Drain and Well Maintenance and Rehabilitation for Dam Safety: Review with Recommendations

Submitted in Partial Fulfillment of Project Order 05PG810219 Clogging Research

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Introduction

No independent research revelation is necessary to understand that working, safe dams are important to the mission of the Bureau of Reclamation and to life in the U.S. West where Reclamation serves. Since ancient times, people have depended on water engineering and management to provide reliable and sufficient water supplies in this arid climate. Billington et al. (2005) ably provide historical background on the evolution and issues of dam siting, design and construction in the United States, including those under the jurisdiction of Reclamation.

By the late 1970s, concern about the safety of large dam structures resulted in systematic inspection, design review, and (where necessary) rehabilitation. Wahl (2001) documents the outcomes of some of these studies. As discussed in "Draft Drainage for Dams and Associated Structures" (Fiedler, 2001) and described in Garland et al. (1995) for the Brazos River Morris Sheppard Dam in Texas, Reclamation considers properly functioning drainage structures to be necessary for dam safety and proper function. This doctrine is also followed by the U.S. Army Corps of Engineers (USACE), but others (e.g., Indiana Department of Natural Resources, 2003) emphasize dam dimensions and other features to control seepage, and view drainage as a remedial activity.

The issue of dam maintenance and the consequences when maintenance (including seepage control) is neglected is only rarely surfaces in the public consciousness, usually in the aftermath of a serious fault or recently in the context of homeland security preparedness. An example of dam safety in popular fiction, the novel *Julie* by Catherine Marshall (1984), is set in the mid-1930s. The scenario was that a poorly maintained private dam (whose problems were covered up) attracted concern, and then failed after a hurricane-fueled major rainfall event, destroying towns in a western Pennsylvanian valley. In real life, the maintenance of levees was a factor in property loss along the Mississippi during the 1993 floods. Levees with properly designed and maintained wells were less susceptible to underseepage and development of sand boils and related ultimate failure. Mansur and Kaufman (1957) and Mansur et al. (2000) describe mechanisms of levee undermining and seepage control design to counteract undermining. On March 14, 2006, as this report was being drafted, the privately managed earthen Kaloko Reservoir dam on the island of Kaua'i, Hawai'i, built in 1890, burst during a period of heavy rains in the islands, releasing more than 300 million gallons and causing several deaths as well as widespread devastation. Modeling of the event was underway almost immediately, according to news and web reports.

Methods developed for engineering agricultural drainage, made systematic by Reclamation engineers in the 1940s and early 1950s, were adapted for Reclamation dam seepage control (TeKrony et al., 2004). As is true of other drainage or pumping structures (including levee relief wells), drainage systems of dams are rendered less effective by a range of natural mechanisms, including geochemical incrustation and biological fouling. Several mechanisms of structural deterioration have been documented (McCook, 2000; Fiedler, 2001):

1) Deterioration of clay pipes – resulting in collapse and spreading and pipes and resulting soil infiltration into pipes.
2) Corrosion of corrugated metal pipe – especially at outlets where they are exposed to the atmosphere.
3) Deterioration of wooden well screens in relief wells (widely documented in USACE studies).
4) Changes in the properties of granular filters and drains or geotextile components. Most common changes are siltation and cementation according to McCook (2000).
5) Frost and other earth matrix expansion heave that buckles rigid construction structures such as those formed from concrete.

Not to be overlooked are structural degradation, such as piping or “blowouts” due to high-velocity seepage from talus and other high-conductivity (high-k) fill (Dewey, 1993). Such circumstances require reconstruction or lining of dams.

According to Reclamation reports, effective, long lasting cleaning of pressure-relief drainage systems remains an elusive goal. The USACE has had notable success with vertical dam and levee relief wells, but as we will discuss, wells are les challenging to maintain. Consequently, it is well recognized that preventive maintenance programs (PM) that include a protocol for monitoring clogging mechanisms is beneficial to dam safety.

This report will not presume to critique Reclamation drainage system engineering except where it makes drain maintenance difficult, and to suggest features that make maintenance more practical. The report will focus on mechanisms of clogging, existing and potential methods of monitoring systems for clogging symptoms, and potential methods of maintenance to mitigate clogging.

This literature review builds on prior reports by this project team, including Smith-Comeskey Ground Water Science (2000), addressing problem causes, treatment and recommendations for maintenance of the Close Basin Project wellfield near Alamosa, CO, and Smith and Hosler (2001), a report with recommendations for the Pablo Canyon Dam, Montana. It also borrows from published experience with clogging and system maintenance experience gained in agricultural drainage, environmental management drainage (e.g., landfill drains), and ground water applications, as these offer many parallels to hydraulic drainage of dams.

Drain Design and Planning

Fiedler (2001) conveniently describes drainage system designs for Reclamation dams and USACE (1992) describes the design and construction of relief wells in the USACE system. Drains and relief wells (in contrast to extraction wells) are designed to provide little resistance to water inflow and to move water whether the earth matrix has a high hydraulic conductivity (k) or not. Some (as with the Garrison Dam) are situated to manage flow associated with high-k zones. Consequently, drains and wells often have large contrasts in k between surrounding matrix and the immediate vicinity of the drain. Wells often do not follow classic extraction well design and placement, and are rightly considered as a separate class of wells along with construction dewatering wells that have their own design and maintenance features (Powers, 1992; Fiedler, 2001). They may operate intermittently and with highly variable flows. Drains (and sometimes vertical shaft drains or wells) are often located deep within dam structures and may not be easily accessed for reconstruction or by cleaning tools and applied force. Because of their remote locations and the lack of the kind of strong symptoms feedback one would receive from an extraction well, drainage well and drain systems need to be designed to be optimal hydraulically for their function (USACE, 1992; Vlotman, 1998; Fiedler, 2001) and passive operation with a minimum of trouble, but accessible for testing and cleaning as needed.

Clogging Mechanisms

There are a number of important clogging mechanisms, including physico-chemical and biological clogging. These are considered separately in the following for the purpose of discussion, but following the advice of Bonala and Reddi, 1998, various kinds of clogging mechanisms should be considered interactive with one another and with the physical and hydraulic environment. Bonala and Reddi (1998) consider filter design criteria that do not include consideration of biological and chemical clogging mechanisms to be inadequate.

Mineralization: Ground water that is relatively high in dissolved solids can contribute to clogging due to the deposition of salts and subsequent cementation of granular media around screens, perforations in drain pipes and on geotextiles. Cementation identified by U.S. Bureau of Reclamation (1995) includes iron and calcium carbonates, accumulations of iron and manganese hydroxides, and products of decomposition from lignite beds. All of these, except possibly some carbonate deposition, are in some way affected by biological activity. Some carbonate deposition is caused by the release of carbon dioxide as pressure drops across matrix-drain or –well interfaces (e.g., U.S. Army Corps of Engineers, 1992), at seeps and cracks (Fiedler, 2001) or due to oxidation of methane as often occurs in wells and tunnels.

Carbonate clogging of extended hydraulic structures is known from antiquity. For example, Hauck and Novak (1987) describe the mechanisms of carbonate clogging in the Roman aqueduct that served the Roman colony at the present city of Nîmes in southern France. The source water is high in calcium, low in manganese, hard and alkaline, with most of the hardness being bicarbonate. They attributed the extensive deposition to H^+ loss (expressed as depressed pH) from biocarbonate in a manganese-undersaturated environment, resulting in bulky carbonate deposition.

In a study supported by the Electric Power Research Institute (EPRI), Ryan et al. (1991) studied drain clogging and cleaning methods. In the EPRI study, carbonate deposition was the dominant form of incrustation at each of the 17 dams studied. They concluded that pressure played a role in the formation of calcium carbonate deposits. The greater the pressure confining water in the system, the more $CaCO_3$ and CO_2 can be kept in solution. Thus dams with high pressure at the heel of the dam would be more susceptible to heavy calcite deposition. As pressure decreases when water approaches foundation drains, CO_2 degasses and $CaCO_3$ is deposited. The primary source of the $CsCO_3$ in these dams was the concrete of the dam itself and grouting, along with calcite seams in foundation rock.

