Report of Investigations with Recommendations, Biological Fouling of the Pressure Relief Drainage System, Pablo Canyon Dam, Montana

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I. Overview

The Pablo Dam located in the Montana Flathead Irrigation District (between Missoula and Kalispell, MT) is a earthen dam approximately 3000 feet long and was originally constructed and reinforced in the late nineteen tens. It has undergone two major phases of further construction activity, reinforcement in 1934, and a new toe drain system installation in 1993-4. The toe drain system drainage flows into a wetland below the dam. Over time there has been a 30 -50% water flow reduction in the toe drains and some minor sloughing of the dam side slopes has occurred. Blockages in the drainage network by biofouling (complicating sediment and mineral clogging) are suspected of causing of this flow reduction.

As discussed in "Draft Drainage for Dams and Associated Structures," properly functioning drainage structures are necessary for dam safety and proper function. A fact worthy to note was that out of 4,000 dams in the dam database where 46 dam failures were reported, 21 had documentation available. Only <u>one</u> out of those 21 failed dams had a drain system in place, which leads to the conclusion that drains are vital to dam safety (Reclamation). As is true of other drainage or pumping structures, drainage systems of dams are rendered less effective by a range of natural mechanisms, including geochemical incrustation and biological fouling. Effective, long lasting cleaning of these systems remains an elusive goal. Consequently, it is well recognized that preventive maintenance programs (PM) that include a protocol for monitoring clogging mechanisms is beneficial to dam safety.

Suspected biofouling materials in samples received from Pablo Reservoir in early 2001 were tentatively identified as iron bacteria. Based on this preliminary information pointing to biological fouling of the pressure relief drainage system, a study to sample and analyze the biofouling and water quality of the accessible parts of the drain well and toe drain system was organized. The Reclamation Geotechnical Engineering Group conducted several studies of the Pablo drain system, which included site photos and video monitoring of the undisturbed drains (Appendix 1). The USBR Integrated Pest Management Team (IPMT) designed a Phase I Assessment for FY 2001 and provided oversight for the drain system microbial community evaluation and species identification. The IPMT conducted the evaluation in cooperation with Stuart Smith, Ground Water Consultant of Smith-Comeskey Ground Water Science, and Dr. Eleanore Robbins, USGS Microbiologist.

The Pablo Dam drainage system consists of two different drain systems, the embankment drainage system, which includes the toe drains and the outlet works where the weep drains exist. The primary dam drainage system is the toe drain, which facilitates the drainage at the toe or base of the dam. These drains run into manholes (MH-6, MH-7, MH-10, MH-11, MH-12, MH-13, MH-14, MH-15, & MH-16) that also collect drainage from the lateral outfall drains. The manhole drainage then flows into a weir that seeps into the wetland below the dam. Secondarily, there are a series of seep drains that drain into the outlet works where the gate controls the irrigation outflow (Figures 1-4).

Figure 1. Manhole and weir

Figure 2. Manhole Drains The larger pipes with caps are the toe drains. Accumulated biofilm in the toe drains is visible.

Figure 3. Outlet Works Entrance to the Outlet works, where the seep drains are located.

Figure 4. Seep Drains S-4 which is located in the southern Outlet Works Tunnel.

This report is a summation of the data collection efforts of the Phase I work. The recommendations are of a general nature, and while the authors have some specific treatment recommendation to offer, the feasibility of those options remain in question until further site-specific information is obtained.

II. Field work and Data collection

During mid-April, the Geotechnical Engineering Group conducted a video survey of the Pablo Dam toe drain system below the reservoir, which provides visual proof of the extent of the biofouling problem (Appendix 1). On April 23, 2001, Denise Hosler and Stuart Smith with the assistance of Ronan, Mt. Area Office personnel conducted a site survey and data collection. Water samples were analyzed onsite for pH, temperature, conductivity, and redox potential (Eh). Additionally, water and biofilm samples were collected for chemical analysis and biofoul culture and analysis in the laboratory.

Biofouling analysis

Methods chosen were intended to (1) rapidly define the active microbial ecology present and (2) also to provide a detailed description of biofouling components to aid in selecting cleaning methods. Cultural methods and light microscopy were chosen to permit a relatively rapid and useful analysis of the presence or absence (P/A) of metabolic/respiratory and morphologically distinct types of micro flora present.

