CURRENT RESEARCH IN DAM DRAIN CLOGGING AND ITS PREVENTION

Stuart A. Smith[1] *and Denise M. Hosler*[2]
[1]*Smith-Comeskey Ground Water Science, Upper Sandusky, OH USA;* [2]*Ecological Applications and Research Group, Bureau of Reclamation, U.S. Department of Interior, Denver, CO*

Introduction

As is true of other drainage or pumping structures (including relief wells), drainage systems serving dams are rendered less effective by a range of natural mechanisms, including geochemical incrustation and biological fouling. Like other U.S. state and federal agencies, the Bureau of Reclamation (Reclamation) has an inventory of aging dams to manage and maintain. Reclamation has documented clogging in drainage structures that has the potential to reduce drainage function in some structures. Clogging has resulted in changes in hydraulic head profiles and resulted in the need for drain cleaning and replacement.

This paper summarizes the available body of recent work related to dam drain clogging and reviews the findings of recent research and demonstration work defining clogging mechanisms and their practical mitigation to improve dam maintenance procedures.

Drain Clogging Overview

There are a number of important clogging mechanisms, including physico-chemical and biological clogging. In general, both Reclamation and U.S. Army Corps of Engineers (USACE) experience finds that it is necessary to consider them as operating interactively.

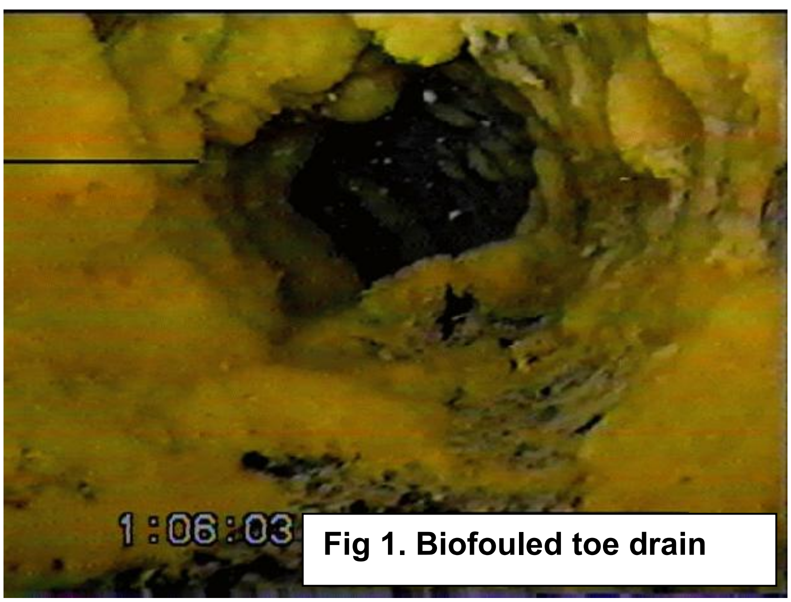

Fig 1. Biofouled toe drain

Cementation, as identified by Reclamation (1), includes iron and calcium carbonates, accumulations of iron and manganese hydroxides, and products of decomposition from lignite beds. Carbonate clogging of extended hydraulic structures is known from antiquity. In a study supported by the Electric Power Research Institute (EPRI), Ryan et al. (2) 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. Some carbonate deposition is caused by the release of carbon dioxide as pressure drops across matrix-drain or –well interfaces, at seeps and cracks, or due to oxidation of methane as often occurs in wells and tunnels (3, 4).

In addition to contributing to clogging due to deposition of salts, ground water (including seepage) that is relatively high in dissolved solids can contribute to cementation of granular media around screens, perforations in drain pipes and on geotextiles. Increasing fluid ionic strength improves the conditions for deposition of particles. 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 (5).