According to Bonala and Reddi (1998), “the surface chemistry of fine particles and their interaction with the pore fluid plays a significant role in the release/capture of fine particles in the porous medium [e.g., of a dam drain]. A slight change in the pore fluid chemistry can alter the net attractive/repulsive forces between particles and can change the permeability of the porous medium to a significant extent.” Increasing fluid ionic strength improves the conditions for deposition of particles.

Biological clogging: Biofouling is well-described as a problem causing reduced hydraulic performance of hydraulic structures in dams and hydraulic structures (e.g., Klaus, 1993; Kissane and Leach, 1993; Fiedler, 2001; Geibel, 2004). Descriptions of the occurrence of biofouling and its effects in wells and other structures and systems go back into the mid-19th Century and continue to be described by modern researchers (e.g., Smith, 1992 and 1995; Alford and Cullimore, 1999; Bloetscher et al., 2001; Houben, 2002). Bacteria that form biofilms are considered to be ubiquitous in terrestrial and aquatic environments and capable of a wide range of material transformations (e.g., Krumholz, 2000). These activities include the following that are relevant to drain clogging:

- Extracellular polymeric substance (EPS) formation – cellulosic filaments and fibers formed from organic carbon substrate and involved in material trapping and natural in-place geotextile formation
- Oxidation of soluble ferrous iron, manganous manganese, and other metals to poorly soluble oxide states.
- Transformation of sulfur species (oxidation and slime formation or reduction and combination with Fe to form insoluble Fe sulfides).
- Deposition of carbonates due to manipulation of organic and inorganic C states.

In addition to “bacteria” (generally heterotrophic and chemoautotrophic eubacteria), cyanobacteria (photosynthetic eubacteria, aka “blue-green algae”), fungi, and certain eukaryotic algae (notably diatoms) are important biofilm-forming and material-transforming microorganisms in terrestrial environments. Biological clogging of porous media is typically modeled as a gradual pore volume reduction process (Hajra et al., 2000) although Cooke et al. (2001) describe a process of biofouling development (controlled by nutrient availability) that proceeds to a steady state, augmented by mineral precipitation that proceeds arithmetically. Hajra et al. (2000) were able to demonstrate a direct relationship between clogging potential and 1) substrate availability and 2) bacterial numbers.

Ferrous iron oxidation and deposition as ferric oxides of various sorts has an ambiguous relationship with microbial activity. In fact, it appears that biological and abiotic mechanisms are both active in FeIII oxide deposition in wells and drains. One problem with understanding the role of microorganisms in FeIII oxide deposition is to understand the mechanisms they might employ in inducing Fe transformation. Fe auto-oxidation can occur at temperatures, pressures and oxidation-reduction (redox) potentials commonly encountered in terrestrial and fresh water environments. Respiratory Fe oxidation to provide protons for carbon dioxide fixation has long been described among acidophiles found in acid mine drainage, but wells and drains rarely have extremely acid environments. Although long suspected in the case of the stalked proteobacterium *Gallionella ferruginosa*, unambiguous proof of CO_2 fixation powered by FeII oxidation at circum-neutral pH was a long time coming (Sobolev and Roden, 2004). However, a strong microbiological influence on FeII oxidation due to catalytic and surface effects (high surface pH on polysaccharide sheaths) has long been assumed and seems essential for high performance in iron removal (e.g., Hatva et al., 1985). The predominant mineral formed by microbial activity is ferrihydrite (Hatva et al., 1985; Tuhela et al, 1993), which recrystallizes to lepidocrocite or goethite unless silica or organic matter is present. These prevent redissolution of colloidal ferrihydrite and recrystallization (Carlson et al., 1980; Vuorinen and Carlson, 1983).

Clogging by manganese oxides is mediated by biogeochemical mechanisms. The transformation of soluble MnII to insoluble MnIII and MnIV forms is effected by microorganisms in natural waters (Hatva et al, 1985; Robbins et al., 1999; Tani et al., 2003;White, 2004) and Mn oxidation rates and mass transfer do not necessarily correlate with those of Fe oxidation. Whether or not Mn oxidation is prominent in drain clogging locally depends on matrix mineralogy (e.g., limestone provides HCO_3^- that aids oxidation) and other factors such as local redox potential, and water organic content. Water with relatively high TOC such as recharge or seepage from rivers and lakes can support the microflora that oxidize MnII. Mn oxidation is often described as occurring at sharply defined redox interfaces such as between O_2 and H_2S-rich waters. Such biogenic Mn oxide minerals may be amorphous or take a buserite (minimally organized) structure (Tani et al., 2003), with subsequent recrystallization.

A further common form of biofouling is caused by sulfur-oxidizing biofilms. Reduced inorganic sulfur compounds like sulfide or thiosulfate are oxidized by different 'sulfur bacteria'. In most cases the sulfur compounds are oxidized to sulfate and used as electron donors for anoxygenic photosynthesis or for aerobic and anaerobic chemolithotrophic growth. Furthermore, several bacteria are able to detoxify sulfide by oxidation. In many cases sulfur globules of 'elemental sulfur' are formed as an intermediate of reduced sulfur compound oxidation and deposited either inside or outside the cells (Prange et al., 2002).

Significant work on iron and sulfur biofouling of drains and drip irrigation systems was conducted by Harry W. Ford and others in the 1970s at the University of Florida's Agricultural Research and Education Center, Lake Alfred. Ford and Tucker (1975) documented microbial causal agents of drip irrigation systems, including sulfur sludges, with *Thiothrix*, a filamentous S-oxidizer, in the lines (identified in toe drains at Pablo Canyon dam, Smith and Hosler, 2001) and another type, *Beggiatoa*, at emitters (higher flow and aeration), and "ochre" (Fe biofilm) of *Gallionella* and *Leptothrix*.

The most extreme biofouling environment in common geotechnical drain experience is that of landfill leachate drains (e.g., Fleming et al, 1999; Fleming and Rowe, 2004; Cooke et al., 2001). Due to their very high organic loading and solids content, clogging often occurs much more rapidly. However, experience with these systems is illustrative and can be extrapolated to the (typically) less-extreme dam drain environment. Most of the clogging occurs in the saturated zone and such clogging can be modeled empirically and mathematically (Cooke et al., 2001).

When excavated, such drains exhibit surficial biofouling, extensive matrix clogging outside of the drains (including mineral bioconcretions of iron sulfide and calcium carbonate).

Biological influence on carbonate and clay deposition seems to be larger than previously understood. Carbonates are abundantly deposited by CO_2-fixing microflora. Among the best known microbial CO_2 precipitators are photosynthetic cyanobacteria, which are bacteria that employ oxygen-generating photosnthesis similar to that used by algae and plants. Stromatolites, or cyanobacterial reefs, are among the oldest fossils in earth history, found in Archaen rocks formed 3.5 billion years BP, and the dominant mode of life over 7/8th of the history of life (The Virtual Fossil Museum (undated). Although much reduced in extent, both marine and fresh water (actually hard water) stromatolite formation by cyanobacteria persists.

Lithic cyanobacterial biofilm formation proceeds much like other types of microbial biofilm development progression (Reid, R.P., 2001):

1. Pioneer communities: Photosynthetic, nitrogen-fixing cyanobacteria lay down copious extracellular polymer (exopolymer) layers, trapping and binding sediment.
2. Mature communities: Films of exopolymer, heterotrophic aerobic, and anaerobic bacteria overlay dense populations of filamentous cyanobacteria, operating as mutually beneficial consortia. In addition to fixed organic C, calcium cabonate precipitates on the bacterial layer due to ion gradients formed among the layers.
3. “Climax” or senescent communities include endolithic coccoid cyanobacteria and calcite layers solidify.

