16. Appendix D. Report on Erodibility Characteristics of Reservoir Sediment by Agricultural Research Service

Erodibility Characteristics of Bottom Deposits from Three Klamath River Reservoirs, California and Oregon

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INTRODUCTION

Dam decommissioning has become an important aspect of restoring the nation's streams and rivers. The U.S. Bureau of Reclamation among other federal agencies and entities such as the U.S. Army Corps of Engineers are responsible for these types of projects while minimizing off-site impacts such as erosion of reservoir deposits and the potential for damage to downstream water quality and aquatic habitat. To minimize potential adverse effects of dam decommissioning, it is critical to understand and quantify the dominant processes and rates of erosion during dam removal and reservoir drawdown.

Studies are underway to support the Secretarial Determination on Klamath Dam Removal and Basin Restoration. The dams and associated reservoirs are Copco 1 1, John C. Boyle and Iron Gate.

Predicting of rates of erosion under given hydrologic and hydraulic conditions is in part a function of determining the erodibility characteristics of the reservoir deposits. As most of these deposits are fine grained silts and clays, conventional analytic methods used for non-cohesive materials which are based on particle size and weight may not valid for predicting incipient motion criteria in these cohesive deposits. The resistance of cohesive materials to erosion is a function of the strength of the electro-chemical bonds between charged clay particles. Still, to analyze the potential for and magnitude of hydraulic erosion, results must be parameterized using variables that can be associated to equations that rely on comparison of resistance values to the applied hydraulic shear stress. These variables are critical shear stress (τ_c) and the erodibility coefficient (k) and can be obtained from direct testing of the deposits with a submerged jet-test apparatus (Hanson, 1990).

Information obtained from testing the erodibility characteristics of the reservoir deposits will then be used with the Bureau's two-dimension flow and sediment transport model SRH-2D to predict incipient motion and erosion of the deposits. The model has been recently enhanced to include the National Sedimentation Laboratory's (NSL) Bank-Stability and Toe Erosion Model (BSTEM).

Erosion by Hydraulic Shear

Whether sediment is entrained by a moving fluid depends on both the properties of the fluid (i.e. its density, viscosity and velocity) and the physical properties of the sediment, such as its size, shape, density and arrangement (Knighton, 1998). A basic distinction exists between the entrainment of non-cohesive sediment (usually coarse silt, sand, gravel and boulders or cobbles) and cohesive sediments, because the entrainment of the latter is complicated by the presence of cohesion (Knighton, 1998). In both cases, most approaches to sediment transport have relied upon the concept of a critical value of some parameter. The present paper utilizes the applied shear stress, τ_o as the independent variable.

Mechanisms of Cohesive Sediment Erosion: Mechanistically, the detachment and erosion of cohesive (silt- and clay-sized) material by gravity and/or flowing water is controlled by a variety of physical, electrical, and chemical forces. Identification of all of these forces and the role they

play in determining detachment, incipient motion, and erodibility, of cohesive materials is incomplete and still relatively poorly understood (Winterwerp and van Kesteren, 2004). Assessing the erosion resistance of cohesive materials by flowing water is complex due to the difficulties in characterizing the strength of the electro-chemical bonds that define the resistance of cohesive materials. The many studies that have been conducted on cohesive materials have observed that numerous soil properties influence erosion resistance including antecedent moisture, clay mineralogy and proportion, density, soil structure, organic content, as well as pore and water chemistry (Grissinger, 1982). For example, Arulanandan (1975) described how the erodibility of a soil decreases with increasing salt concentration of the eroding fluid, inducing weakening of inter-particle bonds. Kelly and Gularte (1981) showed that for cohesive sediments, increasing temperature increases erosion rates, particularly at low salinity, while at high salinity, there is less of an effect on erosion.

Cohesive materials can be eroded in three contrasting ways (Mehta 1991): (1) surface erosion of bed aggregates; (2) mass erosion of the bed; and (3) entrainment of fluid mud. Partheniades (1965) showed that clay resistance to erosion seemed to be independent of the macroscopic shear strength of the bed, provided that the bed shear stresses did not exceed the macroscopic shear strength of the material. Once the bed shear stress exceeds some critical value, then following Ariathurai and Arulanandan (1978) the rate of erosion, ε, of cohesive materials can be predicted by:

$$\varepsilon = k_d \left(\frac{\tau_o}{\tau_c} - 1 \right)^a \qquad \text{(for } \tau_o > \tau_c\text{)}$$

$$\varepsilon = 0 \qquad \text{(for } \tau_o \leq \tau_c\text{)} \qquad (1)$$

where k_d = erosion rate coefficient (m s^{-1}), τ_o = bed shear stress (Pa), τ_c = critical shear stress (Pa), and a = exponent assumed to equal 1.0. Equation 1 may also be written as (Partheniades, 1965):

$$\varepsilon = \frac{k_d}{\tau_c}(\tau_o - \tau_c) = k(\tau_o - \tau_c) \qquad \text{(for } \tau_o > \tau_c\text{)}$$

$$\varepsilon = 0 \qquad \text{(for } \tau_o \leq \tau_c\text{)} \qquad (2)$$

where k = erodibility coefficient (m^3/N-s). Note, however, that this simple approach does not differentiate between the different modes of erosion.

OBJECTIVES and SCOPE

The overall objective of the study was to determine erodibility characteristics of reservoir deposits from Copco 1 1, John C Boyle and Iron Gate Reservoirs in the upper Klamath River System, California and Oregon (Figure 1). An attempt was to be made to determine how these characteristics varied under different moisture contents and degrees of compaction.