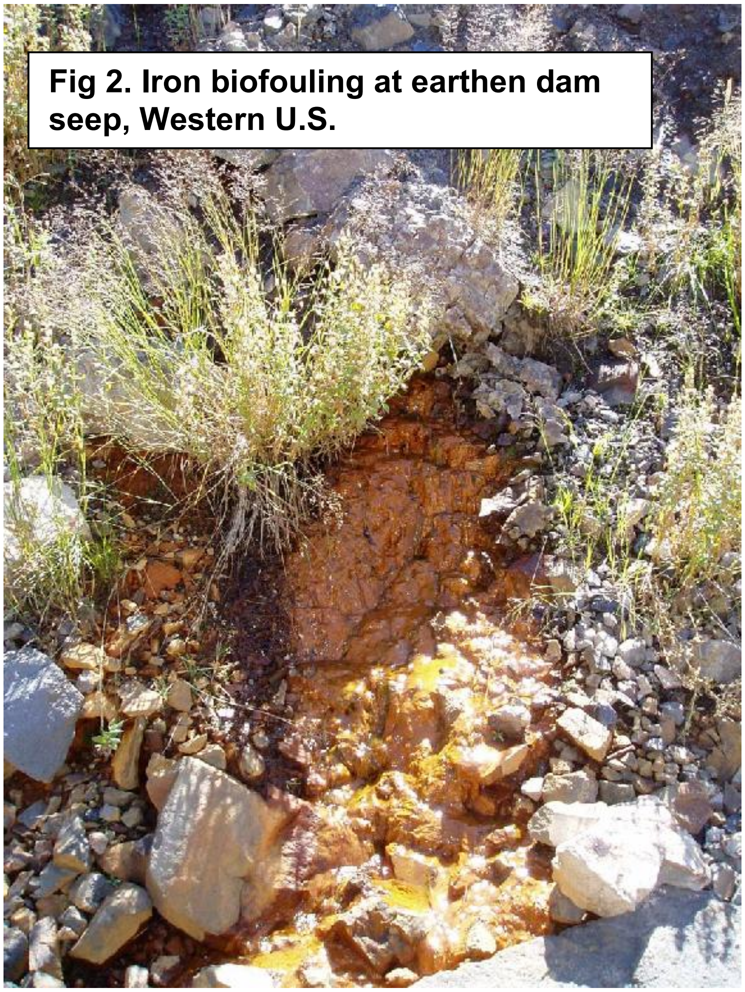

Fig 2. Iron biofouling at earthen dam seep, Western U.S.

Biological Clogging

All of these processes, to one degree or another (including carbonate deposition), are in some way affected by biological activity. Biofouling (deposition influenced by biological activity) is cited by multiple agencies and authors (e.g., 4, 6-8) as a problem causing reduced hydraulic performance in dams and hydraulic structures. Descriptions of the occurrence of biofouling and its effects in hydraulic structures and systems go back into the Renaissance in Europe. Biofouling effects depend on the local environment and the vulnerability of the system to clogging or other deterioration. Hajra et al. (9) were able to demonstrate a direct relationship between clogging potential and 1) substrate availability and 2) bacterial numbers, which is obvious in landfill drains, but most water in most dam drains is much more oligotrophic and clogging depends on other processes in addition to biomass accumulation.

Iron oxidation and deposition is the best known. It appears that biological and abiotic mechanisms are both active in FeIII oxide deposition in wells and drains. Fe auto-oxidation can occur at temperatures, pressures and oxidation-reduction (redox) potentials commonly encountered in terrestrial and fresh water environments. 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 (10).

Clogging by manganese oxides appears to be almost entirely mediated by biogeochemical mechanisms. The transformation of soluble MnII to insoluble MnIII and MnIV forms is effected by microorganisms in natural waters (10-13) 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.

A further common form of biofouling is caused by sulfur-oxidizing biofilms. Reduced inorganic sulfur compounds like sulfide or thiosulfate are oxidized by a variety of 'sulfur bacteria'. The resultant deposits are sticky and readily agglomerate clogging particles.

Biological influence on carbonate and clay deposition seems to be larger than previously understood. Several studies (14-16) 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). 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 (15). According to Cooke et al. (14), $CaCO_3$ 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 causing the reduction of effective hydraulic conductivity of the system. Bioclogging, especially in more advanced forms, results in greatly altered flow paths in hydraulic systems (17). 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. 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.

Interactive Factors

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 (18) 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.

As with wells, manipulating the water environment within a drain system has been shown to reduce or eliminate troublesome clogging buildup (19). 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 could 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 exopolysaccharides (EPS) structures that affect local hydraulic conductivity and surface properties (e.g., increased slickness), and provide varied environments that harbor high microbial diversity (20)

Monitoring and Detection of Clogging Mechanisms

The evaluation of clogging appears to be an important part of predicting future clogging, detecting clogging in progress in time to clean it effectively, and for understanding current problems. Fiedler (4) 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 (21-23)

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 (24). The questions for implementation are: What should be monitored? At what intervals? In what detail? Using what methods?