Numerous other bacteria and archaeans (members of the third domain of life – the other two are the familiar Eubacteria and Eukaryotes) are chemoautotrophs (C-fixing from CO_2 but using chemical redox transformations to generate “reducing power”). Other low-energy anaerobic photosynthetic bacteria (such as purple sulfur bacteria) also fix CO_2. Most chemoautotrophs operate in anaerobic, acidic, or other extreme environments. However, chemoautotrophs do operate at more typically ambient oxygen and solute conditions. For example, the mesophilic filamentous sulfur-oxidizing bacterium *Beggiatoa* has been demonstrated to fix CO_2 autotrophically and incorporate CO_2 as organic C at a rate of over 135 nmol CO_2 fixed per milligram of protein per minute (Patritskaya et al., 2001). *Beggiatoa* are common in terrestrial aquatic environments such as wells and springs where sulfide and oxygen are available and in downstream drains (e.g., Ford and Tucker, 1975), and are readily cultivated as biofilms.

Calcite deposition is often observed in wells where methane is present and being oxidized to CO_2 by microbial oxidation. These usually take the form of a calcified slime and can subsequently develop as speleothem cave deposits (e.g., Melim et al., 2004).

Some calcite deposition is a result of rock “mining” by burrowing by cyanobacteria and organic-C processing by associated biofilms (Hladil et al., 2003). Clays can be formed as microbes oxidize dolomite ($MgCa(CO_3)_2$) to release CO_2 for carbon fixation in organic C-deprived systems (Kreate et al., 2004).

Cooke et al. (2001), Rittman et al. (2003), and Fleming and Rowe (2004) describe microbial reactions as being important drivers of $CaCO_3$ precipitation in modeled high-COD (landfill leachate drain) systems. Here, the system drivers can be as common as the oxidation by microorganisms of common organic acids, found in leachate water, but also in other organic-rich (e.g., impounded surface water). As these compounds are oxidized, pH rises and $CaCO_3$ precipitated. Another related mechanism (Rittman et al., 2003) is fermentation of volatile substrates (e.g., fatty acids) to short-chain organic acids, typically acetate, carbonic acid and methane. Acetate fermentation to CH_4 and H_2CO_3 drives $CaCO_3$ precipitation by increasing carbonate availability in the system and raising pH. As organic acid salts (e.g., acetate and proprionate) are used in forming biomass and CO_2 is released, $CaCO_3$ deposition is enhanced (Rittman et al., 2003). According to Cooke et al. (2001), $CaCO_3$ is deposited first at the inlet, then proceeding downgradient in the model system, and not stabilizing at a steady state as the biomass does. Thus drain clogs can be expected to propogate in this way. Acetate is also relatively common in organic-rich natural waters as a degradation product of hydrocarbon oxidation.

The effects of biological clogging on drains and wells relate to the influence of the biofouling and associated mineral build up on the reduction of effective hydraulic conductivity of the system. Bioclogging, especially in more advanced forms, results in greatly altered flow paths in hydraulic systems (Engesgaard et al. 2005). However, research on artificially constructed filters shows that a large amount of biofouling (biomass and associated organic matrix and inorganic debris) can build up in a porous media system (filter or aquifer around a well) before a head loss across the screen surface (reflected in lowered specific capacity) is detected. This can take a long time to develop. In high hydraulic conductivity (k) systems, biofilm dimensions can be a small fraction of pore dimensions until there is a build up of insoluble products (Umble and Smith, 1999). Specific capacity (yield in flow rate per unit drawdown), which correlates to k and is the most commonly used indicator of well performance condition, in a sense is a crude tool in charting well performance change. Initially, as in biological filtration (e.g., Goldrabe et al., 1993; Wang et al., 1995) biofilms have relatively little impact on aquifer or gravel pack pore volume. As "debris" such as iron oxides builds up, pore spaces become more restricted and head losses begin to rise, eventually to be reflected in lowering specific capacity values. Where flow rates in a well or drain are very low relative to the potential calculated yield, laminar flow may be maintained even with a high level of blockage and associated efficiency loss, and the loss undetectable unless the system is tested under higher stress.

The role of interactive factors: Walter (1997a,b) reports studies of iron-related clogging of wells in Suffolk County, New York. Walter (1997a) reports that wells in the Magothy aquifer with at least a 5 percent per year loss in specific capacity have higher concentrations of iron, manganese, phosphate and dissolved sulfate, and lower concentrations of dissolved oxygen, nitrate, total alkalinity, and pH compared to other Magothy wells. Similar distinctions can be seen for upper glacial aquifer wells in the same area. Walter (1997b) reported operational, microbiological, and lithologic differences among wells, in addition to water quality differences. These findings are reflected elsewhere in the world (e.g., Olanczuk-Neyman, 1990).

In related work, Rinck-Pfeiffer et al. (2000) modeled biogeochemical issues at the model scale that might affect aquifer storage and recovery (ASR) wells. They found complex interactive factors. For example, biofouling increased clogging initially, but then biological byproducts reduced the effect of calcite clogging. Since ASR systems are showing performance issues in practice, such studies need to be considered in context, but illustrate how influences can be additive or counteractive.

Hydrologic properties greatly influence biofouling effects on well clogging. Wells with similarly advanced and abundant biofouling show different performance results. Following what can be expected from filter practice, aquifers with lower hydraulic conductivity (k) show more rapid and more intense performance loss than wells in higher-k aquifers (e.g., Smith-Comeskey Ground Water Science, 2001). Limestones and dolomites with solution channel openings can contain massive biofilms without detectable loss in well performance. Earth materials that have highly mixed particle sizes (such as disturbed matrix around and in an earthen dam) have typically low and unpredictable k. Clogging can be expected to occur at the drain or drain-filter and soil matrix interface.

It is also widely accepted that most iron and manganese precipitation (and sulfur oxidation and precipitation) occurs at sharp redox zone interfaces (e.g., Jones, 1986; Smith, 1995). These "redox fringes" can shift depending on changing ground water chemistry or flow conditions (McGuire et al., 1999). The installation of wells and drains changes redox conditions in an earthen matrix, generally introducing a new oxidizing interface. FeII that would have remained dissolved in flowing ground water is now subject to oxidizing conditions and deposition. Where maintenance planning (see following) relies on ground water quality judgments, analyses should be repeated after the flow system geochemistry "matures."

Soil-environment "patchiness" with zones of widely variable redox potential and soil quality are likely to be typical in earthen dam matrices. Soil manipulation and stockpiling alter soil properties (Harris and Birch, 1990) and then these altered soils are mixed during construction. This again, would be an expected condition that cannot necessarily be controlled, but understood and observed during maintenance monitoring.

Where there are significant redox drivers such as coincidental occurrence of hydrogen sulfide and iron, multiple clogging can occur (e.g., Ford and Tucker, 1975; Spilde, 2004). Hydrogen sulfide (sources in dam systems could be rotting buried vegetation) supports sulfur oxidizers such as *Thiothrix* and various ξ-proterobacteria. When Fe is present, iron sulfide mineral formation and clogging can be expected. In water wells with both iron and sulfide water, deep-set FeS_x deposition overlain by gelatinous S-oxidizing biofilms can form an effective caulk-like clog.

Obviously, various components of the carbon cycle interact. For example, methane (CH_4) may be recently biogenic by archaen methanogens or escaping from geologic reserves (generated by similar microflora or abiotic mechanisms in the past). Methanotrophs convert it to CO_2 and subsequently into organic C (used by other organisms), or it may be incorporated or deposited by other lithoautotrophic microflora , and carbonate deposited due to local supersaturation. Local pressure changes also affect solubility. The presence of such biogenic CH_4 and CO_2, as well as slippery biofilms, can be safety hazards in drainage structures such as manholes and tunnels (Pearson and Brown, 1990).

As with wells, manipulating the water environment within a drain system has been shown to reduce or eliminate troublesome clogging buildup (e.g., Abeliovich, 1990). This works mostly for iron “ochre” build up. Such manipulation toward a “mid-range” anoxic (nitrate-reducing) environment is unlikely to be practical, but if system design can include provisions for maintaining the redox potential of drains below the FeII/FeIII oxidation point at local pH, temperature and pressure, maintenance cleaning can be reduced.