Cultural Biological Activity Reaction Test (BART) methods: BART methods (heterotrophic culturing) and their application are explained in the report appendix. 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.

Light microscopy: 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. Water samples containing solids were observed as wet mounts.

Scanning electron microscopy (SEM) and elemental dispersive scatter (EDS) analysis: As analysis of the composition of materials by light microscopy is inexact, 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.

Additional insight into the composition of solids accumulated in biofilms and on surfaces was provided by ICP metal analysis.

III. Summary of Data Results

Observations of manholes and toe drains

Several of the manholes and associated toe drains and drain wells exhibited visible evidence of biofouling (Appendix 2). Toe drains (in particular those entering manholes (MH-10, -11, -12, -13 and -14) had light tan to black biofouling at or below the water level in the drain. The sump at MH-14 was heavily populated by soft, filamentous biofouling lining the walls, submerged surfaces, and as globules in the water. Additionally, similar growth was visible in the MH 14 discharge weir, growing on the weir plate (Figures 5 and 6). Weep drains also revealed evidence of microbial growth, with the occurrence of dark tan, black, and white biofilm. Aside from the visual observation of biofilm, the chemical data indicates that several microbial processes are effecting the chemical reactions that contribute to the sediments in the drain system.

Figure 5. Manhole 14 (Above)
Sump heavily populated by filamentous biofilm.

Figure 6. Manhole 14 weir (Right)
Biofilm evident in weir and downstream.

Field vs. lab physical parameters:

The general water chemistry analyses revealed suitable conditions for long-term microbial growth, that is, a neutral pH, with abundant dissolved oxygen, total organic carbon, nitrogen, and phosphorus available for metabolic processes. Conductivity (μS) and pH measurements taken in the field and again in the lab differ, conductivity going up in the lab and pH dropping (Figure 7). Both instrumentation differences and microbial activity within the samples may account for these variations.

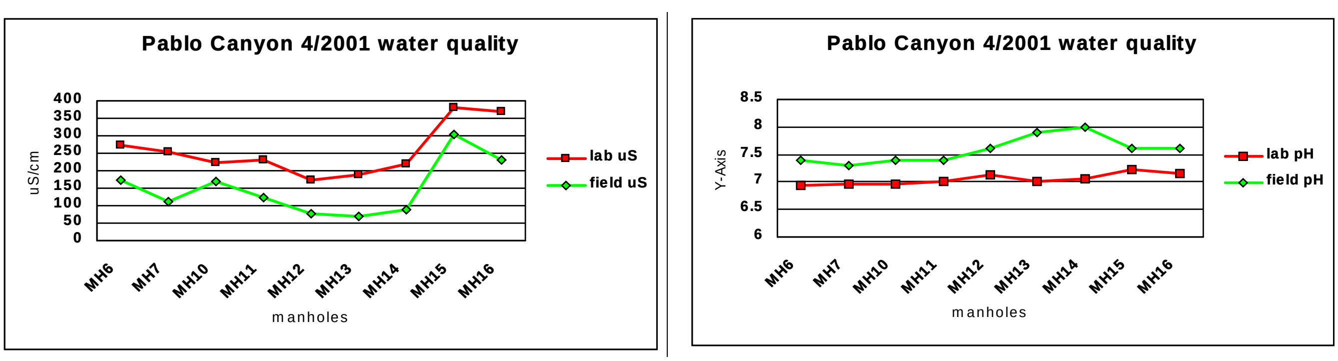

Figure 7. Graphs of Field and Laboratory Conductivity and pH Measurements

The redox measurement in the field reported as bulk mVs, was adjusted to Eh (in reference to H+) and plotted vs. pH. The Eh is generally in the range of $Fe(OH)_3$ deposition (Hem, 1985). The Fe^{3+} (total Fe - Fe^{2+}) was 66-99 % of total Fe in samples evaluated, indicating ample Fe^{3+}

availability for deposition. Additionally, the presence of Mn-containing deposits suggests that microbial deposition of MnIV oxides is occurring, as Eh-pH values are outside the range of autooxidation of Mn oxide deposition and Mn^{2+} was the predominant Mn form in water samples except in MH-7 and MH-16.

