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Evaluating High pH for Control of Dreissenid Mussels

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Executive Summary

When dreissenid mussels (*Dreissena polymorpha* – zebra mussel and *Dreissena bugensis* – quagga mussel) are present in the source of raw cooling water they become a serious problem for industrial facilities using this water unless defensive steps are taken. The treatment of choice for most facilities tends to be one of chemical control, as it is convenient and effective. The major advantage offered by chemical treatments is that they can be engineered to protect most of the facility, from intake to discharge. A wide variety of chemical treatment strategies is available for controlling mussel populations; however, minimizing local environmental impact is frequently difficult. Chlorine, widely used for dreissenid control, creates undesirable by-products. Proprietary compounds used for mussel control generally have to be detoxified by bentonite clay. Both chlorine and proprietary products tend to be non-selective and therefore may be toxic to all forms of aquatic life.

As dreissenid mussels have a relatively narrow range of pH tolerance, with the optimum range being pH 7.5 to 9.3, it was hypothesized that by manipulating this environmental variable it may be possible to control the growth, settlement, and survival of dreissenids in raw water systems by increasing the pH level with a single point addition. Two field experiments were carried out using a custom built flow-through laboratory to test the effect of elevated pH on dreissenid mussels. The first experiment was carried out on quagga mussels in the lower Colorado River and the second was performed on zebra mussels using water from San Justo Reservoir in San Benito County, California. Both experiments tested the ability of dreissenid pediveligers to settle under conditions of elevated pH, the long term survival of the adult dreissenids under the same conditions, and the influence on experimental conditions on corrosion rates for carbon steel, stainless steel, and copper.

The experiment on the lower Colorado River could not be carried out at the desired pH due to the unexpected formation of a precipitate, most likely calcium carbonate (calcite). Raw water at the lower Colorado River has an average calcium concentration of 80 mg/L, a temperature of 24°C, an alkalinity of 130 mg $CaCO_3$/L, a conductivity of 920 μS/cm, and a pH of 8.3. These values result in a calcite saturation index ($SI_{calcite}$) of 0.88, which is considered oversaturated. When the pH of the water was raised with the addition of sodium hydroxide, the $SI_{calcite}$ also increased thereby causing the formation of a calcite precipitate. At the target pH levels there was unmanageable precipitate and the pH test levels had to be decreased for the experiment to continue.

The settlement of dreissenid pediveligers at the lower Colorado River was inhibited with increasing pH. At the maximum achieved pH of 9.1 there was approximately 90% reduction in the maximum settlement observed in the controls. However, the settlement was almost as low in pH of 8.9 as at pH of 9.1 (85% reduction in settlement). These results suggest that perhaps the inhibition in settlement was due to the presence of the precipitate rather than the increase in background pH. No mortality of adults was observed at the experimental pH levels. The shell length to total dry weight relationship did not vary between treatments and control suggesting that the adult mussels at the lower Colorado River were not under any under any growth limiting stress.

The results from the experiment on zebra mussels at San Justo Reservoir are similar to those for the lower Colorado River, without the formation of a precipitate. Settlement decreased with increasing pH; at the highest pH tested (pH 9.6) new settlement by zebra mussels was almost entirely absent. The observed mortality of adult zebra mussels was low, but did tend to increase with increasing pH. As with the quagga mussels on Lower Colorado River, the shell length to total dry weight relationship did not vary between treatments and control suggesting that the adult mussels were not under any growth limiting stress.

At San Justo Reservoir, we also tested the response of adult zebra mussels to very high pH levels. This work was prompted by the observation of rapid death of adult quagga mussels when they were accidentally exposed to a pH of 12. In May 2011, a small sample of adult zebra mussels was exposed to pH of 10, 11, and 12 at San Justo Reservoir. After 12 hours, 90% mortality of adults was recorded at pH 12. Due to the small sample size and possible poor physical condition of the adults in San Justo Reservoir in the spring, the experiment was repeated in October, 2011. In this October 2011 experiment, 90% mortality of adults at pH 12 was reached only after 120 hours. At the same time, significant mortalities were observed both at pH 10 and pH 11.

In order to examine the effects of elevated pH on materials of construction, corrosion coupons were placed in all test tanks for the duration of the experiments. In the lower Colorado River experiment, elevated pH had little effect on the corrosion rates for carbon steel and copper, but there was a significant increase in the corrosion penetration for stainless steel. However, the corrosion rates for stainless steel were quite low in absolute terms in all treatments. At San Justo Reservoir, the corrosion coupons showed decreased corrosion rates, compared to the control, for all three alloys.

From this study, we conclude that pH elevation could be used both as a preventative treatment to eliminate settlement by dreissenid mussels and as an end of season treatment to eliminate adults, provided the source water does not have a high calcite saturation index. The high pH treatment would have to be tailored to the site water quality. Particularly, if high pH was to be used as end of season treatment, longer treatment at lower pH (10) may be preferable to shorter treatment at higher pH (11 or 12) if the calcite saturation index for the source water is high.

The pH levels in the current study were adjusted using sodium hydroxide. Sodium hydroxide is currently registered by the US EPA as a pesticide and is primarily used as an herbicide, fungicide, algaecide, and indoor disinfectant. An application for an amendment to the registration of sodium hydroxide would be required prior to its use in mussel control.

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1 Introduction

When dreissenid mussels invade a new system, calcium and pH are two of the most important environmental variables which determine the success or failure of the invasion. Without sufficient calcium (>15 mg/L), dreissenids are unable to build their shells. How pH limits the dreissenid success is less understood. Most adult mollusks have an upper and lower lethal threshold for pH, the lower limit is generally near 6.5 and the upper is near 9 (Harman 1974). It is assumed that veligers have lower tolerance to pH extremes than adults.

Few studies have been done on the upper pH limit for dreissenid survival. Most authors place the upper pH limit for long term dreissenid survival between 9.3 and 9.5. This assumption appears to be based on very sparse data. Most authors quote the paper by Sprung (1993) which states that veligers develop to settlement stage when pH ranges from 7.4 to 9.4 with an optimal pH of 8.4 at temperatures of 18-20˚C. These values are used by a number of authors when constructing invasion models (Naddafi *et al.* 2011) or assessing invasion risk for dreissenids in North America (Cohen and Weinstein 1998; Cohen 2008; Hayward and Estevez 1997) and in Europe (Trichkova *et al.* 2007).

The only other pertinent study found on upper pH tolerance of adult dreissenids was done by Bowman and Bailey (1998). Their laboratory experiment used a very small sample size and very small treatment containers, and the final pH levels were uncertain. The authors concluded that the upper pH limit for zebra mussels was 9.3-9.6. This conclusion was based on the results obtained after 30 days of exposure where 100% of adults were alive in the low NaOH treatment (final pH = 9.3) and control, 60% were alive in the medium NaOH treatment (final pH = 9.50), and 10% were alive in the high NaOH treatment (final pH = 9.55).

The purpose of this study was to carry out a "proof of principle" experiment to determine the upper pH at which quagga and zebra mussel veligers will not settle even at adequate calcium levels, and to assess the impact of this elevated pH has on adult mussels. In addition, we examined existing regulations regarding the use of sodium hydroxide as a pesticide to determine its potential for mussel control.

2 Methodology

The "proof of principle" experiment to determine the upper pH limit for quagga and zebra mussels and to test the ability of elevated pH to prevent adult settlement or cause mortality was carried out in two parts. In the first part, a mobile laboratory was set up at Lake Havasu, Arizona. Water containing quagga mussel veligers was drawn from Lake Havasu on the lower Colorado River. Settlement and adult mortalities were monitored for eight weeks. The experiment was terminated when settlement was observed in control tanks. Upon completion of the Lake Havasu experiment, the mobile laboratory was disassembled, disinfected, and moved to San Justo Reservoir in California where the entire experiment was repeated on zebra mussel veligers.

2.1 Experimental set-up

On location, raw water containing dreissenid veligers was drawn into the field laboratory. The water was then split into four streams and entered 160 L mixing tanks. Three tanks had pH individually increased by the addition of sodium hydroxide solution, the fourth stream acted as control at background pH. On exiting the mixing tanks, each water stream was further subdivided into three streams which flowed into individual settling tanks (Figure 1).

