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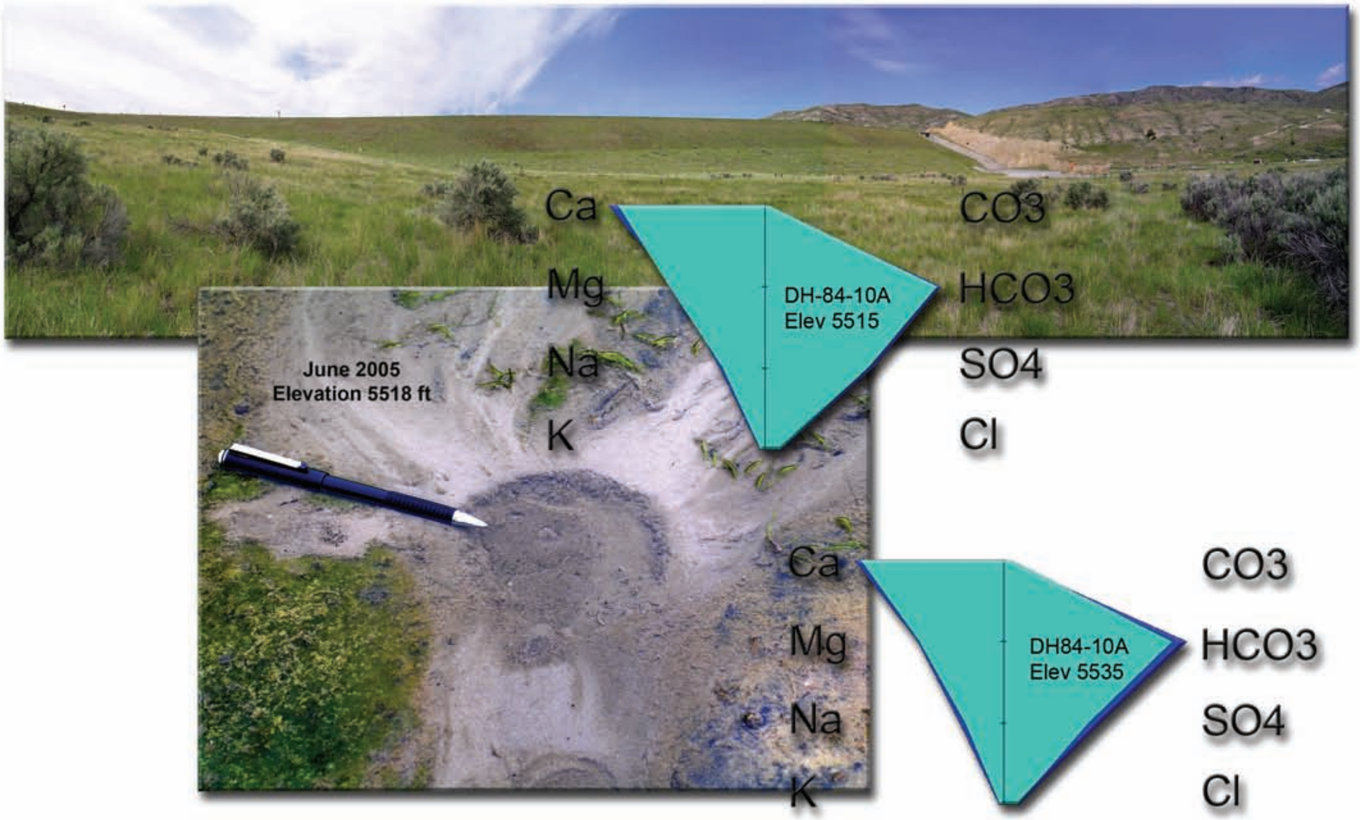
Technical Memorandum 86-6829010

Seepage Geochemistry and Mineral Dissolution at Clark Canyon Dam, Pick-Sloan Missouri Basin Project, East Bench Unit, Montana



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This report summarizes an evaluation of soluble mineral dissolution in the foundation, abutments, and embankment of Clark Canyon Dam, Montana, USA. Seepage and reservoir samples were collected in October 2005 (reservoir elevation 5,515 ft. - 1,681 m), and in May 2006 (reservoir elevation 5,535 ft. - 1,687 m), to represent seepage conditions at low and high reservoir surface elevations. Mineral dissolution was evaluated by comparing the chemistry of the reservoir and seepage samples from wells, toe drains, and surface seeps. Mineral saturation indices for reservoir and seepage water were calculated using the PHREEQE chemical equilibrium model. Void formation rates were estimated for soluble minerals using concentration difference data for the toe drain outlets and other measured seeps. The results of this assessment suggest that dissolution of calcite, gypsum or anhydrite, and amorphous silica is an active process at Clark Canyon Dam at both low and high reservoir elevations. The greatest seepage volumes and void formation rates appear to follow the old Beaverhead River channel that lies beneath the central section of the dam. The void formation rates suggest that seepage flow will increase over time and future monitoring of mineral dissolution would be best accomplished by enhanced frequency and accuracy of seepage flow measurements and water levels in piezometer wells.

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Denver, Colorado

October 2006

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DISCLAIMER

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EXECUTIVE SUMMARY

This report summarizes an assessment of potential dissolution and void formation associated with gypsum, anhydrite, calcite, dolomite, and amorphous silica in the embankment, foundation, and abutments of Clark Canyon Dam, East Bench Unit, Pick-Sloan Missouri Basin Project, Dillon, Montana. This study was performed as a consequence of the 2003 Comprehensive Facility Review (CFR) (Major, 2003) performed for Clark Canyon Dam.

Seepage and reservoir samples were collected in October 2005 (reservoir elevation 5,515 ft. - 1,681 m), and in May 2006 (reservoir elevation 5,535 ft. - 1,687 m), to represent seepage conditions at low and high reservoir surface elevations. Because of recent drought in southwestern Montana, however, the high reservoir elevation in this study was around 25 ft below the 1984 maximum reservoir surface elevation.

Mineral dissolution was evaluated by comparing the chemistry of the reservoir with seepage samples from wells, toe drains, and surface seeps. Data were evaluated following Reclamation methods (Craft, 2006) using comparative Stiff diagrams (Stiff, 1951), calculation of mineral saturation indices (SI's) using the PHREEQE chemical equilibrium model (Parkhurst, et al., 1980), and assessment of mineral dissolution using chemical concentration differences between reservoir and seepage and the application of a simplified mass balance model (Drever, 1988). The results of this assessment can be summarized as follows:

1. **Mineral Dissolution:** Mineral dissolution is an ongoing active process at Clark Canyon Dam. Most seepage is very similar to reservoir water, but slight increases in all seepage concentrations relative to the reservoir suggest that calcite, gypsum or anhydrite, and amorphous silica continue to be dissolved as reservoir water seeps beneath and through the embankment. The chemical evidence for mineral dissolution is corroborated by identification of massive to particulate deposits of limestone (calcite) in geologic drill logs (Calcagno, Jr., 1985) and recent petrographic detection of chert, opal, and calcite particles in suspended particles in seepage samples and boil area materials (Hurcomb, 2005; 2006).

2. **Reservoir Water:** Saturation indices calculated for the reservoir and outlet works samples suggest that the reservoir water is more aggressive towards calcite during spring runoff and associated higher reservoir elevations. The reservoir water is undersaturated with respect to gypsum, anhydrite, and amorphous silica during both low and higher reservoir elevations.

3. **Foundation Seepage:** The similarity of both Left and Right Side Well concentrations to reservoir suggests that seepage flows throughout the year in the upper 30 - 50 ft (9 -15 m) of the foundation at both low and high reservoir elevations. These flowpaths are through the Madison/Lodgepole Limestone Formation, the Alluvium, and the Beaverhead Conglomerate. The similarity in chemistry suggests that the foundation is fairly permeable, especially in the

upper 30 ft of Alluvium associated with the old river channel, and that seepage transit residence times are short - on the order of days to weeks. The chemistry conclusions are supported by observed flows in the boil area downstream of the toe drain outlets during both low and high reservoir elevations.

4. **Flow near the Foundation-Embankment Interface:** The toe drain chemistry suggests that foundation seepage flows are greatest beneath the right center of the embankment along the path of the old Beaverhead River channel. The Left Toe Drain samples suggest possible gypsum dissolution in the embankment below the phreatic surface, or in the left side foundation along the embankment-foundation contact.

5. **Seepage Transport of Solids:** Suspended sediments were observed in several well and manhole samples, suggesting possible transport of fine sediments through the Alluvium, the Madison/Lodgepole, and Beaverhead Formations, and possibly the embankment. While suspended sediments can be a consequence of disturbing soil or other solid materials when collecting samples from some surface seeps and the Boil Area, in wells and manholes, suspended sediments should be presumed to represent possible transport of fine particulates through the embankment or foundation. This fine material transport will contribute to void formation and increased permeability along seepage flow paths, and will add to voids caused by mineral dissolution.

   Fine sediments containing clays and clay-sized mineral grains were found in the toe drain manhole LT 3+69, suggesting that the toe drains are collecting sediments transported by seepage. We do not know the quantity of this accumulation, or how it may vary with reservoir elevation. Sediment in-filling of toe drains was a problem noted in the early 1980's that prompted replacement of the toe drains. We still do not know with certainty whether these sediments are from the foundation Alluvium, or from the embankment below the phreatic surface. Either scenario suggests possible long-term clogging of toe drains and justifies continuing inspection and assessment of this problem.

   Sediments may also be transported through the deeper foundation materials as suggested by Left and Right Side Wells intercepting seepage in the Madison/Lodgepole and Beaverhead Formations. Suspended sediments containing clay minerals were found in left side well DH84-10A, and right side wells DH-140, and DH-84-5. DH-140 samples at both low and high reservoir elevations contained suspended materials.

6. **Mass Wasting and Void Formation Rates:** Mass wasting and void formation rates from mineral dissolution were estimated for the toe drain outlets and the surface seeps (tables 5b and 6b). The greatest uncertainty about these estimates is our knowledge of accurate seepage flows. An unknown volume of seepage is upwelling in the old river channel at both high and low reservoir elevations, and the RT Seep surfacing in the Beaverhead outcrop near the toe drain outlets has no weir to measure flows. We also found evidence that the flow gages in the toe drain weirs are not accurate. Given the uncertainty of seepage flow paths at

Clark Canyon Dam, the void formation estimates suggest caution, but not alarm, with respect to mineral dissolution.

Results from this study suggest the following recommendations:

1. **No Additional Chemical Testing... Unless:** Further sampling and analysis of reservoir and seepage samples is not recommended unless reservoir elevations reach historic maximum levels, or unless seepage patterns or instrument readings suggest a progressive worsening of seepage or potential structural impairment.

2. **Enhance Physical Monitoring:** The primary mode for assessing progression of mineral dissolution should continue the monitoring of seepage flows, piezometer levels, and other instrument readings - especially at higher reservoir surface elevations. Because mineral dissolution and sediment transport are ongoing phenomena at Clark Canyon Dam, and foundation permeability and seepage will increase over time, it is very important to ensure that all seepage flows are quantified accurately at suitable intervals, and that piezometer levels are likewise monitored.

3. **Pay Attention to Flows along the Dam Center:** Because of the potentially large volume of seepage flowing along the old Beaverhead River channel beneath the embankment, the central section of the embankment should be more closely monitored during spring runoff (reservoir surface elevation > 5,530 ft - 1,686 m), and especially when reservoir surface elevations exceed 5,540 ft (1,689 m).

4. **Suggested Action Items:** The Dam Safety Office and the Montana Area Office should consider the following actions:

    4.1 Calibrate all height gages in current weirs to ensure that all flows are accurately measured.

    4.2 Install a calibrated permanent weir at the RT Seep station and consistently monitor seepage flows. Install traps to monitor fine sediment transport.

    4.3 Install some means of measuring - or experimentally determining - the total seepage volume flowing through the old river channel sand boil area. This is a critical piece of missing information.

    4.4 Install at least two recording piezometers in the central downstream section of the embankment over the old river channel. One piezometer should intercept the foundation alluvium below the embankment, the other should intercept a structurally appropriate zone in the bedrock. Further assessment of piezometric gradients and the geology should establish whether the seepage is flowing primarily through the Alluvium.

4.5 Consider establishing a tiered monitoring schedule that increases frequency of surface seepage flow measurements, piezometer water levels, and sediment accumulation in the toe drains during spring runoff and maximum reservoir elevations. Establish an instrument calibration check process prior to spring runoff to assure accurate readings and personnel familiarity at all required monitoring stations.

4.6 Better information concerning seepage flow paths and seepage contact volumes (the volume of foundation, abutment, ot embankment materials exposed to seepage water along a given seepage flow path) would produce more accurate assessments of the engineering consequences of mineral dissolution. This effort should include a detailed geologic fracture and joint assessment along suspected flow paths, geophysical testing to identify flowpaths, perhaps followed up with dye tracing tests.

INTRODUCTION

Dam Safety and the Bureau of Reclamation

Established in 1902, the Bureau of Reclamation (Reclamation) is a federal water resource management and development agency that operates in the 17 Western States under the Department of the Interior (DOI). Reclamation constructed and is responsible for management of 348 storage reservoirs impounded by 471 dams and dikes (Reclamation, 2005a), that provide water for agricultural, residential, municipal and industrial uses to more than 31 million people in the arid west. Irrigation water is provided by Reclamation to 140,000 Western farmers tilling 10 million acres of farmland that produce 60 percent of the nation's vegetables and 25 percent of its fruits and nuts. Reclamation also operates 58 hydroelectric powerplants with annual average power generation of 42 billion kilowatt-hours (DOI, 2005).

Because of the potential threat to the public posed by dam failures, Reclamation's Dam Safety Program was officially implemented in 1978 with passage of the Reclamation Safety of Dams Act, Public Law 95-578. This act was amended in 1984 under Public Law 98-404. Program Development and administration of safety of dams activities is the responsibility of Reclamation's Dam Safety Office located in Denver, Colorado (Reclamation 2005b). Reclamation's dam safety activities are also coordinated under the National Dam Safety Program managed by Federal Emergency Management Agency (FEMA) (FEMA, 2005).

The Reclamation Dam Safety Office completed a Comprehensive Facility Review (CFR) for Clark Canyon Dam in 2003 (Major, 2003) as part of the Safety Evaluation of Existing Dams (SEED) program. The CFR risk analysis of failure modes from dissolution of limestone leading to foundation erosion resulted in Safety of Dams (SOD) recommendation 2003-SOD-A to develop and implement a water quality testing program for Clark Canyon Dam. This report summarizes a geochemical seepage chemistry evaluation performed at Clark Canyon Dam, Pick-Sloan Missouri Basin Project, East Bench Unit, Montana, during 2005 and 2006, to comply with 2003-SOD-A.

Mineral Dissolution and Dam Seepage Chemistry

Gypsum, anhydrite, calcite, dolomite, and a variety of other simple minerals are water-soluble and common to the geology of the western United States. Because these minerals are common, they are often found in the foundations and abutments of many Reclamation dams. It may seem odd that materials we think of as "rock" can actually dissolve in water, but it really does happen. Most caves and caverns in limestone were created when groundwater dissolved the mineral calcite ($CaCO_3$) and left behind void spaces (Davies, 1960; Thrailkill, 1968; Ford and Ewers, 1978).

In a dam, the impounded reservoir water is the source water that becomes seepage flowing around and beneath the dam, interacting with soluble minerals in the structural geology. When soluble minerals present in the foundation or abutments of dams are dissolved by seepage water, the void spaces that form can lead to greater permeability and flows along established flow paths, or the development of new seepage flow paths. If the seepage progresses, excessive flows may develop that lead to erosion, piping, and eventual structural failure. Increasing seepage volumes near embankments have often been associated with structural failure and downstream flooding (Cedergren, 1989; James and Lupton, 1978; James and Kirkpatrick, 1980; James, 1985; Maksimovich and Sergeev, 1983; Muckenthaler, 1988).

Seepage chemistry is a term used in this report that refers to the set of measured concentrations of chemical constituents in seepage water, usually known as the major ions. The major ions include positively charged ions (cations) calcium (Ca^{2+} or Ca, concentration expressed in milligrams per liter - mg/L), magnesium (Mg^{2+} or Mg, mg/L), sodium (Na^{+} or Na, mg/L), and Potassium (K^{+} or K, mg/L), and negatively charges ions (anions) carbonate (CO_3^{2-} or CO3, mg/L), bicarbonate (HCO_3^{-} or HCO3, mg/L), sulfate (SO_4^{2-} or SO4, mg/L), and chloride (Cl^{-} or Cl, mg/L). Other important chemical constituents and variables to compare include water temperature (˚C), pH (standard units, SU), electrical conductivity (EC, microsiemens per centimeter, µS/cm), and trace constituents silicon (as silica, SiO_2 or SiO2, mg/L), dissolved organic carbon (DOC, mg/L), iron (Fe, micrograms per liter, µg/L), manganese (Mn, µg/L), and aluminum (Al, µg/L). These measured constituents in seepage water (or seepage concentrations) can be compared to the chemistry of the reservoir water (the reservoir concentrations) to evaluate whether changes between the reservoir and seepage chemistry are caused by mineral dissolution (Craft, 2006).

Dissolution of minerals can contribute to seepage problems that require monitoring by water resource managers and engineers responsible for dam safety issues. When mineral dissolution is suspected at a dam, seepage water samples may be collected, analyzed and compared to reservoir water to help determine whether soluble minerals pose a structural safety problem. However, the evaluation of changes in seepage relative to reservoir is not simple because concentration increases may be the result of several concurrent processes that occur during seepage transit. These processes include mineral dissolution; mixing of seepage with a higher concentration local, pre-impoundment groundwater; delayed emergence of higher concentration reservoir water; or bacterial processes (Craft, 2006; Atlas and Bartha, 1998; Stumm and Morgan, 1996). A careful assessment of reliable seepage chemistry data is needed to distinguish causes for increased seepage concentrations.

Clark Canyon Dam: Clark Canyon Dam (figures 1a - 1c, and plan map in figure 2a) was constructed from 1961 to 1964 on the Beaverhead River in southwestern Montana around 20 miles (32 km) southwest of Dillon, Montana. The dam, with a structural height of 147 ft (44.8 m) and crest length of 2,950 ft (899 m) at crest elevation 5,578 ft (1,700 m), is a zoned earthfill structure that impounds a reservoir (Clark Canyon Reservoir - figure 1c) currently containing around 174,000 acre-ft (2.15×10^8 cubic meters - m^3) at elevation 5,546 ft (1,690 m). Median reservoir surface elevation is around 5,540 ft (1,689 m); with a historical average seasonal range of 5,531 - 5,547 ft. (1,686 - 1,691 m) (Horn and Kucera, 2005). During the past 6 years, however, an extended severe drought has reduced runoff and maximum reservoir elevations (Reclamation, 2005a; Major, 2003).

FIGURE 1A.— Aerial view of Clark Canyon Dam looking west. Official Reclamation photograph.