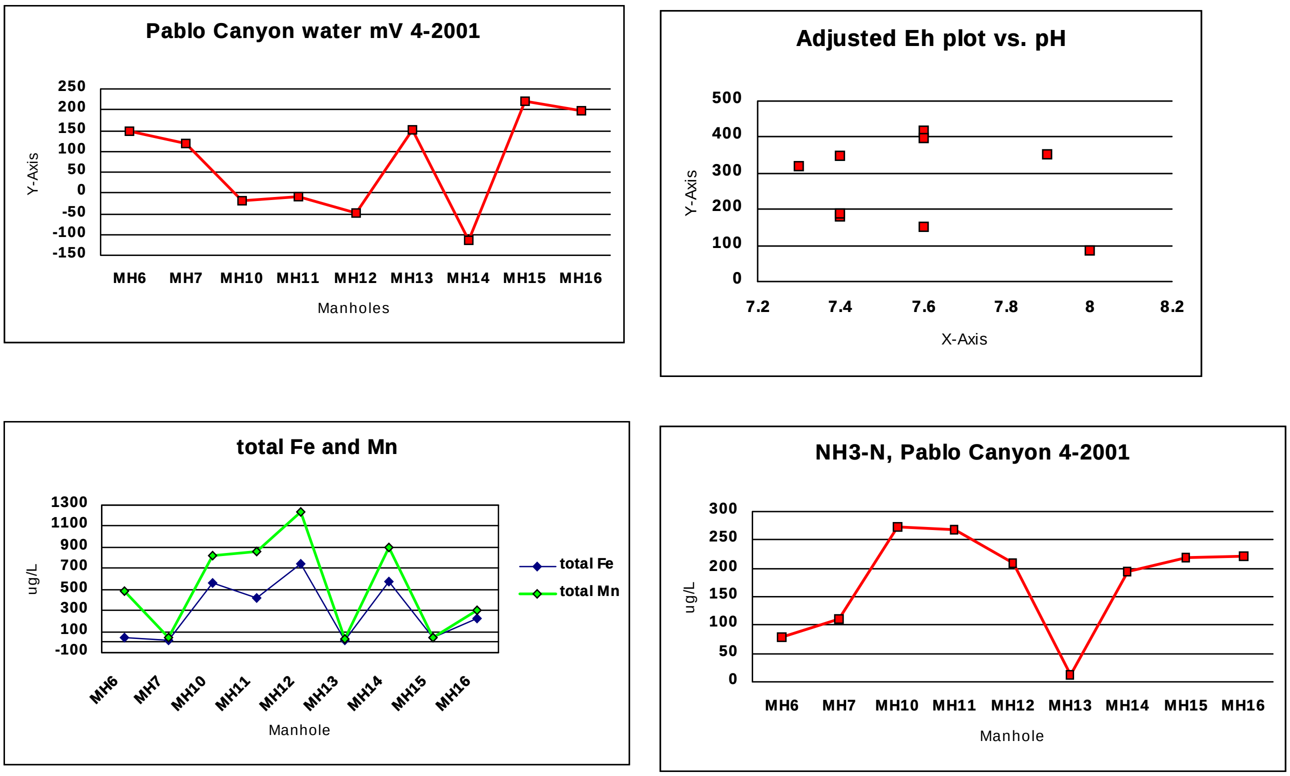

Figure 8. Graphs of Field and Laboratory Parameters

There were other indicators of the influence of microbial activity on the drain system and they included:

- High concentrations of Fe and Mn generally occurred in samples from locations with low mV readings in water (see graph). This is possibly due to Fe and Mn reduction, as there does not seem to be any lack of Fe and Mn oxide deposition.
- All samples except MH 15 basin had Mn values greater than Fe values, indicating active Mn reduction is occurring.
- High Fe and Mn also appear to match up to higher NH_3-N levels.
- NH_3-N parallels with lower mV values and reactivity rate (see chart, with MH 10, MH 11, and MH 14 NH_3-N elevated).
- MH 14 water (all three clear water samples), which exhibited extensive biofouling had among the lowest in organic P, evidence of microbial uptake of P.
- Among solids, ICP/ES indicated that Mn was greater than Fe in seep biofouling solids samples, the reverse of manhole solids. This suggests variety in microbial deposition.