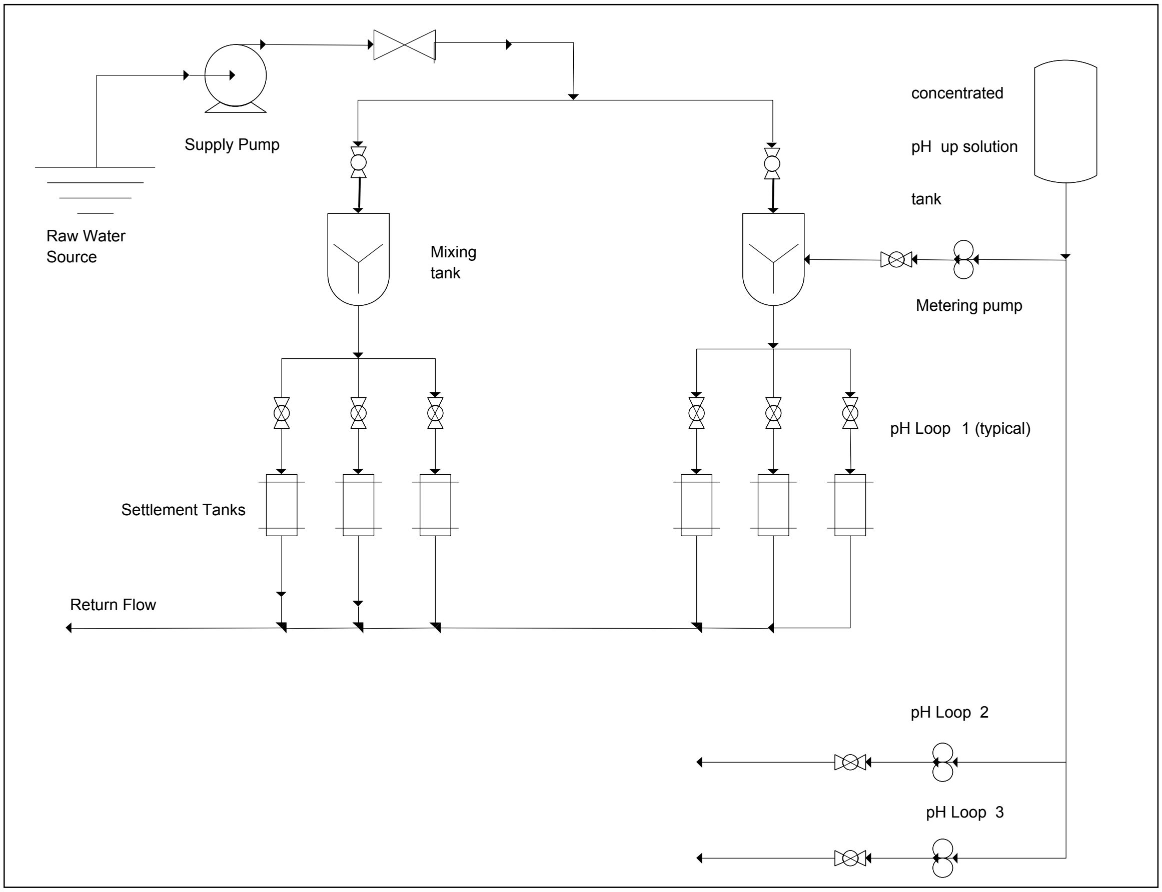

Figure 1. Schematic of the experimental layout showing two out of the four experimental loops in detail.

The settling tanks were insulated coolers with capacity of 45 L. The coolers had been filled with lake water for approximately one week prior to the experiment to condition them and remove any possible contaminants. Immediately prior to the start of the experiment, the coolers were emptied and dried with paper towels. Once each cooler was filled with lake water and adjusted to the proper pH, a 20 cm x 10 cm mesh bag containing live adult dreissenid mussels collected on location was placed in each cooler. A rack containing four settlement plates and six corrosion coupons was also placed in each cooler (Figure 2 and Figure 3). Two corrosion coupons each of carbon steel, stainless steel, and copper were arranged in such a manner as to avoid galvanic coupling to dissimilar metals. Corrosion coupons were supplied by and analyzed by Metal Samples Company, Inc. Average corrosion penetration rates were determined gravimetrically and all coupons were visually inspected to assess the nature of any attack (i.e. general etching versus localized attack).

All tanks were monitored continuously for pH and temperature using electronic probes connected to a programmable logic controller. The controller adjusted the pH by adding a concentrated solution of sodium hydroxide via the metering pumps. All tanks were monitored weekly for settlement.

Prominent Beta-4 pumps were used for the addition of the concentrated sodium hydroxide solution to three of the four mixing tanks. All four tanks were continuously mixed using stainless steel propeller style paddles. Water exited each tank on the bottom, through a housing containing a flow sensor, temperature probe, and pH probe supplied by Prominent Controls. These probes, together with the control module (Dulco Marin 2), monitored and recorded all pH and temperature values and if necessary, sent an adjustment signal to the sodium hydroxide solution addition pumps to add more solution to raise the pH (Figure 4). Each cooler was tested twice per day with a hand held pH meter. The readings were compared to the pH readings for the mixing tank displayed on the control module and recorded on a log sheet.

Figure 2. Rack with settling plates and corrosion coupons.

Figure 3. Settlement chamber with settlement plates, corrosion coupons, and mesh bag containing live adult mussels.

Figure 4. Flow-through laboratory in operation.

2.2 Settlement prevention and long term impact on quagga mussel adults by elevated pH

The first part of the "proof of principle" experiment was carried out on the lower Colorado River. The mobile laboratory was put into full operation on March 4, 2011. The ambient water temperature was 13ºC and the number of veligers in the water was very low, approximately 2 veligers/L. No ready-to-settle veligers were observed in the incoming stream and no new settlement was observed on the adults collected in the forebay and placed in the mesh bags.

The pH adjustment was set at 9.1, 9.3, and 9.5. The adjustment was initially done using soda ash (sodium carbonate, Na_2CO_3). After the first 24 hours, a significant amount of precipitation was observed in all settlement coolers, the amount deposited increasing with increasing pH (Figure 5). The nature of the deposit was assumed to be calcium carbonate precipitating from solution due to the elevated pH. This level of precipitation was unexpected.

Figure 5. Precipitate observed after 24 hours at pH 9.3.

The use of soda ash was discontinued and the system was drained and cleaned of all deposit. On Monday, March 7, 2011, the system was returned to service using sodium hydroxide to adjust the pH. The use sodium hydroxide avoids the introduction of additional carbonate and was found to reduce the propensity for calcium carbonate deposition. However, within 48 hours it was clear that the amount of precipitate was still unacceptable at a pH of 9.5, coating all upper surfaces in the settling tanks and instrument probes.

On March 9, 2011, the portion of the system running at a pH of 9.5 was shut down and drained. Bags of adult mussels were rinsed and the adults were checked for mortality and placed in separate containers with ambient water from the river. The system was de-scaled using Safety Acid (an inhibited hydrochloric acid formulation marketed as Magic Acid) solution. The corrosion coupons were wiped clean with dry paper towel.

On March 11, 2012, the system was returned to service. The three pH treatments now tested were revised as follows:

System A - 8.9
System B - 9.0
System C - 9.1
System D - Control

Temperature and pH data were collected in a daily log (Appendix I) both for the mixing tanks and for the individual settlement chambers starting March 12, 2011.

To increase mussel settlement within settlement tanks, additional plankton was collected daily from the forebay. A sump pump was used to lift water from the forebay through a garden hose at a rate of approximately 1,000 L/hr. The garden hose emptied into a plankton net (1 m mouth diameter, 53 micron net and bucket mesh) positioned within a large tank (approximately 200 L) filled with water (Figure 6). This arrangement was observed to minimize the trauma to the plankton collected. The collection of plankton through the net was done continuously. Twice each day (9:00 am and 5:00 pm) the collected plankton was removed from the net collection bucket into a separate vessel. The collected volume was diluted with river water to 4 L, mixed with a glass rod, and quickly divided into four parts. Each mixing tank received 1 L of the concentrated plankton. The incoming veliger count increased throughout the experiment, peaking at approximately 150 veligers/L.

2.3 Settlement prevention and long term impact on zebra mussel adults by elevated pH

The second part of the “proof of principle” experiment was carried out at the San Justo Reservoir located in San Benito County, California. The flow-through laboratory was sterilized after the end of the experiment on the lower Colorado River and re-located to San Justo Reservoir at the end of April 2011. At this time the reservoir was still in the process of being re-filled with a mix of water from San Luis Reservoir and Sacramento Delta water. It appeared that there had been a significant kill of zebra mussels in the reservoir during the winter. Only a small number of live adults was found on several buoys in the reservoir, the water was too high to locate any on the shoreline. The water from the reservoir was brought to the laboratory through a 2 inch potable water polyethylene pipe using a 1.5 hp submersible Champion pump. The distance from the pump intake to the laboratory was approximately 400 ft.

2.3.1 Short term exposure of adult zebra mussels to high pH

The mobile laboratory was put into operation at San Justo Reservoir during the first week in May. The first test carried out was to determine the effect of very high pH on adult zebra mussels. Live adult mussels were placed in mesh bags and introduced into each of the coolers in the lab. The number of mussels per bag varied between 10 and 27. Mussels in the bags were in clusters; the clusters of mussels were randomly selected from a small pool of adults available. Any adults with perforated shells were excluded. The three treatments tested were as follows:

System A - pH 10
System B - pH 11

System C - pH 12
System D - Control, background pH of 8.8 to 8.9

Each bag of adults was checked for mortality after 12, 24, 36, and 48 hours.

As a result of potentially harsh winter conditions in the San Justo Reservoir, the adult zebra mussels collected in May 2011 may have been under physiological stress leading to quick mortalities during the high pH experiment. The experiment was repeated in October 2011 to verify that the mortalities observed in the May experiment were a result of elevated pH conditions alone and not due to a combination of high pH and the impact of stressful winter conditions. Larger numbers of adults were exposed in each pH tested in October 2011. Mortality was recorded after 24, 48, and 72 hours.

2.3.2 Settlement prevention and long term impact on zebra mussel adults using elevated pH at San Justo Reservoir

The methodology for this experiment was the same as that described in Section 2.2. Once pH stabilized in all settlement tanks, the experiment commenced on May 22, 2011. There was no problem with precipitation in the test tanks at San Justo Reservoir and we were able to adjust the test pH to the desired upper level. The three treatments tested were now as follows:

System A - pH 9.2
System B - pH 9.4
System C - pH 9.6
System D - Control

The veliger numbers in the plankton were very low throughout the experiment (average density 53 veligers/L). Settlement was detected in the control tanks in mid-July. At that time, the veliger numbers were declining rapidly in the plankton. Although settlement was observed in the control tanks, the experiment was terminated because further settlement was not expected due to declining veliger counts in the plankton. On July 29, 2011, the corrosion coupons were removed and sent for analysis. On July 30, 2011, the bags containing adults were examined and a detailed examination of the settling plates was performed. On July 31, 2012, the flow was stopped, the system was drained, and all experimental vessels were examined for settlement.