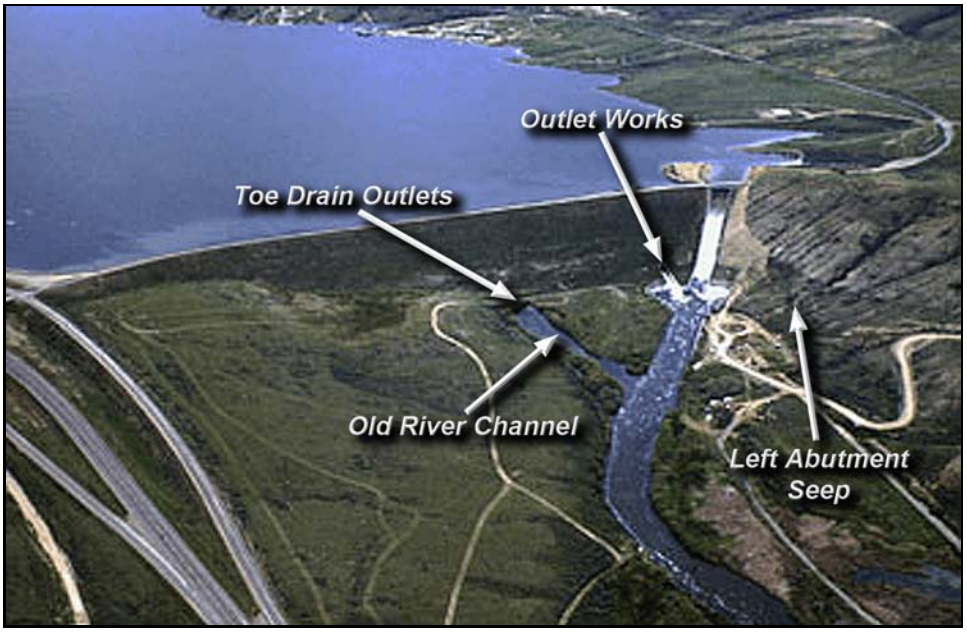
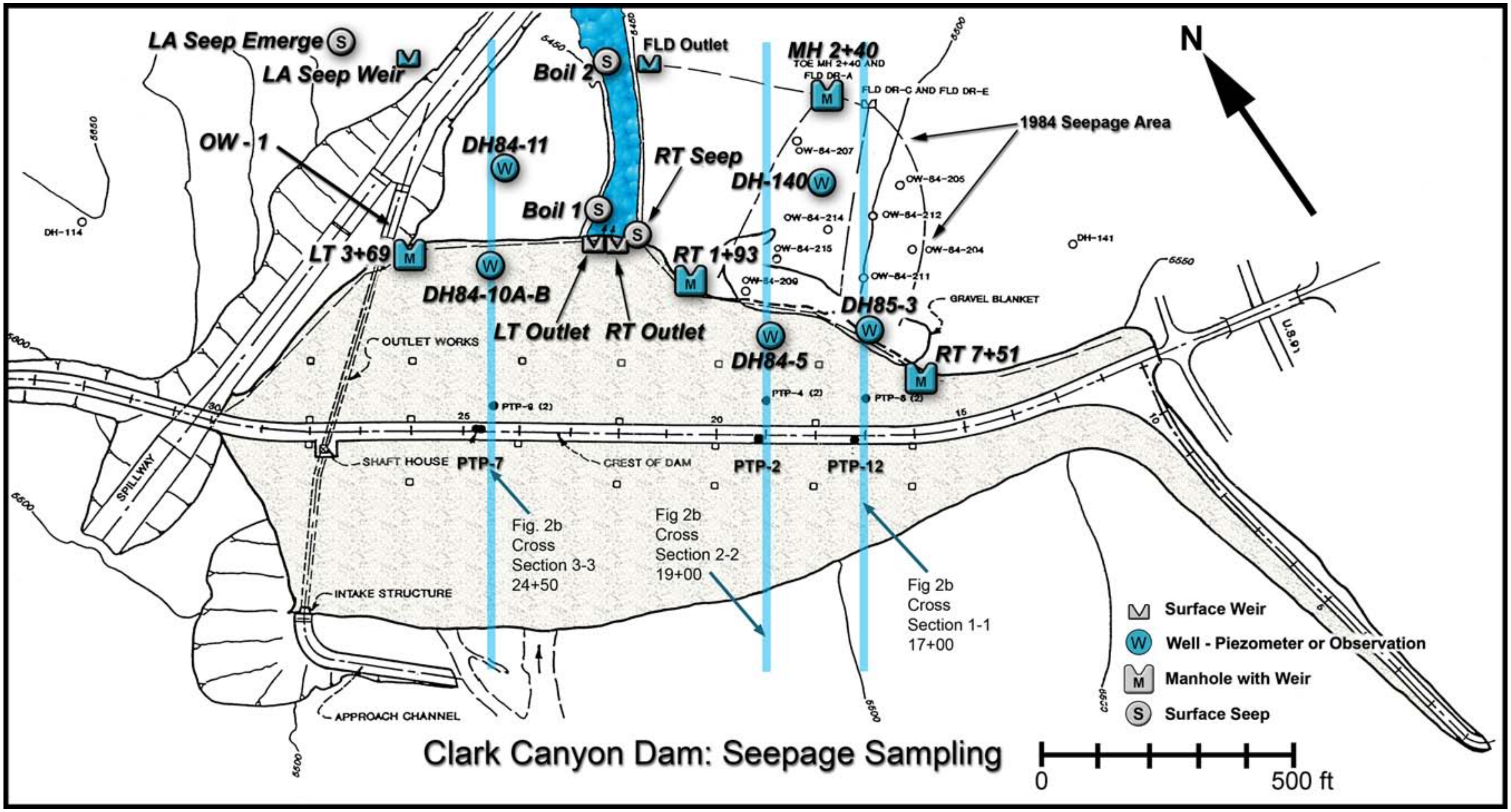


FIGURE 1B.— View looking west at the face and left abutment of Clark Canyon Dam. Reclamation photograph by Doug Craft.

FIGURE 1C.— View looking west of Clark Canyon Reservoir at surface elevation 5,518 ft. Reclamation photograph by Doug Craft.

FIGURE 2A.— Plan map of Clark Canyon Dam showing seepage sampling locations. The light blue lines perpendicular to the dam axis show the approximate locations of the geological cross sections of the dam seen in figure 2b.



In the wet years of the early 1980's, higher reservoir elevations produced increased seepage on the right abutment. This seepage and in-filling of soil materials observed in the original tile toe drain prompted replacement of the toe drain and installation of a new agricultural style drainage field below the dam to the right of the old Beaverhead River channel. Seepage samples were collected and analyzed in August 1986 to address the issue of potential mineral dissolution (Timblin, 1987). Since the 1984-1985 repairs, seepage and toe drain performance has been acceptable; however, maximum reservoir elevations have not approached the June 1984 maximum of 5,564.7 ft. (1,696.1 m) (Major, 2003).

Geology at Clark Canyon Dam: All the foundation geology at Clark Canyon Dam contains soluble minerals; however, the deposits vary in origin and lithology from the left abutment across to the right abutment. Figure 2b contains 3 geological cross section drawings (Calcagno, Jr., 1985) of Clark Canyon Dam that show the subsurface geology across the face of the dam. The blue lines perpendicular to the dam axis in the figure 2a plan map show the approximate locations of these cross sections.

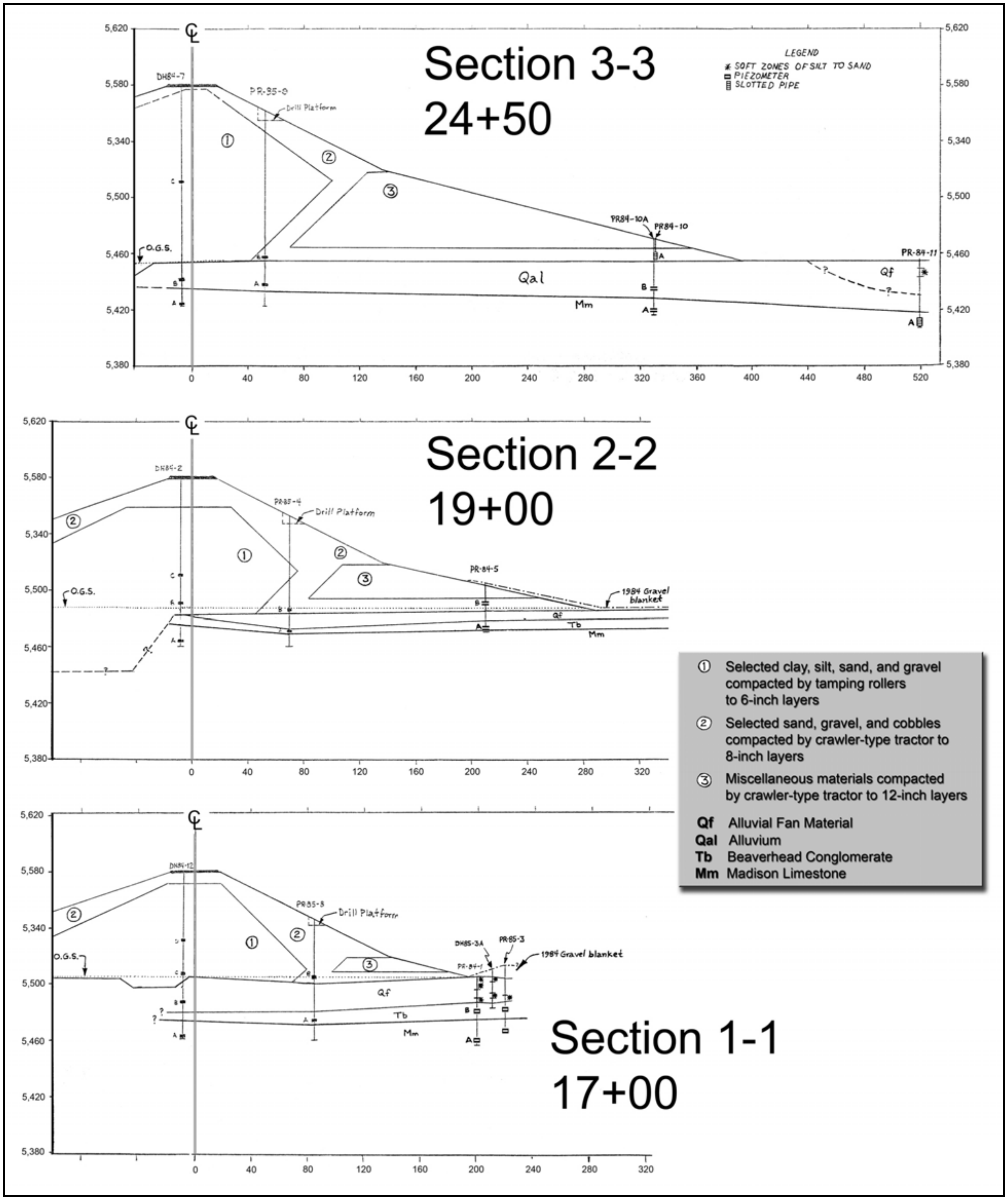
The steep left abutment is composed of fractured and jointed Lodgepole Limestone Formation of the Mississippian-age Madison Group, and the spillway and outlet works are founded in the Lodgepole Limestone. The Lodgepole Limestone is a gray, thin to medium bedded fossiliferous strata containing calcite, dolomite, and localized chert. Preconstruction drill core logs indicated evidence of dissolution voids (Major, 2003; Elliot, 1959; Calcagno, Jr., 1985).

Moving from the left abutment, the central section of the dam foundation is composed of fairly permeable Holocene Alluvium that overlays the Madison Group strata. The alluvium is composed of silty to clayey sands and finer gravels that are up to 30 ft (9.1 m) thick and contains moderate to significant amounts of gray limestone gravels. Drilling logs indicate strong reactions to hydrochloric acid in most depths of the alluvium, suggesting presence of soluble calcite (Reclamation, 1961).

On the right bank of the river channel and right abutment, the Tertiary-age Beaverhead Formation appears beneath the Alluvium and above the horizontal Madison Formation. The Beaverhead Formation is a compacted heterogeneous conglomerate composed primarily of weakly cemented limestone gravel, slightly calcitic sands, and various non-plastic fines (Major, 2003; Reclamation, 1961). Drilling logs suggest that the Beaverhead conglomerate is crumbly and friable, and sands and gravels within non-plastic fines will likely disaggregate in flowing water (Calcagno, Jr., 1985).

Exact seepage flow paths and fracture and joint patterns are not currently known at Clark Canyon Dam. Because of this lack of knowledge, interpretation of void formation rates from mineral dissolution must rest on crude estimates of seepage paths and seepage contact volumes along flow paths in the foundation, abutments, and embankment.

FIGURE 2B.— Geologic cross sections of Clark Canyon Dam from the left side (top) to the right side (bottom), showing structural materials, the Alluvium, the Beaverhead Conglomerate, and the Madison/Lodgepole Limestone formations (Calcagno, Jr., 1985). Also shown are some of the piezometer and observation wells sampled in this study and the depth of the screen or piezometer.



METHODOLOGY

Selection of Sampling Sites and Sampling Events

Initial sample locations were selected after a site visit in June 2005 and subsequent research of drilling logs and geologic cross sections (Calcagno, Jr., 1985) to identify wells and seeps associated with limestone formations and structural concerns identified in the CFR (Craft et al., 2005). These initially recommended sampling locations were modified based on practical feasibility after the initial low reservoir elevation sampling event on October 20, 2005 at reservoir surface elevation 5,515 ft (1,681 m) (Cain, 2005). After consultation with the Reclamation Montana Area Office, Great Plains Regional Office, and the Dam Safety Office, a decision was made in December 2005 to perform one additional sampling event to characterize higher reservoir levels when surface elevation next exceeded 5,530 ft (1,686 m), and the field *Schedule for Periodic Monitoring* document (L-23) was amended and distributed (Welch, 2006). Because of higher than expected (historically average) runoff in the Beaverhead River watershed during spring 2006, the high reservoir elevation samples were collected May 16-17, 2006 at reservoir elevation 5,535 ft (1,687 m) (Cain and Sullivan, 2006).

The plan map in figure 2a shows the locations selected for seepage sampling at Clark Canyon Dam, and figure 2b shows the geologic cross sections and the relative depths of the different strata at the site. Besides seepage samples collected recently, this evaluation also included samples from August 1986 (Timblin, 1987) to provide a historical comparison of changes in seepage chemistry concentrations for several stations sampled during all events. Table 1 summarizes the sampling stations and supplemental information for all 31 seepage and reservoir samples evaluated in this report.

Sample Collection and Quality Assurance Procedures

August 1986 Seepage samples were collected by personnel from the East Bench Irrigation District. Procedures followed for collection are not known, and no quality assurance (QA) duplicates, blanks, or other blind QA samples were submitted with seepage samples. October 2005 and May 2006 samples were collected by personnel from the Technical Service Center (TSC) and followed established consensus methods for well and surface water sampling published by the American Society for Testing and Materials (ASTM, 1992, 2003, 2004, 2005), the U.S. Environmental Protection Agency (USEPA, 1981, 1982), the U.S. Geological Survey (USGS, 1995), and Reclamation (Reclamation, 1981; Craft, 2006).

All wells were purged and allowed to refill prior to sample collection using either pumps or bailers, and pump tubing and bailers were rinsed between sampling stations using deionized water. Wells that could be pumped were purged and sampled using either a Geotech Model GEO-675SS18 bladder pump with GeoControl Pro Low Flow model sampler controller, or a 12-volt (DC) 1.5-in (outside dimension - O.D.) Geosquit centrifugal pump using 3/8-in (internal diameter - I.D.) tygon delivery tubing. Geotech Environmental Equipment reusable teflon 1.25-in O.D., and disposable polyethylene 0.75-in O.D. hand bailers were used for wells that could not be conveniently pumped.

Water temperature, EC, and pH were measured on site in seepage samples using instruments calibrated at the outset of each sampling day. Temperature and EC was measured using a Hach Model 44600-00 Conductivity-Temperature meter calibrated using Oakton Instruments 447- and 1413-µS /cm standard

TABLE 1.— Sample log for Clark Canyon Dam seepage chemistry. NS = not sampled, NA = not applicable, DS = downstream.

Sample ID	***Date Sampled***	***Time Sampled***	***Description - Other Names Used***	***Lithology***	***Location***	***Axis Offset***	***Distance from Axis, ft***
RESERVOIR							
RES-1	9/5/1986		Reservoir Surface	NA	Behind Dam - Right Abutment	16+00	-200
RES-1	10/20/2005	13:55	Reservoir Surface	NA	Behind Dam	29+00	-300
OW-1	10/20/2005	10:00	Reservoir Outlet Channel	NA	Left side reservoir outlet sampled in stilling basin on right bank	26+00	650
OW-1	5/17/2006	15:35	Reservoir Outlet Channel	NA	Left side reservoir outlet sampled in stilling basin on right bank	26+00	650
LEFT SIDE WELLS							
DH84-10A Red	10/20/2005	11:00	Well PTP-10A - Red Tube	Madison Limestone	Left Embankment 175 ft Right of LT 3+69	24+60	320
DH84-10A Red	5/16/2006	12:00	Well PTP-10A - Red Tube	Madison Limestone	Left Embankment 175 ft Right of LT 3+69	24+60	320
DH84-10B Green	5/16/2006	11:25	Well PTP-10B - Green Tube	Alluvium	Left Embankment 175 ft Right of LT 3+69	24+60	320
DH84-11	10/20/2005	13:00	Well SPP-11	Madison Limestone	Left Foundation b/t Outlet Works and Old Channel	24+70	510
DH84-11	5/17/2006	9:12	Well SPP-11	Madison Limestone	Left Foundation b/t Outlet Works and Old Channel	24+70	510
RIGHT SIDE WELLS							
DH84-5	5/17/2006	10:41	Well PTP-5	Madison-Beaverhead	Right Embankment US of Gravel Blanket	19+25	200
DH85-3 Red	10/20/2005	9:35	Well PTP-3 - Red Tube	Madison Limestone	Right Toe in Gravel Blanket	16+90	210
DH85-3 Red	5/17/2006	9:00	Well PTP-3 - Red Tube	Madison Limestone	Right Toe in Gravel Blanket	16+90	210
DH85-3B Green	5/17/2006	9:38	Well PTP-3	Beaverhead Conglomerate	Right Toe in Gravel Blanket	16+90	210
DH-140	10/20/2005	11:50	Well DH-140	Madison Limestone	Right Foundation in 1984 Seepage Zone	18+00	500
DH-140	5/17/2006	11:22	Well DH-140	Madison Limestone	Right Foundation in 1984 Seepage Zone	18+00	500
MH 2+40	9/5/1986		Manhole 2+40 DS of Right Side Drain Field	Alluvium - Beaverhead	Right Foundation DS of 1984 Seepage near Field Drain A	17+10	650
LEFT TOE DRAIN							
LT 3+69	5/17/2006	15:35	Manhole on Left Toe Drain	Dam Materials	Left Toe near Outlet Works	26+00	340
LT- Outlet	9/5/1986		Left Toe Drain + Weir	Dam Materials	Center Toe at Old River Channel	22+50	380
LT- Outlet	5/17/2006	14:06	Left Toe Drain + Weir	Dam Materials	Center Toe at Old River Channel	22+50	380
RIGHT TOE DRAIN							
RT- Outlet	9/5/1986		Right Toe Drain + Weir	Dam Materials	Center Toe at Old River Channel	22+40	380
RT- Outlet	5/17/2006	14:15	Right Toe Drain + Weir	Dam Materials	Center Toe at Old River Channel	22+40	380
RT 1+93	5/17/2006	15:55	Manhole Center Right Toe Drain	Dam Materials	Right Toe ~200 ft Right of RT Outlet	20+75	290
RT 7+51	NS	NS	Manhole Far Right Toe Drain (DRY)	Dam Materials	Right Toe 150 ft South of Well DH85-3	16+00	110
LEFT SIDE SEEPS							
LA Seep Emerge	5/16/2006	13:40	Seep - LT Access - Left Abutment @ Emergence	Madison Limestone	Left Abutment at DS Campground	30+00	740
LA Seep Weir	5/16/2006	13:19	Seep - LT Weir - Left Abutment @ Weir	Madison Limestone	Left Abutment at DS Campground	26+50	740
Boil 1	10/20/2005	9:20	Seep - Sand Boil Near Toe Drain Pipes	Alluvium - Beaverhead	Old River Channel Near LT-Outlet	22+60	500
Boil 1	5/17/2006	14:39	Seep - Sand Boil Near Toe Drain Pipes	Alluvium - Beaverhead	Old River Channel Near LT-Outlet	22+60	500
Boil 2	5/17/2006	15:10	Seep - Sand Boil Near River Confluence	Alluvium - Beaverhead	Old River Channel DS on Left Bank	22+50	650
GS-1	10/20/2005	13:00	Seep - Gordon Springs	Madison Limestone	Left Abutment DS	~21+00	4,700
GS-1	5/16/2006	14:19	Seep - Gordon Springs	Madison Limestone	Left Abutment DS	~21+00	4,700
RIGHT SIDE SEEPS							
RT-Seep	10/20/2005	9:00	Seep - Right of Toe Drain Outlet	Beaverhead	Along Old Channel Bank in Beaverhead	21+80	400
RT-Seep	5/17/2006	13:45	Seep - Right of Toe Drain Outlet	Beaverhead	Along Old Channel Bank in Beaverhead	21+80	400
FLD Outlet	NS	NS	Weir on Right Side Field Drain (DRY)	Alluvium - Beaverhead	On Old Channel Bank 350 ft DS of Toe	21+40	750

solutions. The Hach instrument temperature was checked against a separate laboratory thermometer (VWR Scientific). pH was measured using an Oakton Instruments Model pHTestr 2 meter calibrated using Oakton pH 4.0 and 7.0 buffer solutions prepared on site. Depth of water in wells was determined at the time of sampling using a Roctest Model CPR6 meter. All 2005 and 2006 field observations, calibration data, and measurements were recorded on Reclamation field data sheets archived with the sampling event travel reports (Cain, 2005; Cain and Sullivan, 2006). Low seepage flows in gallons per minute (gpm) were estimated by field crews based on experience, so flow measurements in this report must be considered qualitative. There is also reason to suspect that the scales located behind the V-notch outlet in weirs are not currently calibrated.