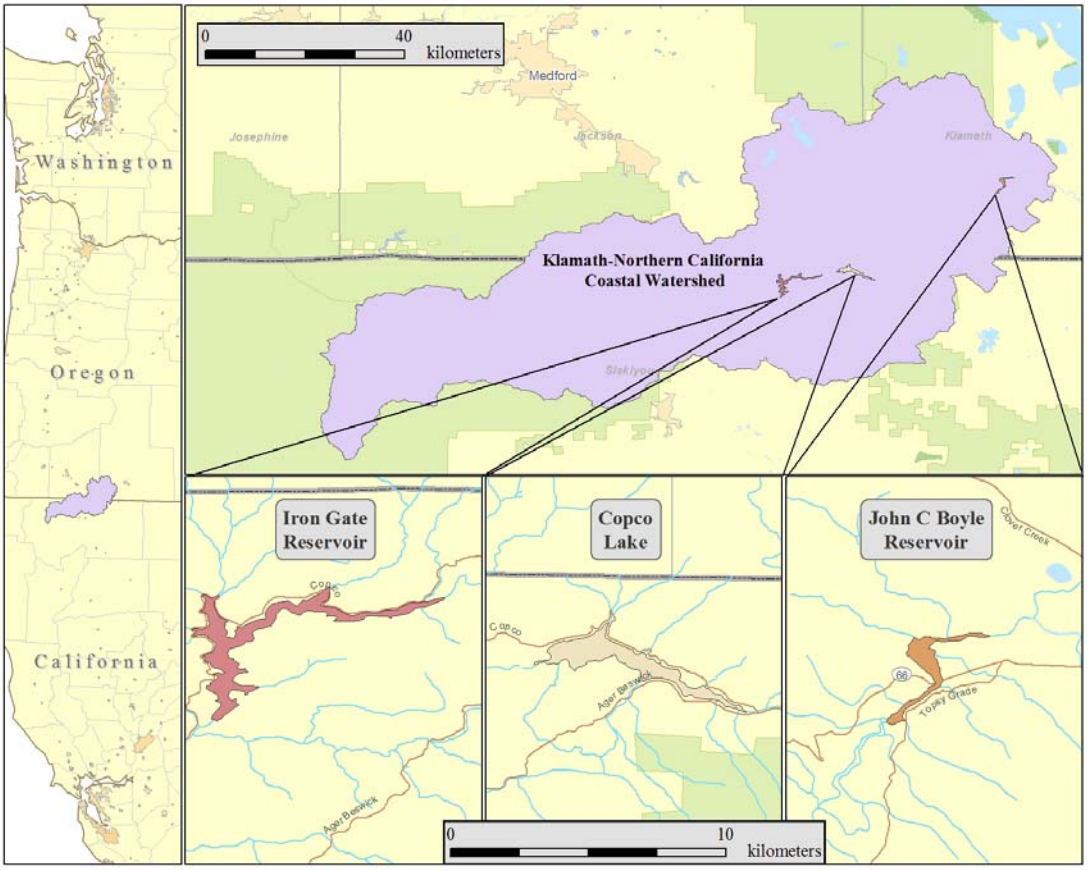

Figure 1- Location map of Iron Gate, Copco 1 1 and John C. Boyle Reservoirs in the Klamath River System.

METHODS

The methods employed in this study can be classified as field and analytic. Field methods were restricted to sample collection as all sample testing was conducted in a laboratory setting.

Sample Collection

Field-data collection of reservoir deposits was carried out on November 18 and 19, 2009 from a boat. Samples collection was attempted at three locations in each reservoir as determined by the Bureau. A spring-loaded Ponar grab sampler was lowered by cable through the water column to the bed and retrieved by winching the sampler back up into the sampling boat. Material was then dumped into 5-gallon buckets, labeled and sealed for shipment back to NSL. In total 15 buckets were retrieved from the nine sampling locations (Table 1). A particularly firm or coarse-grained bed was identified at sampling location 486 in Iron Gate Reservoir making sample recovery difficult. Ultimately, an insufficient sample mass (5.2 kg) was obtained from this location to conduct erodibility tests. In general however, the bulk samples flowed easily from out of the Ponar sampler into the buckets.

Table 1. Summary of bulk samples obtained from the reservoirs on November 18-19, 2009. [1]Site identification numbers provided by the Bureau.

Reservoir	Site Number[1]	Number of Buckets	Total Weight (kg)
Copco 1	489	2	41.9
Copco 1	490	2	41.9
Copco 1	491	2	44.1
Iron Gate	485	2	44.3
Iron Gate	486	1	5.2
Iron Gate	488	1	17.5
John C Boyle	482	2	40.8
John C Boyle	483	1	22.0
John C Boyle	484	2	41.4

Sample Preparation

Initial data provided by the Bureau and observations of material exhumed from the Ponar sampler indicated that the reservoir deposits were generally highly organic and too soft for erosion testing. It was, therefore, understood that the samples would have to undergo a certain degree of drying and compaction to make them conducive to testing. Before this could take place however, an initial sample density was required to determine how much compaction would be required to produce a sample, bulk unit weight of 12 kN/m^3, representing the initial testing condition. An initial sample density (ρ_s) was obtained by determining the weight of the soil-water mixture and dividing by the volume of the sample within each bucket ($\pi r^2 h$; where r = radius of the bucket and h = the height of the sample in the bucket). Bulk unit weight of the material (γ_s) was then obtained by multiplying (ρ_s) by 9.81/1000.

Initial unit weights were remarkably consistent, ranging from 10.5 to 11.6 kN/m^3 with an average of 11.0 kN/m^3 (standard error = 0.0868). Table 2 shows the initial, calculated bulk unit weights for each bucket.

Compaction of samples: 20.3 centimeter by 40.6 centimeter boxes were constructed and prepared to permit sample drainage during application of a vertical load. The box was constructed of this size to be able to accommodate two submerged jet tests as well as other instruments to characterize erodibility. A flat metal plate was also constructed to fit just inside the top box and on top of the sample while compaction occurred. The initial volume that the sample filled within the each box was calculated to determine the volume required to reach 12 kN/m^3.

Each sample was poured into a separate box and the height of the sample in the box was recorded. Initial compaction was carried out using static weights placed on top of the metal insert. This allowed the sample to shed some of it's water in preparation for more aggressive compaction with a hydraulic press. The static load used was 40.8 kg and was kept on the

samples from 2 to 5 days and sometimes longer depending on the availability of the hydraulic press.

Table 2. Initial bulk unit weights (γ_s) of samples obtained with the Ponar sampler. [1]Site identification numbers provided by the Bureau.

Reservoir	Site Number[1]	Bucket #	Bulk unit weight (kN/m^3)
Copco 1	489	1	10.8
Copco 1	489	2	10.8
Copco 1	490	1	11.1
Copco 1	490	2	10.8
Copco 1	491	1	11.3
Copco 1	491	2	11.3
Iron Gate	485	1	11.5
Iron Gate	485	2	11.2
Iron Gate	486	1	11.2
Iron Gate	488	1	11.2
John C Boyle	482	1	10.6
John C Boyle	482	2	10.5
John C Boyle	483	1	11.6
John C Boyle	484	1	10.7
John C Boyle	484	2	10.7

To shorten the time required to obtain the desired bulk unit weight, a hydraulic press was used. An initial load of 136 kg was applied to the samples coming from the static load press. Over time, the sample absorbed the load from the hydraulic press as the sample compacted and reduced in volume and the hydraulic arm of the press remained at the same position. For this reason, the load was reapplied over a period of 3 to 5 days by periodically lowering the hydraulic arm. As the sample became more difficult to compact, the load was increased to approximately 295 kg, depending on the integrity of the box the sample was contained in. The volume of the sample was continuously monitored during the period of compaction permitting back-calculation of bulk unit weights as the sample volume decreased. The target bulk unit weight of 12 kN/m^3 was achieved using the hydraulic press.