3 Results

3.1 Results from the experiment on the lower Colorado River

3.1.1 Settlement prevention

The experiment ran from March 12, 2011 to April 21, 2011. The system was plagued by problems caused by precipitation and required extensive labour to continue to function. The pH fluctuated in all treatments (Figure 7) on daily basis due to the on-going fouling of the pH probes. On April 2, 2011, system B, which was supposed to maintain a pH of 9.0, accidentally overdosed to a pH of 12. As the overdose happened during the night, the high pH persisted for more than 10 hours in the settlement chambers. Subsequent to this overdose, we found all adults in the mesh bags were dead and no settlement was recorded in system B.

From Table 1, the settlement appeared lower both in the system A tanks and the system C tanks compared to the control (system D).

Table 1. Settlement of quagga mussels in test tanks.

System	Cooler	Number of Settlers				
		In Coupons	In Rack	In Cooler	In Washed	Total No.
A	1	2	1	12	N/A	15
A	2	0	5	18	N/A	23
A	3	0	1	4	N/A	5
B	1	0	0	0	N/A	0
B	2	0	0	0	N/A	0
B	3	0	0	0	N/A	0
C	1	0	4	6	N/A	10
C	2	0	2	12	N/A	14
C	3	2	4	9	N/A	15
D	1	5	16	4	22	47
D	2	10	84	3	30	127
D	3	3	83	6	56	148

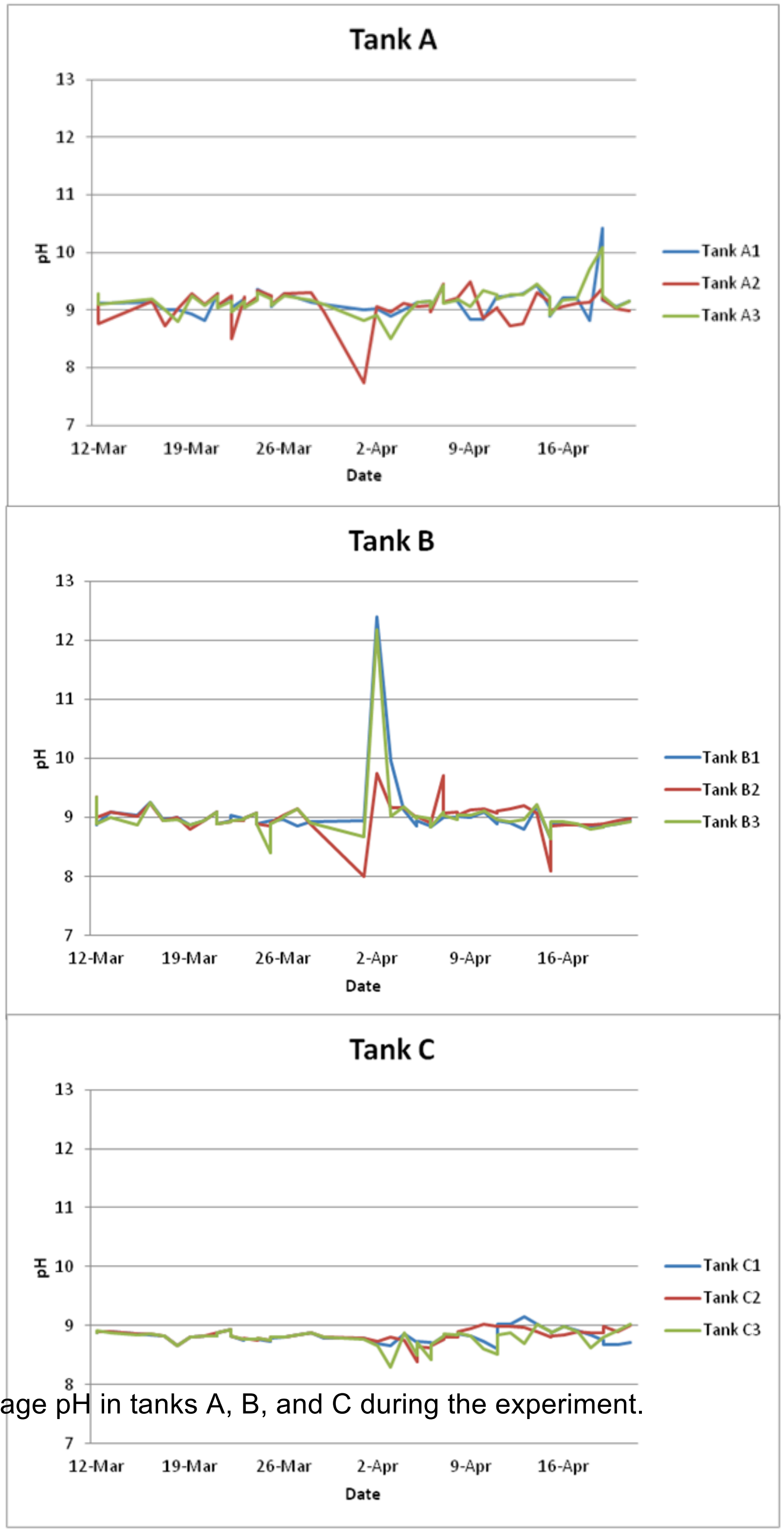

Figure 7. Average pH in tanks A, B, and C during the experiment.

A one-way analysis of variance was used to test if the total numbers of settled quagga mussels counted in the end of experiment differed among the pH treatments. Before this analysis, the counts were log(x + 1) – transformed to achieve their normality. As there was no settlement in the B-series, that series was excluded from the analysis.

Average numbers of settled quagga mussels were found to significantly differ among the treatments (P < 0.007, one-way ANOVA; Figure 8). The Tukey HSD test was used to find which particular group differed from the others. This test showed no differences between treatment C (pH 9.1) and A (pH 8.9) (P = 0.99), while both A and C significantly differed from D (P = 0.011 and P = 0.012, respectively; Figure 9).

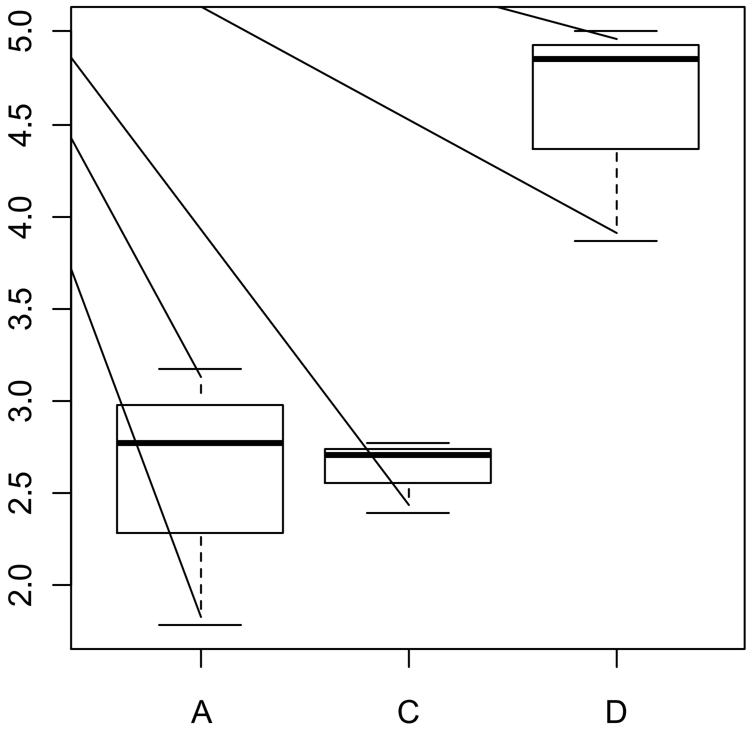

Figure 8. Boxplot of the log-transformed counts of settled quagga mussels.

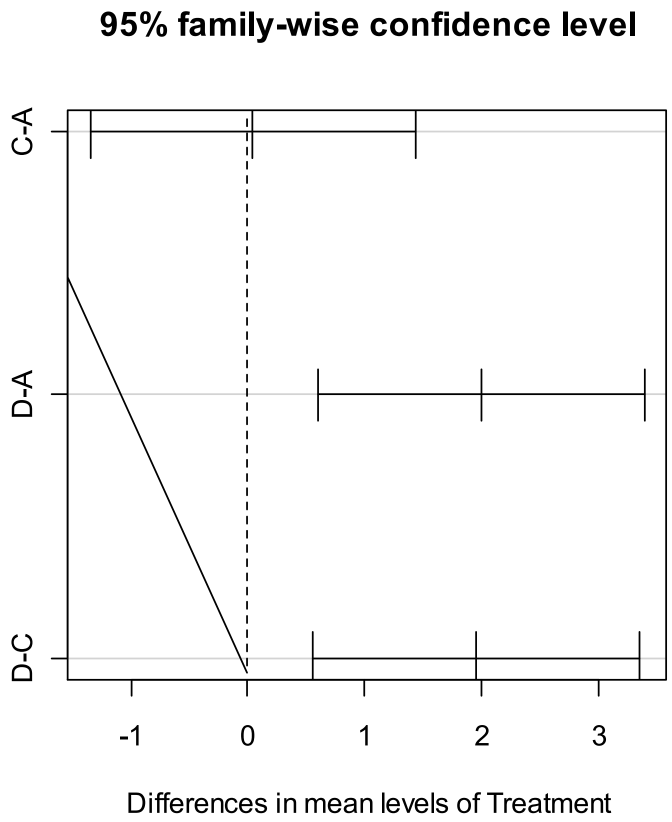

Figure 9. Ninety-five percent confidence intervals of the differences in mean values of log-transformed numbers of settlers in three experimental pH treatments. If an interval includes zero, there is no statistically significant difference between the two means under comparison.