Samples were collected in certified clean, high-density polyethylene containers (500-mL wide mouth bottles, Eagle Picher, Inc.). Sample bottles were rinsed with sample prior to filling, and then labeled, sealed in zip-lock plastic bags, and placed on ice in picnic coolers prior to overnight shipping to the chemical analysis laboratory. Filtration and subsequent sample preservation was performed by the analysis laboratory to minimize field contamination. QA samples were collected and submitted with the 2005 and 2006 samples. QA blind samples included a field blank, a bailer rinseate blank, and 1 randomly selected duplicate sample.

Chemical Analysis Methods and Laboratory Quality Control

August 1986 samples were analyzed by the Reclamation Engineering and Research Center Chemistry Laboratory, Denver, Colorado (Timblin, 1987). At this time, the Denver Laboratory did not operate under a formal quality control (QC) plan. Analytical methods conformed with those established by the American Public Health Association's (APHA) *15th Edition Standard Methods*, (APHA, 1981). The 2005 and 2006 samples were analyzed by the Pacific Northwest Regional Water Quality Laboratory, Boise, Idaho. Samples were analyzed using consensus methods established by the USEPA (USEPA, 1983; 1986) and the APHA (APHA, 1998). The Boise Laboratory operates under a QC program consistent with standards established by the USEPA (USEPA, 1972), ASTM (ASTM, 2003), and the American National Standards Institute and the American Society for Quality Control (ANSI-ASQC, 1991). QC Reports for each batch of seepage samples were provided with analysis results. Samples for DOC, CO3, HCO3, Fe, Mn, Al, and Si as SiO_2 were filtered by lab personnel through a 0.45-µm pore-size polycarbonate membrane disk (Millipore or Gelman) prior to preservation and subsequent analysis.

Petrographic Examination and Analysis

After both October 2005 and May 2006 sampling events, seepage samples containing suspended particles were filtered through 0.45-µm polycarbonate filter disks, and the disks with retained solids were sent to the TSC Materials Engineering Laboratory for petrographic examination and mineralogical identification (Hurcomb, 2005; 2006).

These solid samples were examined microscopically using grain mounts, tested for effervescence (an indication of the presence of calcite) using hydrochloric acid (HCl), and analyzed using a Scientag XDS 2000 X-ray diffractometer (XRD) and a JEOL JSM-5400LV scanning electron microscope (SEM) with an X-ray fluorescence (XRF) microprobe.

Data Analysis Methods

Chemistry data were evaluated using the approach outlined in Reclamation's *Seepage Chemistry Manual* (Craft, 2006), involving use of Stiff diagrams (Stiff, 1951), calculation of mineral saturation indices (an indication of whether minerals are likely to dissolve in a given sample), difference data (calculated by subtracting same date reservoir concentrations from seepage concentrations), and a simplified mass balance model (Plummer and Back, 1980; Thurman, 1985; Hem, 1992; Drever, 1988) to evaluate mineral dissolution. Overall chemistry data quality was validated using cation-anion balance calculations (APHA, 1998). Mineral dissolution mass wasting and void volume formation rates were calculated using procedures described by Reclamation (Bartholomew and Murray, 1985; Craft, 2006).

Chemistry data were archived and evaluated using Microsoft® *Excel* 2002, version SP3, and Waterloo Hydrogeologic *AquaChem,* version 4.02. Excel was used for calculating ion balance percentages, difference data, and mass wasting rates. AquaChem was used to plot Stiff diagrams and Photoshop CS, version 8, was used to create comparative diagrams that superimposed the reservoir chemistry diagram over the seepage chemistry diagram, and to create figures comparing Stiff diagrams of seepage samples. The appendix provides a complete set of the 27 comparative Stiff diagrams for seepage samples.

Saturation indices (SI's) were calculated for carbonate-containing minerals (calcite, dolomite, magnesite), and sulfate minerals anhydrite and gypsum using the PHREEQE chemical equilibrium program (Parkhurst, et al.,1980) contained within the AquaChem program. The SI's were calculated with field measured temperature and pH. Trace elements (Al, Fe, Mn) reported below detection limits were re-coded as one-tenth the reported limit of detection for input into the PHREEQE model. Negative SI values suggest under saturation and that the water will tend to dissolve the mineral. Positive SI values suggest over saturation and that the mineral will tend to precipitate out of solution. SI values near 0 suggest that the mineral is in equilibrium with the seepage water, and that the particular mineral dissolution reaction may control the constituent ion concentrations in seepage.

Flow-weighted mass wasting and void volume formation rates: Flow-weighted mass wasting and estimated dissolution void volume rates were calculated for seepage outfalls with flow data using procedures described by Bartholomew and Murray (1985) and Craft (2006). The following assumptions were applied for calculating Clark Canyon Dam seepage mass wasting and void volume formation rates:

1. **Net change in seepage concentration:** For each analyzed constituent, same date reservoir or outlet works mg/L is subtracted from seepage mg/L to calculate net difference mg/L. Overall net difference was calculated by subtracting reservoir mg/L sum of ions from seepage mg/L sum of ions.

   $mg/L_{\text{seepage}} - mg/L_{\text{reservoir}} = mg/L_{\text{net}}$

   Sum of ions = $(Ca + Mg + Na + K + HCO_3^- + CO_3^{2-} + OH^- + SO_4^{2-} + Cl^-)$, mg/L

2. **Simplified geochemical model:** While the geology at Clark Canyon Dam is not uniform, several simplifying assumptions about dissolution reactions were used to calculate seepage mass wasting and dissolution void space formation rates. Mass wasting and void volume formation rates were assumed to be caused only by mineral dissolution of gypsum or anhydrite, calcite, and amorphous silica. This simplified model does not account for all the concentration difference data, and therefore is not based on stoichiometric mass balance where all concentration changes are fully resolved. It does, however, provide for a conservative estimate of mass wasting and void formation rates from mineral dissolution.

   All increases in SO_4^{2-} were assumed to be caused by gypsum or anhydrite dissolution. All increases in HCO_3^- were assumed to be caused by dissolution of calcite. All increases in SiO_2 were assumed to be caused by dissolution of amorphous silica. Gypsum is less dense than anhydrite, so void volume rate estimates calculated assuming gypsum will be higher than those assuming anhydrite. These two density assumptions provide a general range of void formation rates for soluble sulfate minerals.

3. **Specific assumptions:**

   a. Net loadings expressed as a mineral were calculated based on millimoles per liter (mmol/L) data, which were converted to mass using the following factors: Calcium = Ca = 40.078 mg/mmol, Sulfate = SO_4 = 96.0636 mg/mmol, Gypsum = $CaSO_4 \cdot 2H_2O$ = 172.1416 mg/mmol, Anhydrite = $CaSO_4$ = 136.1416 mg/mmol, Limestone (Calcite) = $CaCO_3$ = 100.0874 mg/mmol, Silica = SiO_2 = 60.0843 mg/mmol.

   b. The higher reported density values (Deer, et al., 1992) were used to calculate void volume formation rates: Gypsum = 2.30 to 2.37 g/cm^3, Anhydrite = 2.94 to 3.00 g/cm^3, Calcite = 2.72 to 2.94 g/cm^3, Silica = 2.62 to 2.65 g/cm^3.

   c. Conversion factors for units of flow and volume: 1 gpm = 3.7854 L/min = 5,451 L/d 1 ft^3 = 0.028317 m^3 = 28.317 L = 28,317 cm^3.

4. **Mass wasting calculation, g/day:**

   $(mg/L_{\text{net}}) \times$ (seepage flow, gal/min) × (1,440 min/day) × (3.7854 L/gal) × $(1.0 \times 10^{-3}$ g/mg)

5. **Void volume formation calculation, cm^3/day:**

cm^3/day = ((mineral loading, g/day) ÷ (mineral density, g/cm^3))

Precautions using Mineral Wasting and Void Volume Formation Rate Data: There are several important issues to consider before using or interpreting mass loading or void formation rate data. First, we do not clearly understand the distribution of joints and fractures in the foundation geology, or the locations, paths, and contact volumes of *any* specific seepage flows at Clark Canyon Dam. Assessment of the significance of mineral dissolution from seepage depends strongly on how well we understand flows and contact volumes associated with specific flows.

Because mass wasting and void formation rates are calculated for single events, it would be inappropriate to extrapolate any observed daily loading or void formation rates to annual or multi-year periods without accounting for the changes in seepage flow observed throughout the year. Seepage flow will vary throughout the year depending on the hydrostatic head at changing reservoir elevations and the flow path properties for a particular seep - which are currently not known.

Finally, a portion of the seepage increase in ions may be caused by biologically mediated processes (respiration and metabolism) and other unknown mineral weathering reactions and local mixing phenomena. Depending on seepage transit time, bacterial respiration can produce pH changes and some of the increases observed for HCO_3^- and CO_3^{2-} ions in seepage. Finally, incongruent mineral reactions where one mineral partially dissolves to release some ions and form another mineral, may account for a small portion of the net cations and SiO_2.

RESULTS AND DISCUSSION

As seen in the table 1 listing of samples, the seepage chemistry data will be presented and discussed according to the following groupings of samples:

- Reservoir: including surface samples collected from the reservoir behind the dam, and from the Outlet Works, OW-1
- Left Side Wells: including piezometer and observations wells DH84-10A, DH84-10B, and DH84-11
- Right Side Wells: including piezometer and observation wells DH85-3, DH85-3B, DH84-5, DH-140, and field drain manhole MH 2+40
- Left and Right Toe Drains: including manholes and toe drain outlets LT 3+69, LT-Outlet, RT-Outlet, and RT 1+93
- Left and Right Side Seeps: including surface flows from LA Seep Emerge, LA Seep Weir, Boil 1, Boil 2, GS-1, and RT Seep.

Reservoir Samples

In almost all dams, the reservoir is the source water for seepage near the structure. Table 2 summarizes the field measurements, the major ions concentrations, and SI's for soluble minerals for the reservoir and outlet works samples. Stiff diagrams for reservoir chemistry from the same sampling event are found on all figures summarizing seepage chemistry samples and also in the appendix. Additional information on the historical and recent chemistry and limnology of Clark Canyon Clark Canyon Reservoir has been summarized by Horn and Kucera (2005). Because the outlet works at Clark Canyon Dam draw water from the bottom of the reservoir, the OW-1 reservoir discharge samples are used when available as the reservoir sample most related to the source water for seepage. It is recommended that the outlet works be sampled in the future as the single reservoir source water for all seepage samples.

Clark Canyon Reservoir (figure 1c) is located on the confluence of Horse Prairie Creek and the Red Rock River, two tributary streams that join to form the Beaverhead River. Reservoir samples in this report show similar total dissolved solids (TDS, calculated here as sum of ions) ranging from 447 mg/L in August 1986, up to 527 mg/L in October 2005. For comparison, reservoirs that drain more pristine and higher elevation watersheds (for example, Horsetooth Reservoir, Ft. Collins, Colorado) usually range below 100 mg/L TDS. The major ions concentration proportions are also fairly consistent and similar, even over a 20-year period. The lowest concentrations were seen for the wet-year August 1986 reservoir sample. While the recent reservoir samples are very similar (527 mg/L TDS in October 2005 vs. 493 mg/L in May 2006), the low elevation October 2005 sample showed slightly elevated SO_4^{2-}, visible as a slight sag on the lower right side of the Stiff diagrams.

TABLE 2.— Field and chemistry data, and calculated mineral SI's for reservoir and outlet works samples from Clark Canyon Dam. The less-than sign (<) means "not detected" or "below the detection limit" indicated by the number value.

RESERVOIR				
Sample ID	***RES-1***	***RES-1***	***OW-1***	***OW-1***
Date Sampled	9/5/86	10/20/05	10/20/05	5/17/06
Time Sampled		13:55	10:00	15:35
Reservoir Surface Elevation, ft	5534.73	5514.78	5514.78	5535.02
Q - Flow, cfs				483
Field Temperature, °C		12.2	10.2	14.0
Field pH, SU		**7.60**	**7.70**	**7.00**
Lab pH	6.91	8.60	8.50	8.50
Field EC - Conductivity, µS/cm		**551**	**559**	**548**
Lab EC - Conductivity, µS/cm	545			591
Sum of Ions, mg/L	447	525	527	493
Ca - Calcium, mg/L	61.0	72.1	72.1	70.2
Mg - Magnesium, mg/L	23.9	28.2	28.6	25.2
Na - Sodium, mg/L	22.4	24.2	23.8	21.8
K - Potassium, mg/L	4.20	4.30	4.20	3.90
HCO3 - Bicarbonate, mg/L	241	257	259	253
CO3 - Carbonate, mg/L	0	5.27	3.35	5.75
SO4 - Sulfate, mg/L	82.0	121	122	100
Cl - Chloride, mg/L	12.8	13.9	13.8	12.4
Fe, Filtered Iron, µg/L		20	30	< 20
Mn, Filtered Manganese, µg/L		20	20	< 10
Al, Filtered Aluminum, µg/L		< 10	< 10	< 10
Silica, Filtered, as SiO2, mg/L		17.1	17.3	16.6
Dissolved Organic Carbon, DOC, mg/L		3.60	3.50	4.30
Al, Total Aluminum, µg/L				130
Fe, Total Iron, µg/L				40
Mn, Total Manganese, µg/L				20
Saturation Index - Anhydrite	-1.99	-1.79	-1.78	-1.87
Saturation Index - Gypsum	-1.76	-1.53	-1.52	-1.62
Saturation Index - Calcite	-0.483	0.181	0.246	-0.393
Saturation Index - Dolomite	-1.09	0.117	0.218	-1.049
Saturation Index - Quartz		0.631	0.668	0.591

The dominant reservoir cation is Ca, with lesser amounts of Mg and Na, and the dominant anion is HCO_3^- with lesser but still significant amounts of SO_4^{2-}, and minor but measurable Cl^-. Dissolved silica is also present in concentrations of 16 - 18 mg/L. Geochemically, these data are consistent with watershed-scale mineral dissolution of gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_4$, anhydrous), calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), marine salt deposits ($MgSO_4$, NaCl), and weathering of ferromagnesian chain silicates (inosilicates) such as pyroxene and amphibole, and amorphous silica as found in opal and chert (noted in the geology drill logs in the Madison formation) (Hem, 1992; Drever, 1988; Stumm and Morgan, 1994).

Mineral SI data (bottom rows of table 2) suggest that the reservoir water is always undersaturated with respect to gypsum and anhydrite. These minerals can be expected to dissolve in seepage under both low and high reservoir elevation conditions. Calcite and dolomite, however, appear more likely to dissolve in seepage when reservoir elevations are above 5,520 ft and reservoir TDS is 500 mg/L or lower. During low reservoir elevations when TDS > 500 mg/L, the reservoir water appears to be saturated with both calcite and dolomite.

Positive SI's in low elevation reservoir water, however, do not necessarily mean that calcite or dolomite will not be dissolved by lower elevation reservoir water. Bacterial activity during seepage transit can change the chemistry, notably lowering the pH and increasing acidity. The reservoir appears to have clearly detectable levels of DOC ranging from 3.5 to 4.3 mg/L. These results suggest that once the reservoir water permeates underground and becomes seepage, there is an adequate supply of carbon to fuel bacterial metabolism, depletion of dissolved oxygen, and the subsequent development of anaerobic, chemically reducing conditions. The following chemical equation (Drever, 1988; Thurman, 1985) for bacterial breakdown of DOC suggests that some increases in bicarbonate, and decreases in pH (an influential variable in calcite solubility) can occur during seepage transit making the water more aggressive to calcite and dolomite:

$$\begin{aligned}\overset{\textit{organic carbon}}{CH_{2.48}O_{1.04}N_{0.151}P_{0.0094}} + 1.3O_2 + H_2O \Longleftrightarrow\ & \overset{\textit{bicarbonate}}{HCO_3^-} + \overset{\textit{nitrate}}{0.151NO_3^-} + \overset{\textit{phosphate}}{0.0094HPO_4^{2-}} + \\ & 1.15H_2O + 1.17H^+\end{aligned}$$

Left and Right Side Wells

These wells are part of the network of porous tube piezometers installed through the embankment of Clark Canyon Dam, and have well screens located from 30 - 50 ft below the foundation that intercept seepage flowing through the Alluvium, the Beaverhead Conglomerate, and the Madison/Lodgepole Formation. These wells represent the deeper seepage flow paths beneath Clark Canyon Dam and are indicative of seepage interacting only with the foundation geology. Figures 3a – 3b show the Left Side Wells DH84-10A (figure 3a – the red tube with screen intercepting the Madison), DH84-10B (figure 3a right - the green tube with screen intercepting the Alluvium-Beaverhead), and DH84-11 (figure 3b – with screen intercepting the Madison Limestone). The comparative chemistry data are summarized using Stiff diagrams in figure 3c. Data and calculations are summarized in table 3a (field and major ions concentrations and SI's) and table 3b (concentration difference data). Figures 4a – 4c show the Right Side Wells, DH84-5 (figure 4a – with screen intercepting the Madison - Beaverhead contact) , DH-140 (figure 4b - with screen intercepting the Madison Limestone), DH84-3 (figure 4c - the red tube with screen in the Madison Limestone) and DH83-5B (figure 4c – the green tube with screen in the Beaverhead Conglomerate) are found in figures 4a – 4c, and the comparative chemistry data are summarized using Stiff diagrams in figure 4d. Data and

FIGURE 3A.— Left Side Well DH84-10A, located on the embankment. The left image shows Chuck Sullivan collecting the May 2006 sample while the right image shows the red and green 5/8-in piezometer tubes in DH84-10A. The red piezometer intercepts the Alluvium, while the green piezometer intercepts the Madison Formation. Reclamation photographs by Curtis Cain and Doug Craft.