Given an average, initial bulk unit weight of 11.0 kN/m^3, it was somewhat surprising that attaining the target bulk unit weight of 12 kN/m^3 (a 9% increase) took 3-5 days under a load of up to 295 kg. This was attributed to the generally organic nature of the deposits and delayed erosion testing copnsiderably.

Sample drying: Given that one of the objectives of this research was to determine to what degree erosion parameters varied between moist and dried conditions, several methods were tested by which samples could be dried efficiently while minimizing surface cracks. They were:

- Air drying—spreading the sample out evenly in a pre-fabricated box and allowing it to dry inside the laboratory;
- Oven-assisted drying—spreading the sample out evenly in a pre-fabricated box and drying it out in a convection oven set to a temperature of 60°C;
- Heat lamp assisted drying—spreading the sample out evenly in a prefabricated box and placing a heat lamp over the sample at various heights;
- Pressing then air drying—spreading the sample out evenly in a prefabricated box, pressing it to a unit weight of 12 kN/m^3 then allowing it to air dry for several days.

Although air drying tended to take the most time, it was a more effective method in reducing surface cracking. Moisture contents (by volume) were obtained with a digital moisture meter using time-domain reflectometry (TDR) technology at various stages of the drying process. As erosion testing with the jet-test apparatus and other instruments was destructive to the prepared sample, the compaction and drying process had to be repaeated after samples were remixed and brought to moisture contents similar to the initial.

Characterization of Erodibility

To characterize the erodibility of the reservoir deposits several types of tests were carried out on the prepared samples. The most important were those used to determine values of the hydraulic-erosion parameters τ_c and k. Ancillary data on moisture content, bulk unit weight, total shear strength and compressive strength were also collected.

Erosion Testing with Jet-Test Device: A submerged jet-test was developed by the Agricultural Research Service (Hanson, 1990; Figure 2) for testing the *in situ* erodibility of surface materials (ASTM, 1995). This device was developed based on knowledge of the hydraulic characteristics of a submerged jet and the characteristics of soil-material erodibility. In an attempt to remove empiricism and to obtain direct measurements of τ_c and k, Hanson and Cook (1997) developed analytical procedures for determining soil k based on the diffusion principles of a submerged circular jet and the corresponding scour produced by the jet. These procedures are based on analytical techniques developed by Stein et al. (1993) for a planar jet at an overfall and extended by Stein and Nett (1997). Stein and Nett (1997) validated this approach in the laboratory using six different soil types.

As the scour depth increases with time, the applied shear stress decreases due to increasing dissipation of jet energy within the plunge pool. Detachment rate is initially high and asymptotically approaches zero as shear stress approaches the critical shear stress of the bed material. The difficulty in determining equilibrium scour depth is that the length of time required to reach equilibrium can be large. Blaisdell *et al*. (1981) observed during studies on pipe outlets that scour in cohesionless sands continued to progress even after 14 months. They developed a function to compute the equilibrium scour depth that assumes that the relation between scour and time follows a logarithmic-hyperbolic function. Fitting the jet-test data to the logarithmic-hyperbolic method described in Hanson and Cook (1997) can predetermine τ_c. k is then estimated by curve-fitting measured values of scour depth versus time and minimizing the error

of the measured time versus the predicted time. Both k and τ_c are treated as soil properties and the former does not generally correlate well with standard soil mechanical indices such as Atterberg limits. Instead, k is dependent on the physio-chemical parameters that determine the inter-particle forces characteristic of cohesive sediment (Parchure and Mehta, 1985; Mehta, 1991).

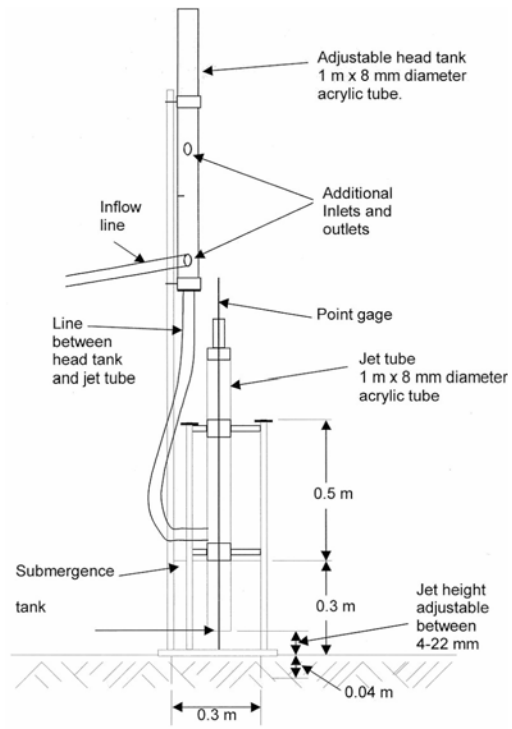

Figure 2. Schematic of jet-test device (from Hanson and Simon, 2001).

To provide an erosion-testing apparatus that could be used in remote field locations as well as in smaller laboratory setups, the National Sedimentation Laboratory, requested to Dr. Greg Hanson of the Agricultural Research Service in Stillwater, OK to design and construct a miniature version of the jet-test device. This was developed in 2008 (Figure 3) and extensively used by NSL in various field locations across the United States. The mini-jet apparatus consists of an electric submersible 60 liters/second pump powered by a portable generator, a scaled-down 0.12 m- diameter submergence tank with an integrated, rotatable 3.18 mm-diameter nozzle, depth gauge, and delivery hoses. This was the instrument used for erosion testing in this study. An example of test results are shown in Figure 4.