Monitoring strategy

A doctrine for drain maintenance monitoring can probably follow the lead in well maintenance monitoring (21-23). Coauthor Smith (25) proposed a detailed maintenance program, including maintenance monitoring, for Reclamation's 130-well Closed Basin Project wellfield that augments Colorado flow for the Rio Grande. The intent of the Closed Basin project report and plan was to provide a framework for selective monitoring of different classes of wells, using locally practical methods, and modifications to their construction and operation to improve maintenance and service life. While this methodology can be a template for dam safety monitoring, methods likely can be simplified for a drain system due to greater mechanical and hydraulic simplicity.

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.

Fortunately, recent decades-long body of modern work has resulted in practical methods to monitor drain environments for clogging potential. Reclamation's Ecological Applications and Research Group (EARG), working with coauthor Smith and the Dam Safety Group, has explored the use of available testing methods for drain-system troubleshooting (24). In these cases, portable water quality analytical equipment or file water quality was used to characterize the physical-chemical environment of the drains, and a range of environmental microbial testing methods (see following) used to assess biofouling conditions. After application at several sites, troubleshooting by remote review of water quality became feasible (understanding drain clogging principles to be analogous to other engineered environments).
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Geochemical Monitoring

Hydrogeochemistry for predicting and describing clogging issues is commonplace in water supply and environmental well management (22, 23, 26) and described for horizontal wells, which resemble pressure relief drains. Wilhelms et al. (27) 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.

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 (28), 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.

. As in the case study of Smith and Hosler (24), 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 a drain hydrogeochemical system at any particular sample point, and spatially. For example, in the charts (Figure 3), the pattern of ammonia and total Mn and Fe co-occurrence across the drain system at one earthen dam can be seen.

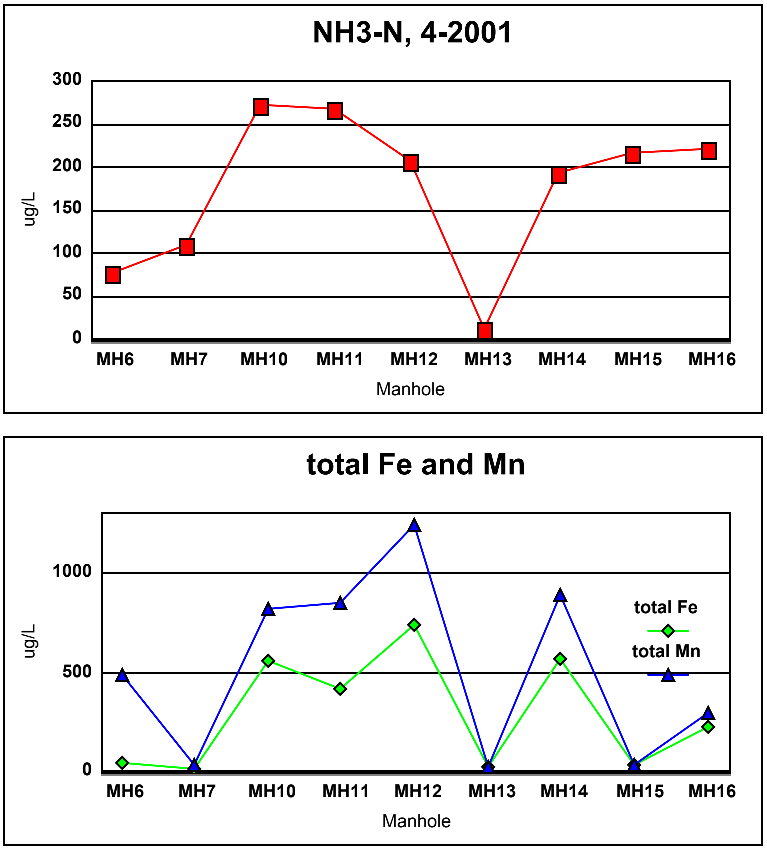

Fig 3. Ammonia and Fe and Mn in manhole water, Montana earthen dam drain system

Biofouling Analysis

There are numerous methods for monitoring biofouling. One study (24) provides an example of the use of a range of methods to characterize biofouling in the dam maintenance application. As with physical-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. Experience shows that:

- 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.

Use of Biological Activity Reaction Test (BART) methods: BART methods are a heterotrophic culturing technique developed by Droycon Bioconcepts, Inc., Regina, Saskatchewan, Canada. BART function and application are explained in available literature (21, 24, 30, and 31). 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 (Figure 4) and time it takes for a reaction to occur.