3.1.2 Long term survival of adult quagga mussels

As seen from Table 2, there was virtually no mortality of adult quagga mussels in any of the test coolers. The exception was the coolers in system B where a period of high pH (pH of 12) caused almost complete mortality.

Table 2. Adult survival in the high pH experiment.

System	Cooler	Number of adults	
		Alive	Dead
A	1	169	1
A	2	117	0
A	3	201	0
B	1	0	143
B	2	2	158
B	3	0	80
C	1	146	0
C	2	255	0
C	3	177	0
D	1	123	1
D	2	128	2
D	3	138	0

3.1.3 Changes in shell weight to length ratio in adult quagga mussels

The live mussels from each of the mesh bags were placed in individual aluminum pans and dried for 3 hours at 350ºF. Subsequently, each mussel shell was measured using electronic calipers (Powerfist) and weighed to the nearest milligram using an electronic scale (GemPro-500). Graphical summary of the dataset that was available for statistical analysis is presented in Figure 10. This figure clearly reveals the presence of “outliers” in 5 out of 9 experimental tanks (B tanks were eliminated from the analysis). Although these unusual observations might not be real outliers from the biological point of view, their inclusion in statistical analyses considerably distorted the major pattern of the relationship between shell length and total dry weight of quagga mussels. As a result, none of the available modeling options yielded a statistical model that would satisfactorily describe the data. Thus, it was decided to remove the most notable outliers from the dataset. The resulting dataset is summarized graphically in Figure 11.

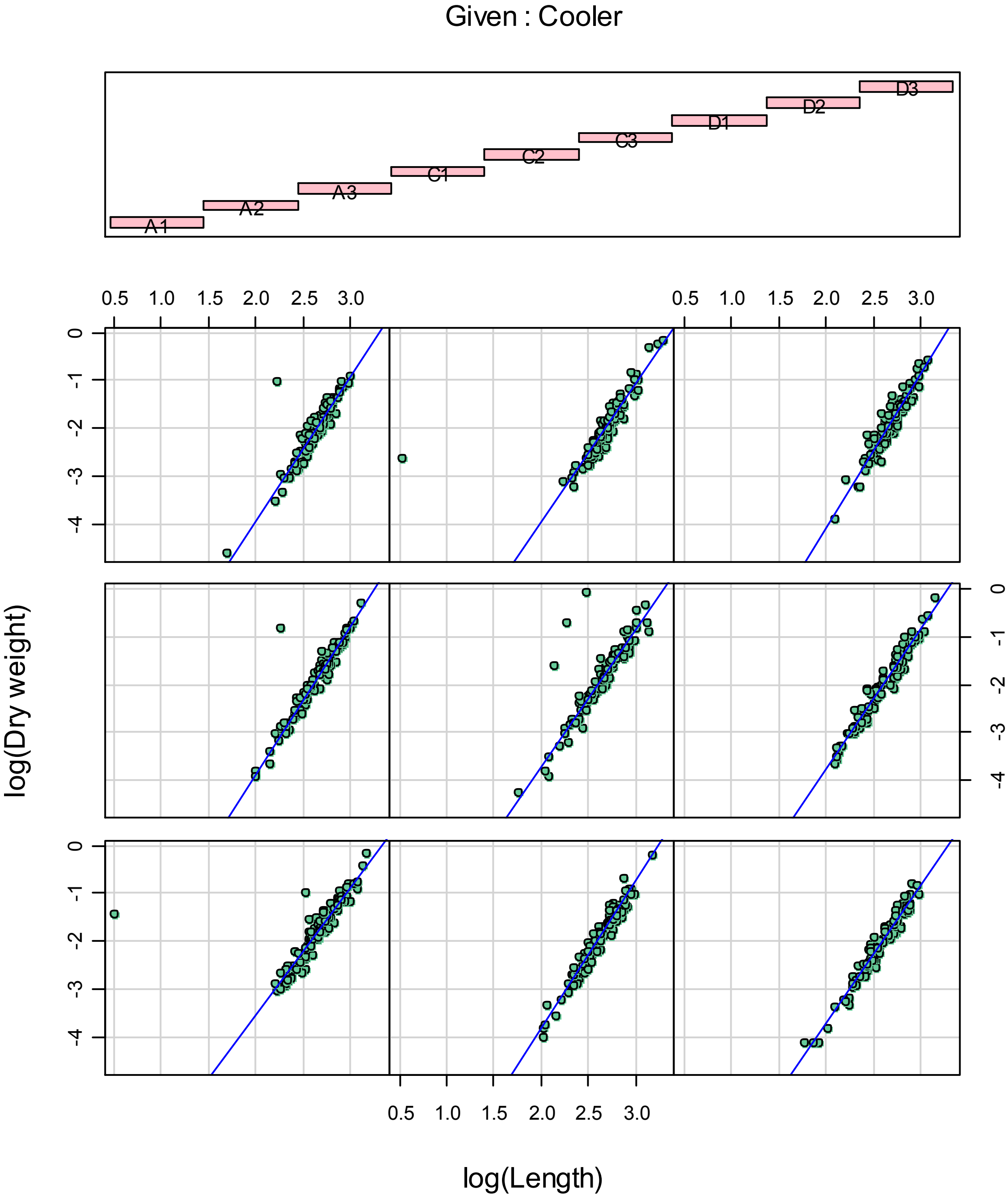

Figure 10. Relationship between quagga shell length and dry weight (initial dataset). The x-axis represents log-transformed shell length of quagga mussels. The y-axis represents log-transformed dry weight of quagga mussels. Log-transformation of both shell length and tissue weight was performed in order to linearize the relationship between these two variables. Blue lines are the tank-specific regression lines reflecting average changes of dry weight with shell length. Bars A1-A3, C1-C3, and D1-D3 denote tanks from the series A, C, and D, respectively.

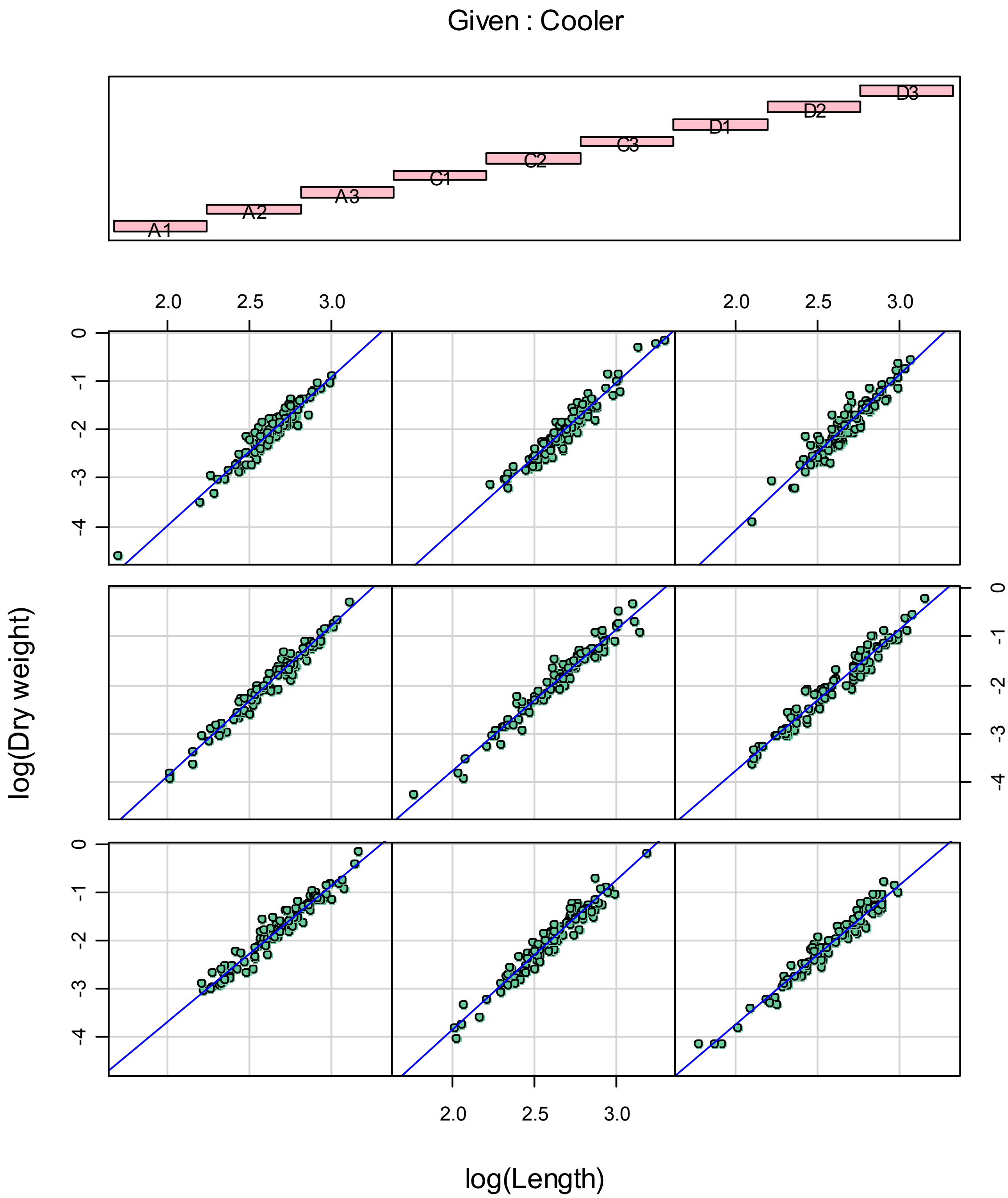

Figure 11. Relationship between quagga shell length and dry weight (dataset with outliers removed). The x-axis represents log-transformed shell length of quagga mussels. The y-axis represents log-transformed dry weight. Log-transformation of both shell length and tissue weight was performed in order to linearize the relationship between these two variables. Blue lines are the tank-specific regression lines reflecting average changes of dry weight with shell length. Bars A1-A3, C1-C3, and D1-D3 denote tanks from the series A, C, and D, respectively.