BART analysis:

BART cultures demonstrated positive results for Iron Related Bacteria (IRB), Slime Forming Bacteria (SLYM), and to a lesser extent Sulfate Reducing Bacteria (SRB). The number of days until the appearance of bacterial growth listed in Table 1. Details of the BART culture results may be found in the Appendix 2: Field Notes and 3: BART Photographs. Based upon the days until appearance or days of delay before cultures appear, the populations or colony forming units per milliliter may be estimated using Table 2.

Table 1. BART Reactions

Sample	BART Type and Days to Reaction				
Location	IRB 1*	IRB 2	Slym	SRB 1	SRB 2
MH 6	3**	4	4	4	0
MH 7	3	4	4	4	0
MH 10	3	4	4	0	0
MH 11	3	4	4	3	0
MH 12	3	4	6	4	0
MH 13	4	5	2	0	0
MH 14	6	8	8	5	0
MH 15	4	5	3	4	6
MH 16	5	7	3	2	5
Seep 1	1	3	2	0	0
Seep 2	2	3	2	1	1
Seep 3	1	4	2	1	0
Seep 4	1	1	2	4	0

* IRB = iron related bacteria, Slym = slime-forming bacteria, SRB = sulfate-reducing bacteria. IRB 1 is the first IRB reaction and IRB 2 the second observed, same with SRB. SRB 1 was usually BT (blackening at top).

** These are days until a reaction occurred (days of delay or time lag) after inoculation. A '0' indicates no reaction.

Table 2. Relationship between DD and log CFU/ml for BART used (DBI, 1999)

Time lag (DD)	IRB	SRB	SLYM
0.5	6.6	6.6	6.8
1.0	6.0	6.0	6.6
1.5	5.8	5.8	5.8
2.0	5.0	5.0	5.6
3.0	4.0	4.6	4.6
4.0	3.6	4.0	3.0
5.0	3.0	3.6	2.6
6.0	2.0	3.0	2.0
7.0	2.0	2.0	1.0
8.0	2.0	2.0	1.0

DD are expressed as days until a reaction occurs. The CFU/ml conversions are expressed as log CFU/ml. Thus, for a culture in an IRB-BART tube (results vary among types), DD 2 = 10^5 CFU.

The IRB reaction types tended to be those of anaerobic or facultatively anaerobic heterotrophs. Heterotrophic bacteria are present at $10^{3.5\text{-}4.0}$ CFU/ml (less in some) in water samples tested (IRB-BART and SLYM-BART), and sulfate-reducing bacteria (SRB) at $10^{4\text{-}4.6}$ (when present). Days of delay are converted to cells per milliliter values using the relationship Table 2.

Light Microscopy

Filamentous bacteria in the light tan toe drain biofilms were colorless (lacking Mn or Fe staining) and had abundant, irregularly separated small cells in sheaths lacking partitions. These were identified as Thiothrix on this basis. Leptothrix (iron-stained and incrusted) were identified in MH 14. Crenothrix polyspora, typically not iron encrusting, and having large cylindrical cells, was also present in MH 14.

Table 3. Light microscopy observational results are as follows for samples with identifiable structures:

MH 10	*Thiothrix* (fine, thin nonmotile light-colored filaments with minor inclusions)
MH 12	*Thiothrix, Leptothrix ochracea, Sphaerotilus, and* occasional ciliates
MH 13	*Thiothrix*, probably *Leptothrix* or *Sphaerotilus*
MH 14	*Thiothrix*, Fe-encrusted *Leptothrix* or *Sphaerotilus*, *Crenothrix polyspora* (wall), cyanobacteria, abundant ciliates
S-2 weep	*Leptothrix ochracea*, Mn oxides (buserite), *Thiothrix*, abundant ciliates
S-2 weep wall	Flocular Mn oxide particles
S-3	similar to S-2

Eleanora Robbins, Ph.D., United States Geological Survey, May 25, 2001

Scanning Electron Microscopy (SEM) and Elemental Dispersive Scatter (EDS) Analysis

The SEM images are qualitative, but reinforce light microscopy observations and show finer detail, useful in interpreting future results. It is apparent that clogging by filaments and a variety of mineral deposits is to be expected. The SEM images and EDS graphs may be found in Appendix 4, and the results summarized in Table 4. While not quantitative, a significant number of elements found in the solid material are identified. Many deposits appear to be the expected Fe-Mn oxides, but much silicate material is present, some possibly deposited by microbial action, based on morphology.