A more likely situation is to understand that toe drain systems are highly dynamic, and performing at the saturated-unsaturated interface. This environment is poorly understood, but includes microbial adaptations that differ from those found in the saturated zone or in the seldom-saturated vadose zone. Microflora at the saturated-unsaturated interface appear to develop extensive three-dimensional EPS structures that affect local hydraulic conductivity and surface properties (e.g., increased slickness), and provide varied environments that harbor high microbial diversity (Or, 2003).

Monitoring and Detection of Clogging Mechanisms

Dam and associated drainage structure inspection and monitoring are important functions in dam operations and maintenance (O&M). Structural and hydraulic monitoring methods and requirements are ably described by others (U.S. Army Corps of Engineers, 1986, 1992, 1995, 1996; Fiedler, 2001; Indiana Department of Natural Resources, 2003). The evaluation of clogging is an important part of predicting future clogging, detecting clogging in progress in time to clean it effectively, and for understanding current problems. Fiedler (2001) advises that being able to predict the types and rates of clogging (including the overall site geology and structure) facilitates rational maintenance planning. Detecting clogging in practice (e.g., before performance impairment sets in) improves the chances of effective cleaning, particularly with biofouling (Smith, 1992; 1995; Alford et al, 2000). How to incorporate this type of analysis in Reclamation dam and wellfield O&M is part of the scope of the current “Bioclog S&T” work and still in the evaluation phase (Smith-Comeskey Ground Water Science, 2000; Smith and Hosler, 2001).

The questions for implementation are: What should be monitored? At what intervals? In what detail? Using what methods? A doctrine for drain maintenance monitoring can probably follow the lead in well maintenance monitoring (e.g., Smith, 1992 and Alford et al., 2000), but the procedures likely can be simplified. Smith (1992) documented work to design a maintenance-monitoring program for wells affected by biofouling that is practical for a local water plant to implement with modest resources. Smith-Comeskey Ground Water Science (2000) took a similar approach in recommendations for Reclamation’s Closed Basin Project wellfield. That report should be supplemental reading along with this and associated other documents produced by the current project. Alford et al. (2000) is oriented toward aiding maintenance in the severe environment of pumping wells on hazardous, toxic, and/or radioactive waste sites. Wells on these sites, usually employed in containing and extracting water for cleanup, pump very challenging (corrosive, solids-laden, biologically active) water. Wells can fail within a few months without aggressive maintenance. The recommended maintenance monitoring is stringent.

A recommended methodology with goals similar to Smith (1992) and Smith-Comeskey Ground Water Science (2000) but using significantly different methodology has been proposed by Schneiders (2003).

Smith-Comeskey Ground Water Science (2000) proposed a detailed maintenance program, including maintenance monitoring, for the 130-well Closed Basin Project. The intent of the Closed Basin project report and plan was to provide a framework for selective monitoring of different classes of wells, and modifications to their construction and operation to improve maintenance and service life. This maintenance program is going to differ significantly from that anticipated for a dam: It involves 130 pumping wells located over a large area that are instrumented for monitoring. However, parameter monitoring will be similar.

Monitoring strategy: No dam manager is supplied with resources to conduct a detailed, long-term experimental research program, and typically this would not seem to be necessary for maintenance monitoring to assure safety. However, a certain baseline of information is necessary to understand the nature of clogging and other drain or well deterioration and how to address it. Consequently, testing can be divided functionally:

1) Diagnosis and baseline analysis: A program capable of defining the performance of the system at some benchmark, and defining the hydrogeochemistry, biological, hydraulic, engineering and operational components of the system in enough detail to formulate a maintenance (and if necessary rehabilitation) plan.
2) Routine maintenance monitoring: A much more limited suite of parameters, defined during benchmark diagnosis as being a) indicative of deterioration and b) changeable, is monitored on a regular basis, with results guiding ongoing O&M planning.
3) Treatment-related and special-condition diagnostic testing: Testing conducted when repairs and rehabilitation are conducted to quantify results or testing to define a newly identified condition (such as a newly developed seep).

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What to monitor

Geochemistry for predicting and describing clogging issues is commonplace in water supply and environmental well management (Smith, 1992, 1995, 1996; Howsam et al., 1995; McLaughlan, 1996; Walter, 1997a,b; Alford et al., 2000; Schneiders, 2003) and described for horizontal wells, which resemble pressure relief drains. Wilhelms et al. (2001) describe geochemical use in describing horizontal hydrocarbon extraction wells. They demonstrated that geochemistry could be used in detection of barriers to flow (including clogs), and unintended leaks in long, narrow, porous structures. This body of experience suggests that analyses and modeling of the results to define what clogging can be expected should be part of baseline maintenance planning for drainage systems and wells.

Smith-Comeskey Ground Water Science (2000) discussed physico-chemical monitoring recommended for maintenance analysis. There are a number of factors that contribute to plugging and other problems associated with biofouling. The occurrence of specific levels of microbial nutrients, electron acceptors, or metabolites (C, H, N, P, S, O, Fe or Mn in various forms) has been suggested for predictive monitoring (Cullimore, 1990), but much more work still needs to be done before chemical constituents can be used to construct models for biofouling potential, although substantial research has been conducted on encouraging microbial growth in soil for bioremediation. For example:

1) Dissolved oxygen has been suggested to be a limiting factor in the rate at which biofouling buildup occurs in a well. However, there are too many variables involved in iron biofouling to make any useful predictions based on oxygen content alone.
2) Several investigators have recommended redox potential measurements in combination with pH measurement for routine monitoring purposes and as indicators of potential plugging problems. Armstrong (1978), Borch et al. (1993), Smith (1992), and McLaughlan (1996) describe methods for using redox potential measurements for making assessments of the well environment.

Redox potential measurements reflect the relative ratio of oxidized and reduced species of Fe, Mn, S and other minor constituents in the water sampled. Elevated redox potential levels indicate an environment in which oxides of Fe(III) and (occasionally) Mn(III-IV) are precipitated, which could result in increased plugging. The redox potential is a generalized measurement of the sampled environment and cannot by itself identify the responsible ion pairs and microenvironments present in the well (Smith, 1992; McLaughlan, 1996). For example, MnIV oxide precipitation can occur in ground water with bulk Eh readings far below the +600 mV value at pH 7 indicated by Hem (1985) as the threshold for MnO_2 and MnOOH stability (the actual minerals formed are chemically more complex). Such oxidation and precipitation is attributed to surface enzymatic activities of *Leptothrix* spp. bacteria in Mn-depositing biofilms (Tuhela, Carlson and Tuovinen, 1997). However, over time, patterns can emerge. For example, results of Eh analyses by Smith (1992) in three wellfields, when plotted on scatter diagrams, were generally consistent with the pattern of biological activity. It is probably these activities driving bulk redox potential and not vice versa (see following).
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As in the case study of Smith (1992) and Smith and Hosler (2001), field analytical instruments can be used to obtain data that provide information on physico-chemical properties of water, such as pH, redox potential, conductivity, temperature and metals that can reveal much about the geochemical system at any particular sample point, and spatially.

Biofouling: There are numerous methods for monitoring biofouling. Smith-Comeskey Ground Water Science (2000) and Smith and Hosler (2001), a study of Pablo Canyon Dam in Montana, provide examples of the use of a range of methods to characterize biofouling in the Reclamation setting. The former reference provides some background on the evolution and recent development of biofouling sampling and analysis methods. As with physico-chemical analysis, biological monitoring largely comprises sampling and analysis of the contents of samples. The appropriateness of both activities affects the validity of the results of the monitoring activity.

- Samples must be collected in such a way that biofouling indicators are detected, and detected at a level that permits a practical response.
- Analytical methods should be able to provide a way to detect, and in some fashion, quantify the biofouling components present.

For the purpose of biofouling analysis for treatment, the analysis is most effective when the chemical and mineralogical components are analyzed along with the microbial.