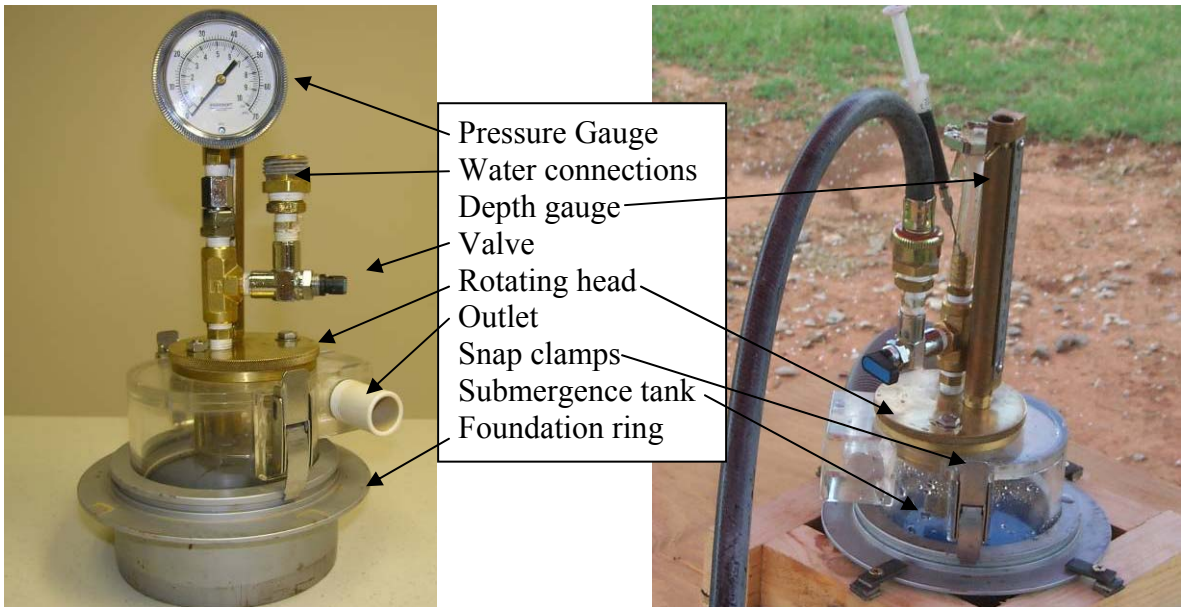

Figure 3. Mini-Jet (~0.12 m diameter) including foundation ring, submergence tank, rotating head, outlet, water delivery connections, gauge, valve, outlet, snap clamps, and depth gauge.

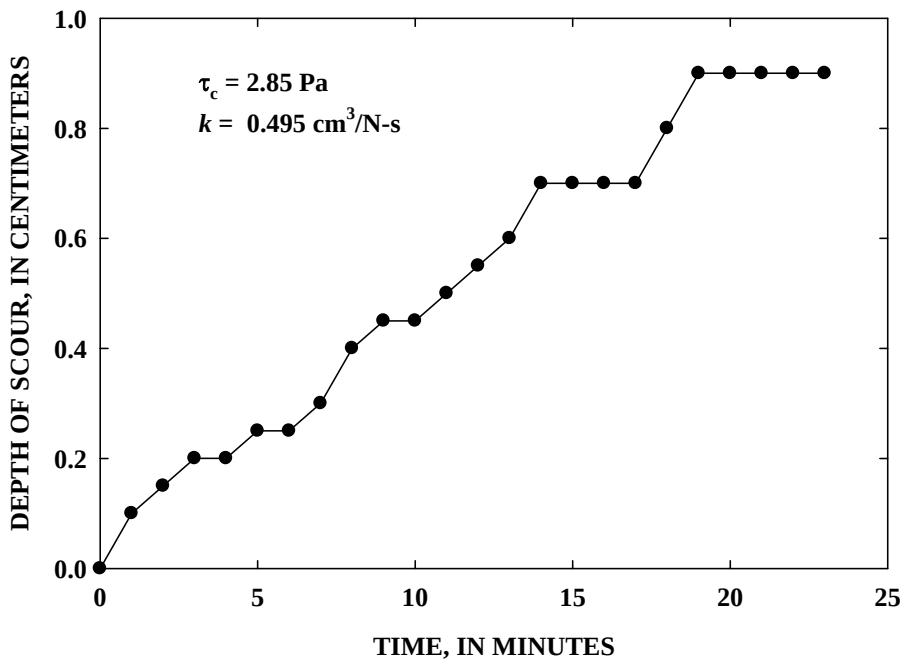

Figure 4. Example of erosion-test results for Iron Gate 488 using the mini-jet device.

Geotechnical measurements: Although we rely on erosion tests that provide hydraulic-resistance parameters (as with the jet-test device), geotechnical forces actually control the resistance of cohesive materials. Rapid geotechnical measurements that minimize sample disturbance or additional sample preparation were conducted to test whether relations could developed between shear strength and τ_c and k. Measurements of geotechnical shear strength (τ_f) were obtained with a Torvane shear device. A cylindrical vane was inserted vertically into the

sample to the depth of the vanes. The head of the device was then rotated until the material encompassing the vane shears (fails). As the head of the device is spring loaded, a needle points to the maximum shear strength value (in kg/cm^2) that was resisted prior to failure. Values are then converted to kPa by multiplying by 98.0665.

A pocket penetrometer was used to measure the unconfined compressive strength of the samples. The tip of the spring-loaded instrument was pushed vertically into the sample until it has been embedded a distance of 6.35 mm. Compressive strength (in kg/cm^2) is then read directly off the shaft of the instrument. These tests were conducted before the samples were tested with the mini-jet device and throughout the drying process.

RESULTS OF MATERIAL and EROSION TESTING

Laboratory tests were conducted by the Bureau from core samples and were provided to NSL as background information on the nature of the reservoir deposits. The soft, and semi-fluid nature of the materials can be identified by both the average moisture contents (by weight) which ranged from 176 to 297%, and by the fact that these moisture contents generally exceeded the liquid limit of the materials by almost a factor of two (Table 3). Because moisture contents exceeded the liquid limit of the sample materials (Table 3), erosion tests that were attempted prior to any compaction failed because the materials were far too soft and fluidized to create a seal around the base of the jet-test device.

Table 3. Average values of reservoir-deposit characteristics. Original data provided by the U.S. Bureau of Reclamation.

Reservoir	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Liquid Limit (%)	Plasticity Index	Moisture content (% by weight)
Copco 1	51.1	42.5	6.4	0.0	152	71.0	297
Iron Gate	45.8	31.2	16.0	7.0	88.3	43.7	176
John C Boyle	29.7	40.0	25.4	4.9	152	58.5	265

Hydraulic-Erosion Test Results

A total of 33 tests at a sample bulk unit weight of 12 kN/m^3 were conducted with the mini-jet device during the study. Tests were conducted at moisture contents ranging from 48 to 82% (by volume). Samples that had not been dried (per se) but only compacted had moisture contents greater than 67% and were considered “moist” for the purposes of this study. Samples with moisture contents less than this and were subjected to drying, were considered “dried”.

For all tests, critical shear stresses (τ_c) ranged over six orders of magnitude, from 0.0008 to 114 Pa. Generally, however, reservoir average (τ_c) for moist samples at 12 kN/m^3 were equivalent to sand-sized materials, ranging from 0.58 to 1.1 Pa (Table 4). Erodibility coefficients (k) ranged

from 0.05 to about 5.6 cm^3/N-s with moist, reservoir-average values being very consistent at 0.90 to 2.2 cm^3/N-s. An example of sample material post jet test is shown in Figure 5.

Table 4. Summary of reservoir-average erosion-testing results.