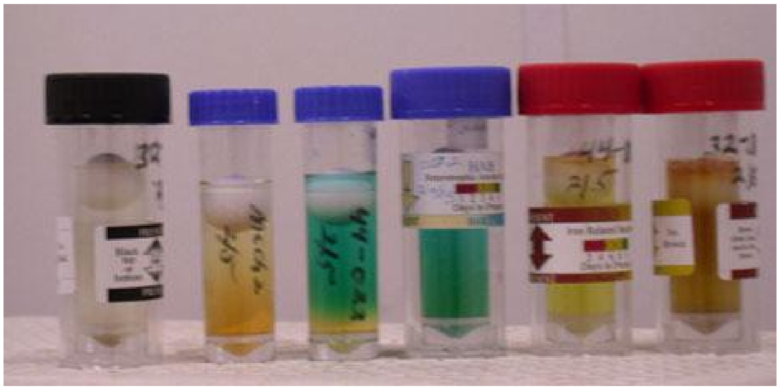

Fig 4. A variety of reacted BART tubes showing reactions

Like all such cultural methods, they depend on sampling to capture viable microflora and typically only grow a fraction of the biomass present. 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 (29)).

Fig 5. Sampling in drain manhole

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 (29). Therefore, light microscopic examination has traditionally been the method of choice for confirming and identifying iron bacterial structures.

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

In (24), light microscopy was employed to describe the types of biofilms present in samples, and provide presumptive identification of biofouling microflora 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, attempts have been made (21, 24) to define (qualitatively) the composition of biofouling and other solids deposited in toe drains, drain wells, and manhole sumps. SEM (Figure 6) 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.

Additional insight into the composition of solids accumulated in biofilms and on surfaces has been provided by ICP metal analysis (24). The most complete picture of biofilm structure, composition and function is provided by a range of complementary methods (21, 32) rather than relying on a single method such as BARTs.

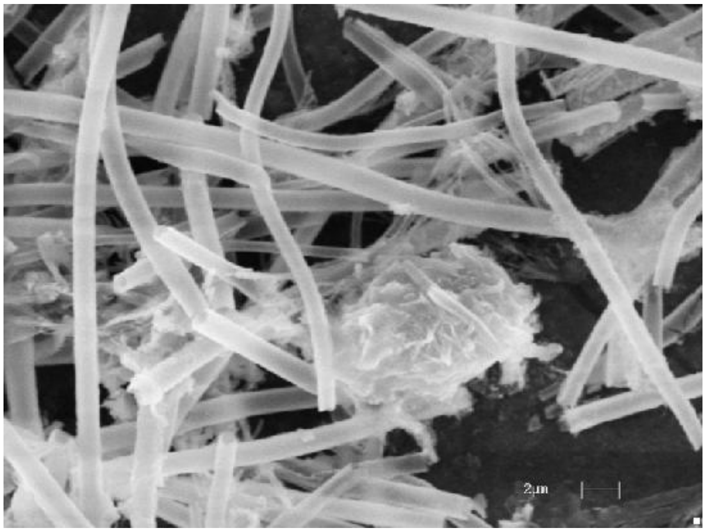

Fig 6. Scanning electron micrograph, filamentous biofouling, earthen dam drain deposits

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.

Current Cleaning Methods Used and their Benefits and Drawbacks

Cleaning of drains is widely recommended to prevent a decrease in their effective radius and to ensure continued effectiveness (33, 34). USACE conducted extensive work on relief well cleaning in the 1980s and 1990s. USACE works (3, 35, 36) described cleaning methods for relief wells as employed in the USACE 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 (36) show that agitation by airlifting alone was sufficient to improve hydraulic performance of relief wells, while chemicals provided 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 (37). 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. (2) studied cleaning methods used on 17 concrete gravity dams. They noted that “although a variety of cleaning methods currently are in use, they are rarely used in any systematic way.” Methods they described 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 20,000 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 (4).
- 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 (2) was simply to fill the obstructed dam drains with reservoir water after drilling through obstructions and letting it soak for about one month.

Fiedler (4) 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. (2) suggested soaking and flushing drains regularly to reduce the amount and hardness of calcite deposits.

In the 1980s and 1990s, USACE financed and documented improved cleaning methods to address one of the most aggravating problems plaguing their relief wells: biofouling. Kissane and Leach (7) documented an improved cleaning method, Blended Chemical Heat Treatment (BCHT) (31, 38), used on relief wells serving levees. 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. BCHT was later streamlined and widely used on USACE-affiliated projects (8, 22, 31). The USACE research (7, 31) showed that heating properly chosen chemicals is beneficial, but also that mechanical development is crucial and should be maximized. However, improvement is not permanent.