FIGURE 3B.— Curtis Cain collecting the May 2006 sample from Left Side Well DH84-11, located downstream of the dam toe and in-between the outlet works stilling basin and the old Beaverhead River channel. Reclamation photograph by Chuck Sullivan.

FIGURE 3C.— Comparing the chemistry of the Left Side Wells at Clark Canyon Dam. These Stiff diagrams show the major ions concentrations for reservoir water (green polygons) superimposed over seepage water (darker blue polygons). The upper row of Stiff diagrams are from the low reservoir sampling in October 2005 (elevation 5,515 ft), while the lower row diagrams are from the high reservoir elevation sampling event in May 2006 (elevation 5,535 ft).

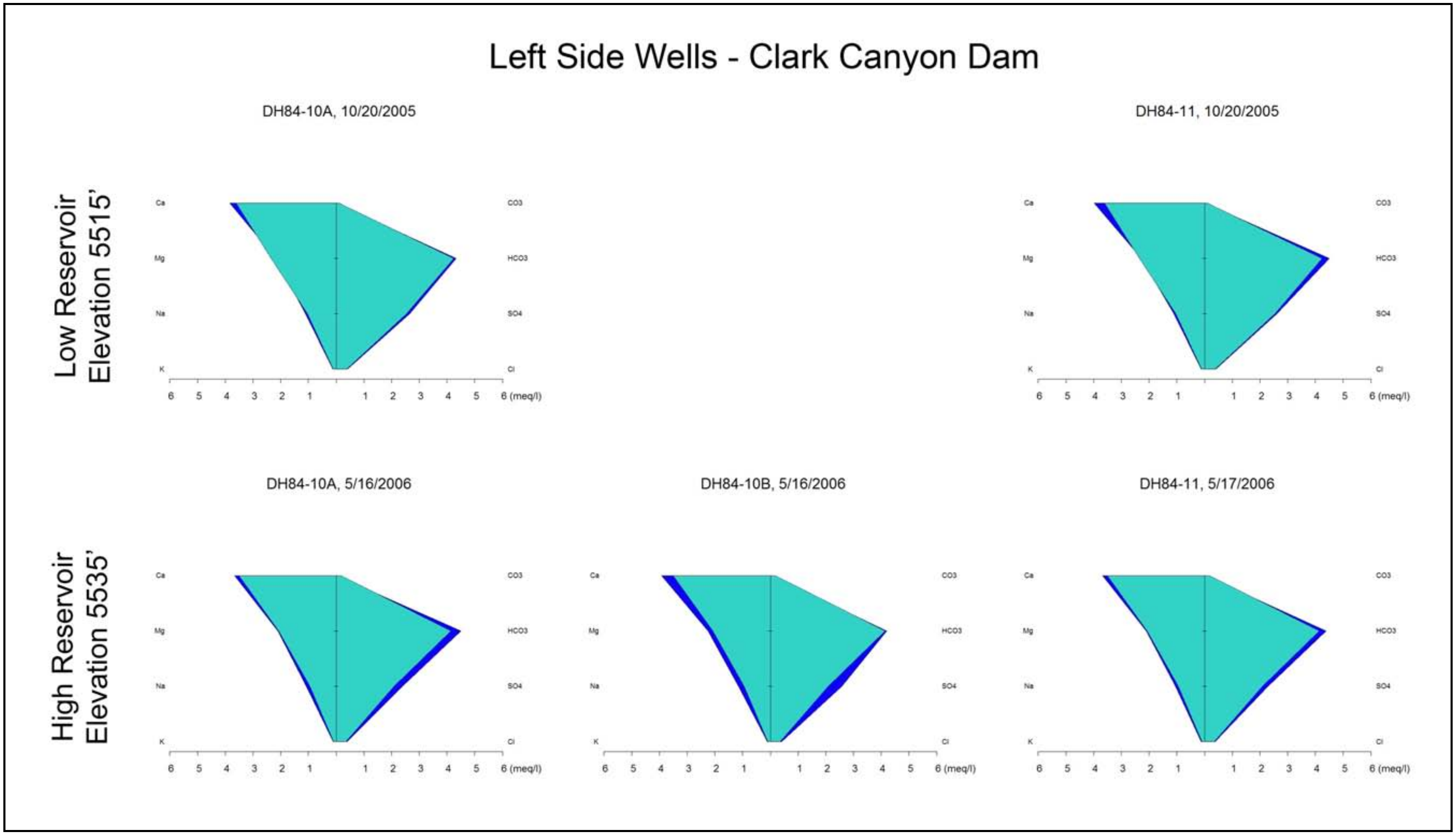


TABLE 3A.— Field and chemistry data, and calculated mineral SI's for Left Side Wells seepage samples from Clark Canyon Dam. The less-than sign (<) means "not detected" or "below the detection limit" indicated by the number value.

LEFT SIDE WELLS					
Sample ID	***DH84-10A Red***	***DH84-10A Red***	***DH84-10B Green***	***DH84-11***	***DH84-11***
Date Sampled	10/20/05	5/16/06	5/16/06	10/20/05	5/17/06
Time Sampled	11:00	12:00	11:25	13:00	9:12
Reservoir Surface Elevation, ft	5514.78	5535.24	5535.24	5514.78	5535.02
Static Water Level, ft	-23.6	-21.2	-20.3	-8.00	-6.07
Field Temperature, °C	9.4	20.9	13.4	13.6	8.22
Field pH, SU	**7.60**	**8.00**	**7.60**	**7.80**	**7.40**
Lab pH	7.90	7.90	7.80	8.30	7.80
Field EC - Conductivity, µS/cm	**557**	**515**	**656**	**590**	**610**
Lab EC - Conductivity, µS/cm		645	678		650
Sum of Ions, mg/L	539	533	531	553	520
Ca-Calcium, mg/L	76.8	73.3	78.6	79.8	73.8
Mg- Magnesium, mg/L	26.4	25.5	27.3	27.6	25.6
Na - Sodium, mg/L	25.4	24.9	26.3	25.3	24.1
K - Potassium, mg/L	4.70	4.50	4.50	4.70	4.60
HCO3 - Bicarbonate, mg/L	264	275	256	275	268
CO3 - Carbonate, mg/L	0	0	0	0	0
SO4 - Sulfate, mg/L	127	115	124	125	110
Cl - Chloride, mg/L	14.4	13.9	14.8	14.8	13.7
Fe, Filtered Iron, µg/L	< 20	< 20	< 20	< 20	< 20
Mn, Filtered Manganese, µg/L	< 10	< 10	400	< 10	< 10
Al, Filtered Aluminum, µg/L	< 10	< 10	< 10	< 10	< 10
Silica, Filtered, as SiO2, mg/L	22.3	22.2	21.3	24.4	23.3
Dissolved Organic Carbon, DOC, mg/L	3.70	1.90	2.40	2.20	2.00
Al, Total Aluminum, µg/L		19,800	980		260
Fe, Total Iron, µg/L		26,100	1,480		250
Mn, Total Manganese, µg/L		190	460		< 10
Saturation Index - Anhydrite	-1.74	-1.81	-1.75	-1.74	-1.80
Saturation Index - Gypsum	-1.48	-1.57	-1.50	-1.49	-1.54
Saturation Index - Calcite	0.157	0.715	0.214	0.449	-0.063
Saturation Index - Dolomite	-0.037	1.27	0.152	0.623	-0.496
Saturation Index - Quartz	0.792	0.605	0.707	0.762	0.832

TABLE 3B.— Difference data calculated for the Left Side Wells at Clark Canyon Dam. Changes in seepage concentrations were calculated by subtracting same date reservoir concentrations from seepage concentrations.

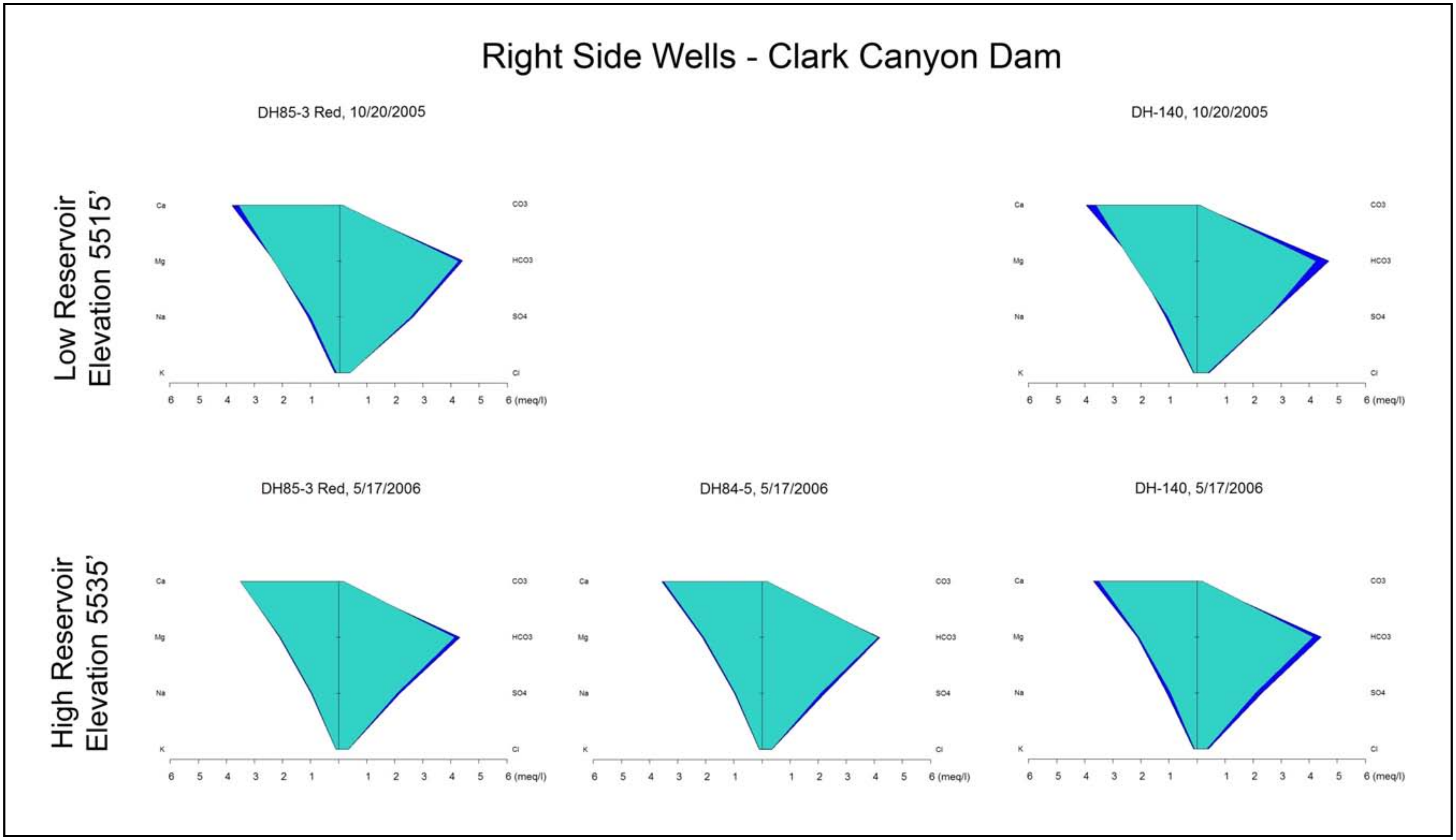
	LEFT SIDE WELLS				
Sample ID	***DH84-10A Red***	***DH84-10A Red***	***DH84-10B Green***	***DH84-11***	***DH84-11***
Date Sampled	10/20/05	5/16/06	5/16/06	10/20/05	5/17/06
Time Sampled	11:00	12:00	11:25	13:00	9:12
Reservoir Surface Elevation, ft	5514.78	5535.24	5535.24	5514.78	5535.02
ΔField Temperature, °C	-0.8	6.9	-0.6	3.4	-5.78
ΔField pH, SU	**-0.10**	**1.00**	**0.60**	**0.10**	**0.40**
ΔLab pH, SU	-0.60	-0.60	-0.70	-0.20	-0.70
ΔField EC - Conductivity, µS/cm	**-44**	**-33**	**108**	**51**	**62**
ΔSum of Ions, mg/L	12	40	39	26	27
Change in Seepage, Total, Percentage	**2.26**	**7.48**	**7.26**	**4.70**	**5.24**
ΔCa - Calcium, mg/L	4.7	3.1	8.4	7.7	3.6
ΔMg - Magnesium, mg/L	-2.2	0.30	2.1	-1.0	0.40
ΔNa - Sodium, mg/L	1.6	3.1	4.5	1.5	2.3
ΔK - Potassium, mg/L	0.50	0.60	0.60	0.50	0.70
ΔHCO3 - Bicarbonate, mg/L	5.0	22	3.0	16	15
ΔCO3 - Carbonate, mg/L	-3.35	-5.75	-5.75	-3.35	-5.75
ΔSO4 - Sulfate, mg/L	5.0	15	23	4.0	10
ΔCl - Chloride, mg/L	0.60	1.5	2.4	1.0	1.3
ΔSilica, Dissolved, as SiO2, mg/L	5.0	5.6	4.7	7.1	6.7
ΔDissolved Organic Carbon, DOC, mg/L	0.2	-2.4	-1.9	-1.3	-2.3

FIGURE 4A.— Right Side Well DH84-5 looking across the dam. Reclamation photograph by Chuck Sullivan.

FIGURE 4B.— Right Side Well DH-140 looking towards the dam. Reclamation photograph by Curtis Cain.

FIGURE 4C.— Right Side Well DH85-3. Reclamation photograph by Curtis Cain.

FIGURE 4D.— Comparing the chemistry of the Right Side Wells at Clark Canyon Dam. These Stiff diagrams show the major ions concentrations for reservoir water (green polygons) superimposed over seepage water (darker blue polygons). The upper row of Stiff diagrams are from the low reservoir sampling in October 2005 (elevation 5,515 ft), while the lower row diagrams are from the high reservoir elevation sampling event in May 2006 (elevation 5,535 ft).



calculations are summarized in table 4a (field and major ions concentrations and SI's) and table 4b (concentration difference data). Data from the field drain manhole, MH 2+40, installed after the 1984 right side seepage problems, are also included in tables 4a and 4b.

SI data for calcite and dolomite for the Left and Right Side Wells (tables 4a and 5a) show that the seepage water is generally oversaturated at both low and high reservoir surface elevations for wells located on the embankment behind the toe. Left side DH84-10A and right side DH84-5 both show oversaturated SI's. However, left side DH84-11 and right side DH85-3 red, located at or below the toe, were slightly undersaturated at high reservoir elevation. Generally, the SI's for calcite and dolomite are more positive at lower reservoir surface elevations, suggesting slower seepage flow through most wells at low reservoir. These results suggest that reservoir elevations at 5,530 ft. and higher will tend to produce subsurface flows that remain aggressive towards calcite and dolomite farther downstream.

Total ion increases in tables 3b and 4b vary from less than 1 percent (DH85-3B green intercepting the Beaverhead) up to 7.5 percent (DH84-10A in May 2006). Increases on the Left Side Wells (table 3b) show greater percentage concentration increases at higher reservoir elevation, suggesting that the May 2006 samples – the first in the past 6 years with reservoir above 5,530 ft. (1,686 m) – may be "washing out" higher concentration, more stagnant, and older seepage along the flow paths. Increases for the Right Side Wells (table 4b) are more consistent between low and high reservoir elevations.

The comparative Stiff diagrams in figures 4c and 5d show that the chemistry of the Left and Right Side Wells are very similar to the reservoir water. While only a small amount of darker blue extends beyond the green reservoir polygons for the seepage sample, there are changes in concentrations (tables 4b and 5b) that are greater than measurement error of around ± 1 mg/L. The general conclusion for the figure 4c and 5d Stiff diagrams is that the seepage intercepted by these wells is very much like the reservoir water, suggesting a relatively short foundation residence time – on the order of weeks. The consistent loss of DOC, however, shows that seepage transit time is sufficient for bacterial activity to alter the chemistry.

The Left Side Wells show consistent slight increases for Ca (3.1 to 8.4 mg/L), Na (1.5 to 4.5 mg/L), and Cl (0.6 to 2.4 mg/L), while the Right Side Wells, except for DH-140, show only minor to negligible increases in Na and Cl. Because there are no known massive halite (NaCl) or evaporative caliche deposits noted in the foundation materials near the dam, the minor increases in Na and Cl cannot be fully explained. Perhaps there is a higher concentration groundwater at depths greater than 50 ft that may diffuse upward, or flow upward along vertical fractures from the reservoir hydrostatic head.

The notable concentration changes for the Left and Right Side Wells are seen in increases for SiO_2, HCO_3, and SO_4. SiO_2 increases from +4.7 to +7.1 mg/L on the Left Side Wells, and from +1.4 to +8.5 mg/L on the Right Side Wells. The SiO_2 increases suggest potential dissolution of amorphous silica that may be present as opal or chert, or as a cementing agent in the Alluvium, Beaverhead, or Madison Formation. A small portion (1-5 percent) of the observed HCO_3 increases are caused by bacterial oxidation

TABLE 4A.— Field and chemistry data, and calculated mineral SI's for Right Side Well seepage samples from Clark Canyon Dam. The less-than sign (<) means "not detected" or "below the detection limit" indicated by the number value.