Features of note from selected SEM images found in Appendix 4:

- 1-1 and 1-1s (and others): Thiothrix-type filaments
- 1-2: Typical larger magnification of filaments with inclusion
- 1-3, 3-7 Gallionella stalk also identified (not identified by light microscopy).
- 1-7, also 3-3 and others: Leptothrix-type filament fragments and amorphous solids, possibly Fe-Mn oxihydroxides
- 3-4: Good view of incrusted filament fragment
- 4-1: Typical of deposits in MH 14 drain well
- 4-4: Includes highly degraded and incrusted fine filaments and 4-5 is typical of incrustation that started around filaments
- 6-4: Typical of Leptothrix ochracea associated Mn oxide deposits (buserite, low-order).
- 7-3 Has the appearance of a HMS *Titanic* style rusticle: deposit with passages.
- 8-1 and others: roughly spherical mineral deposits (probably buserite).

Table 4. SEM and EDS Analysis

Summary of SEM and EDS Analysis							
					Solids total metals (% of total mass)		
SEM images	source		EDS analysis		Fe	Mn	
1-6	MH 12	biofilm inclusion	1-6a	Al-Si-O-Fe			mineral: andalusite, sillimanite
1-2	MH 12	stalks	1-b	Fe-Mn-Ca-P-Si-Al-O			Fe-Mn oxides, biological with impurities
1-2	MH 12	fluff among stalks	1-c	Fe-Ca-P-Si-Al-O-C	31.11	0.689	Fe-Mn oxides, biological with impurities
1-7	MH 12	biofilm	1-d	Mn-Fe-Ca-P-Si-Al-O-C			Fe-Mn oxides, biological with impurities
2-4	MH 10	filaments with glob	2-4a	C-O-F-Al-Si-Ca			mineral (incl. fluorite)+polymer
2-4	MH 10	filaments (fine, smooth)	2-b	C-O-Al-Si-P-S-Ca-Fe			Fe and S oxides, biological with impurities
2-5	MH 10	globular mineral deposits	2-c	Al-Cl-O			mineral: weathered clay or biologically deposited Al
2-6	MH 10	filaments w/ amorph dep	2-d	Mn-O-Al-Si-Ca-Fe	16.3	1.01	Fe-Mn oxides, with impurities
3-2	MH 14	incrusted filaments from wall	3-a	Mn-Fe-Ca-P-Si-O-C	23.8	0.69	Fe-Mn oxides, biological with impurities
3-4	MH 14	amorph incl. among incrust filaments	3-b	Ca-Si-Fe-Mg-Al-O-C	20.5	1.08	calcite w/ impurities, poorly crystalline
3-5	MH 14	amorph incl. among incrust filaments	3-c	Fe-Ca-Si-Al-P-O-C	20.5	12.75	Fe oxides, biological with impurities
3-7	MH 14	filaments and twisted stalk	3-d	Fe-O-C-Al-Si-P-Ca-Cu			presumed incrusted Gallionella stalk
4-3	MH 14	from screen, highly incrusted	4-a	Si-O			silica
4-3	MH 14	stalk part of this feature	4-b	Fe-O-Mn-Si-Al-O-P-K-Ca			incrusted Gallionella stalk and filaments
4-5	MH 14	amorphous incrust from screen	4-c	Fe-Mn-Si-Ca-Al-P-O-C			Fe-Mn oxides, biological with impurities
4-7	MH 14	globular mineral deposits	4-d	Al-Cl-O			mineral: weathered clay or biologically deposited Al
5-3	MH 13	analysis of crystal	5-a	Si-Al-O-C-K-Mn-Fe			Al silicate with impurities, rhombohedral (andalusite, sillimanite)
5-5	MH 13	poorly crystalline deposit	5-b	Si-Al-Mg-K-O-Ca-Mn-Fe-Cu-C	2.02	3.82	Mineral deposition (garnet group of silicates)
5-5	MH 13	clump in deposit	5-c	Mg-Si-Al-O-K-Fe	4.76	4.51	More of same, less impurity
5-6	MH 13	large globular structure	5-d	Si-Al-O-K-Ca-Fe-C			weathered silicate
6-4	S-2	amorphous round deposits	6-a	Fe-Mn-Ca-Cl-S-P-Al-O-C			Fe-Mn oxides, biological with impurities
6-5	S-2	globular mineral deposits	6-b	Fe-Mn-Ca-Cl-S-P-Al-O			Fe-Mn oxides, with impurities
6-6	S-2	globular mineral deposits	6-c	Al-S-Cl-O			mineral: weathered clay or biologically deposited Al
6-6	S-2	crusty area in 6-6	6-d	Fe-Mn-Ca-Cl-S-P-Al-Si-O			Fe-Mn oxides, with impurities
7-1	S-2	globular mineral deposits	7-a	Al-Cl-O			mineral: weathered clay or biologically deposited Al
7-1	S-2	floc in the 7-1 image	7-b	Fe-Mn-Ca-K-Cl-Si-Al-Mg-Na-O-C			Fe-Mn oxides, biological with impurities
7-1	S-2	globular mineral deposits	7-c	Al-Cl-O-C-Ca-Mn			mineral: weathered clay or biologically deposited Al
7-1	S-2	floc in the 7-1 image	7-d	Mn-Ca-Cl-Si-Na-Mg-O			Mn oxides with impurities
8-2	S-3	stacked disk from image 8-2	8-a	Mn-Ca-Cl-Al-O			Muscovite or biotite with impurities
8-2	S-3	floc from image 8-2	8-b	Mn-Ca-Cl-S-Al-Na-O			Mn oxides (busarite?) with impurities
8-2	S-3	smooth blob in 8-2	8-c	Al-Cl-O			mineral: weathered clay or biologically deposited Al
8-3	S-3	floc and muscovite-type mineral	8-d	Al-Cl-S-O-Mn	15.4	25.8	Mn oxide mineral with impurities