As there were multiple measurements originating from the same experimental tanks, a mixed-effects linear modeling approach was applied to account for the likely tank effect (i.e. the intercepts of the linear regressions were allowed to vary among tanks). The following model was initially fitted to the dataset where outliers were removed:

$$\log(Weight_{ij}) = \alpha + \beta_1 \times \log(Length_{ij}) + \beta_2 \times pHlevel_{ij} + \beta_3 \times \log(Length_{ij}) \times pHlevel_{ij} + a_i + \varepsilon_{ij} \quad (1)$$

where $\log(Weight_{ij})$ is the log-transformed total dry weight for observation j from tank i; similarly, $\log(Length_{ij})$ is the log-transformed shell length; $pHlevel_{ij}$ is a nominal variable with three levels (A, C, D); β_1, β_2, and β_3 are the coefficients that reflect the effect of shell length, pH level, and the interaction of these two factors, respectively; a_i is a random intercept, which is assumed to be normally distributed with mean 0 and variance σ^2_a; the residuals ε_{ij} are assumed to be normally distributed with mean 0 and variance σ^2. Both random intercept and residuals are assumed to be independent of each other.

This analysis was conducted with help of the *lme4* package for the R statistical computing environment (R Development Core Team 2011) following the protocols described in Zuur *et al.* (2002).

The coefficient β_3 in Model (1), i.e. the effect of interaction between quagga shell length and pH level, appeared to be statistically insignificant, suggesting that the regression lines for all experimental tanks had the same slope. Model (2) thus was reduced to

$$\log(Weight_{ij}) = \alpha + \beta_1 \times \log(Length_{ij}) + \beta_2 \times pHlevel_{ij} + a_i + \varepsilon_{ij} \quad (2)$$

All predictors in Model (2) were statistically significant ($P < 0.01$, *F*-test). In addition, the variance of random intercept ($\sigma^2_a = 0.043$) in this model appeared to be significantly different from 0 (lower 95% confidence limit: 0.022; upper 95% confidence interval: 0.082), indicative of a significant tank effect.

According to Model (2), the relation of log total dry weight to log shell length in the control group (D series) could be well described by the following equation:

$$\log(Weight) = -9.905 + 2.972 \times \log(Length) \quad (3)$$

In the A series, the average total dry weight was significantly higher than in the control, resulting in the following equation:

$$\log(Weight) = (-9.905 + 0.190) + 2.972 \times \log(Length) = -9.715 + 2.972 \times \log(Length) \quad (4)$$

On the original scale, total dry weight of quagga mussels from the A series was 20.9% higher than for quagga mussels from the D series ($e^{0.190} = 1.209$).

In the C series, the total dry weight of quagga mussels was also significantly higher than in the control, though not as high as in the A series:

$$\log(Weight) = (-9.905 + 0.161) + 2.972 \times \log(Length) = -9.744 + 2.972 \times \log(Length) \qquad (5)$$

On the original scale, the total dry weight of quagga mussels from the C series was 17.5% higher than for quagga mussels from the D series ($e^{0.161}$= 1.175).

At the same time, the difference in the total dry weight between the A and C series was small, i.e. only 2.9% ($e^{(-9.715 + 9.744)} = e^{0.029}$ = 1.029).

3.1.4 Corrosion coupon test results for the lower Colorado River

The long-term (1056 hours) exposure results for the various materials at each treatment level are summarized in Table 3 and further details are given in Appendix II. Table 3 shows that the pH treatment had little effect on the corrosion rates for carbon steel and copper, compared to the control (D). However, the pH adjustment with sodium hydroxide was found to significantly increase the corrosion penetration for stainless steel compared to control, although in all treatments the corrosion rates for 304 SS were quite low in absolute terms (i.e. ca 0.3 to 0.4 mpy). The 304 SS corrosion took the form of a uniform light etch, while the C1010 carbon steel showed evidence of some limited localized attack, in addition to general corrosion. In treatment A, grade CDA110 copper corrosion was generally a uniform light etch, whereas Treatments B, C, and D showed spotty etching. Further details are given in Appendix III.

Table 3. Summary of corrosion rates for materials in the long-term pH treatments for the Lower Colorado tests.‡

pH Treatment	Material		
	304 Stainless Steel	C1010 Carbon Steel	Grade CDA110 Copper
A	0.388 ± 0.067	3.029 ± 0.370	0.448 ± 0.041
B	0.340 ± 0.023	3.294 ± 0.246	0.502 ± 0.068
C	0.308 ± 0.044	3.380 ± 0.318	0.548 ± 0.062
D Control	0.001 ± 0.001	3.163 ± 0.262	0.583 ± 0.042

‡ 1056 hr nominal exposure time; mpy = mils per year; to convert to μm/year multiply mpy values by 25.4

3.2 Results from San Justo Reservoir

3.2.1 Short term exposure of adult mussels to high pH

During the May 2011 experiment, the highest mortality occurred in System C (pH 12) where after 12 hours 90% mortality was recorded in all three test coolers. The remaining mussels, except for a few in cooler A (99% mortality), died in the next 24 hours. Mortalities were low for the other two pH treatments; 5% at 12 hours and an additional 2% mortality after 36 hours in System A (pH 10) and only 1.5% mortality at 36 hours in System B (pH 11). No mortality was found in System D.

When the experiment was repeated in October 2011, lower mortalities were observed in all treatments at any given time (Table 4). A mortality of 90% at pH 12 was only reached after 120 hours. Also after 120 hours, significant mortality was observed at both pH 10 and pH 11.

As shown in Figure 12, pH 11 seems to cause low mortality in the first 48 hours, but during continued treatment, mortality follows a steep curve. During both experiments (May and October), mortality appeared to be accompanied by the swelling and rapid disintegration of body tissues (Figure 13).

Table 4. Cumulative percent mortality of adult zebra mussels in high pH treatments.

Time (h)	**% Mortality**		
	pH 10	**pH 11**	**pH 12**
24	1.5	0.4	64.5
48	4.5	4.3	80.6
72	13.5	21.7	86.6
96	31.1	46.2	89.5
120	37.8	58.2	89.9
144	44.0	69.9	91.2

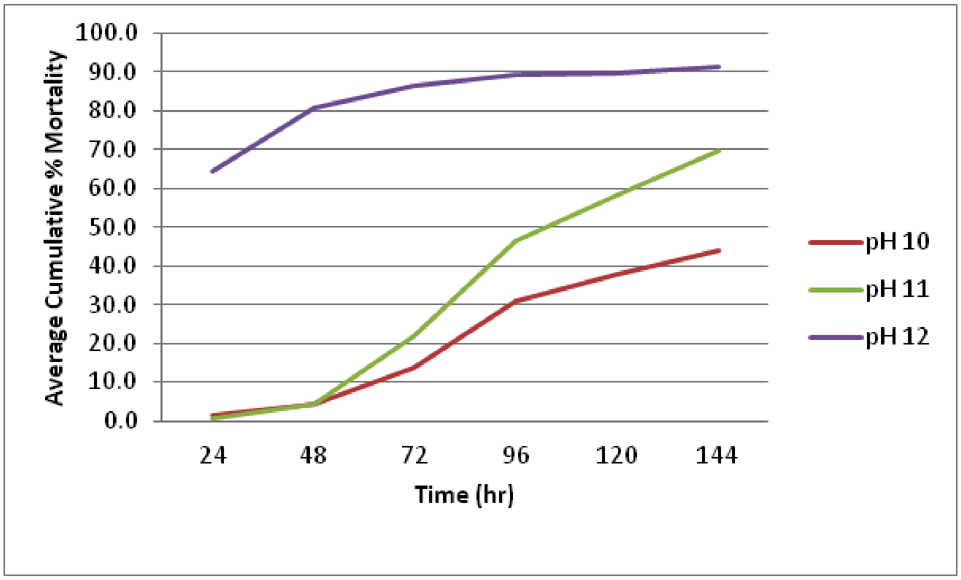

Figure 12. Cumulative percent mortality from Table 4.

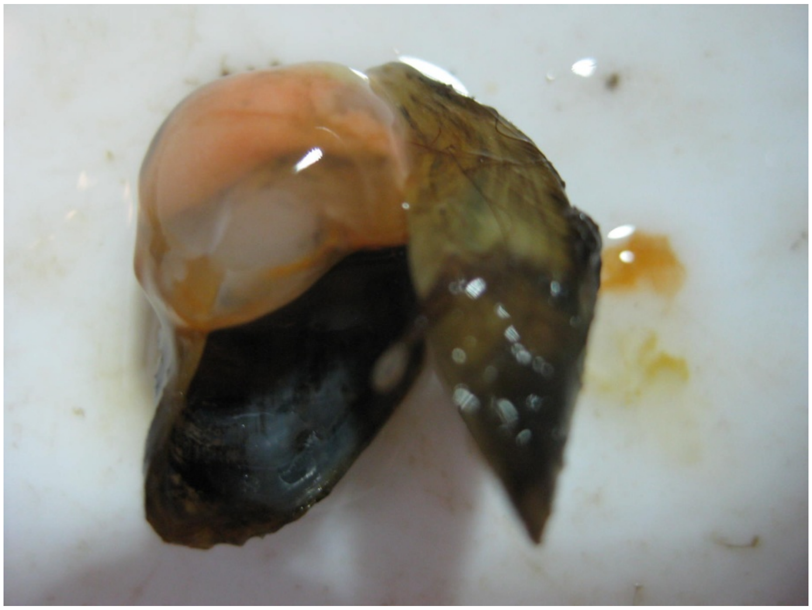

Figure 13. Dead mussel removed from the pH 12 treatment after 24 hours.