RIGHT SIDE WELLS							
Sample ID	***DH84-5***	***DH85-3 Red***	***DH85-3 Red***	***DH85-3B Green***	***DH-140***	***DH-140***	***MH 2+40***
Date Sampled	5/17/06	10/20/05	5/17/06	5/17/06	10/20/05	5/17/06	9/5/86
Time Sampled	10:41	9:35	9:00	9:38	11:50	11:22	
Reservoir Surface Elevation, ft	5535.02	5514.78	5535.02	5535.02	5514.78	5535.02	5534.73
Static Water Level, ft	-22.1	-40.4	-21.4	-21.4	-27.5	-12.2	
Field Temperature, °C	16.6	9.6	12.0	13.2	9.2	9.2	
Field pH, SU	**7.80**	**7.60**	**7.10**	**7.60**	**7.60**	**7.60**	
Lab pH	7.80	8.10	7.90	7.80	8.00	7.90	7.33
Field EC - Conductivity, µS/cm	**594**	**577**	**585**	**563**	**585**	**582**	
Lab EC - Conductivity, µS/cm	630		620	618		662	589
Sum of Ions, mg/L	499	545	503	497	563	525	485
Ca - Calcium, mg/L	71.5	76.2	69.8	70.7	79.2	73.9	72.8
Mg - Magnesium, mg/L	25.8	27.8	25.6	25.5	27.1	26.0	19.6
Na - Sodium, mg/L	22.5	25.1	22.5	22.3	25.7	24.6	22.5
K - Potassium, mg/L	3.70	5.30	3.80	3.80	4.70	4.60	4.77
HCO3 - Bicarbonate, mg/L	256	269	264	257	287	270	272
CO3 - Carbonate, mg/L	0	0	0	0	0	0	0
SO4 - Sulfate, mg/L	107	128	105	105	123	111	85.0
Cl - Chloride, mg/L	12.6	14.2	12.5	12.6	15.6	14.6	8.32
Fe, Filtered Iron, µg/L	< 20	< 20	< 20	< 20	< 20	< 20	
Mn, Filtered Manganese, µg/L	< 10	< 10	< 10	< 10	< 10	< 10	
Al, Filtered Aluminum, µg/L	140	< 10	< 10	210	< 10	< 10	
Silica, Filtered, as SiO2, mg/L	18.3	25.8	18.8	18	25.4	24.3	
Dissolved Organic Carbon, DOC, mg/L	2.60	2.50	2.20	2.80	2.00	2.20	
Al, Total Aluminum, µg/L	24,800		190	31,300		1,680	
Fe, Total Iron, µg/L	33,400		310	44,100		8,200	
Mn, Total Manganese, µg/L	350		20	2680		340	
Saturation Index - Anhydrite	-1.84	-1.74	-1.85	-1.85	-1.74	-1.80	-1.91
Saturation Index - Gypsum	-1.59	-1.48	-1.59	-1.59	-1.48	-1.55	-1.67
Saturation Index - Calcite	0.427	0.164	-0.329	0.179	0.201	0.154	0.057
Saturation Index - Dolomite	0.646	0.006	-0.936	0.095	0.046	-0.038	-0.172
Saturation Index - Quartz	0.597	0.852	0.660	0.637	0.852	0.833	

TABLE 4B.— Difference data calculated for the Right Side Wells at Clark Canyon Dam. Changes in seepage concentrations were calculated by subtracting same date reservoir concentrations from seepage concentrations.

	RIGHT SIDE WELLS						
Sample ID	***DH84-5***	***DH85-3 Red***	***DH85-3 Red***	***DH85-3B Green***	***DH-140***	***DH-140***	***MH 2+40***
Date Sampled	5/17/06	10/20/05	5/17/06	5/17/06	10/20/05	5/17/06	9/5/86
Time Sampled	10:41	9:35	9:00	9:38	11:50	11:22	
Reservoir Surface Elevation, ft	5535.02	5514.78	5535.02	5535.02	5514.78	5535.02	5534.73
ΔField Temperature, °C	2.6	-0.6	-2	-0.8	-1	-4.8	
ΔField pH, SU	**0.80**	**-0.10**	**0.10**	**0.60**	**-0.10**	**0.60**	
ΔLab pH, SU	-0.70	-0.40	-0.60	-0.70	-0.50	-0.60	0.42
ΔField EC - Conductivity, µS/cm	**46**	**26**	**37**	**15**	**23**	**34**	44
ΔSum of Ions, mg/L	7.0	19	10	4.0	36	32	38
Change in Seepage, Total, Percentage	**1.35**	**3.42**	**2.06**	**0.895**	**6.39**	**6.07**	**7.77**
ΔCa - Calcium, mg/L	1.3	4.1	-0.40	0.5	7.1	3.7	11.8
ΔMg - Magnesium, mg/L	0.60	-0.80	0.40	0.3	-1.5	0.80	-4.30
ΔNa - Sodium, mg/L	0.70	1.3	0.70	0.5	1.9	2.8	0.10
ΔK - Potassium, mg/L	-0.20	1.10	-0.10	-0.10	0.50	0.70	5.87
ΔHCO3 - Bicarbonate, mg/L	3.0	10	11	4.0	28	17	31
ΔCO3 - Carbonate, mg/L	-5.8	-3.4	-5.8	-5.8	-3.4	-5.8	0.0
ΔSO4 - Sulfate, mg/L	7.0	6.0	4.0	5.0	2.0	10	3.0
ΔCl - Chloride, mg/L	0.20	0.40	0.10	0.20	1.8	2.2	-4.48
ΔSilica Dissolved, as SiO2, mg/L	1.7	8.5	2.2	1.4	8.1	7.7	
ΔDissolved Organic Carbon, DOC, mg/L	-1.7	-1.0	-2.1	-1.5	-1.5	-2.1	

of DOC, however, the remainder are likely from dissolution of calcite during seepage transit. Limestone (calcite) presence was noted in drill logs at most depths in the Alluvium and is present as massive deposits in the Madison Formation Lodgepole Limestone. Increases in SO_4 are likely from dissolution of gypsum or anhydrite; however, these deposits were not specifically noted in the geologic reports in the vicinity of the dam.

Suspended Particles in Foundation Seepage Samples: A greater concern is that there is evidence that fine, clay-sized particles may be transported by seepage flows through more porous gravels in the Alluvium or bedrock fractures intercepted by the Left and Right Side Wells. Suspended solids were collected from the left side well DH84-10A (intercepting the Madison) and right side wells DH-140 (intercepting the Madison), and DH-84-5 (intercepting the lower Beaverhead Conglomerate at the Madison boundary). Petrographic examination showed that the October 2005 DH-84-10A sample contained clay size mineral grains composed of chiefly illite/mica and quartz with lesser kaolinite and calcite (Hurcomb, 2005). The May 2006 sample did not contain suspended sediments, so the materials at lower reservoir elevation may have been caused by disturbing a shallower water column in the well – or removal of suspended sediments by the October 2005 sampling.

DH-140 showed suspended sediments for both the October 2005 and the May 2006 sampling events. The October 2005 DH-140 sample contained suspended clay- and silt-size grains composed chiefly of quartz, calcite, and illite/mica (or possibly mixed-layer illite/mica-smectite with lesser amounts of kaolinite) along with a few miscellaneous minerals including apatite. The May 2006 DH-140 sample clay size minerals were chiefly less than 0.01 mm with a few particles up to 0.05 mm in size. This material was chiefly composed of the clay minerals illite-mica, smectite, and kaolinite with minor amounts of calcite and quartz (Hurcomb, 2005; 2006).

Suspended sediments in the May 2006 DH84-3 sample (no seepage sample was collected in October 2005) were clay size minerals mostly less than 0.01 mm with a few particles up to 0.02 mm in size. The material was chiefly composed of the clay minerals smectite, illite-mica, and kaolinite with minor amounts of calcite, quartz, and hematite.

Left and Right Toe Drains

The toe drain is collecting seepage from both the foundation directly below the embankment, as well as the embankment beneath the phreatic surface. So, these seepage samples are likely mixtures. We would expect to see compacted embankment material seepage to flow very slowly and show a much greater increase in dissolved concentrations compared to foundation seepage. Because the toe drain outlets and manholes have weirs, we also have flow data that can be used to estimate mass wasting and void formation rates for mineral dissolution. Photographs of the Left and Right Toe Drain stations, manhole LT 3+69, LT Outlet, RT Outlet, and manhole RT 1+93 are found in figures 5a – 5e, and the comparative chemistry is summarized using Stiff diagrams in figure 5f. Manhole RT 7+51 (figure 5e) was dry during both 2005 and 2006 sampling events, suggesting that the phreatic surface is below the drain on the far right side. Chemistry data are summarized in Table 5a (field and major ions chemistry and SI's) and Table 5b (concentration difference data and soluble mineral mass wasting and void formation rates).

The comparative Stiff diagrams in figure 5f show the toe drain samples arranged from left to right. LT 3+69, sampled only during May 2006, shows the greatest increases in concentrations (46.0 percent increase in total ions). Across the dam approximately 350 ft to the right, LT Outlet shows an apparent dilution of the water seen at LT 3+69. The RT Outlet shows the greatest similarity to reservoir water and the lowest percentage increases in total ions (7.3 to 8.6 percent). Manhole RT 1+93, near the RT Outlet was flowing in May 2006 (estimated at 0.5 to 2.0 gpm) and showed a 21.6 percent increase in concentration compared to the reservoir. RT 7+51 (figure 5e) was dry at elevation 5,535 (1,687 m) and no previously deposited sediments were observed. The suggestion from the Stiff diagrams is that seepage flows and dilution cfrom reservoir seepage mixing with toe drain water are greatest along the old Beaverhead River channel.

SI data (table 5a) show that the LT Outlet is oversaturated with respect to calcite at low reservoir elevation, but is undersaturated at high reservoir elevation. The RT-Outlet appears to be undersaturated at both low and high reservoir elevations. The difference data in table 5b suggest that calcite, gypsum and/or anhydrite, and amorphous silica are dissolving, with possible mixing of nearby seepage in the foundation and the embankment below the phreatic surface.

Void Formation Rates from Mineral Dissolution: Void formation rates were calculated in table 5b using flows estimated by the field crew to be 2.0 gpm for LT

FIGURE 5A.— Toe Drain Manhole LT 3+69 on the left side of Clark Canyon Dam. The right image shows seepage below the weir in May 2006. Reclamation photographs by Doug Craft and Curtis Cain.

Figure 5b.— The Left Toe Drain outlet and weir, LT Outlet. No discharge from the outlet pipe was seen at reservoir elevation 5,518 ft. (left), however some seepage is present beneath the toe behind the weir. The right image show higher seepage levels in May 2006 with a flow of 26.5 gpm. Reclamation photographs by Doug Craft and Curtis Cain.

Figure 5c.— The Right Toe Drain outfall and weir, RT Outlet. No seepage was seen emerging from the outfall pipe, but a flow of approximately 0.5 to 2.0 gpm was observed at reservoir elevation 5,518 ft. (left). The right image was from the May 2006 sampling event, with flow of around 15.7 gpm.

Figure 5d.— Right Toe Drain Manhole RT 1+93 located on the right side of Clark Canyon Dam near RT Outlet. The right image shows seepage at or just above the measurement weir at the bottom of the manhole. Reclamation photographs by Doug Craft and Curtis Cain.

Figure 5e.— The Right Toe Drain Manhole RT 7+51. This manhole was dry during sampling at both reservoir elevations of 5,515 ft and 5,535 ft.

Figure 5f.— Comparing the chemistry of the Left and Right Toe Drains at Clark Canyon Dam with the same reservoir elevations over a 20-year period. These Stiff diagrams show the major ions concentrations for reservoir water (green polygons) superimposed over seepage water (darker blue polygons). The upper row of Stiff diagrams are from an August 1986 sampling event, while the lower row diagrams are from the May 2006 sampling event. Reservoir elevations were around 5,535 ft for both sampling dates.

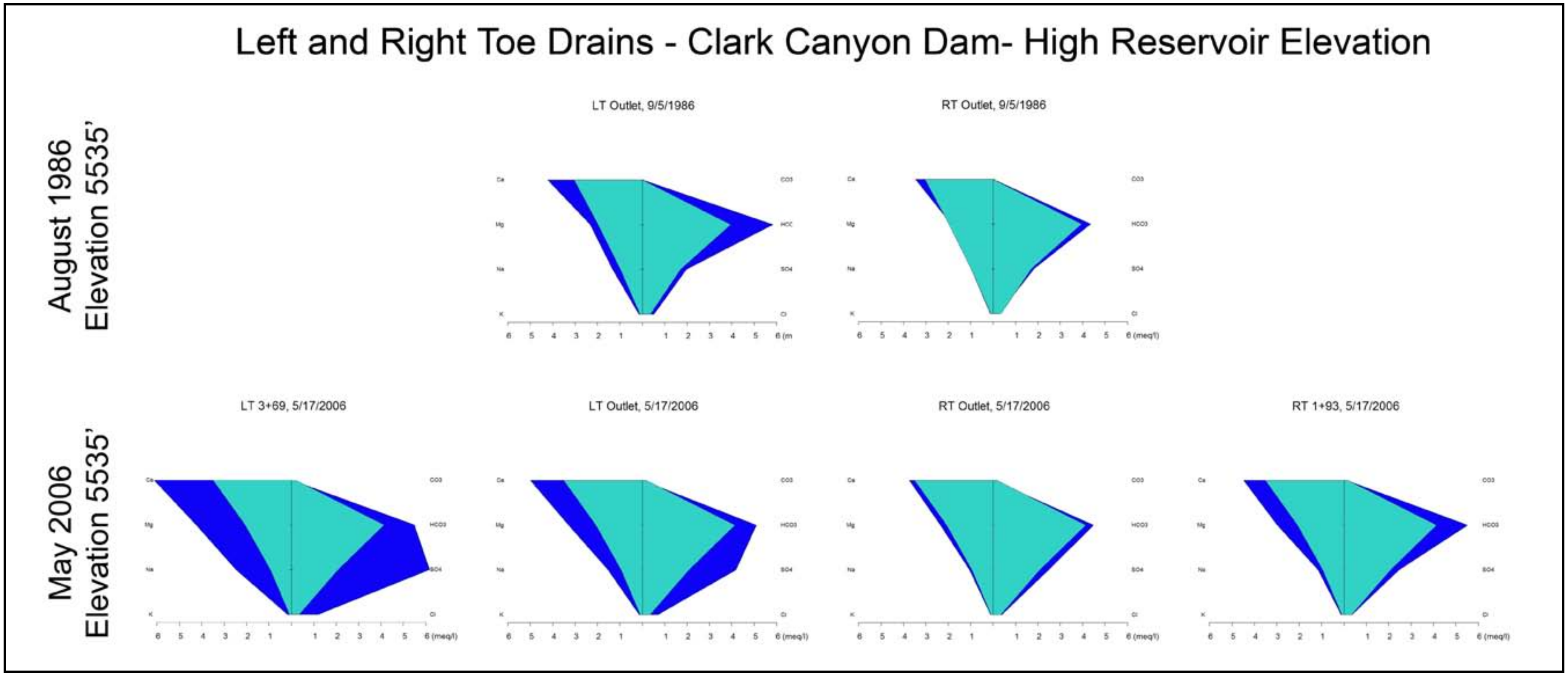


TABLE 5A.— Field and chemistry data, and calculated mineral SI's for Left and Right Toe Drain seepage samples from Clark Canyon Dam. The less-than sign (<) means "not detected" or "below the detection limit" indicated by the number value.

	LEFT TOE DRAIN			***RIGHT TOE DRAIN***		
Sample ID	***LT 3+69***	***LT- Outlet***	***LT- Outlet***	***RT- Outlet***	***RT- Outlet***	***RT 1+93***
Date Sampled	5/17/06	9/5/86	5/17/06	9/5/86	5/17/06	5/17/06
Time Sampled	15:35		14:06		14:15	15:55
Reservoir Surface Elevation, ft	5535.02	5534.73	5535.02	5534.73	5535.02	5535.02
Q - Flow, gpm	0	0	2.00	0	15.7	0.500
Field Temperature, °C	13.6		12.1		9.80	8.80
Field pH, SU	**7.60**		**7.10**		**7.10**	**8.10**
Lab pH	7.90	7.53	8.10	7.26	8.00	8.40
Field EC - Conductivity, µS/cm	**1,100**		**832**		**610**	**726**
Lab EC - Conductivity, µS/cm	1,200	721	903	594	677	799
Sum of Ions, mg/L	912	619	718	483	539	629
Ca - Calcium, mg/L	123	84.7	100.0	69.5	74.9	89.6
Mg - Magnesium, mg/L	51.8	28.2	39.9	22.8	28.6	36.1
Na - Sodium, mg/L	56.9	30.3	35.2	22.3	24.0	26.5
K - Potassium, mg/L	6.80	5.87	5.50	4.66	4.30	4.90
HCO3 - Bicarbonate, mg/L	335	356	311	266	274	337
CO3 - Carbonate, mg/L	0	0	0	0	0	3.83
SO4 - Sulfate, mg/L	296	95.0	201	88.0	119	118
Cl - Chloride, mg/L	42.9	18.8	25.0	9.46	13.9	12.8
Fe, Filtered Iron, µg/L	< 20		< 20		< 20	< 20
Mn, Filtered Manganese, µg/L	60		30		< 10	< 10
Al, Filtered Aluminum, µg/L	< 10		< 10		< 10	< 10
Silica, Filtered, as SiO2, mg/L	24.9		22.8		19.9	23.5
Dissolved Organic Carbon, DOC, mg/L	5.0		3.9		2.5	3.4
Al, Total Aluminum, µg/L	780		20		20	30
Fe, Total Iron, µg/L	7,100		80		< 20	140
Mn, Total Manganese, µg/L	14800		30		< 10	1,110
Saturation Index - Anhydrite	-1.32	-1.85	-1.50	-1.92	-1.77	-1.74
Saturation Index - Gypsum	-1.06	-1.61	-1.25	-1.68	-1.52	-1.48
Saturation Index - Calcite	0.441	0.411	-0.158	-0.044	-0.326	0.804
Saturation Index - Dolomite	0.694	0.629	-0.552	-0.288	-0.951	1.316
Saturation Index - Quartz	0.773		0.760		0.737	0.822

TABLE 5B.— Difference data calculated for the Left and Right Toe Drains at Clark Canyon Dam. Changes in seepage concentrations were calculated by subtracting same date reservoir concentrations from seepage concentrations. Mass wasting and void formation rates were calculated based on a simplified mass balance model assuming dissolution of dolomite + calcite, gypsum, and silica.

	LEFT TOE DRAIN			***RIGHT TOE DRAIN***		
Sample ID	***LT 3+69***	***LT- Outlet***	***LT- Outlet***	***RT- Outlet***	***RT- Outlet***	***RT 1+93***
Date Sampled	5/17/06	9/5/86	5/17/06	9/5/86	5/17/06	5/17/06
Time Sampled	15:35		14:06		14:15	15:55
Reservoir Surface Elevation, ft	5535.02	5534.73	5535.02	5534.73	5535.02	5535.02
Q - Flow, gpm	0.5		2.0	0	15.7	0.5
ΔField Temperature, °C	-0.40		-1.9		-4.2	-5.2
ΔField pH, SU	**0.60**		**0.10**		**0.10**	**1.1**
ΔLab pH, SU	-0.60	0.62	-0.40	0.35	-0.50	-0.10
ΔField EC - Conductivity, µS/cm	**550**	180	**280**	49	**62**	**180**
ΔSum of Ions, mg/L	419	170	230	35.0	46.0	136
Change in Seepage, Total, Percentage	**46.0**	**27.7**	**31.4**	**7.34**	**8.62**	**21.60**
ΔCa - Calcium, mg/L	53	24	30	8.5	4.7	19
ΔMg - Magnesium, mg/L	27	4.3	15	-1.1	3.4	11
ΔNa - Sodium, mg/L	35	7.9	13	-0.10	2.2	4.7
ΔK - Potassium, mg/L	2.9	5.9	1.6	5.9	0.40	1.0
ΔHCO3 - Bicarbonate, mg/L	82	120	58	25	21	84
ΔCO3 - Carbonate, mg/L	-5.8	0	-5.75	0	-5.8	-1.9
ΔSO4 - Sulfate, mg/L	200	13	101	6.0	19	17
ΔCl - Chloride, mg/L	31	6.0	12	-3.3	1.5	0.4
ΔSilica Dissolved, as SiO2, mg/L	8.3		6.2		3.3	6.9
ΔDissolved Organic Carbon, DOC, mg/L	0.70		-0.40		-1.8	-0.90
Mass Wasting, Anhydrite, g/day			143		27.0	24.7
Mass Wasting, Gypsum, g/day			2,000		2,950	86.2
Mass Wasting, Calcite, g/day			946		2,160	372
Mass Wasting, Silica, g/day			68.6		286	19.1
Void Formation, Anhydrite, cm^3/d			532		786	23.0
Void Formation, Gypsum, cm^3/d			869		1,280	37.5
Void Formation, Calcite, cm^3/d			350		798	138
Void Formation, Silica, cm^3/d			32.7		136	9.08
LOW Void Formation, TOTAL, cm^3/d			**915**		**1,720**	**170**
HIGH Void Formation, TOTAL, cm^3/d			**1,250**		**2,220**	**184**

Outlet and 0.5 gpm for flow in manhole RT 1+93. Difference data and a range of estimated flows suggest that void formation from mineral dissolution on the left side of the dam is between 900 and 1,300 cm^3/day during higher reservoir elevations. On the right side, higher flows at RT Outlet produce void formation rates of around 1,700 to 2,200 cm^3/day. Assuming a water year with 60 days of discharge at 3,500 cm^3/day, and 200 days at 500 cm^3/day, around 3.1 m^3 of voids would be expected to form over a 10-year period.