Reservoir	Total number of tests	τ_c (Pa)		k (cm^3/N-s)		Average τ_c (Pa)			Average k (cm^3/N-s)		
		Average	Median	Average	Median	Moist	Dried	% difference	Moist	Dried	% difference
Copco 1	10	3.26	1.18	0.741	0.555	0.578	5.93	926	1.11	0.370	-66.8
Iron Gate	11	20.8	2.72	1.43	0.654	0.934	55.7	5860	2.19	0.098	-95.5
John C Boyle	12	2.51	0.815	0.778	0.614	1.12	9.47	743	0.903	0.152	-83.2

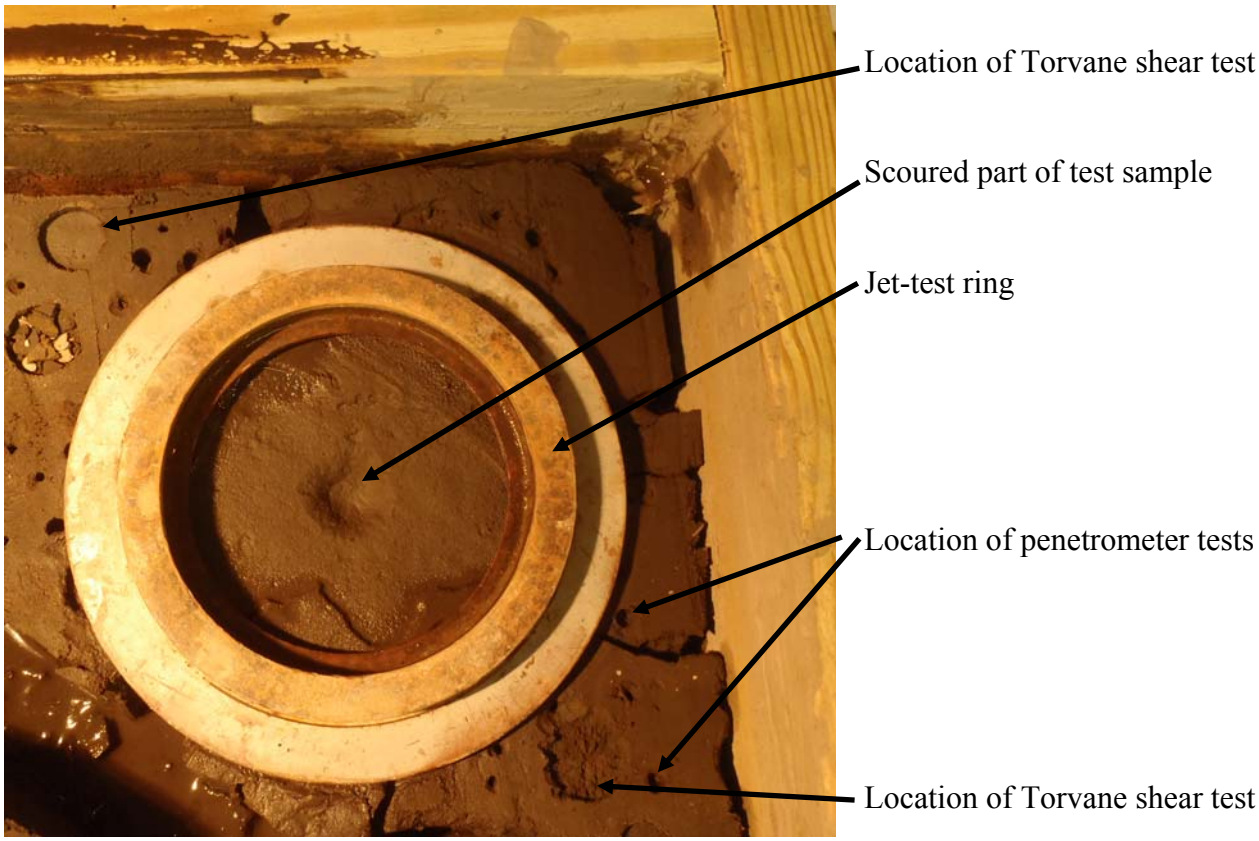

Figure 5. Photograph of surface of test sample after completion of a mini-jet test. The depression in the center of the sample surface represents the material scoured by the jet.

The effects of drying on erosion resistance and erodibility (τ_c and k) were significant with reservoir-average values of τ_c increasing by at least an order of magnitude (743 to 5860%) (Table 4). Associated decreases in k also occurred with sample drying, but not to the extent of the increases in critical shear stress. Reservoir-average values of the erodibility coefficient decreased between 67 and 96% (Table 4). This increase in resistance for dried samples equates to τ_c-values equivalent to those of gravel and cobbles (5.9 for Copco 1 to 56 Pa for Iron Gate), indicating that if the drawdown of the reservoir was very slow and the deposits were left to dry, resistance of the materials would increase considerably and erosion rates would be reduced.

Erosion-testing results of cohesive sediments are often disseminated as a relation between τ_c and *k* for the purpose of being able to estimate *k* from tests or estimates of critical shear stress. Results from the mini-jet testing of the Klamath River reservoir deposits shows a typical relation between these two variables with the relation flattening off at τ_c-values less than about 0.1 Pa (Figure 6) (Simon *et al*., 2010). The form of this relation has been observed in data sets collected in cohesive deposits from diverse regions. These findings imply that *k* does not vary by an inverse power function under conditions of very high excess shear stress (in the range of 100 to 1,000), but reaches a maximum value as a function of the nature of the eroding materials.This can be attributed to: (1) the mass erosion and/or (2) entrainment of fluid mud erosion mechanisms proposed by Mehta (1991). Truncating the relation shown in Figure 6 at a critical shear stress of 0.1 Pa provides a significant relation (r^2 = 0.89) between these two important erosion-rate variables that can be used to predict *k* from τ_c (Figure 7). In fact, the strength of the relation as indicated by the r^2-value is better than any other relation the authors have developed for other field locations (Simon et al., 2010).

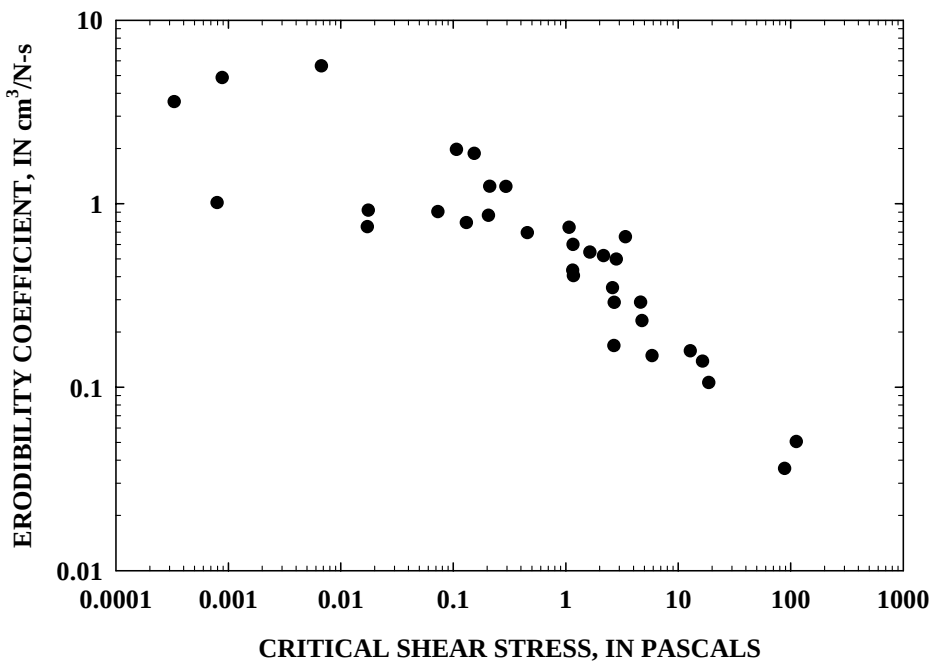

Figure 6. Relation between critical shear stress and the erodibility coefficient for mini-jet tests at 12 kN/m^3 on Klamath River reservoir deposits.