3.2.2 San Justo 2011 pH experiment: Settlement Prevention

The settlement prevention at high pH experiment ran from May 22 to July 30, 2011. The system functioned well maintaining the pH within the selected levels (Figure 14) with few exceptions due to airlocks in the system. During these times, the pH dropped until the system flow was restored.

Settlement in all coolers was relatively low compared to settlement recorded on the lower Colorado River. The low settlement was due to the low remaining population of zebra mussels in the San Justo reservoir in the spring of 2011 which resulted in low veliger counts. Table 5 shows summary of the data collected on settlement. As shown in Figure 15, there is a dramatic difference between the controls and system C (pH 9.6).

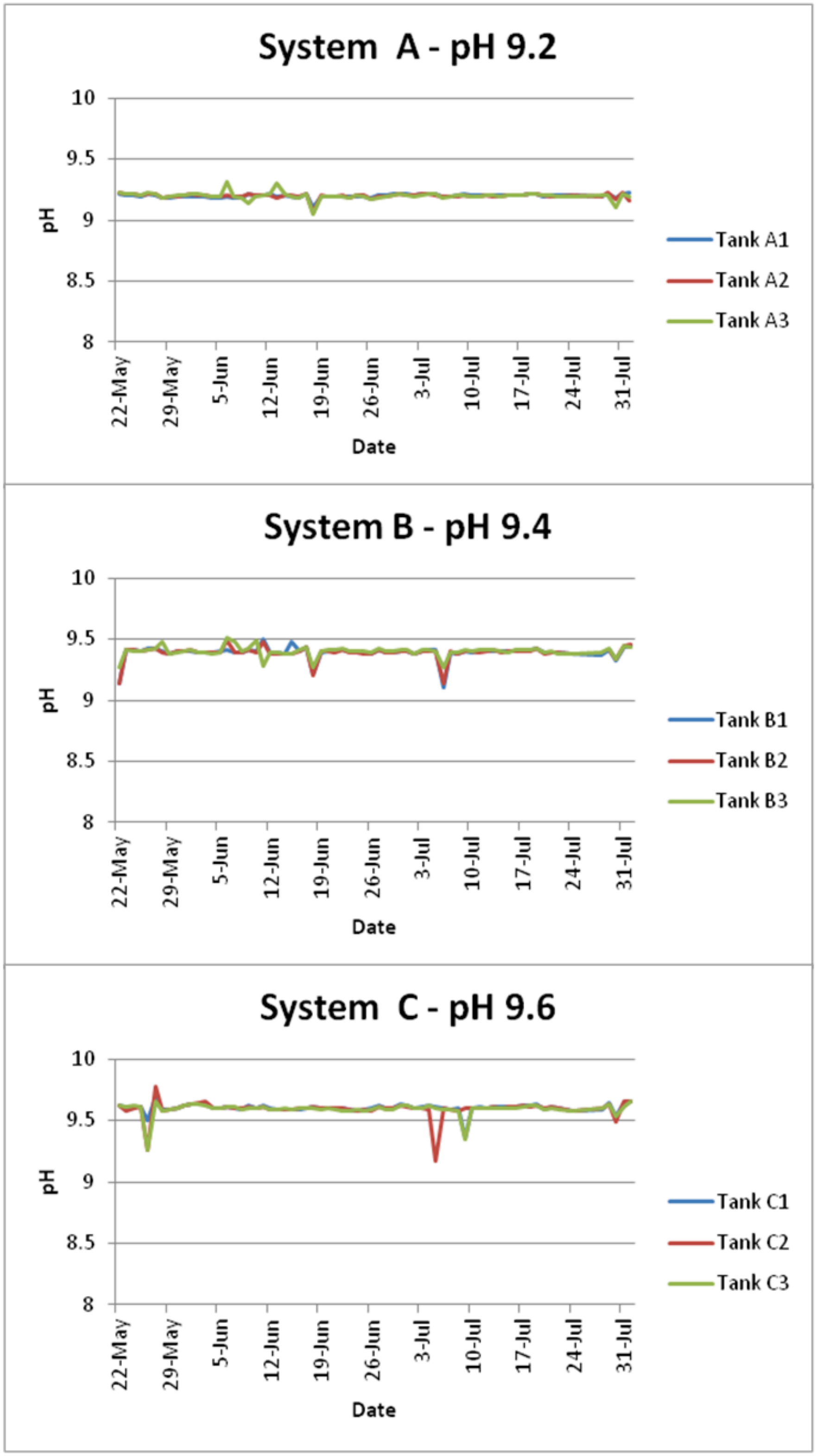

Figure 14. pH levels in systems A, B, and C for San Justo Reservoir from May 22, 2011 to July 30, 2011.

Table 5. Summary of settlement in the 2011 San Justo Reservoir high pH experiment.

System	**Cooler**	**Number of Settlers**			
		On Adults	**In Rack**	**In Cooler**	**Total No.**
A	1	2	0	11	13
A	2	0	2	10	12
A	3	0	1	8	9
B	1	4	0	21	25
B	2	3	6	15	24
B	3	5	2	10	17
C	1	1	0	1	2
C	2	1	0	0	1
C	3	0	0	1	1
D	1	13	3	16	32
D	2	11	3	30	44
D	3	0	7	24	31

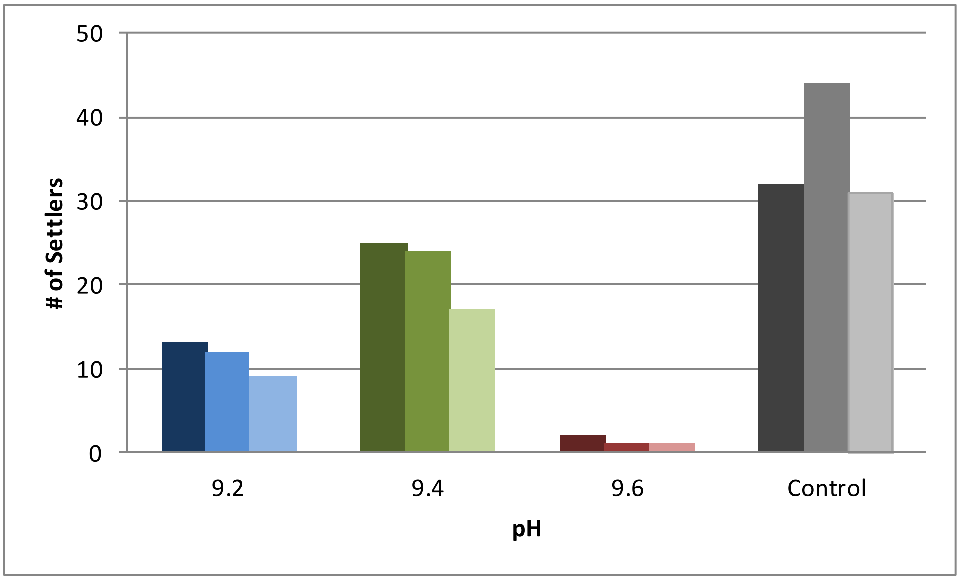

Figure 15. Total number of settlers in each cooler for each pH level at San Justo Reservoir.

The experimental data are summarized graphically in Figure 16. As is seen from that figure, there was a considerable variation of the mussel counts in control replicates. To test statistically whether there was a difference in settler counts among the pH levels, a Generalized Linear Model (GLM) with a quasi-Poisson error structure (Zuur *et al.* 2002) was applied (no model formula is given here to for the sake of simplicity). The model was fitted with the help of *nlme* package for the R statistical computing environment (R Development Core Team 2011).

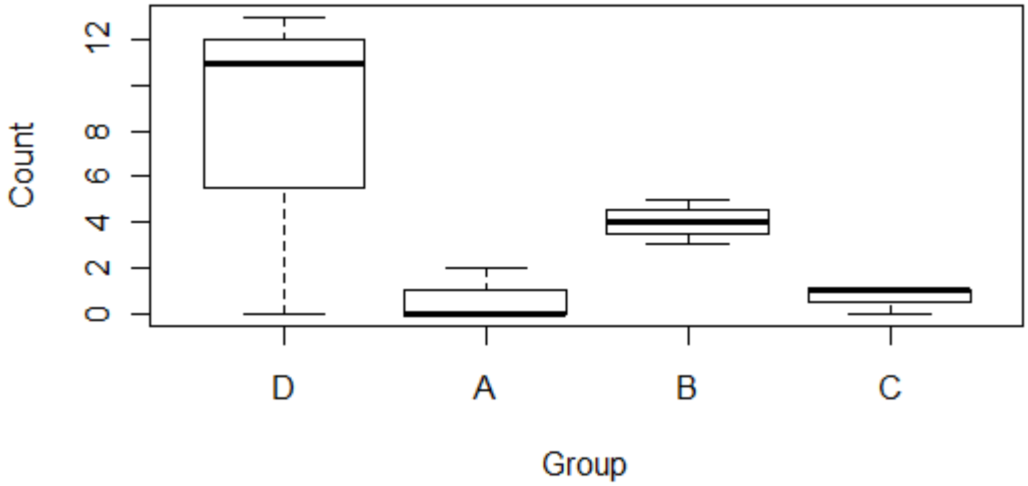

Figure 16. Boxplot of the settler counts under four experimental conditions (D-control, A-pH 9.2; B-pH 9.4; C-pH 9.6). Horizontal lines within the boxes represent median values. The height of the box corresponds to the interquartile range (IQR). Whiskers are 1.5xIQR.