The obvious question arises, "Is this a structurally significant amount of void volume formation?" Because we do not know the seepage flow paths or contact volumes, this question cannot be answered with any accuracy. However, increasing porosity does affect rock mechanical strength, and seepage is much more likely to find more restricted flow paths through embankment or foundation materials. Since seepage is not a uniform process and the data suggest that mineral dissolution is ongoing, accurate and regular measurement of toe drain flows and piezometer levels is highly recommended.

Suspended Particles in Toe Drain Seepage Samples: Suspended particles were found in the May 2006 LT 3+69 manhole sample (figure 5a). The material in LT 3+69 contained clay size particles chiefly less than 0.01 mm with a few particles up to 0.02 mm in size, and was composed chiefly of the clay mineral illite-mica with kaolinite and minor amounts of calcite and quartz.

The suspended sediment in seepage was likely caused by disturbance during sample collection; however, the presence of sediments in the manhole suggests that fine materials are being transported into the left toe drain. This finding should be of concern, the unanswered question being: Where are these clay materials coming from - the embankment or the foundation? Sediment in filling of toe drains was a problem prior to the 1985-1986 toe drain replacement, so it does appear likely that fine clay materials present in the Beaverhead Conglomerate, the embankment, and the Alluvium continue to be transported by seepage into the toe drains as well as possibly through the foundation.

While no suspended sediments were collected in the flowing right side manhole RT 1+93 (figure 5d), similar sedimentation may be occurring, and this manhole should be inspected for sediment deposition when reservoir levels are lower. Similarly, the dry and clean manhole RT 7+51 (figure 5e) should be monitored when reservoir levels are high enough to cause flows farther on the right side of the dam.

Surface Seepage Samples

Photographs of the Left and Right Side Seeps LA Seep Emerge, LA Seep Weir, Boil 1, Boil 2, RT Seep, FLD Outlet, and GS-1 are found in figures 6a – 6e. Surface seepage principally emerges in the old Beaverhead River channel directly downstream of the toe drain outlets where samples Boil 1 (figure 6b) and Boil 2 (figure 6c) were collected. These seeps are a concern because of the areal extent of the active boil area is large, and seepage flow volumes are not monitored. Additional localized surface seeps emerge near the dam. On the left abutment is the LA Seep Emerge (figure 6a, left) and LA Seep Weir (figure 6a, right), which only flowed at the higher reservoir elevation. RT Seep (figure 6d, left), is located in the bank of the old river channel in a suspected Beaverhead Formation outcrop near the RT Outlet, and is an unmonitored seep. No surface seepage was seen in the FLD Drain (figure 6d, right) during either sampling event. At nearly 1 mile downstream from the dam, the seep at Gordon Springs, GS-1 (figure 6e) was flowing and collected during both sampling events, however, these data are only provided for baseline reference. The comparative chemistry of the surface seepage is summarized using Stiff diagrams in figure 6f.

FIGURE 6A.— The Left Abutment Seep LA Seep Emerge (left) and LA Seep Weir. The emergence point is indicated by the darker green foliage right of center. Seepage was dry at reservoir elevation 5,518 ft., and estimated at approximately 2 gpm in May 2006 at elevation 5,535 ft. Reclamation photographs by Doug Craft and Curtis Cain.

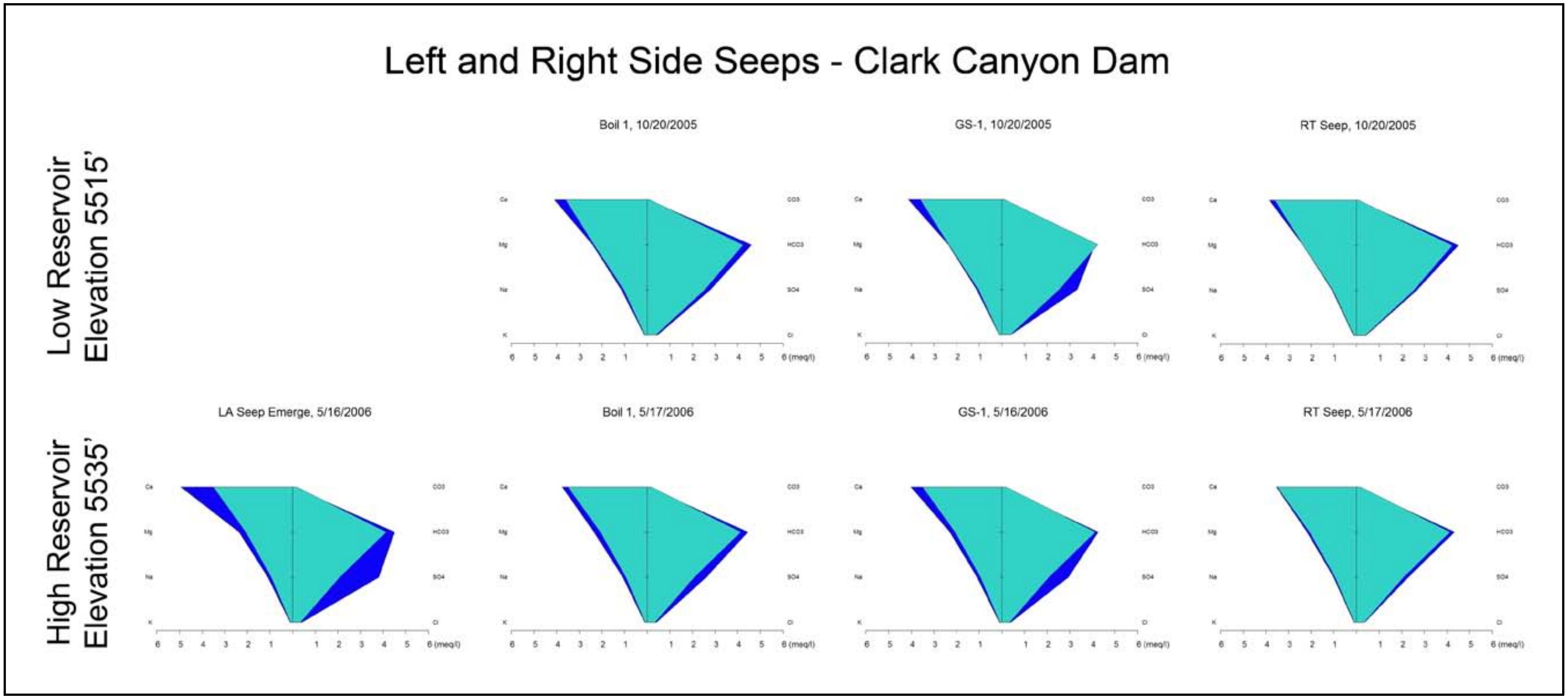
FIGURE 6B.— Surface seepage in the Boil area emerging from below the old Beaverhead River channel during low reservoir elevation of 5,518 ft in June 2005. The left image shows the boil area, while the right image shows a closeup of typical boils at station Boil 1. Reclamation photographs by Doug Craft.

FIGURE 6C.— The old river channel at higher reservoir elevation of 5,535 ft. showing water at a depths of 0.5 to 1 ft. It is not known how much of this water is from boil area seepage - or backup from higher reservoir discharges in the Beaverhead River. The left image shows sampling in May 2006 at Boil 1, and on the right at Boil 2. Reclamation photographs by Curtis Cain.

FIGURE 6D.— On the left is the May 2006 sample collection at RT Seep, located on the right bank of the old river channel near the dam. Seepage at RT Seep is discharging beneath the water surface. The right image shows the FLD Outlet weir near the old river channel bank below the 1985-1986 field drain. This station was not flowing at either the low or higher reservoir elevation sampling events. Reclamation photographs by Curtis Cain and Doug Craft .

FIGURE 6E.— Surface seepage emerging approximately 0.9 mi downstream of the dam at the Gordon Springs station GS-1. Seepage flows (inset images) were estimated at approximately 75 gpm during the May 2006 sampling event.

FIGURE 6F.— Comparing the chemistry of the Right Side and Left Side Surface Seepage samples at Clark Canyon Dam. These Stiff diagrams show the major ions concentrations for reservoir water (green polygons) superimposed over seepage water (darker blue polygons). The upper row of Stiff diagrams are from the low reservoir sampling in October 2005 (elevation 5,515 ft), while the lower row diagrams are from the high reservoir elevation sampling event in May 2006 (elevation 5,535 ft).



Data are summarized in Table 6a (field and major ions chemistry and SI's) and Table 6b (concentration difference data and soluble mineral mass wasting and void formation rates).

Seepage Below the Center of the Dam: The figure 6f stiff diagrams show that the seeps located along the old river channel (Boil 1, Boil 2, and RT Seep) are very similar to the Left and Right Side Well samples. The chemistry of these seeps is very similar to the reservoir, with minor but detectable increases in Ca, HCO_3 and SO_4, and total ions increases on the order of 3.8 to 9.4 percent compared to reservoir concentrations (table 6b). Silica consistently increased in all seepage samples. These increased concentrations relative to the reservoir are consistent with dissolution of calcite, gypsum or anhydrite, and amorphous silica. Boil 1 total ions (table 6a) decreased only slightly between low and high reservoir elevations, suggesting that flow paths through the old river channel are mature. The RT Seep also showed a decrease in total ions between low and high reservoir.

Calcite SI data suggest that the Boil 1 seepage was near equilibrium with calcite (SI near zero) at low reservoir elevation, but slightly oversaturated at high reservoir elevation. The RT Seep sample, however, was near equilibrium with calcite at low reservoir, but undersaturated at high reservoir. This result suggests that the seepage flow path is shorter at RT Seep, and that the seepage transit time is shorter compared to the Boil area.

Petrographic examination of suspended sediments in these center seepage samples (Hurcomb, 2005; 2006) revealed the presence of fine sand-sized particles composed of chert, feldspar, quartz, and clay minerals as well as several unidentified rock types, diatoms, opaline plant fragments, and miscellaneous minerals. The possibility that there may be some fine particle transport occuring along the central seepage paths at Clark Canyon Dam cannot be discounted. Because we do not know the flow paths associated with the boils, or the nature of vertical flows in the foundation contacted by seepage, the origin of the fine particulates remains a mystery. However, the mineralogy observed in these sediments corroborates the observed changes in chemistry and indications of ongoing mineral dissolution.

Left Abutment Seepage: The left side seepage was not flowing at low reservoir. The May 2006 seepage samples from LA Seep Emerge and LA Seep Weir show a much greater increase in concentrations compared to Boils 1 and 2 and the RT Seep, suggestive of a likely longer flow path in a semicircle around the left abutment and greater seepage residence time. The Stiff diagram in figure 6f shows a clear bulge associated with increased SO_4 and Ca, suggestive of dissolution of gypsum or anhydrite in the abutment. Interestingly, the total ions in seepage at LA Seep Weir (around 100 ft downstream of the emergence point) showed an increase of 9.9 percent in total ions. The calcite SI at LA Seep Emerge suggests near equilibrium conditions, but the SI's slightly downstream show oversaturation, perhaps suggesting additional interaction with near surface deposits of calcite or mixing with another seepage emergence point along the surface drainage path.

TABLE 6A.— Field and chemistry data, and calculated mineral saturation indices for Surface Seepage samples from Clark Canyon Dam. The less-than sign (<) means "not detected" or "below the detection limit" indicated by the number value.

Sample Type	***LEFT SIDE SEEPS***							***RIGHT SIDE SEEPS***	
Sample ID	***LA Seep Emerge***	***LA Seep Weir***	***Boil 1***	***Boil 1***	***Boil 2***	***GS-1***	***GS-1***	***RT-Seep***	***RT-Seep***
Date Sampled	5/16/06	5/16/06	10/20/05	5/17/06	5/17/06	10/20/05	5/16/06	10/20/05	5/17/06
Time Sampled	13:40	13:19	9:20	14:39	15:10	13:00	14:19	9:00	13:45
Reservoir Surface Elevation, ft	5535.24	5535.24	5514.78	5535.02	5535.02	5514.78	5535.24	5514.78	5535.02
Q - Flow, gpm	2.0	2.0	0.2	4.0	2.0	25.0	75.0		
Field Temperature, °C	20.2	27.4	9.00	13.8	13.2	13.3	15.9	8.60	10.7
Field pH, SU	**7.20**	**7.30**	**7.40**	**7.80**	**7.60**	**7.70**	**7.40**	**7.50**	**7.20**
Lab pH	7.90	8.00	8.30	8.00	7.90	8.20	7.90	8.30	7.90
Field EC - Conductivity, µS/cm	**617**	**708**	**581**	**629**	**613**	**617**	**619**	**531**	**584**
Lab EC - Conductivity, µS/cm	787	865		677	664		702		639
Sum of Ions, mg/L	629	691	572	544	537	566	553	551	512
Ca - Calcium, mg/L	99.0	107.0	82.0	75.2	75.2	82.6	80.4	76.8	70.9
Mg - Magnesium, mg/L	28.7	32.6	29.2	28.6	27.0	28.7	27.8	28.6	26.5
Na - Sodium, mg/L	25.2	28.4	26.1	24.9	25.4	25.4	25.2	24.5	23.2
K - Potassium, mg/L	4.30	5.90	4.80	4.50	4.60	4.30	4.20	4.60	4.50
HCO3 - Bicarbonate, mg/L	275	293	281	271	271	251	260	275	264
CO3 - Carbonate, mg/L	0	0	0	0	0	0	0	0	0
SO4 - Sulfate, mg/L	183	212	133	125	119	160	141	127	110
Cl - Chloride, mg/L	14.4	12.4	16.0	14.8	15.1	14.0	14.0	14.4	13.0
Fe, Filtered Iron, µg/L	< 20	< 20	30	< 20	< 20	30.0	< 20	< 20	< 20
Mn, Filtered Manganese, µg/L	< 10	< 10	140	10.0	20.0	< 10	< 10	< 10	< 10
Al, Filtered Aluminum, µg/L	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Silica, Filtered, as SiO2, mg/L	18.6	21.6	24.2	20.2	22.4	18.3	18.6	24.6	20.3
Dissolved Organic Carbon, DOC, mg/L	1.90	3.30	2.40	2.50	2.10	1.60	1.80	2.40	2.20
Al, Total Aluminum, µg/L	410	80.0		130	50.0		30.0		1,460
Fe, Total Iron, µg/L	1,090	450		180	50.0		< 20		1,800
Mn, Total Manganese, µg/L	30.0	30.0		20.0	40.0		30.0		120
Saturation Index - Anhydrite	-1.53	-1.44	-1.70	-1.77	-1.78	-1.63	-1.69	-1.74	-1.82
Saturation Index - Gypsum	-1.29	-1.23	-1.44	-1.51	-1.53	-1.38	-1.45	-1.48	-1.57
Saturation Index - Calcite	0.017	0.260	0.001	0.421	0.219	0.310	0.062	0.061	-0.246
Saturation Index - Dolomite	-0.218	0.373	-0.342	0.613	0.172	0.343	-0.113	-0.209	-0.783
Saturation Index - Quartz	0.534	0.501	0.835	0.677	0.732	0.643	0.610	0.848	0.731

TABLE 6B.— Difference data calculated for the Left and Right Side Seeps at Clark Canyon Dam. Changes in seepage concentrations were calculated by subtracting same date reservoir concentrations from seepage concentrations. Mass wasting and void formation rates were calculated based on a simplified mass balance model assuming dissolution of dolomite + calcite, gypsum, and silica.

	LEFT SIDE SEEPS							***RIGHT SIDE SEEPS***	
Sample ID	***LA Seep Emerge***	***LA Seep Weir***	***Boil 1***	***Boil 1***	***Boil 2***	***GS-1***	***GS-1***	***RT-Seep***	***RT-Seep***
Date Sampled	5/16/06	5/16/06	10/20/05	5/17/06	5/17/06	10/20/05	5/16/06	10/20/05	5/17/06
Time Sampled	13:40	13:19	9:20	14:39	15:10	13:00	14:19	9:00	13:45
Reservoir Surface Elevation, ft	5535.24	5535.24	5514.78	5535.02	5535.02	5514.78	5535.24	5514.78	5535.02
Q - Flow, gpm	2.00	2.00	0.20 - 0.40	2.0 - 4.0	2.0 - 4.0	25.0	75.0	2.0 - 4.0	2.0 - 4.0
ΔField Temperature, °C	6.2	13	-1.2	-0.20	-0.80	3.1	1.9	-1.6	-3.3
ΔField pH, SU	**0.20**	**0.30**	**-0.30**	**0.80**	**0.60**	**0.00**	**0.40**	**-0.20**	**0.20**
ΔLab pH, SU	-0.60	-0.50	-0.20	-0.50	-0.60	-0.30	-0.60	-0.20	-0.60
ΔField EC - Conductivity, µS/cm	**69**	**160**	**70**	**81**	**65**	**60**	**71**	**25**	**36**
ΔSum of Ions, mg/L	137	199	46.0	51.0	44.0	39.0	60.0	24.0	19.0
Change in Seepage, Total, Percentage	**21.7**	**28.7**	**8.01**	**9.36**	**8.24**	**6.97**	**10.9**	**4.44**	**3.80**
ΔCa-Calcium, mg/L	29	37	9.9	5.0	5.0	11	10	4.7	0.70
ΔMg- Magnesium, mg/L	3.5	7.4	0.6	3.4	1.8	0.1	2.6	0.0	1.3
ΔNa - Sodium, mg/L	3.4	6.6	2.3	3.1	3.6	1.6	3.4	0.70	1.4
ΔK - Potassium, mg/L	0.40	2.0	0.60	0.60	0.70	0.10	0.30	0.40	0.60
ΔHCO3 - Bicarbonate, mg/L	22	40	22	18	18	-8.0	7.0	16	11
ΔCO3 - Carbonate, mg/L	-5.8	-5.8	-3.4	-5.8	-5.8	-3.4	-5.8	-3.4	-5.8
ΔSO4 - Sulfate, mg/L	82	112	12	24	18	38	41	5.0	10
ΔCl - Chloride, mg/L	2	0	2.2	2.4	2.7	0.2	1.6	0.60	0.60
ΔSilica Dissolved, as SiO2, mg/L	2.0	5.0	6.9	3.6	5.8	1.0	2.0	7.3	3.7
ΔDissolved Organic Carbon, DOC, mg/L	-2.4	-1.0	-1.1	-1.8	-2.2	-1.9	-2.5	-1.1	-2.1
Mass Wasting, Anhydrite, g/day	116	158	16.4	34.2	25.8	54.3	58.1	7.7	13.6
Mass Wasting, Gypsum, g/day	1,630	2,210	23.0	955	361	9,490	30,500	53.5	190
Mass Wasting, Calcite, g/day	293	620	33.7	441	220	-2,590	785	114.2	93.5
Mass Wasting, Silica, g/day	22.1	55.3	7.63	79.6	64.1	138	829	40.4	40.9
Void Formation, Anhydrite, cm^3/d	434	589	6.12	254	96.0	2,530	8,110	14.2	50.7
Void Formation, Gypsum, cm^3/d	708	962	10.0	415	157	4,130	13,300	23.3	82.7
Void Formation, Calcite, cm^3/d	109	229	12.5	163	81.7	-958	291	42.3	34.6
Void Formation, Silica, cm^3/d	10.5	26.3	3.63	37.9	30.5	65.8	395	19.2	19.5
LOW Void Formation, TOTAL, cm^3/d	**553**	**845**	**22.2**	**456**	**208**	**1,630**	**8,800**	**75.8**	**105**
HIGH Void Formation, TOTAL, cm^3/d	**827**	**1,220**	**26.1**	**617**	**269**	**3,230**	**13,900**	**84.8**	**137**

Void Formation rates from Mineral Dissolution in Surface Seeps: There are important uncertainties regarding seepage flow estimates for surface seepage at Clark Canyon Dam. Seepage flow rates were estimated at the specific Boil area sample locations and RT Seep based on field crew experience. A much more significant problem regarding the Boil area is that sand boils may be present in other areas of the old river channel down to the confluence with the current river channel. This means that mass wasting and void formation rates for Boil 1 and Boil 2 samples may grossly under represent the total amount of seepage flow – and mass wasting – occurring in this area. Also, while a weir is present at LA Seep Weir, there is some question regarding the veracity of gage readings at this station.