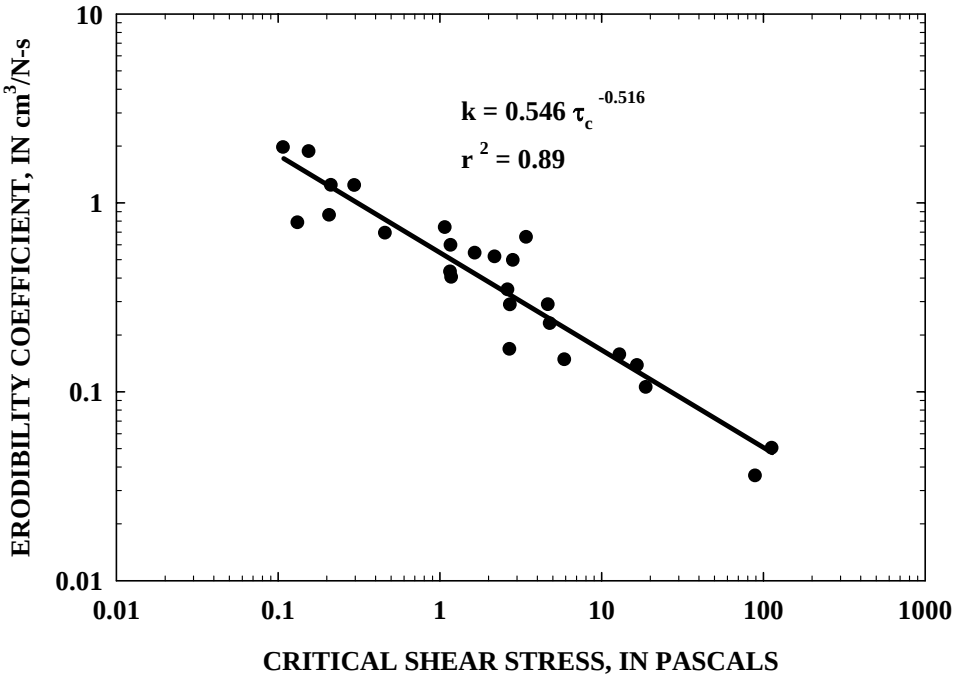

Figure 7. Relation between critical shear stress (τ_c) and the erodibility coefficient (*k*) for mini-jet tests on Klamath River reservoir deposits. Data truncated at τ_c-values less than 0.1 Pa after Simon et al. (2010).

Further investigation of the original relation with all test points at 12 kN/m^3 (Figure 6) provides clear evidence of the effect of sample drying on values of the erosion variables (Figure 8). The majority of the more resistant tests are those that have been dried to less than 67% moisture

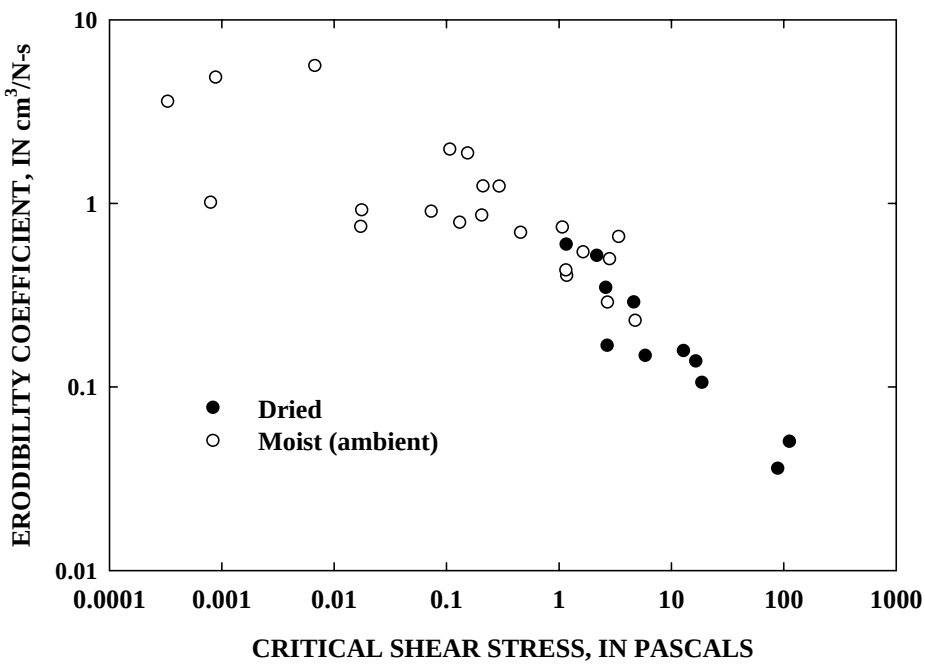

Figure 8. Original relation between critical shear stress and the erodibility coefficient showing that most of the more resistant samples are representative of dried conditions.

content, with the most resistant tests (τ_c > 5 Pa) all having been dried. This effect is further substantiated in investigating the relation between the hydraulic-erosion variables and the associated geotechnical variables that theoretically control resistance to erosion.

Geotechnical Test Results

The geotechnical tests conducted by NSL as part of this study were meant to be rapid, reproducible procedures to be used as ancillary data to the hydraulic-erosion testing. They were not meant to replace the direct shear or triaxial shear tests being conducted by the Bureau for use as model input in bank-stability algorithms. Still, results provided by the Torvane shear device in particular have been useful in understanding the nature of the reservoir deposits. Analysis of the geotechnical tests was again relative to compaction to 12 kN/m^3 and represents both "moist" and "dried" samples. A summary of test results is provided in Table 5.

Table 5. Results of geotechnical tests on Klamath River reservoir samples compacted to 12 kN/m^3.