Overall, there was a statistically significant effect of pH on the mussel settlement (P = 0.0017, Chi-squared test of the GLM deviance). Pairwise comparisons of the pH treatments revealed a (marginally) significant difference between Control and Treatment A (P = 0.053, t-test), as well as Control and Treatment C (P = 0.053, t-test), whereas there was no difference between Control and Treatment B (P = 0.225, t-test). Also, there was a (marginally) significant difference between Treatment A and Treatment B (P = 0.0498, t-test), but no difference between A and C (P = 1.00, t-test). The presented results should be interpreted with much care as they are based on very small sample sizes (n = 3 in each experimental group).

3.2.3 San Justo 2011 pH experiment: analysis of the adults survival

The experimental data are summarized graphically in Figure 17. In the control group (D), the mean mortality was as low as 0.9±0.9%. To test statistically whether there was a difference in mortalities among the pH treatments, a Generalized Linear Model (GLM) with a binomial error structure (Zuur *et al.* 2002) was applied (no model formula is given here to for the sake of simplicity). The model was fitted using base functionality of the R statistical computing environment (R Development Core Team 2011).

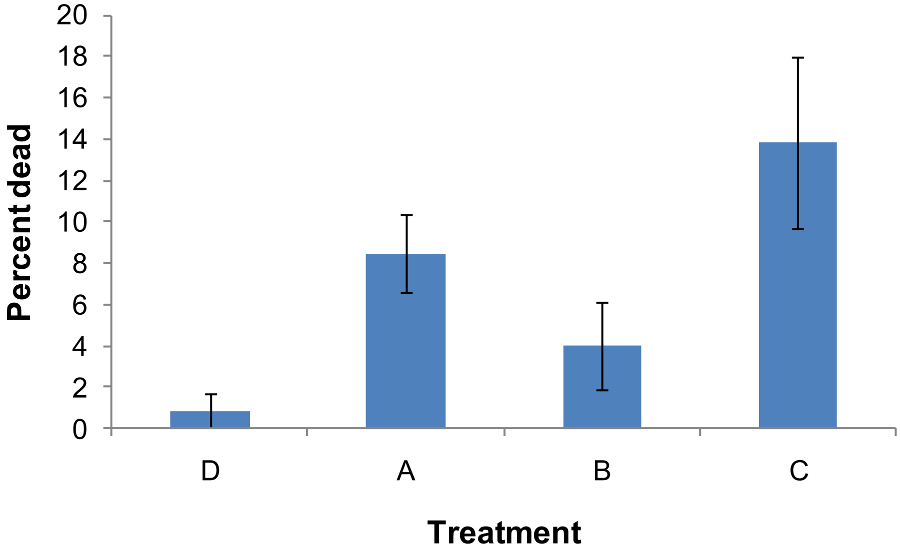

Figure 17. Mean percent mortality (±SE) of the adult mussels in the four experimental pH treatments (D-control; A-pH 9.2; B-pH 9.4; C-pH 9.6).

Overall, there was a statistically significant effect of the pH on the mortality of adult mussels ($P < 0.001$, Chi-squared test of the GLM deviance). The particular differences were revealed between Control and Treatment A ($P = 0.025$, z-test) and between Control and Treatment C ($P = 0.005$, z-test). At the same time, there was no difference between Control and Treatment B ($P = 0.147$, z-test).

3.2.3.1 Analysis of the shell length-total dry weight relationship in zebra mussels

Statistical analyses on shell length and total dry weight of zebra mussel adults was conducted to answer the following questions: (i) Was there an overall difference among treatments in terms of the regression slopes? (ii) Was there a difference between individual treatments and interaction between the pH level and shell length (iii) Was there a random effect of the individual experimental tanks. An exploratory analysis revealed two outliers which were removed from the subsequent analysis. The resulting dataset is summarized graphically in Figure 18.

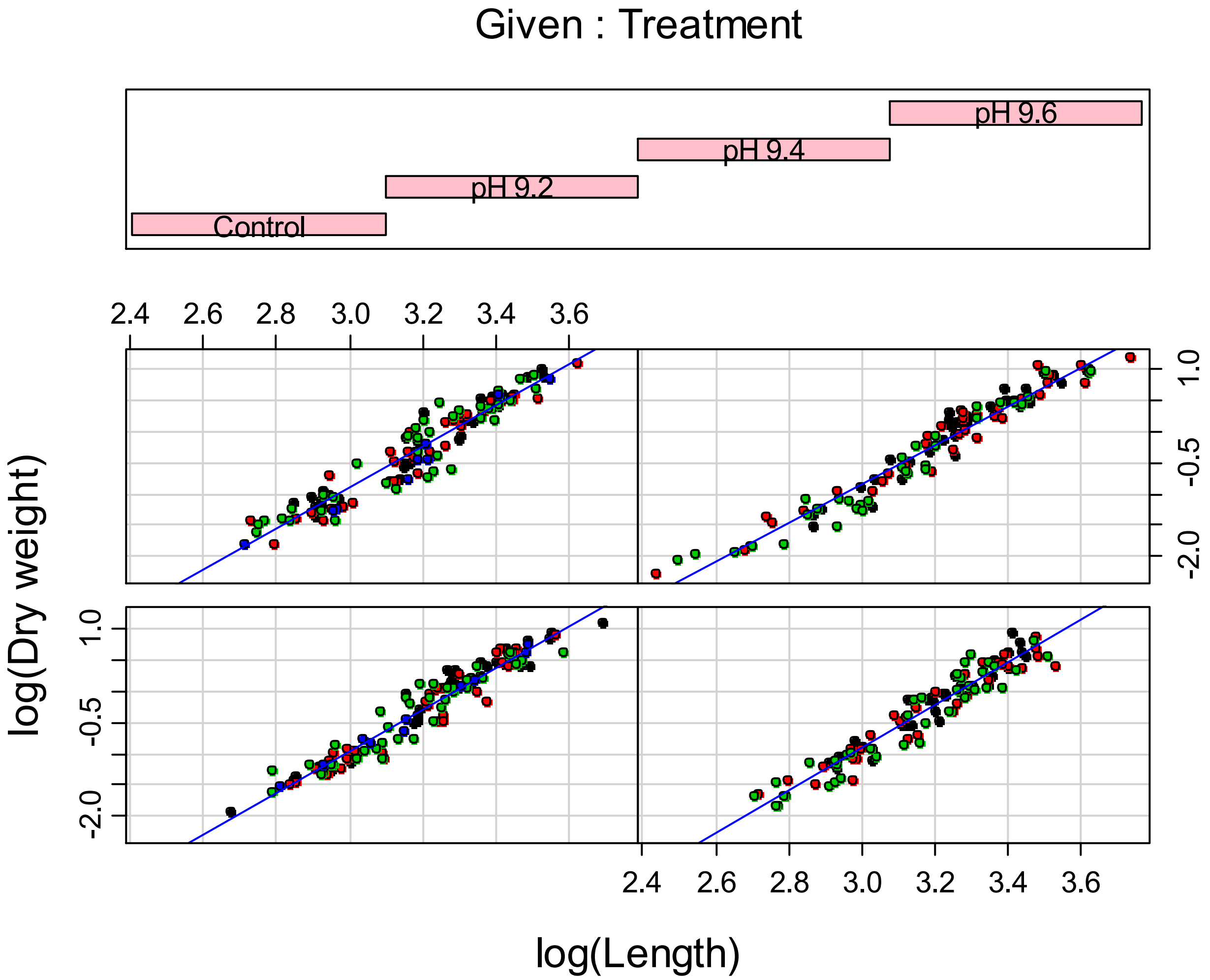

Figure 18. Relationship between shell length and total dry weight in zebra mussels (two outliers were removed from the dataset). The x-axis represents log-transformed shell length of zebra mussels. The y-axis represents log-transformed total dry weight of zebra mussel tissues. Log-transformation of both shell length and total dry weight was performed in order to linearize the changes of total dry weight with shell length. Three different colors denote data coming from three different replicates within a treatment (observe the absence of any clustering in data originating from the same replicate).

A number of alternative statistical models were tested to find a model that would optimally fit this dataset and help answer the questions listed above. Two families of models were considered:

- Linear Mixed-Effects Models (LMEs) that answer all of the aforementioned research questions, as well as to account for heterogeneity of variances in treatment groups;

- Generalized Least Squares models (GLSs), which are similar to LMEs but do not incorporate the random barrel effect (see Zuur *et al.* 2002 for details).

LMEs and GLSs were fit with the help of *nlme* package for the R statistical computing environment (R Development Core Team 2011). Selection among the competing models was based on examination of values of the Akaike Information Criterion. Model validation was performed via visual examination of the distribution of residuals (Zuur *et al.* 2002).

None of a number of the fitted alternative LMEs showed that the tank effect was statistically significant, suggesting that this effect could be eliminated from further analysis, and that a GLS model would better fit the data. The following simple linear regression was finally found to be optimal:

$$\log Weight = -10.643 + 3.250 \times \log Length \qquad (1)$$

where log*Weight* is the log-transformed total dry weight and log*Length* is the log-transformed shell length (see also Figure 19). Overall, Model (1) was highly significant statistically ($P < 0.001$, F-test) and explained 92.8% of the variance in data. Accordingly, all of its coefficients were also highly significant ($P < 0.001$, t-test).