Laura Tuhela-Reuning, Ph.D, and Stuart Smith, Smith-Comeskey Ground Water Science, June 2001.

IV. Conclusions & Recommendations

Conclusions

(1) Biofouling is widespread and significant problem in a variety of piped water systems, and documentation reveals that drain systems in dams are no exception. In the case of Pablo Dam, bacteria exist that left untreated are capable of clogging drain inlets, as described in other case histories (Bureau of Reclamation, 2001). Aside from the bacterial mass, significant deposits of metal oxides, carbonates and silicates are present in solids analyzed, indicating a "clogging synergism" between bacteria and minerals exists in the system.

(2) A wide range of microbial activity is identified indirectly by type of heterotrophic growth, identified micro flora or products. These activities contribute to the chemical environment by facilitating sulfate reduction, ammonification, Mn and Fe reduction and oxidation, and sulfide oxidation. These chemical reactions result in the precipitation and deposition of solid reactants.

(3) There is a strikingly wide range of deposited solids present, creating clear evidence of the complexity these environments generate. Physical and chemical data revealed differences among drain water quality associated with a variety of hydrochemical environments, with greater visibility of accumulated solids in the more saturated environments.

(4) Of the Analytical Activities Conducted:

- BART analysis has the benefit of being relatively simple to use and requires few facilities and may be employed as part of a systematic PM program.
- Onsite physical and chemical analysis (pH, Eh, conductivity) has the potential to be highly useful in PM monitoring and problem characterization.
- Laboratory analysis of major ion and metal suites can be used in reconnaissance and periodic evaluation at scheduled intervals.
- Light microscopy is a useful adjunct. With SEM having reinforced light microscopy results, site personnel may be trained to identify the various bacteria and mineral structures that are related to the depositions found in the drain system.
- The ICP/ES and EDS methods of characterizing solids metals/material content complemented one another and together, using data reported, permitted a reasonable conclusion to be drawn about materials present. ICP/ES provided quantitative results so that a mineral identification for solids can be made for bulk samples. Although EDS does not provide quantitative results, it permits "spot" identification of individual structures (individual crystals, etc.) so that the variety of materials present can be appreciated. This type of analysis can be done infrequently in the reconnaissance phase of problem identification in structures.