Cultural Methods of biofouling analysis: APHA, AWWA, and WEF (2000) Section 9240 presents several formulations for nutrient media for heterotrophic iron-precipitating bacteria, Mn-oxidizing organisms, and for *Gallionella* enrichment (for example, as employed by Sangre de Cristo Laboratories for Reclamation's Closed Basin Division). Media for iron-precipitating bacteria have been used with mixed success. No effort has been made to standardize these media with reference cultures from well water systems and thus the recovery efficiency of iron bacteria from ground water samples remains unknown at the present time (Tuhela et al., 1993).

Biological Activity Reaction Test (BART) methods: BART methods are a heterotrophic culturing technique developed by Droycon Bioconcepts, Inc., Regina, Saskatchewan, Canada. Their application is an example of using cultural methods to grow microorganisms that appears to be improving on the Standard Methods status quo (they are not yet included in Section 9240). BART function and application are explained in Droycon Bioconcepts Inc. (2004), and in the appendix to Smith and Hosler (2001), as well as in prior references (e.g., Smith, 1992; Alford and Cullimore, 1999). Briefly, BART tubes contain a dehydrated selective or differential culture medium selected for the microbial group of interest (iron-related bacteria, etc.), and a plastic ball in a 15-mL tube. Adding sample water hydrates the medium, and a redox gradient forms between the ball and the medium in the bottom. Interpretation is based on observation of the medium appearance and time it takes for a reaction to occur. Other kinds of similar heterotrophic growth media (e.g., the MAG system developed independently in Argentina by Gariboglio (Garibogio and Smith (1993)) can be substituted. However, BART are highly functional and easy to use and widely available in North America. Like all such cultural methods, they depend on sampling to capture viable microflora and typically only grow a fraction of the biomass present.

Utilizing specially fabricated plate and culturing methods may at times prove necessary in addition to BART testing. For example, Smith (1992) and Smith-Comeskey Ground Water Science (2000) describe FeIII-amended heterotrophic plates being overrun by actinomycetes (filamentous soil bacteria). These microflora, also capable of drain clogging, would be expected to be a problem in some Reclamation dam drain systems. A BART method (nor any other "canned" system) is not available for their analysis.

Light microscopy: Microscopic examination of water samples as well as metal oxide biofouling encrustations can reveal stalk and sheath fragments of bacteria presumed to be involved in iron, manganese and sulfur biofouling. Therefore, light microscopic examination has traditionally been the method of choice for confirming and identifying iron bacterial structures. APHA, AWWA, WEF (2000) and ASTM D 932 document the commonly used procedures for sampling and analyzing samples by light microscopy for "iron bacteria" (including manganese deposition) and "sulfur bacteria." In many instances, iron biofouling may be difficult to diagnose in this fashion since the biofouling may not include the filamentous or stalked bacteria in some instances.

On the other hand, light microscopy also provides information on nonmicrobial biofilm or deposit components, which is not available from cultural analysis. In addition, light microscopy reveals microorganisms present that would not be identified through biochemical means (e.g., diatoms or protozoa) that add to clogging or environmental health concerns.

In Smith and Hosler (2001), Light microscopy was employed to describe the types of biofilms present in samples, and provide presumptive identification of biofouling micro flora and metal oxide particles by morphology. A major advantage of using light microscopy is its relative availability and usefulness in observing biofilm components.

Scanning electron microscopy (SEM) and elemental dispersive scatter (EDS) analysis: As analysis of the composition of materials by light microscopy is inexact, in Smith and Hosler (2001) and other characterization reports (e.g., that for the Yellowknife Dam foundation drains), an attempt was made to define (qualitatively) the composition of biofouling and other solids deposited in toe drains, drain wells, and manhole sumps. SEM was employed to confirm light microscopy identifications and to provide more detailed photographs for analysis. Associated EDS (in conjunction with SEM-revealed deposit structure) provided insight into deposition mechanisms. These electron techniques are not widely available for commercial analysis and generally more suitable for experimental analysis. However, they provide useful information during the diagnostic phase.

In Smith and Hosler (2001), additional insight into the composition of solids accumulated in biofilms and on surfaces was provided by ICP metal analysis. The most complete picture of biofilm structure, composition and function is provided by a range of complementary methods (e.g., Smith, 1992; 1996) rather than relying on a single method such as BARTs.

Most of these microbiological methods are relatively cumbersome for routine maintenance analysis of drain clogging at remote dam installations. They probably have their best use as baseline analytical techniques used to understand a system, design cleaning and maintenance procedures, and select ongoing (simplified) monitoring.

Sampling for Physico-Chemical and Biofouling Analysis

Most sampling from drains, collectors and wells is going to consist of grab sampling of water samples (e.g., Smith and Hosler, 2001). A related function is dipping instruments directly into water for physical property (redox potential, pH, temperature, conductivity) analysis.

The validity of grab sampling for biofouling analysis assumes that biofilm bacteria and their characteristic structures are also present in the water column (planktonic phase). This is always a qualified, and probably an invalid assumption. The absence of bacteria in samples taken this way may simply mean that the bacteria are attached, not that they are actually absent in the sampled well or drain system.

Among the potential limitations of grab sampling is the "snapshot" nature of the samples, which represent the water quality only at the time that the sample was taken. Shedding events may provide slugs that transiently increase microbial counts or the concentration of iron and manganese water. Most bacteria in pumped water samples under these circumstances have been sloughed off the attached biofilm, and represent only a tiny fraction of the population and diversity of organisms that comprise the biofilm.

After a period of sustained pumping, biofilms will yield very little of the turbid material for microscopic examination. Samples taken after prolonged pumping may fail to detect the presence of chemical and microbiological parameters that would indicate the presence of biofilms. Time-series sampling can improve the information obtained from sampling, although more so for pumping wells than relief wells or drains.

Filtration or centrifugation as recommended in *Standard Methods* increases the odds of recovery of material useful for microscopic identification. Improvements in the sampling further enhance the odds. Filter cartridges, such as those used for collecting *Cryptosporidium* or *Giardia* or other particulates (microscopic particulate analysis, MPA) in a flowing water stream, or membrane filters may be substituted for the flowcell slide approach, as specified in D 932 for iron bacteria or in the U.S. Environmental Protection Agency (EPA) "consensus method" for MPA (U.S.EPA, 1992).

Smith (1992; 1996), Tuhela et al. (1993), and APHA-AWWA-WEF (2000) describe collection methods to improve sampling of biofilm components using coupons on which biofilms develop. These methods are derived from efforts by others as described in Borch et al. (1993), Smith (1992), and Smith-Comeskey Ground Water Science (2000). In summary, these samplers can be immersed passively in a static or dynamic system (well or drain) or installed in sidearm fashion on a pressurized system. Water flows through the sampler and biofilm collects on coupon surfaces, which can be removed and analyzed.

Among coupons available, glass slides have the advantages of being readily available, inexpensive, and noncorrodible. They can also be directly examined microscopically, or sampled for chemical or mineralogical analysis and for cultural recovery of microorganisms. Other coupon materials can be substituted for glass to provide more realistic surfaces to be examined by electron microscopy or evaluated for encrustation and corrosion potential (e.g., Pryfogle, 2005). For example, metal coupons can be directly substituted and used for corrosion-wasting analysis. Collection surfaces can be placed at various locations in a hydraulic system (e.g., drains, pumped water system). The existing samplers described by Smith are robust but relatively specialized for pumping well systems. However, these devices have proven to be readily field-serviceable, as well as being adaptable for a variety of collection applications and use as laboratory models (e.g., Tuhela et al., 1993). Simplified systems adapted for the current S&T bioclogging project will be described in the laboratory model report in progress

Instrumenting Analysis

Fiedler (2001) describes conceptually useful instrumentation for dam maintenance, including those for:

- Hydrostatic and uplift pressure (changes indicating potential drain system malfunction)
- Water levels in piezometers and relief wells (related to hydrostatic pressure and clogging)
- Drainage flow rates (indicates clogging, especially if evaluated in conjunction with pressure)

- Seepage flows
- Drain hole depths (clogging)
- Visual observations (directly by observer as possible and documented with still and video imaging) that can be analyzed for information on clogging type and progress.