Calculations suggest that void formation rates for the RT Seep vary from 76 - 85 cm^3/day at low reservoir, up to 110 - 140 cm^3/day at high reservoir. These void formation rates are around 10 times less than those calculated for the toe drain LT Outlet and RT Outlet (920 - 2,200 cm^3/day). It is safe to conclude that void formation from mineral dissolution along the RT Seep flow path is minor. However, sediment transport along this seepage flow path may be more significant. Because we know so little about the extent of seepage emergence and seepage flow paths for the sand boils, void formation rates for the entire acive Boil area may represent a greater problem. Boil 1 *site* void formation rates ranges from 22 to 26 cm^3/day at low reservoir, up to 390 cm^3/day at high reservoir.

A reasonable assessment will consider that relatively small changes in flowpath void percentage can increase permeability and affect rock mechanical strength, and that seepage is much more likely to find more restricted flow paths through embankment or foundation materials. It seems prudent to assume that mineral dissolution is ongoing. Therefore, accurate and regular measurement of seepage flows, sediments being transported in seepage, and the implementation of some method to measure or estimate total seepage flows from the old river channel are highly recommended.

Comparing Seepage Chemistry - 1986 vs. 2006

By coincidence, both the August 1986 and the May 2006 samples were collected at reservoir elevation of 5,535 ft. (1,687 m), offering a reasonably direct comparison of right side seepage and toe drain outlets over 20 years. The two sampling events are different in that the recent May 2006 samples were collected during the maximum reservoir elevation event of the first normal spring runoff after a period of drought in the watershed, while the August 1986 samples were collected well after maximum reservoir elevation during a much higher precipitation and runoff period.

In general, the 1986 samples exhibited very similar properties to more recent samples. The proportions of ions in both reservoir samples are fairly similar with the 1986 sample showing total ions concentration around 10 percent lower than 2006 samples. Sulfate is also proportionally lower in the 1986 reservoir samples.

Right Side Seepage: Figure 7 shows Stiff diagrams comparing the Alluvium field drain manhole MH 2+40 sampled in August 1986, with the recent May 2006 Right Side Well samples. This field drain manhole is located at the downstream end of the 1984 -1985 agricultural drain field, which was installed after elevated right-side seepage during wet years of the early to mid 1980's. Note that the right side field drains were not flowing on May 2006 despite the comparable reservoir elevations. This is thought to be caused by the delayed release of "bank storage" ground water from much higher reservoir elevation seepage earlier in the 1986 runoff season. The 1986 field drain sample suggests dissolution of calcite as seen in the darker blue portions of the Stiff diagram. The recent samples from the Right Side wells show that much less calcite dissolution is ongoing currently; however, the recent samples are intercepting seepage flows below the interface of the alluvium and the Beaverhead formation where the MH 2+40 drain is intercepting seepage.

Toe Drain Seepage: Returning to figure 5f and tables 5a and 5b, we may compare the 1986 and 2006 toe drain outlet samples LT Outlet, and RT Outlet, at reservoir elevation 5,535 ft (1,687 m). The RT Outlet samples show very similar chemistry and indications of some calcite dissolution for both 1986 and 2006 samples. These results suggest that the right side seepage processes have not changed significantly since the mid-1980's installation of the gravel blanket and agricultural-style field drainage system downstream of the right side toe drain. It also suggests that seepage flow paths on the right side respond more quickly to changes in reservoir elevation.

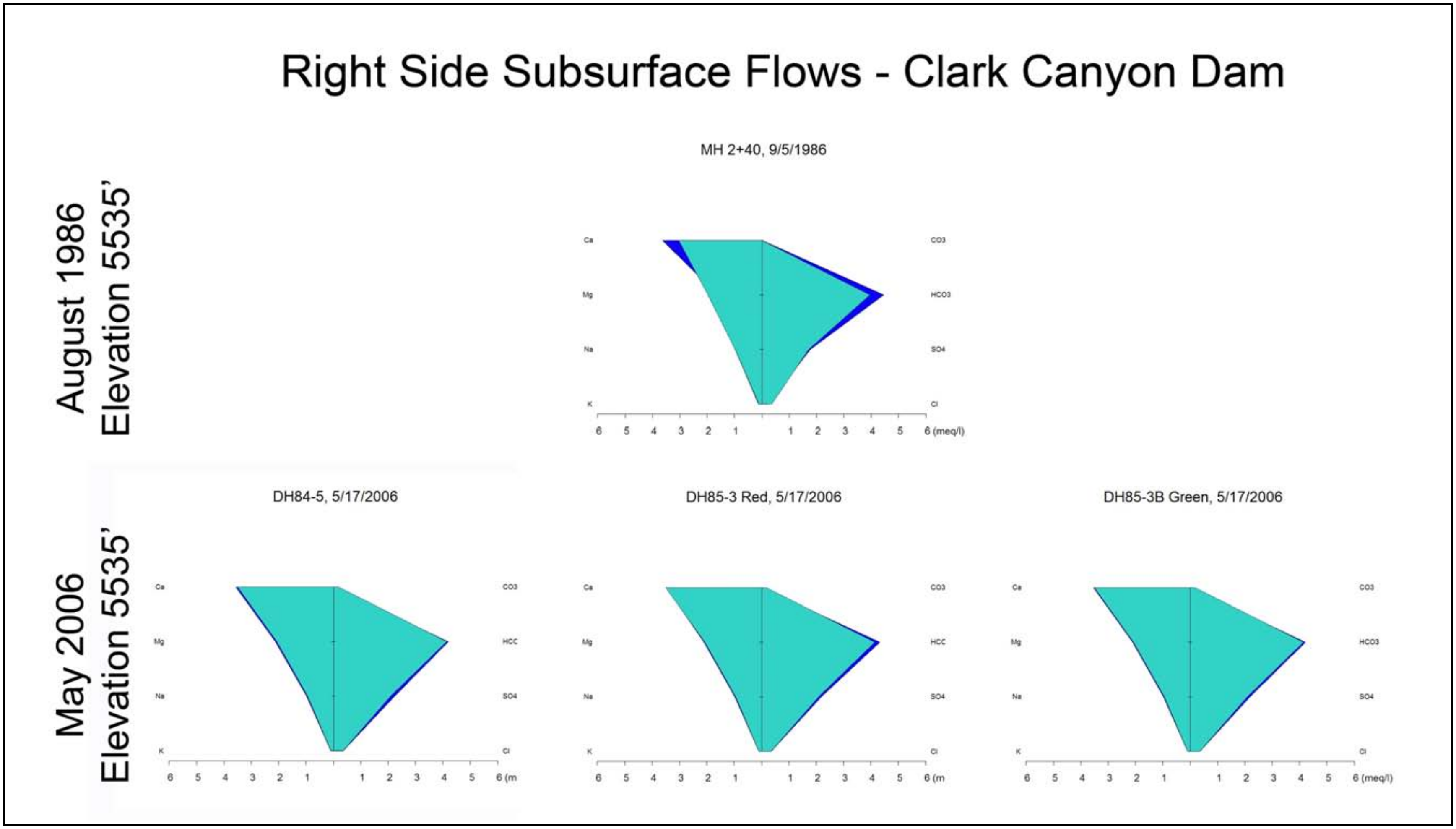
The 2006 LT Outlet sample, however, shows significantly elevated SO_4^{2-} relative to the 1986 sample, indicative of gypsum or anhydrite dissolution on the left side of the embankment and foundation. Both LT Outlet samples show indications of calcite dissolution. These results may indicate that left side seepage is now contacting gypsum or anhydrite deposits present in either the embankment below the phreatic surface, or in the Alluvium along the embankment-foundation contact. Another possibility is that the May 2006 seepage may be higher concentration seepage from earlier in the runoff season that is being flushed by rising reservoir levels. However, if elevated SO_4^{2-} is not due to time-lagged seepage flows, sulfate mineral dissolution may now be occurring. The greater solubility of gypsum and anhydrite implies that seepage flows on the left side could increase in the near term, especially if Clark Canyon Reservoir experiences a series of wet runoff years. Any future sampling of the LT Outlet seepage should address the issue of possible gypsum or anhydrite dissolution.

CONCLUSIONS

The results of this assessment can be summarized as follows:

1. **Mineral Dissolution:** Mineral dissolution is an ongoing active process at Clark Canyon Dam. Most seepage is very similar to reservoir water, but slight increases in all seepage concentrations relative to the reservoir suggest that calcite, gypsum or anhydrite, and amorphous silica continue to be dissolved as

FIGURE 7.— Comparing the chemistry of recent Right Side Wells and 1986 subsurface drain samples at Clark Canyon Dam with similar reservoir surface elevations over a 20-year period. These Stiff diagrams show the major ions concentrations for reservoir water (green polygons) superimposed over seepage water (darker blue polygons). The upper row of Stiff diagrams are from an August 1986 sampling event, while the lower row diagrams are from the May 2006 sampling event. Reservoir elevations were around 5,535 ft for both sampling dates.



reservoir water seeps beneath and through the embankment. The chemical evidence for mineral dissolution is corroborated by identification of massive to particulate deposits of calcite in geologic drill logs and recent petrographic detection of chert, opal, and calcite particles in suspended particles in seepage samples and boil area materials.

2. **Reservoir Water:** Saturation indices calculated for the reservoir and outlet works samples suggest that the reservoir water is more aggressive towards calcite during spring runoff and associated higher reservoir elevations. The reservoir water is undersaturated with respect to gypsum, anhydrite, and amorphous silica during both low and higher reservoir elevations.

3. **Foundation Seepage:** The similarity of both Left and Right Side Well concentrations to reservoir suggests that seepage flows throughout the year in the upper 30 – 50 ft (9 – 15 m) of the foundation at both low and high reservoir elevations. These flowpaths are through the Madison/Lodgepole Limestone Formation, the Alluvium, and the Beaverhead Conglomerate. The similarity in chemistry suggests that the foundation is fairly permeable, especially in the upper 30 ft of Alluvium associated with the old river channel, and that seepage transit residence times are short – on the order of days to weeks. The chemistry conclusions are supported by observed flows in the boil area downstream of the toe drain outlets during both low and high reservoir elevations.

4. **Flow near the Foundation-Embankment Interface:** The toe drain chemistry suggests that foundation seepage flows are greatest though the right center of the embankment along the path of the old Beaverhead River channel. The Left Toe Drain samples suggest possible gypsum dissolution in the embankment below the phreatic surface, or in the left side foundation near the embankment-foundation contact.

5. **Seepage Transport of Solids:** Suspended sediments were observed in several well and manhole samples, suggesting possible transport of fine sediments through the Alluvium, the Madison/Lodgepole, and Beaverhead Formations, and possibly the embankment. While suspended sediments can be a consequence of disturbing soil or other solid materials when collecting samples from some surface seeps and the Boil Area, in wells and manholes, suspended sediments should be presumed to represent possible transport of fine particulate through the embankment or foundation. This fine material transport will contribute to void formation and increased permeability along seepage flow paths, and adds to the increased voids caused by mineral dissolution.

   Fine sediments containing clays and clay sized mineral grains were found in the toe drain manhole LT 3+69, suggesting that the toe drains are collecting sediments transported by seepage. We do not know the quantity of this accumulation, or how it may vary with reservoir elevation. Sediment in-filling of toe drains was a problem noted in the early 1980's that prompted replacement of the toe drains. We still do not know with certainty whether these sediments are from the foundation Alluvium, or from the embankment below the phreatic surface. Either scenario suggests possible long-term clogging of toe drains and justifies continuing inspection and assessment of this problem.

Sediments may also be transported through the deeper foundation materials as suggested by Left and Right Side Wells intercepting seepage in the Madison/Lodgepole and Beaverhead Formations. Suspended sediments containing clay minerals were found in left side well DH84-10A, and right side wells DH-140, and DH-84-5. DH-140 samples at both low and high reservoir elevations contained suspended materials.

6. **Mass Wasting and Void Formation Rates:** Mass wasting and void formation rates from mineral dissolution were estimated for the toe drain outlets and the surface seeps (tables 5b and 6b). The greatest uncertainty about these estimates is our knowledge of accurate seepage flows. A large unknown volume of seepage is upwelling in the old river channel at both high and low reservoir elevations, and the RT Seep surfacing in the Beaverhead outcrop near the toe drain outlets has no weir to measure flows. We also found evidence that the flow gages in the toe drain weirs are not accurate. Given the uncertainty of seepage flow paths at Clark Canyon Dam, the void formation estimates suggest caution, but not alarm, with respect to mineral dissolution.

RECOMMENDATIONS

Results from this study suggest the following recommendations:

1. **No Additional Chemical Testing... Unless:** Further sampling and analysis of reservoir and seepage samples is not recommended unless reservoir elevations reach historic maximum levels, or unless seepage patterns or instrument readings suggest a progressive worsening of seepage or potential structural impairment.

2. **Enhance Physical Monitoring:** The primary method to assess progression of mineral dissolution should be based on continued monitoring of seepage flows, piezometer levels, and other instrument readings – especially at higher reservoir surface elevations. Because mineral dissolution and sediment transport are ongoing phenomena at Clark Canyon Dam, and foundation permeability and seepage will increase over time, it is very important to ensure that all seepage flows are quantified accurately at suitable intervals, and that piezometer levels are likewise monitored.

3. **Pay Attention to Flows along the Dam Center:** Because of the potentially large volume of seepage flowing along the old Beaverhead River channel beneath the embankment, the central section of the embankment should be more closely monitored during periods of spring runoff high water (reservoir surface elevation > 5,530 ft - 1,686 m), and especially when reservoir surface elevations exceed 5,540 ft (1,689 m).

4. **Suggested Action Items:** The Dam Safety Office and the Montana Area Office should consider the following actions:

   4.1 Calibrate all height gages in current weirs to ensure that all flows are accurately measured.

   4.2 Install a calibrated permanent weir at the RT Seep station and consistently monitor seepage flows. Install traps to monitor fine sediment transport.

   4.3 Install some means of measuring - or experimentally determining - the total seepage volume flowing through the old river channel sand boil area. This is a critical piece of missing information.

   4.4 Install at least two recording piezometers in the central section of the embankment behind the toe over the old river channel. One piezometer should intercept the foundation alluvium below the embankment, the other should intercept a structurally appropriate zone in the bedrock. Further assessment of piezometric gradients and the geology should establish whether the seepage is flowing primarily through the Alluvium.

   4.5 Consider establishing a tiered monitoring schedule that increases frequency of surface seepage flow measurements, piezometer water levels, and sediment accumulation in the toe drains during spring runoff and maximum reservoir elevations. Establish an instrument calibration check process prior to spring runoff to assure accurate readings and personnel familiarity at all required monitoring stations.

   4.6 Better information concerning seepage flow paths and seepage contact volumes in the abutments, foundation, and embankment would produce more accurate assessments of the engineering consequences of mineral dissolution. This effort should include a detailed geologic fracture and joint assessment along suspected flow paths, geophysical testing to identify flowpaths, perhaps followed up with dye tracing tests.

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REFERENCES

ANSI-ASQC, 1991. *Quality Management and Quality System Elements for Laboratory - Guidelines*, American National Standard, ANSI/ASQC Q2-1991, American Nation Standards Institute and American Society for Quality Control, Milwaukee, Wisconsin.

APHA, AWWA, WPCF, 1981. *Standard Methods for the Examination of Water and Wastewater*, 15th Edition, edited by Greenburg, et al., American Public Health Association, Washington, DC.

APHA, AWWA, WEF, 1998. *Standard Methods for the Examination of Water and Wastewater,* 20th Edition, edited by L.S. Clesceri et al., American Public Health Association, Washington, DC.

ASTM, 1992. *Standard Practices for Sampling Water*, D 3370-82, American Society for Testing and Materials.

ASTM, 2003. *Standard Guide for Accountability and Quality Control in the Chemical Analysis Laboratory*, E882-87(2003), Subcommittee: E01.22, Book of Standards Volume: 03.05, American Society for Testing and Materials.

ASTM, 2004. *Standard Guide for Sampling Chain-of-Custody Procedures*, D4840-99(2004), Subcommittee: D19.02, Book of Standards Volume: 11.01, American Society for Testing and Materials.

ASTM, 2005. *Standard Guide for Sampling Ground-Water Monitoring Wells,* D4448-01, Subcommittee: D34.01, Book of Standards Volume: 11.04, American Society for Testing and Materials.

Atlas, R.M., and R. Bartha,1998. *Microbial Ecology - Fundamentals and Applications*, Fourth Edition, Addison Wesley Longman Inc., Menlo Park, California, 694 pp.

Bartholomew, C.L, and Murray, B.C., 1985. *Engineering Interpretation of Water Quality Test Data*, Division of Dam Safety, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado.

Cain, C., 2005. *Baseline Seepage Chemistry Program for Clark Canyon Dam*, Travel Report to Regional Director, Great Plains Region and Area Manager, Montana Area Office, November 30, 2005, U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Cain, C., and C. Sullivan, 2006. *Baseline Seepage Chemistry Program for Clark Canyon Dam*, Travel Report to Regional Director, Great Plains Region and Area Manager, Montana Area Office, June 29, 2006, U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Calcagno, Jr., Frank, 1985. *Results of the Minimum Instrumentation Program for the Clark Canyon Dam, East Bench Unit - Three Forks Division. Pick-Sloan Missouri Basin Program, Montana,* September 17, 1985, U.S. Department of the Interior, Bureau of Reclamation, Upper Missouri Region, Billings, Montana.

Cedergren, H.R., 1989. *Seepage, Drainage, and Flow Nets,* Third Edition, John Wiley and Sons, (Wiley Interscience), New York.

