixed with redevelopment chemicals and water used for jetting. Prior to conducting the field activity a potable water source on the refinery needs to be identified or potable water should be transported for use.
5. **LNAPL Removal:** Prior to chemical addition, LNAPL should be removed from the casing using a vacuum truck or other appropriate method.
6. **Well Agitation and Sediment Bailing (Preliminary):** To facilitate the rehabilitation process, preliminary brushing and swabbing should be performed to agitate well water and remove any loose incrustations on the well casing prior to chemical addition. After well agitation, well measurements (Step 4) should be re-recorded and any sediments at the bottom of the well need to be removed via bailer.
7. **Well Volume and Chemical Dosage Calculation:** Calculate the static water level. Use this water level to calculate the chemical dosage according to the manufacturer’s instructions.

The chemical quantity calculations should be documented on the Well Redevelopment Forms provided in Appendix E. All chemicals should be handled in accordance with the Task Specific health and safety plan provided in Appendix A.

1. **Injection Piping and Chemical Delivery:** If LNAPL is floating on the water table, use a flush-threaded 2-inch tremie pipe in the well for to deliver the chemical solution. The acid solution should be added to the well via tremie pipe closet to the blockage point. Adding the chemicals uniformly throughout the well screen, starting at the bottom of the screen and slowly moving upwards. Because the chemical is denser than water, the chemicals will sink to the bottom of the well if left un-agitated. LNAPL can also be removed from the well using a vacuum truck prior to and during the chemical delivery.
2. **Chemical Agitation and Sediment Bailing:** After the pipe/hose is removed, an appropriate diameter swab/brush (depending on casing size) is placed into the well and agitated to mix the chemicals. It is recommended to agitate for ½ hour per 20 feet of intake. Agitation will the chemical into the plugged area and enhance the effectiveness of the cleaning. After well agitation, well measurements (Step 4) should be re-recorded and any sediments at the bottom of the well need to be removed. Sediments left at the bottom of the well can cause increased bioactivity and unfavorable reactions to occur.
3. **Clean up for the day:** Clean up work area and let chemicals stand overnight.
4. **Repeat Agitation:** The next day, repeat agitation as described in step 9.
5. **Chemical Pump-out:** If necessary, reinstall the pump in the well or use an appropriate pump for a monitoring well. Pump water from the well into a waste tank compatible with the chemicals. Extract approximately 3 to 4 borehole volumes to remove presence of residual chemicals. Bail any silt and/or sediment to clean well to original total depth.

# Material List

This section lists the equipment that may be required for the field investigation and well redevelopment activities.

Field Investigation Equipment:

* Polyethylene - plastic sheeting
* Development rig/Pump hoist and development trailer
* Oil/water interface probe or water level meter
* total depth meter
* Sample containers
* Bailer
* 5 gallon bucket with lid
* Camera

Well Redevelopment Equipment:

* Surge block
* Bailer
* Submersible pump
* Discharge Piping
* Tremie pipe or chemical hose
* Development rig/Pump hoist and development trailer
* Vacuum Truck or Fluid Storage tank (< 250 gallons)
* 5 gallon bucket with lid
* Well redevelopment chemicals
* Chemical stirring stick
* Funnel
* pH meter
* Oil/water interface probe or water level meter
* total depth meter
* Fire hydrant hose and valve attachment
* 55 gallon drums, drum dolly, and drum labels
* Drum pump

Miscellanous Equipment:

* PPE
* Watch or time measuring device
* Air Monitors
* Paper Towels
* Spill Kit
* Caution tape and barrier tags
* Delineators
* Tool box (socket wrenches, screw drivers, allen wrenches, crescent wrenches)
* Spay Bottles and LiquiNox Solution
* Adsorbent Pads
* Pipe clamps
* Well box lid hook
* Shade canopy
* Ventiliation fan

# Quality Assurance/Quality Control

Quality Assurance/Quality Control (QA/QC) requirements include the completion of well maintenance forms to document development procedures and chemical additions. The well redevelopment task manager will have the responsibility to oversee and ensure that all well development is performed in accordance with the project specific sampling program, the Health & Safety Manual, Waste Management procedures, task specific health and safety plan, and any other applicable regulatory requirements. In addition, the project manager must ensure that field personnel record all pertinent data on the approved forms.

Field parameter values shall be entered on the Well Development Form along with the corresponding purge volume. Well Development Field Form are provided in Appendix E. Additional observations, comments, and discussion concerning groundwater well development should be documented in the daily notes. Copies of individual Well Development Forms will be placed in well files and a summary of activities will be placed in the project files.

# Performance Monitoring

* Specific Capacity
  + Specific capacity is the flow achieved from the extraction well for a unit drawdown.
    - Specific capacity should be tracked over time and used to identify a schedule for rehabilitation
  + Corrections for varying water-table are only required if the seasonal changes in groundwater elevation represent a change in aquifer transmissivity of more than 5 percent.
* Analytical geochemisty and microbiology
  + Groundwater, scale and biofilm samples can be submitted to laboratory for analysis. These data allow professionals to identify issues related to corrosion, type of microbial fouling and scaling.

# References

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