Each of these can collect data, transmit it to remote locations for analysis and action, and provide record keeping for analysis over time. Each relates directly to dam safety parameters (potential geotechnical hazards) but is a symptom of clogging and other first-order causes.

Clogging parameters: Industrial water systems (cooling towers, cooling systems in power plants, geothermal energy plants) are prone to biofouling and biocorrosion problems, which can become major problems with potentially expensive or even devastating consequences (e.g., First Energy's Davis-Besse power plant containment dome corrosion). Pryfogle (2005) reported that the estimated annual cost of microbial growth could be as high as $500,000 in a 100 MWe geothermal plant. For these reasons, an automated monitoring approach to biofouling and biocorrosion analysis was pioneered and is operational in places. Given the large scale of monitoring drainage systems versus the personnel to do that, implementing instrumention and automation of the task, along the approach of the Closed Basin Project's wellfields, has potential that should be explored aggressively.

This can begin with reconnaissance testing. For example, Williams (2002) describes acoustic waveform analysis, which can be used, much like an inside-out magnetic resonance imaging (MRI) system for imaging clogs in drain systems outside of the visible surface. Christiansen et al. (2000) describe how vibrational spectroscopy can be used (as on the Mars Global Surveyor) to identify minerals in nature. Fundamental vibrations within different anion groups produce well-separate unique bands that can be used to easily identify specific anions. Additional stretching and bending modes among cations (Mg, Fe, etc.) allow further refinement of analysis to what minerals can be identified on site. The specifics of using this technology in the drain and well setting would have to be explored. Obviously, video as already used (Fiedler, 2001) has already proven to be a useful analytical tool.

Routine electronic monitoring to detect and provide trend analysis in clogging would permit remote locations to be instrumented to report to central maintenance locations. Pryfogle (2005) describes a number of approaches. Among the more promising conceptually is described by Mollica (2001) and also by others (e.g., Busalmen and de Sánchez (2003). Both research groups reported that cathodic depolarization on between two dissimilar-metal electrodes in water correlates to growth in their experimental work. The sensors can also detect improvements due to disinfection, and so can be used to track changes over time. As they transmit a signal, records can presumably be kept showing trends.

Among potential sensors are 1) an Italian design known commercially as BIOX, which consists of a stainless steel cathode and a zinc anode connected by a resistor of known potential, and 2) the BIoGEORGE system (Structural Integrity Associates, San Jose, California), which consists of stacked stainless steel disks comprising two identical electrodes, with one electrode polarized relative to the other periodically to take measurements. Biofilm is detected by an increase in the applied current required to achieve the preset potential, and in geothermal system tests, the instrument response follows the trend of increased thermal resistance in the plant (Pryfogle, 2005). Such sensors could be placed in drain junctions, incorporated into the facility's automated monitoring system, and set to trigger an alarm at some action level. These can be set to trigger a request for maintenance at a biofilm resistance level, rather than on a set time schedule. In the plant tests reported in Pryfogle (2005), the BIoGEORGE instruments were not designed to report remotely, but had to be read manually. However, automating the test would seem to be feasible.

A potential issue is data interpretation – what is an appropriate action level, for example (e.g., Lewandowski and Beyenal, 2003)? Industrial cooling systems are understood to tolerate much less growth than toe drains, for example, with relief wells being perhaps intermediate in tolerance. Would existing instruments such as the BIOX or BIoGeorge tool be too sensitive and overwhelmed at a drain tolerance level? Does Reclamation need to develop an instrument on the same principle but different in sensitivity? We would recommend experimenting with these systems in the ongoing work, and investigating how they can be incorporated into a multi-parameter automated data acquisition and recording system at facilities such as dams.

Current Cleaning Methods Used and their Benefits and Drawbacks

Engineering literature related to "rehabilitation" of toe drains and similar systems (e.g., Dewey, 1993) typically refers to their reconstruction (e.g., repair of piping), grouting or other system repair. In interdisciplinary "ground water" literature related to well performance, "rehabilitation" usually refers to aggressive well cleaning to restore performance, whereas "reconstruction" is used for tasks such as casing repair or relining or screen replacement, analogous in engineering terms to dam repair.

Cleaning of drains is recommended to prevent a decrease in their effective radius and to ensure continued effectiveness (Bryant, 1988; Amadei, et al., 1989). The U.S. Army Corps of Engineers conducted extensive work on relief well cleaning in the 1980s and 1990s. U.S. Army Corps of Engineers (1992; 1993) and Klaus (1993), described cleaning methods for relief wells as employed in Corps system generally and the Vicksburg District specifically, and their transition in progress at that time. Prior to the early 1990s, trisodium polyphosphate (TSP), a white, phosphate-containing powder, and calcium hypochlorite (CaOCl) were used in well cleaning. TSP is an effective low-sudsing surfactant, but leaves P on surfaces and available for recovering biofilms to use in metabolism. The CaOCl (dosed at 200 mg/L) is supposed to kill bacteria. Case histories described by Klaus (1993) show that agitation by airlifting alone was sufficient to improve hydraulic performance of relief wells, which chemicals providing additional benefits, although they can be short-lived. Average well specific capacity (unit flow Q per unit head s) in the Yazoo, MS, case histories (wells cleaned every two years) declined to below-cleaning values within two months. The need for repeated treatments with this older regime has been reported (McCook, 2000). Piezometer readings at such dam and levee structures show reduced differential head after well cleaning. .

Less-structurally-robust materials used in wells and drains can be subject to damage during cleaning as a result of surging, jetting or perforation and other blunt-force trauma. PVC or HPDE plastic, fiberglass, wood, clay and concrete pipe and screens are especially susceptible, although steel (especially if corroded) can also be damaged during cleaning.

Ryan et al. (1991) studied the cleaning methods used on 17 concrete gravity dams. They note that "although a variety of cleaning methods currently are in use, they are rarely used in any systematic way." Methods they describe are:

- Rodding: Using a metal rod to pierce the blockage near the mouth of drains – effective if the clog is not too thick, and some deposits remain on the drain surface.
- Mechanical abraders: Rotating rods and tubes with abrasive cutting heads – increased drain flows have been reported and these tools are used regularly.
- High-pressure water blasting: Jetting with 100 to 30,000 pounds per square inch (psi) and flows of 1 to 20 gallons per minute (gpm) – low pressures are used on soft deposits or loose sediments and higher pressures on hard deposits.
- Ultra-high pressure cutters: Using 20-30,000 lb/in^2 (Fiedler, 2001 reports up to 50,000 lb/in^2) and very low flow rates flowing through a fixed or rotating nozzle, and often self-propelled. This equipment is relatively large and cumbersome, and not recommended for drains in earthen dams (Fiedler, 2001).
- Redrilling: Sometimes drains are just redrilled or reamed to their original diameters. Again, the logistics of directional drilling equipment is the challenge.
- A promising method that was tried at Reclamation's Folsom Dam (Ryan et al., 1991) was simply to fill the obstructed dam with reservoir water after drilling through obstructions and letting it soak for about one month.

Fiedler (2001) also reports flushing and airlifting for removing soft and loose deposits. Pressures up to 250 lb/in^2 and flow of 60 gpm were reported. Ryan et al. (1991) suggested soaking and flushing drains regularly to reduce the amount and hardness of calcite deposits.

USACE (1992, 1993) provide a review of cleaning methods employed by the Corps at that time. In the 1980s and 1990s, the USACE financed and documented improved cleaning methods to address one of the problems plaguing their relief wells: biofouling. Kissane and Leach (1993) documented an improved cleaning method, Blended Chemical Heat Treatment (BCHT, U.S. Patent 4,765,410, August 1988, Alford and Cullimore, 1999) used on relief wells serving levees described in Mansur and Kaufman (1957). This method uses conventional well redevelopment and heated, specifically designed well chemistry to remove biofouling. This documentation was conducted at a time when BCHT was in development. It was later streamlined and widely used on USACE-affiliated projects (Smith, 1995; Alford and Cullimore, 1999; Geibel, 2004). The Kissane and Leach research (also summarized in Alford and Cullimore, 1999) showed that heating properly chosen chemicals is beneficial, but also that mechanical develop is crucial and should be maximized, but improvement eventually diminishes.