Reservoir	Total number of tests	Total shear strength (kPa)		Compressive strength (kPa)		Average shear strength (kPa)			Average compressive strength (kPa)		
		Average	Median	Average	Median	Moist	Dried	% difference	Moist	Dried	% difference
Copco 1	10*5	12.2	9.81	15.6	6.36	3.78	22.8	503	4.73	22.6	377
Iron Gate	11*5	15.0	0.67	28.7	4.52	0.516	39.1	7478	3.07	71.5	2231
John C Boyle	12*5	6.75	1.59	21.2	12.1	5.78	10.2	76	24.4	9.90	-59.4

Reservoir-average values of shear strength range from 6.75 to 15.0 kPa while compressive strength values range from 15.6 to 28.7 kPa. As with the hydraulic-erosion variables there were distinct differences between moist and dried samples, with the dried samples showing greater geotechnical strength. The one exception was the apparent decrease in compressive strength with drying for samples from John C Boyle Reservoir (Table 5). This may have bee due to dilatancy and cracking just below the surface in the dried condition. Shear strength values obtained with the Torvane device seem reasonable given the composition of the reservoir deposits (on average, 30 – 51% clay). Reservoir-average values for moist tests ranged from 0.52 to 5.8 kPa in comparison to 10 to 39 kPa for dried tests. The increase in shearing resistance can probably be attributed to the development of matric suction within

To test whether the measured variations in critical shear stress and the erodibility coefficient could be related to the geotechnical characteristics that theoretically control erosion rates in cohesive materials, the two data sets were combined. Results show a reasonably good relation (r^2 = 0.64) indicating that values of critical shear stress can be potentially estimated from total shear strength (τ_f) (Figure 9). Similarly, a relation between total shear strength and *k* (r^2 = 0.65) was developed from the data (Figure 10) again indicating that k could be estimated from τ_f. The advantage of this is that the Torvane shear tests are (1) far less destructive, (2) take much less sample area, and (3) can be conducted considerably quicker than tests with the mini-jet device.

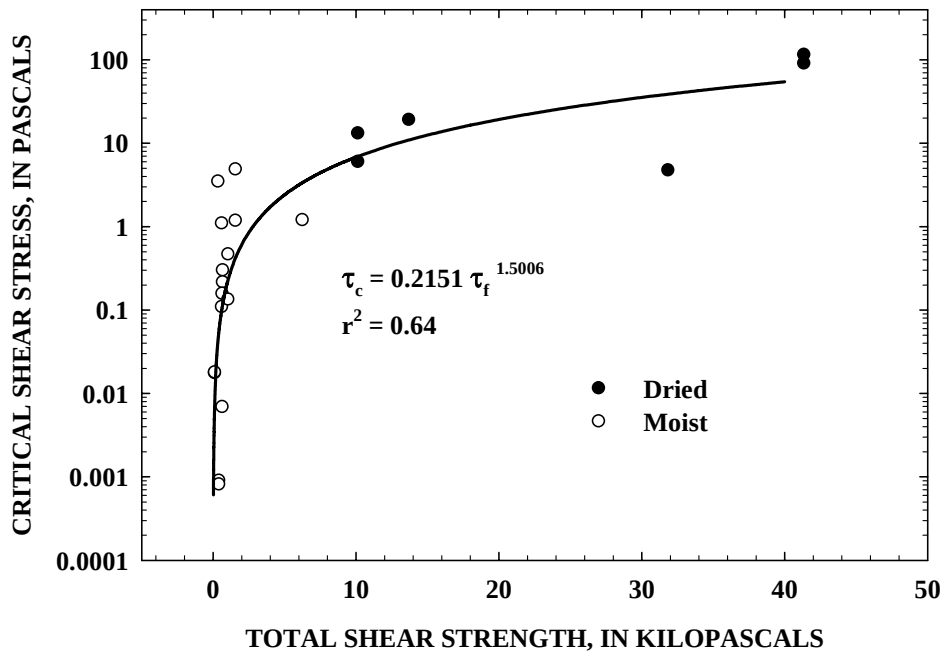

Figure 9. Relation between total shear strength (τ_f) as measured with the Torvane shear device and critical shear stress (τ_c) as measured with the mini-jest device.

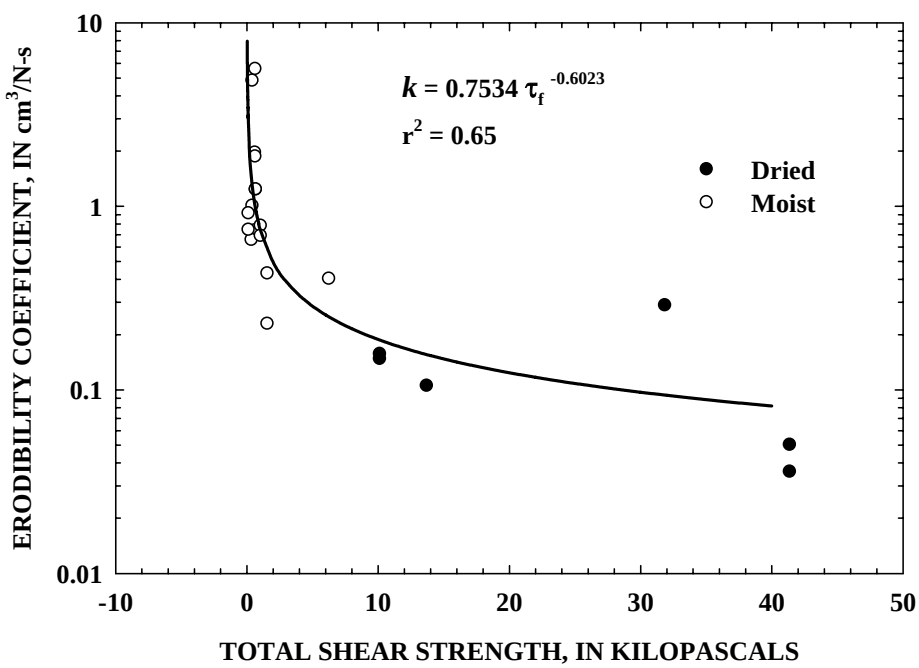

Figure 10. Relation between total shear strength (τ_f) as measured with the Torvane shear device and the erodibility coefficient (k) as measured with the mini-jest device.

SUMMARY and CONCLUSIONS

Hydraulic and geotechnical tests were conducted on samples obtained with a Ponar grab sampler from three reservoirs in the Upper Klamath River System, California and Oregon. In general, the materials were particularly fine grained (silts and clays) that in their in situ state, had moisture contents that exceeded their liquid limits by about a factor of two. In order to conduct tests on these materials, it was agreed that the samples would be compacted to a bulk unit weight of $12kN/m^3$. A total of 33 hydraulic-erosion tests were carried out over a range of moisture contents with a mini jet-test device. A significant regression relation was developed between critical shear stress and the erodibility coefficient that can be used to calculate the erodibility coefficient from critical shear stress.