The Kissane and Leach report (7) 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. 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 (22, 25, 31).

BCHT is comparatively expensive to deploy given the maintenance costs for the heating equipment, but it has proved suitable for treating 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 (8) 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 (4) is an important and recent source of case history information on pressure relief drain cleaning. High pressure flushing was most typically effective for calcite drain clogging in Reclamation dams (4). 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 (4) 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. (2) 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.

The use of recirculation for drain cleaning (where access is available) has been described informally for Reclamation projects. 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) compared to Reclamation's, although the Reclamation 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.

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.

Drainage Planning for Maintenance

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, the use of synthetic biodegradable organic polymers for constructing deep drains has been described (39). 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 these polymers 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 (3, 40).

Fluid, mineral, and clogging properties should also be characterized at some baseline to permit judgments about cleaning details and intervals. Relatively simple and inexpensive monitoring methods can be employed (24). 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

Dam case histories (4, 8) reinforce doctrine in other applications (22, 23, 25) that maintenance monitoring and treatment used in a preventive mode is preferred to reactive rehabilitation after extensive clogging has occurred. Fiedler (4) 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 particular interest.

Experiments with altering fluid ionic strength and the observing the resultant effects of kaolinitic suspensions on permeability (41) show that manipulating water quality affects the influence of fine soil particle accumulation on drainage performance. 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 (4) should be beneficial, with Reclamation settling on systems that suit individual settings. Recirculation treatment 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.

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 (42, 43). 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 (44). 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

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.

There is a significant need yet to 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 the authors and others have explored the three-dimensional nature of bioclogging in aquifers around wells on several projects.

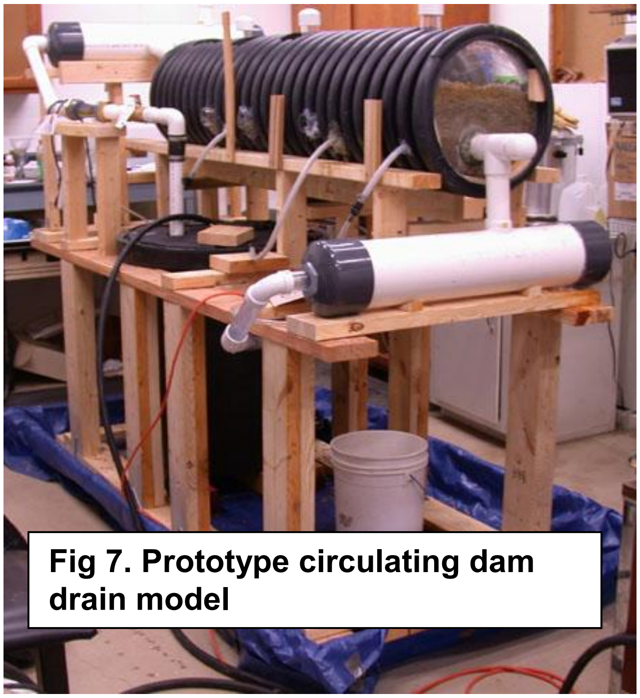

Fig 7. Prototype circulating dam drain model

Currently, the authors are involved in work to explore what clogging around drains looks like at the floor-model scale using available resources made available through the Reclamation Science and Technology Program. Coauthor Smith constructed a recirculating drain model (Figure 7) that was induced to biofoul within six months, exhibiting the capacity to dramatically alter feed-water properties. In this case, removal of 2 to 5 mg/L total iron in the feed water occurs within one hour. Preliminary observation of filter media reveals abundant nonfilamentous biofilm development in the filter matrix. Cultured using BART, these biofilms seem to be mixed aerobic heterotrophic consortia, without strong iron-precipitation patterns. Filamentous *Thiothrix* sulfur-oxidizing bacteria colonize the drain outflow, much as observed in situ (Figure 8) (24). Newly constructed models will explore a wider range of media and physical-chemical environments in the months ahead. These models will also be used to test cleaning methods.

Fig 8. *Thiothrix*-dominated drain biofilms

Instrumentation methods are available at the bench and site scale for use in biofouling and mineral clogging monitoring, using already designed instruments, but devising sensors better suited to the dam drain environment, would be beneficial.

Further testing of cleaning methods such as a flush scenario with chemical mixtures, and the recirculation approach (as well as the impressed-current systems) would be beneficial for refining the drain cleaning toolbox. These will be first reviewed using the floor-scale models.

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