(5) Based upon the previously noted conclusions, it is clear that the clogging mechanisms are highly active and working to restrict the drain system at Pablo Dam. While it is not within the scope of this investigation to evaluate the hydraulic performance of the Pablo

Dam drainage system and its geotechnical engineering (this is being investigated separately by the Civil Engineering section of the TSC), experience shows that clogging of water systems and drains can and do occur under the biogeochemical conditions described. Significant clogging mechanisms based on the above-mentioned results are outlined as follows:

- Microbial Fe and Mn oxide deposition. The volume of deposition is typically increased where Mn and Fe reduction occurs in anaerobic zones, and the Fe^{2+} and Mn^{2+} are subsequently oxidized to their poorly soluble valence states. Mn-oxide formation was observed.
- Where denitrification occurs (ammonia formation), Fe^{2+} and Mn^{2+} may serve as electron acceptors and be oxidized.
- Clogging of drains and weeps by filamentous biofilms, both metal (*Leptothrix* and *Gallionella*) and sulfur-depositing (*Thiothrix*). White sulfur deposition was observed in seeps and *Thiothrix* in toe drain outlets.
- Mineral deposition, including possible microbial aluminum silicate deposition, adds to intergranular clogging around drain and seep openings.

Recommendations

(1) Upon review of the draft *Drainage for Dams and Associated Structures*, we did not note mention of the Army Corps of Engineers' extensive study of methods to clean drainage wells and toe drains of biological fouling.

Action Item: It is recommended that the study team assist the *Drainage for Dams and Associated Structures* editorial team in integrating this parallel body of work.

(2) Further investigations of drain water quality and system performance are recommended over time to provide a more complete picture than is possible from one limited investigation. This can be conducted on site by the following activities:

- Analyzing for physical properties (pH, Eh, conductivity, temperature); and
- Conducting BART bioanalysis (SRB, IRB, SLYM, and adding DN), supplemented by culturing for Mn-precipitating and S-oxidizing micro flora.

Selected metals and ionic properties (including alkalinity) may be analyzed periodically either by formal laboratory analysis which may be supplemented by field-laboratory analysis.

Action Item: It is recommended that a PM investigation program be developed to included monitoring of these parameters both in the field and laboratory with a protocol that makes sense for drain system performance evaluation.

(3) Understanding the ecosystem is vital to the development of treatment systems. In order to study how the microbial ecology of the drainage system operates, experience shows that designing a model system, which mimics the natural system allows for exploration and development of control and cleaning systems without negative impact to the system

itself. An important aspect of decisions about cleaning protocols at Pablo Dam is the potential impact on downstream tribally managed wetlands. Biotoxicity is best studied in a model system in the early phases.

Action Item: It is recommended that the ISTM study team design, develop and test control and cleaning methods on a model system to determine the optimal treatments programs for PM.

(4) We recommend close collaboration with the ongoing geotechnical monitoring to assist in (a) explaining any changes in pressure within the structure and (b) making modifications that would reduce the impact of biological activity on the drainage system's performance. One such recommendation to increase the number of drainage wells to alter the growth environment for the microbes while reducing the impact of clogging at any one point.

Action Item: It is recommended that a list of specific environmental cultural controls developed by the ISTM and Smith-Comeskey team in cooperation with the USBR Geochemical Engineering Team. This list of mechanical control activities should be submitted for consideration in the long-term PM.

(5) Drawing from case history experience and the model study parallel to it, a mild cleaning program demonstrated to be nontoxic to aquatic life downstream of the weirs in conjunction with promising physical cleaning tools can be tested and level of effectiveness determined at the site.

Action Item: Using preliminary model results, it is recommended that some pilot drain and weep cleaning programs be implemented at the site. The initial program would start with MH 14 and a second impacted system, such as MH 13 or MH 10 to demonstrate program efficacy in differing geochemical environments.

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Appendices