Reservoir-average values of critical shear stress under moist conditions ranged from 0.58 to 1.1 Pa, equivalent to the stress required to entrain sand-sized particles. Upon drying to moisture contents less than 67%, hydraulic shearing resistance increased dramatically with reservoir-average values ranging from 5.9 to 56 Pa. Critical shear stresses of this magnitude are equivalent to those for gravels and cobbles. Similarly, reservoir-average erodibility values decreased from 67 to 96% with drying. The increase in erosion resistance was probably due to the development of matric suction in the materials as they dried out. This was further supported by the identification of substantial increases in total shear strength (measured with a Torvane shear device). Reservoir-average shear-strength values for moist conditions ranged from 0.52 to 5.8 kPa compared to 10 to 39 kPa under dried conditions. These shear-strength values are completely reasonable given that reservoir-average clay contents ranged from 30 to 51%.

Data provided from this study will be used by the Bureau as inputs into SRH-2D, a two-dimensional flow and sediment transport model to conduct simulations of possible erosion rates and channel adjustments. To provide data for sensitivity analysis the Bureau will “bracket” erosion parameters to test for the effects of uncertainty of the input variables. For this reason, statistics for the erosion parameters, critical shear stress and the erodibility coefficient are provided that represent the central tendency of the data distribution (Table 6).

The hydraulic and geotechnical data sets were successfully combined to develop relations between total shear strength and both critical shear stress and the erodibility coefficient. This signifies that these two hydraulic-erosion parameters can be estimated with measurements of shear strength as obtained with the Torvane device. This potentially has a great advantage as the Torvane device can be deployed easily and rapidly.

Table 6. Distribution of critical shear stress and erodibility coefficient for each reservoir.

Reservoir	Condition	τ_c (Pa)		k (cm^3/N-s)	
		25th Percentile	75th Percentile	25th Percentile	75th Percentile
Copco 1	All tests	0.494	2.53	0.360	1.110
	Moist	0.214	1.08	0.736	1.23
	Dried	2.20	4.69	0.288	0.516
Iron Gate	All tests	0.0405	10.1	0.152	1.43
	Moist	0.00386	1.51	0.776	3.34
	Dried	13.2	95.6	0.0465	0.145
John C Boyle	All tests	0.104	3.26	0.273	0.800
	Moist	0.0470	1.54	0.457	0.838
	Dried	7.70	11.2	0.149	0.154

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APPENDIX

Appendix 1. Raw test data. * Refers to average moisture content for "moist" samples.

Test date	Reservoir	Site	Unit weight in kN/m^3	Jet test id	Dried or Moist	τ_c in Pa	k in cm^3/N-s	Torvane (total shear strength) in kPa	Penetrometer (compressive strength) in kPa	Avg. moisture content (% vol.)
8/12/2010	**Copco 1**	489	12.0	1	M	1.188	0.402	6.28	6.13	71.9
7/26/2010	**Copco 1**	490	12.0	1	D	18.96	0.11	13.7	0.01	57.8
7/26/2010	**Copco 1**	490	12.0	-	-	-	-	13.7	0.01	80.2
7/26/2010	**Copco 1**	490	12.0	1a	D	4.69	0.29	31.9	45.1	57.8
7/26/2010	**Copco 1**	490	12.0	-	-	-	-	13.3	20.6	64.0
6/7/2010	**Copco 1**	491	12.0	1b	M	0.298	1.23	0.70	6.59	*77.2
6/7/2010	**Copco 1**	491	12.0	2	M	0.214	1.23	0.70	6.59	*77.2
6/7/2010	**Copco 1**	491	12.0	-	M	-	-	40.5	61.8	73.7
8/26/2010	**Copco 1**	491	10.6	1c	D	2.65	0.345	-	-	Dried
8/26/2010	**Copco 1**	491	10.6	2	D	1.177	0.594	-	-	Dried
8/27/2010	**Copco 1**	491	10.6	3	D	2.201	0.516	-	-	Dried
9/9/2010	**Copco 1**	491	10.1	1	M	1.084	0.736	0.63	4.52	72.3
9/9/2010	**Copco 1**	491	10.1	2	M	0.108	1.957	0.63	4.52	72.3
6/24/2010	**Iron Gate**	488	12.0	1	M	0.000894	4.82	0.44	2.66	*77.7
6/24/2010	**Iron Gate**	488	12.0	2a	M	0.000807	1.004	0.44	2.66	*77.7
6/24/2010	**Iron Gate**	488	12.0	1	M	0.0741	0.897	-	-	72.4
6/24/2010	**Iron Gate**	488	12.0	2	M	2.85	0.495	-	-	72.1
6/4/2010	**Iron Gate**	485	12.0	1c	M	3.45	0.654	0.37	0.98	*77.7
7/23/2010	**Iron Gate**	485	12.0	1	D	114	0.0501	41.38	89.2	54.8
7/23/2010	**Iron Gate**	485	12.0	2	D	89.7	0.04	41.38	89.2	54.8
7/23/2010	**Iron Gate**	485	12.0	-	-	-	-	34.62	36.0	71.2
8/30/2010	**Iron Gate**	485	10.8	1	D	16.7	0.137	-	-	Dried
8/31/2010	**Iron Gate**	485	10.8	2	D	2.72	0.167	-	-	Dried
9/9/2010	**Iron Gate**	485	9.7	1	M	0.007	5.579	0.67	4.52	69.1
9/9/2010	**Iron Gate**	485	9.7	2	M	0.156	1.862	0.67	4.52	69.1
6/8/2010	**John C Boyle**	482	12.0	1	M	0.0003	3.57	-	-	*71.3
6/8/2010	**John C Boyle**	482	12.0	2	M	0.208	0.856	-	-	*71.3
6/28/2010	**John C Boyle**	482	12.0	-	M	-	-	34.81	49.03	50.7
6/28/2010	**John C Boyle**	482	12.0	1	M	1.66	0.539	-	-	69.7
6/28/2010	**John C Boyle**	482	12.0	2	M	2.74	0.288	-	-	71.3
8/18/2010	**John C Boyle**	482	9.8	1	D	5.93	0.147	10.16	9.90	50.1
8/18/2010	**John C Boyle**	482	9.8	3	D	13.00	0.156	10.16	9.90	50.1
9/9/2010	**John C Boyle**	482	9.9	1	M	0.133	0.781	1.07	12.1	67.4
9/9/2010	**John C Boyle**	482	9.9	2	M	0.462	0.688	1.07	12.1	67.4
6/23/2010	**John C Boyle**	483	12.0	1c	M	0.0175	0.742	0.15	1.30	*71.3
6/23/2010	**John C Boyle**	483	12.0	2b	M	0.0178	0.913	0.15	1.30	*71.3
7/8/2010	**John C Boyle**	484	12.0	1	M	4.83	0.229	1.59	47.4	67.9
7/8/2010	**John C Boyle**	484	12.0	2	M	1.17	0.430	1.59	47.4	68.9