The Kissane and Leach (1993) report is notable for providing objective data on performance results and descriptive analysis of the biofouling challenge and the treatment effect on biofouling. BCHT remains one of the better-studied cleaning methods (including Smith, 1995; Smith-Comeskey Ground Water Science, 2000). Besides its capacity to improve wells affected by biofouling, BCHT has been favored by USACE for use on relatively delicate wooden-stave screens often used in relief wells. It has also been extensively used in pumping wells for producing water and managing ground water contamination (Smith, 1995; Alford and Cullimore, 1999; Smith-Comeskey Ground Water Science, 2000).

BCHT is generally considered to be highly effective against biofouling. It is primarily developed for vertical wells, but the treatment program can be teamed with an application system suitable for drains. It is comparatively expensive to deploy given the maintenance costs for the heating equipment, but it has proved suitable for multiple wells at a single site, such as a system of relief wells at a sizable dam. A detailed cost-effectiveness analysis has not been published.

Geibel (2004) provides the perspective of maintenance cleaning some years after BCHT cleaning at Garrison Dam, North Dakota. This dam has an eight-well pressure-relief network (the current wells are about 30 years in age). Biofouling has been the primary cause identified for well performance decline. Wells were cleaned in 1990 and 1992, utilizing BCHT. Amazingly, considering the criticality of the work, no performance comparisons were made before and after testing, but the work was considered to be a success. A preventive maintenance treatment was conducted in 1992 without heating. Flow from wells was redistributed among the wells "indicating effective rehabilitation." No cleaning was conducted until 2002, when a blended-chemical treatment using a commercial mixture developed by the BCHT developers was applied along with well development. The wells were packed in to keep chemicals in the wells for a soak period, and then surged with a cable tool rig.

Fiedler (2001) is an important and recent source of case history information on pressure relief drain cleaning. Summarizing:

- Brantley Dam, New Mexico (composite structure): This dam experienced slight uplift, and a program of foundation drain inspection and cleaning was initiated. These foundation drains are 3-in diameter cored holes within the foundation gallery, finishing in foundation bedrock (dolomite, sandstone and siltstone). Drains were flushed with water and probed. Clog was determined to be primarily Mg-Ca carbonate with some sulfates present (consistent with rock described), with some iron bacteria present in all drain holes inspected. In some cases, clogs were resistant to flushing and required chopping out. The conclusion of the discussion mentions chlorination as a means to effectively destroy bacteria with "acid" (undefined) treatment used on mineral clogs.
- Folsom Dam, near Sacramento, California (composite structure): This dam has a single line of 3-1/2-in diameter foundation drains in the embankment section to relieve foundation uplift pressures. $CaCO_3$ was identified as the clogging culprit with several attempts made to clean clogging drains. In 1987, cleaning was conducted using ultrahigh pressure jetting at low flow, and mechanical abrading (Roto-Rooter) in one drain after an unsuccessful sulfamic acid chemical treatment in 1985. The ultrahigh pressure system was effective in removing deposits but could not effectively flush out washings. In addition, the equipment was bulky and impractical logistically. In 1988, high pressure (10,000 lb/in^2, 20 gpm). This system had a range of tools and appeared to provide good results and seemed to be an effective approach. In the next several years, a 3000- lb/in^2 cleaner was used that was not effective against $CaCO_3$.
- In the case of Friant Dam, California, high-pressure (10,000 to 20,000 lb/in^2) cleaning appeared to be effective, increasing drain flow as judged visually. Uplift pressure was relieved. The higher-pressure 17-gpm 1997 treatment produced more positive results. Disappointing results of using insufficient methods was illustrated by way of the concrete gravity dam at an

undisclosed location in the Pacific Northwest, in which calcite could not be adequately removed and flushed.

- Grand Coulee riverbank stabilization relief wells: In this case, 45 relief wells were installed for bank stabilization downstream of the dam. Iron bacteria clogging was identified as a problem by the 1990s, and a "flip-flop" treatment causing extremes in pH (chlorine then acid) was found to be effective, with dramatic increase in well flows. The chlorine treatment was 1000-mg/L calcium hypochlorite, mixed at the surface, and inserted and agitated using the tremie pipe and a surge block. The acid treatment employed a commercial product, Johnson's Nu-Well, which is a mixture of sulfamic and amidosulfonic acid, which is mixed in and agitated. This work was well-documented and adequately considered safety and environmental responsibility.
- Senator Wash Dam, California experienced problems with silting in relief wells. In this case, redevelopment utilizing the surge block technique was employed successfully. Flows improved significantly, but trailed off again rather quickly. This behavior was not explored further, but attributed to soil and engineering factors. Oddly enough, Fiedler (2001) concluded "The surge block method is only recommended for cases where soil particles are plugging the well screen. The method is not recommended for bacterial plugging or mineral incrustation." No explanation for this conclusion was offered, and it contradicts other relief well (including Grand Coulee) and pumping well rehabilitation experience, where the surge block is routinely used for providing surging and flushing action during cleaning.
- At the Sherman Dam, Grand Island, Nebraska, low pressure (1500 lb/in^2) standard sewer cleaning on a mobile tool was employed to clean toe drains that showed flow decline from 29 gpm to 5 gpm unrelated to reservoir changes. Cleaning improved the rate to probably 12 gpm.
- The Upper Stillwater Dam, Utah, illustrates interrelated issues. Sand migration clogged drains and led to concerns about larger structural issues. To eliminate sand migration out of drain, wrapped PVC screen inserts were installed, but these plugged, typically within hours due to biofouling. Grouting mitigated the sanding problem.
- A series of case histories of slope stabilization drainage in California discussed their effectiveness, design and construction, and use. Maintenance was described as essential.

Recognizing that it is not necessarily easy, it does not seem that some of the tests reported in Fiedler (2001) adequately documented test conditions or cause-effect. There was an empirical "try this" approach. Not many hydraulic measurements are reported at dam sites, although (as in the case of Friant Dam), the important measurement (uplift pressure) was measured and showed response to cleaning. The Coulee project (involving wells) was well-documented and described. The Senator Wash Dam experience left more questions than answers, and a more thorough description would help others to understand and critique the conclusions drawn. Visual inspection does not necessarily tell much about cleaning outside of drains, but it is useful as part of a larger analysis; and the lack of video inspection with the Sherman Dam toe drain rehabilitation is frustrating. There seemed to be an "either-or" attitude about using pressure and mechanical cleaning versus chemical cleaning. Doctrine in ground water well cleaning sectors is that both are necessary.

Recommended Cleaning Methods

High pressure flushing was most typically effective for calcite drain clogging in Reclamation dams as described in Fiedler (2001). Causes of ineffectiveness seemed to center around insufficient ability to contact the clog with force and insufficient flushing capability. Utilizing ultrahigh pressure tools at low flow did not seem to be as effective as using somewhat lower force with higher flow rates. Additionally, high-pressure equipment has been described as cumbersome and expensive to operate.

Reclamation's drain-cleaning approach to-date has been focused on physical cleaning. In addition to the physical cleaning methods discussed, Fiedler (2001) describes chemical solutions used in drain cleaning. In this work, sulfamic acid (a white solid) was effective against calcite clogs in foundation drains at Reclamation's Folsom Dam. Clearing up extensively plugged drains with these acids was not effective. Rapidly alternating pH with "bleach" and sulfamic acid caused stress in bacterial deposits.

Ryan et al. (1991) suggested soaking and flushing drains regularly to reduce the amount and hardness of calcite deposits. Probably somewhere in here is a unified, effective and practical solution: presoaking with a chemical solution, jetting and adequate flushing. The need then is to devise a system that can be employed at remote locations with sometimes-poor accessibility.