Craft, D., Torres, R., and C. Cain, 2005. *Reconnaissance Visit to Clark Canyon Dam to begin Implementation of a Seepage Water Testing Program*, Travel Report to Chief Dam Safety Office, July 8, 2005, U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Craft, D., 2006. *Seepage Chemistry Manual*, U.S. Department of the Interior, Bureau of Reclamation, Dam Safety Office and Technical Service Center, Denver, Colorado.

Davies, W.E., 1960. *Origin of Caves in Folded Limestone*, National Speleological Society Bulletin, 22(1), pp5-18.

Deer, W.A., Howie, R.A., and J. Zussman, 1992. *An Introduction to the Rock-Forming Minerals,* Second Edition, Prentice Hall, Harlow, England.

DOI, 2005. *Depart of the Interior Quick facts*, informational website, http://mits.doi.gov/quickfacts/tables_all.cfm

Drever, J.I., 1988. *The Geochemistry of Natural Waters,* Second Edition, Prentice Hall, Englewood Cliffs, NJ.

Elliot, H.C., 1959. *Geologic Report - Clark Canyon Dam Site, East Bench Unit, Jefferson Division, Montana*, U.S. Department of the Interior, Bureau of Reclamation, Upper Missouri District, Billings, Montana.

FEMA, 2005. *National Dam Safety Program*, information website, http://www.fema.gov/fima/damsafe/agencies.shtm

Ford, D.C. and R.O. Ewers, 1978. *The development of limestone cave systems in the dimensions of length and depth*, Can. J. Earth Sci., 15, pp.1783-1798.

Gunnison, D. and J.M. Brannon, 1981. *Characterization of Anaerobic Chemical Processes in Reservoirs: Problem Description and Conceptual Model Formulation*, Technical report E-81-6, Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Mississippi.

Hem, J.D., 1992. *Study and Interpretation of the Chemical Characteristics of Natural Water,* Third Edition, Water-Supply Paper 2254, U.S. Geological Survey.

Horn, M.J., and J. Kucera, 2005. *The Limnological Status of Clark Canyon Reservoir: Report of Findings 2001-2003*, Technical Memorandum 8220-05-05, U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Hurcomb, D., 2005. *Petrographic Examination of Groundwater Sediments - Clark Canyon Dam, East Bench Unit, Three Forks Division, Pick-Sloan Missouri Basin Program, Montana,* Earth Sciences and Research Laboratory Referral No. 8340-04, U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Hurcomb, D., 2006. *Petrographic Examination of Groundwater Sediments - Clark Canyon Dam, East Bench Unit, Three Forks Division, Pick-Sloan Missouri Basin Program, Montana,* Materials Engineering and Laboratory Report No. 8180-06, U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

James, A.N., and A.R.R. Lupton, 1978. *Gypsum and anhydrite in foundations of hydraulic structures*, Geotechnique 28(3), pp. 249-272.

James, A.N., and I.M. Kirkpatrick, 1980. *Design of foundations of dams containing soluble rocks and soils,* Q. J. Eng. Geol, London, 13, pp. 189-198.

James, A.N., 1981. *Solution parameters of carbonate rocks*, Bull. Int. Assoc. Eng. Geol.Aachen-Essen, 24, pp. 19-25.

James, A.N., 1985. *The effects of water interactions on engineering structures*, Hydrol. Sci. J. 30(3), pp. 395-406.

Kelly, W.P., 1948. *Cation Exchange in Soils*, American Chemical Society Monograph No. 109, Reinhold Publishing Corporation, New York.

Major, Jeanne, 2003. Clark Canyon Dam Comprehensive Facility Review, Missouri River Basin Project, Montana, Great Plains Region, U.S. Department of the Interior, Bureau of Reclamation, Dam Safety Program and Technical Service Center, Denver, Colorado.

Muckenthaler, P., 1988. *Hydraulic Safety of Embankment Dams,* Dissertation, Technische Universität München, ISSN 0935-6002, Dissertations-und Fotodruck Frank GmbH, D-8000 Munich 2, Gabelsbergerstrasse 15, Germany.

Mull, D.S., Lieberman, T.D., Smoot, J.L., and L.H. Woosley, 1988. *Application of Dye-Tracing Techniques for Determining Solute-Transport Characteristics of Ground Water in Karst Terranes*, EPA 904/6-88-001, U.S. Environmental Protection Agency, Region IV, Atlanta, Georgia.

Parkhurst, D.L., Thorstenson, D.C. and L.N. Plummer, 1980. *PHREEQE : a computer program for geochemical calculations,* U.S. Geological Survey, Water Resources Division, Reston VA.

Plummer, L.N. and W. Back, 1980. *The Mass Balance Approach: Application to Interpreting the Chemical Evolution of Hydrologic Systems*, American Journal of Science, 280, pp. 130-142.

Quinlin, J.F., 1992. *Ground-Water Monitoring in Karst Terranes: Recommended Protocol and Implicit Assumptions,* EPA/600/-89/050, U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, Nevada.

Reclamation, 1961. *Schedule, General Provisions, Specifications, and Drawings - Clark Canyon Dam - East Bench Unit, Montana*, Specification No. DC-5634, U.S. Department of the Interior, Bureau of Reclamation, Engineering and Research Center, Denver, Colorado.

Reclamation, 1981, *Ground Water Manual: A Water Resources Technical Publication*, Superintendent of Documents, United States Government Printing Office, Washington DC.

Reclamation, 2005a, *Reclamation Fact Sheet*, informational website, http://www.usbr.gov/main/about/fact.html

Reclamation 2005b, *Reclamation Dam Safety Program*, informational website, http://www.usbr.gov/ssle/dam_safety/

Stiff, H.A.,Jr., 1951. Journal of Petroleum Technology, Vol. 3, pp. 15-17.

Stumm, W., and J.J. Morgan, 1996. *Aquatic Chemistry,* Third Edition, Wiley Interscience, New York.

Taylor, J.K., *1987. Quality Assurance of Chemical Measurements*, Lewis Publishers, Chelsea, Michigan.

Thrailkill, J., 1968. *Chemical and Hydrologic Factors in the Excavation of Limestone Caves*, Geological Society of America Bulletin, 79, pp. 19-46.

Timblin, L., 1987. *Chemical Analysis of Water Samples - Clark Canyon Dam - East Bench Unit - Montana*, Memorandum to Regional Director, Billings, Montana, January 8, 1987, U.S. Department of the Interior, Bureau of Reclamation, Engineering and Research Center, Denver, Colorado.

Thurman, E.M., 1985. *Organic Geochemistry of Natural Waters,* Martinus Nijhoff/Dr W. Junk Publishers, Dordrecht, The Netherlands, 1985.

USEPA, 1972, *Handbook for Analytical Quality Control in Water and Wastewater Laboratories*, USEPA, National Environmental Research Center, Cincinnati, Ohio.

USEPA, 1981, *Manual of Ground-Water Quality Sampling Procedure*, USEPA, Office of Research and Development.

USEPA, 1982, *Handbook for Sampling and Sample Preservation of Water and Wastewater*, EPA-600/4-82-029, USEPA, Environmental Monitoring and Support Laboratory, Cincinnati OH.

USEPA, 1983. *Methods for Chemical Analysis of Water and Wastes,* EPA-600/4-79-020, USEPA Environmental Monitoring and Support Laboratory, Cincinnati OH.

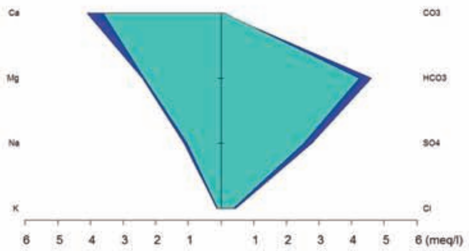
USEPA, 1986. *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods,* Volumes 1A-1D, SW-846, USEPA Office of Solid Waste and Emergency Response, Washington DC.

USGS, 1995. *A Protocol for the Collection and Processing of Surface Water Samples for Subsequent Determination of Trace Elements, Nutrients and Major Ions in Filtered Water*, U.S. Geological Survey, Water Resources Division, Reston, Virginia.

Welch, R. 2005. *Revised Schedule for Periodic Monitoring (L-23) at Clark Canyon Dam*, Memorandum to Area Manager, Montana Area Office, Billings, Montana, December 28, 2005, U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado.

APPENDIX

Stiff Diagrams for Seepage Samples Collected at Clark Canyon Dam



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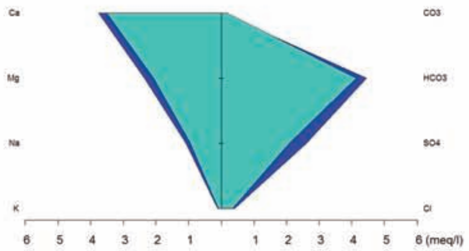

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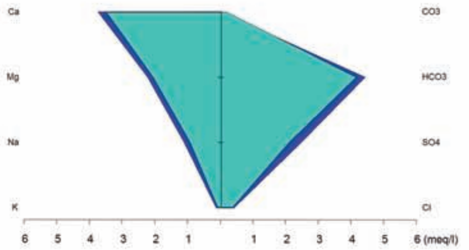

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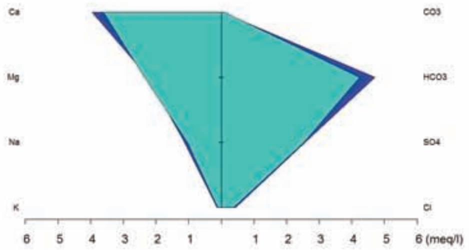

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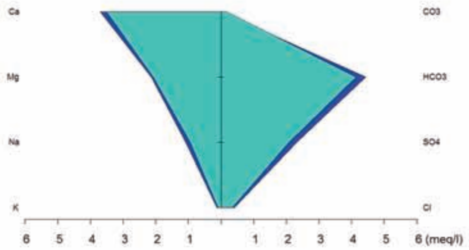

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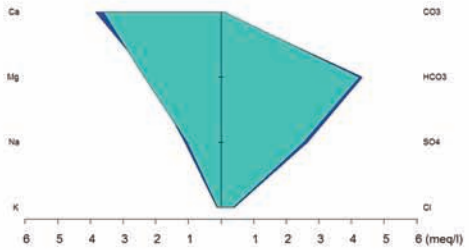

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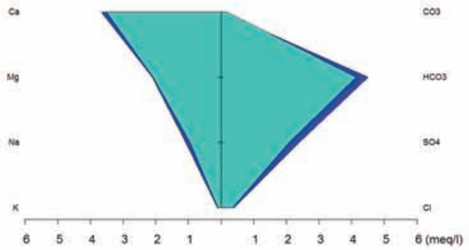

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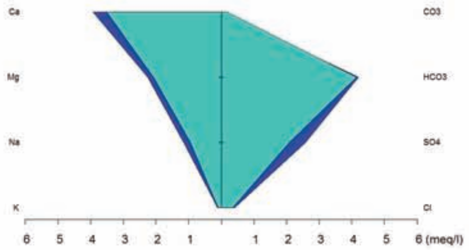

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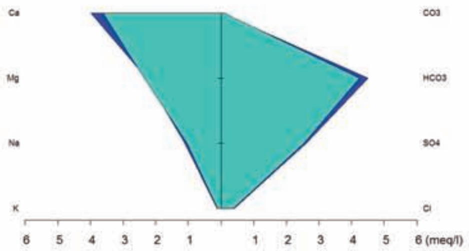

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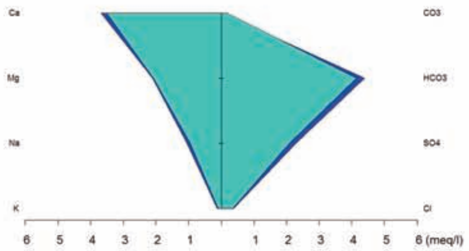

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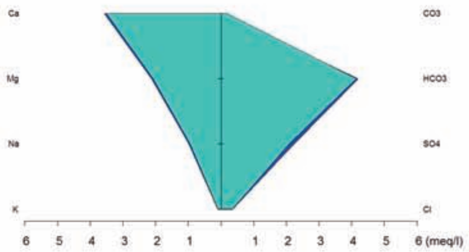

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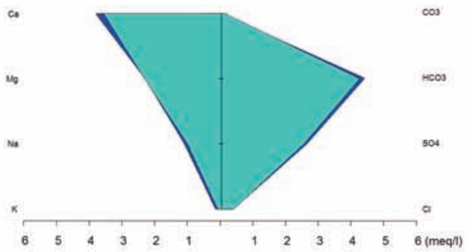

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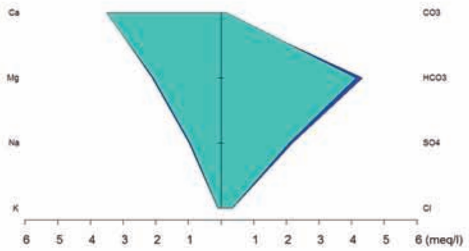

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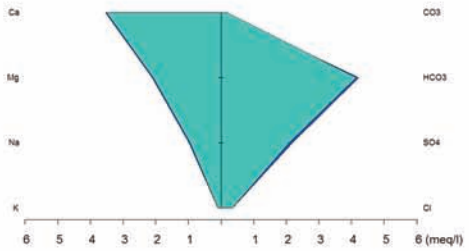

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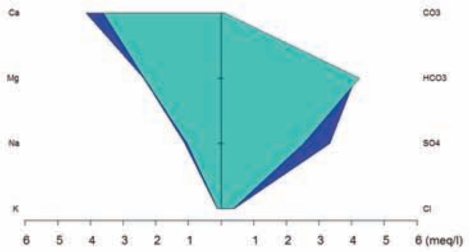

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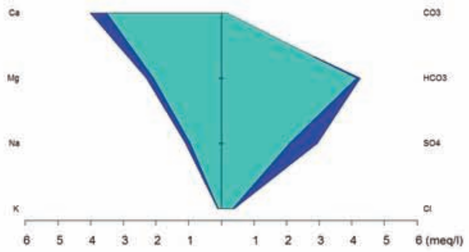

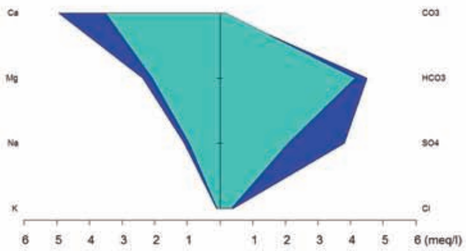
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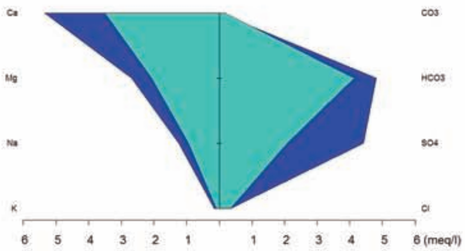
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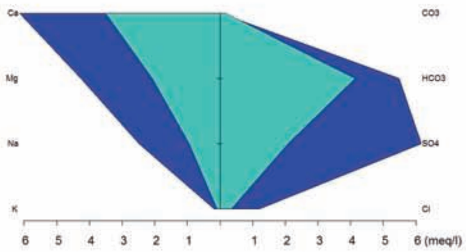
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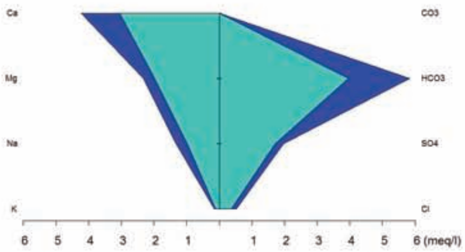
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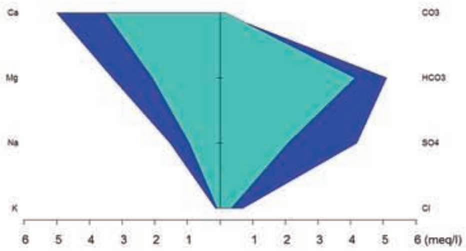
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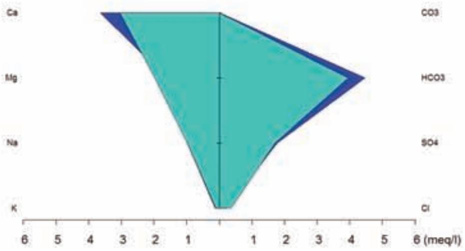
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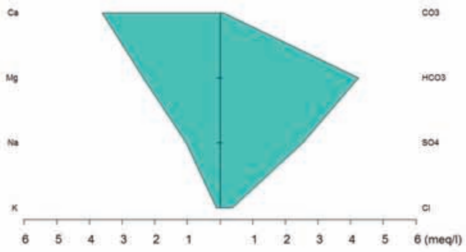
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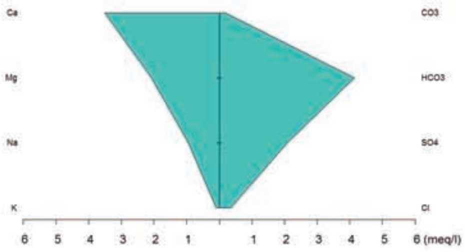
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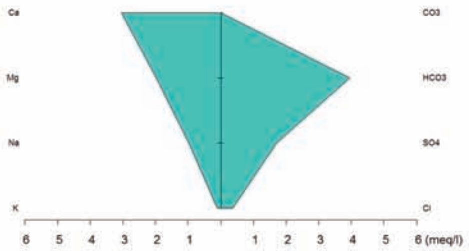

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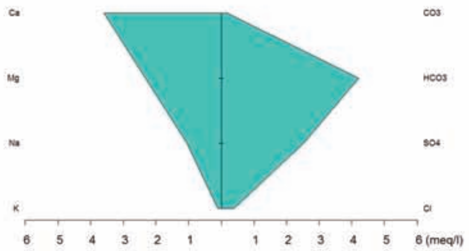

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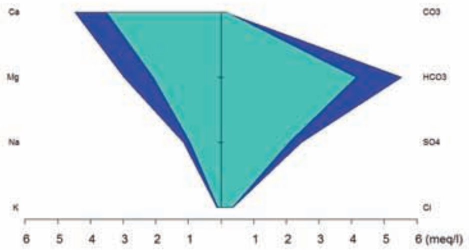

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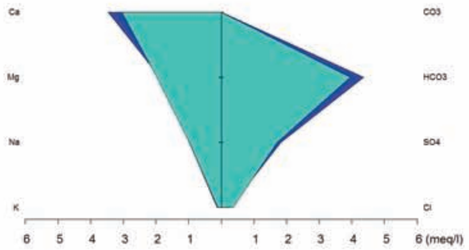

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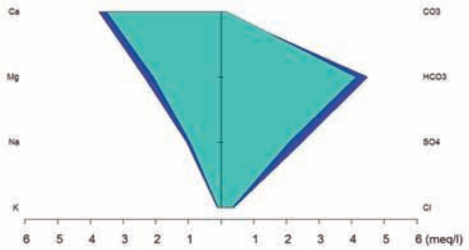

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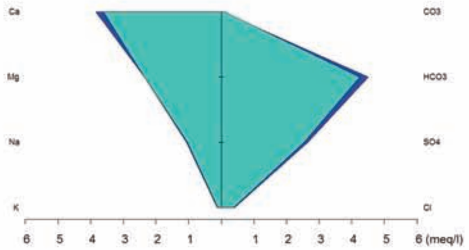

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