Related to Ryan et al. (1991), using recirculation for drain cleaning (where access is available) has been described informally. This system would use low pressure, high flow rates, and chemicals in solution. Arguably, a system could be set up at a remote dam location using filtered reservoir water, amended with calcite and biofilm-removing chemical and recirculated through the filtration system, removing loosened clog debris.

Relief well cleaning seems to be more systematically employed on USACE projects (e.g., Garrison Dam) although the Grand Coulee bank stabilization well cleaning employed an effective pH-reversal and surging protocol. Our recommendation would be to revise the chemical solution to reflect other modern practice as described above, with disinfection and calcite removal also considering the recommendations of Schneiders (2003) as part of a mixed protocol designed around knowledge of the clog.

Potential and Recommended Maintenance Methods

"Maintenance" encompasses practices that to one degree or another prevent or delay deterioration in systems. This is in contrast to reconstruction or rehabilitation. Maintenance can be further divided into preventive, prophylactic, and reactive maintenance practices. Preventive measures include design and material choices and installing (and using) maintenance monitoring practices. Prophylactic measures include scheduled treatments to maintain a status quo in performance. Reactive maintenance generally involves fixing malfunctions such as replacing sensors or motors or repairing structural issues (such as local subsidence or cracking) that do not necessarily impair performance.

Given the potential influence of biological activity on drain performance, seepage remediation construction and engineering choices should be scrutinized for promoting biological clogging. For example, Perry (1993) describes the use of synthetic biodegradable organic polymers for constructing deep drains. These products, intended to provide the open-hole support and cuttings removal capacity of bentonite, have been subject of debate in the ground water construction industry since the mid-1970s. The concept is that chemical breakers and natural biological activity would degrade these chemicals in place, leaving porous media surrounding a well or drain free of clogging material. The problem is that they do not actually disappear and serve as a readily available accessible-carbon starter food for biofilm formation. Drains constructed in this manner would probably be susceptible to clogging if aerobic conditions and abundant oxidizable solids are present. They may work very well in anoxic environments at approximately the redox potential of nitrate reduction if soluble iron is not abundant.

Inspections and Monitoring: There is a general consensus that wells and other critical systems such as hydraulic drains should be visually inspected by knowledgeable eyes for signs of trouble (wet spots, sand discharged, cracking, etc.) and monitored for hydraulic parameters (heads in piezometers, wells and drains, and flow), and some useful suite of biochemical parameters (e.g., U.S. Army Corps of Engineers, 1992, 1993; Mansur et al. 2000).

As described above in this document, fluid, mineral and clogging properties should be characterized at some baseline to permit judgments about cleaning details and intervals. Relatively simple and inexpensive monitoring methods can be employed as per Smith and Hosler (2001). However, a case can be made for instruments as described above and direct observation of clogging using retrievable clog-collection tools. All such incidental work (sampling) can be done on a several-month's interval, with instruments recording continuously within the limits of the recording system.

Preventive treatment

The case histories in Fiedler (2001) and the Garrison Dam experience (Geibel, 2004) reinforce doctrine in other applications (Smith, 1995; Howsam et al, 1996; Alford et al., 2000; Smith-Comeskey Ground Water Science, 2000) that maintenance monitoring and treatment used in a preventive mode is preferred to reactive rehabilitation after extensive clogging has occurred. Fiedler (2001) provides a useful framework and case for routine comprehensive maintenance testing, planning and implementation. As calcite and biofouling appear to be the predominant drain clogging problems, methods to manage and reverse calcite and biofouling clogging that are practical to apply should be of interest.

Shaviv and Sinai (2004) describe the application of a conditioner (e.g., an anionic polymer) to counteract soil compaction around drains that occurs after installation, and also due to silt and clay movement either toward a drain or away from an irrigation emitter, or due to system cleaning. Such movement is driven by a soil "hydraulic failure gradient" (HFG) which is a function of soil composition and structure. HFG around "disturbances" such as drains or emitters is presumably high. The objective of the stabilization is to preserve the disturbed, conductive soil condition around drain structures by minimizing in-soil particle movement. Shaviv and Sinai report good results for applying conditioners via drip irrigation. Higher-molecular-weight (>75,000 Dalton) polymer results were better in their experimental model. Presumably, this principle could be extrapolated to treating hydraulic relief drains with solutions designed to discourage calcite deposition and movement of fines in the dam soil matrix toward drains.

Manipulating water quality affects the influence of fine soil particle accumulation on drainage performance. Hajra et al. (2002) report experiments with altering fluid ionic strength and the observing the resultant effects of kaolinitic suspensions on permeability. Higher ionic strength solutions of KCl and NaOH enhanced kaolinite flocculation, reducing permeability. Thus, higher-TDS and more alkaline waters can be expected to have a similar effect on drains, as would strong, alkaline solutions.

Physical cleaning as described in Fiedler (2001) should be beneficial, with Reclamation settling on systems that suit individual settings. Recirculation treatment as described above under rehabilitation may prove highly practical in many settings. Reclamation is at the beginning of the work to best define such protocols, which can be refined with more systematic observations in some cases.

Other industries offer potentially useful lessons. Marine problems with biofouling have led marine engineers to look at improving slickness and hydrophobicity of drain construction materials to reduce the capacity for deposits to form and build up. However, bacterial conditioning films tend to defeat engineering attempts over time (e.g., Bakker et al., 2004), and such engineered material solutions would need to be combined with active maintenance programs.

Work by the Canadian Prairie Farm Rehabilitation Administration (PFRA) has demonstrated the potential benefit of impressed current treatment to repress biofouling and mineral deposit build up (Globa and Rohde, 2003 and Globa et al., 2004). In this, the biofouled aquifer environment is exposed to an applied electrical field (in laboratory and field). The system produced measurable results in laboratory scale models and improving specific capacity in treated wells until trends plateaued or regressed slightly. Field studies were conducted at the well-documented North Battleford and Qu'Appelle wellfields in Saskatchewan (Prairie Farm Rehabilitation Administration, 1999). Electrical field strength on the order of 25 V/m and current density of 0.077 ma/cm^2 applied midway in well screens caused an increase in specific capacity. The plateau was unexplained. Such a system could potentially be installed in drain systems, especially those that are remote and difficult to reach.

Final Observations and Recommendations

This literature review illustrates that much work has gone into understanding the mechanisms of and responses to drain and relief well clogging. The author can attest that the level of understanding has expanded dramatically in the last 20 years. In particular, analytical methods to characterize clogging and corrosion are practical to use on both a diagnostic and routine monitoring basis.

Reclamation and USACE both have made important contributions to drain and well cleaning, and benefit from the dual efforts over the years. The tools appear to be available to conduct practical cleaning and maintenance.

Based on this literature review and associated experience, we recommend the following:

1) Completion of the drain clogging model studies initiated under the current S&T work, expanded where possible, and using those systems as a platform to study monitoring tools in action.
2) Where possible, increase understanding of what is going on outside the drains and wells in earthen dams through three-dimensional study of the earth-drain systems. This is a very weak area in the literature, although we have explored it on several projects and have study plans to recommend to Reclamation for consideration.
3) Study instrumentation methods at the bench and site scale for use in biofouling and mineral clogging monitoring, using already designed instruments, but probably devising sensors better suited to the dam drain environment.
4) Further test study cleaning methods such as a combined soak, jet and flush scenario with chemical mixtures, and the recirculation approach. It appears that Reclamation can refine its chemical toolbox.
5) Study the PFRA impressed-current system in the drain system environment at the model and field scales for application in Reclamation use.
6) Implementing what has already been recommended on Reclamation projects, such as for the Closed Basin wellfield in Colorado, and systematizing similarly good work described elsewhere in the Reclamation system (Fiedler, 2001).

Such work should prove cost-effective over time in maintaining Reclamation's and the nation's important water management capital assets.

Respectfully submitted,

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