As is seen from the notation of the final Model (1), no differences in regression slopes were found among the pH treatments at intermediate steps of the analysis. Also, there was no interaction between the shell length and pH level. Shell length was the only factor found to be associated with the total dry weight of zebra mussels in San Justo Reservoir. No pH effect was detected.

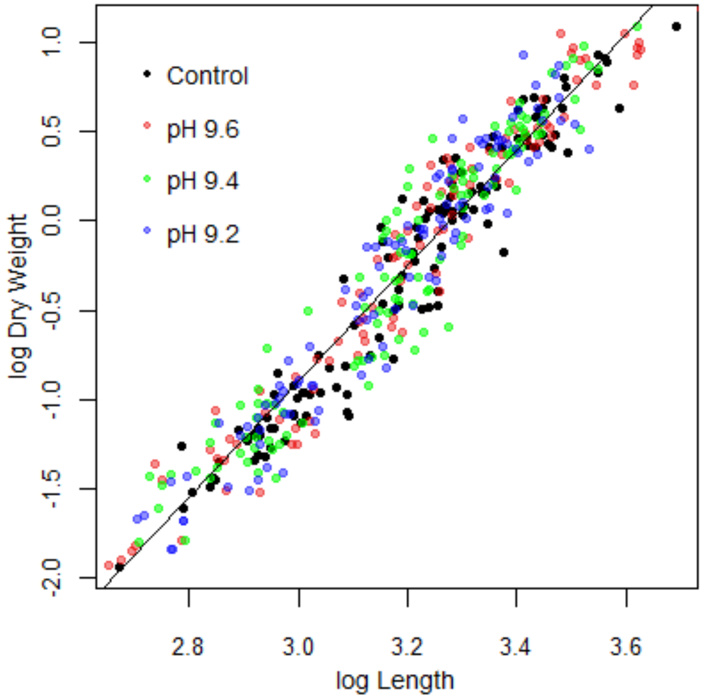

Figure 19. Relationship between the shell length and total dry weight of zebra mussels at San Justo Reservoir. The entire dataset could be sufficiently well described by a single regression line (see model (1) above).

3.2.4 Corrosion coupon test results for San Justo Reservoir

The San Justo Reservoir long-term exposure results for the various corrosion coupon materials at each treatment level are summarized in Table 6, and further details are given in Appendix III. The results shown in Table 6 indicate that Treatment A (pH 9.2) resulted in some decrease in corrosion rates compared to the control, Treatment D, for all three alloys. Further increases in pH (i.e. Treatments B and C) showed little additional benefit. The 304 SS and grade CDA110 copper corrosion took the form of a uniform etch, while the C1010 carbon steel showed evidence of some limited localized attack, in addition to general corrosion. Further details are given in Appendix III.

Table 6. Summary of corrosion rates for materials in the long-term pH treatments for the San Justo Reservoir tests.‡

pH Treatment	Material		
	304 Stainless Steel	C1010 Carbon Steel	Grade CDA110 Copper
A	0.016 ± 0.012	5.490 ± 0.330	0.313 ± 0.024
B	0.026 ± 0.005	5.211 ± 0.317	0.334 ± 0.013
C	0.029 ± 0.004	4.581 ± 0.345	0.309 ± 0.020
D Control	0.024 ± 0.007	6.448 ± 0.286	0.422 ± 0.021

‡ 1680 hr exposure time for Treatment A, B and C; 1656 hr for Treatment D (control);
mpy = mils per year; to convert to μm/year multiply mpy values by 25.4

4 Discussion

4.1 Preventing settlement of dreissenid mussels using elevated pH

Results for the settlement experiment at the lower Colorado River showed that settlement was statistically lower than the control tank at a pH of 8.9 and 9.1. No settlement data were available for the pH 9.0 treatment due to an overdose of sodium hydroxide causing pH to rise to 12 for approximately 10 hours. Regardless of the failure of the pH 9.0 tanks, the lower Colorado River results suggest that elevated pH may hinder settlement of quagga mussels.

The San Justo Reservoir experiment also showed low settlement with statistically significant differences between the control tanks and those at pH 9.2 and between the control tanks and those at pH 9.6. There was not significant difference between the control tanks and the system held at pH 9.4. The low settlement at San Justo Reservoir may have been a result of low veliger counts in the reservoir and, as such, results for this experiment should be interpreted with caution due to the small data set.

Although the lower Colorado River results showed reduced settlement, the experiment was hindered by the production of a precipitate as pH was increased. The pH was originally increased through the addition of sodium carbonate (Na_2CO_3). Since the calcium levels of the lower Colorado River are high, with an average of 80 mg/L, it is believed that the precipitate was calcium carbonate. Even after the exchange of sodium hydroxide (NaOH) for the sodium carbonate, a precipitate formed in the test tanks. This suggests that the lower Colorado River is naturally high in carbonates and, in conjunction with the high calcium concentrations, may have a high calcium carbonate saturation index (SI).

The saturation index is used as an indicator of the scaling potential for water. A saturation index of zero represents a system at equilibrium. A saturation index below zero indicates the system is under saturated and therefore unlikely to precipitate $CaCO_3$, and a saturation index above zero represents a system that is oversaturated and considered likely to precipitate $CaCO_3$. Calcium carbonate exists as three different polymorphs (i.e. calcite, aragonite and vaterite). The most common form in freshwater systems is calcite (American Public Health Association - APHA 2005), thus the saturation index for calcium carbonate is typically based on solubility coefficients for that polymorph. The saturation index for calcite ($SI_{calcite}$) can be calculated from calcium concentration (mg/L), temperature (°C), alkalinity (mg $CaCO_3$/L), conductivity (µS/cm), and pH (American Public Health Association - APHA 2005). Using a calcium concentration of 80 mg/L, temperature of 24°C, alkalinity of 130 mg $CaCO_3$/L, conductivity of 920 µS/cm, and pH of 8.3, the $SI_{calcite}$ at the lower Colorado River site is 0.88. This value indicates that the lower Colorado River is oversaturated with calcite. As pH increases, the $SI_{calcite}$ also increases. With all other variables held constant, increasing pH from 8.3 to 8.9 increases the $SI_{calcite}$ to 1.48. In comparison, the experiment at San Justo Reservoir did not result in the formation of a precipitate. The average calcium concentration at San Justo Reservoir is 18 mg/L, much lower than the calcium concentration at the lower Colorado River. Both the alkalinity and conductivity at San Justo Reservoir are also lower than at the lower Colorado River site. Using a calcium concentration of 18 mg/L, temperature of 24°C, alkalinity of 81 mg $CaCO_3$/L, conductivity of 630 µS/cm, and pH of 8.3, the $SI_{calcite}$ for San Justo Reservoir was only 0.07. At the highest pH tested in the San Justo Reservoir experiment (i.e. pH 9.6), the $SI_{calcite}$ increased to 1.32. Although this value suggests a system with the potential to form $CaCO_3$ at elevated pH, other factors may be influencing the formation of a precipitate (House 1987; House *et al.* 1989; Howard *et al.* 1984; Meyer 1984; Neal *et al.* 2002). Saturation indices do provide some indication of water's potential to form a scale however they are limited in that they do not indicate that a scale will definitely form. As such, the $SI_{calcite}$ can be used as a preliminary indicator of the potential for the system to form a scale, but it should be followed by site specific testing at elevated pH to determine if the system will definitely form a precipitate.

4.2 Impact of elevated pH on adult dreissenid mussels

During the elevated pH experiments, we examined potential effects on adult dreissenid mussels. Specifically, we looked for impacts on adult mortality and on the mussel shell length-total dry weight relationship. The relationship between the shell length and total dry weight of a dreissenid mussel has been frequently used as an index of condition; at any given size, a heavier individual is normally considered to be in better condition. Having a population of organisms of various sizes, a shell length-total dry weight plot can similarly be used to assess their condition. The elevation of the fitted line provides an index of condition, with better condition being indicated by higher elevation of the line. The differences in shell length-total dry weight relationship between treatments can provide an indication that, although not causing mortality, a particular treatment is causing stress to the test animals.

The statistical analyses on results for quagga mussels in the lower Colorado River found that there was a considerable increase in mussel weight with both increase in shell length and pH. It is possible that the precipitate in the test tanks may have settled on the shells contributing to increased shell weight, despite best efforts of rinsing the shells prior to drying them. Irrespective of the pH level, total dry weight increased with shell length at the same rate. This would suggest that there was no additional stress on the animals in the test tanks as opposed to the animals in the controls. The intercepts of the regression lines that described the relationship between the total dry weight and shell length were found to significantly vary among individual tanks at the lower Colorado River. At the San Justo Reservoir, pH had no statistically significant effect on shell length or weight of adult zebra mussels.

Adult quagga mussels in the lower Colorado River experiment experienced very low mortality (e.g. <2%) in all tanks except those in system B. An unexpected overdose of sodium hydroxide occurred in system B causing pH to increase to 12 resulting in complete mortality. The short term exposure experiment at San Justo Reservoir in May 2011 resulted in 90% mortality after 12 hours and 99% mortality after 24 hours. Tanks at a pH of 10 or 11 also experienced some adult mussel mortality, however it was very low (i.e. ≤7% after 36 hours). This experiment was repeated at San Justo Reservoir in October 2011 at which time lower mortalities resulted and a greater length of time was required to achieve similar mortality rates as those seen in May 2011. For example, at a pH of 12, 120 hours were required to reach 90% mortality in October 2011, whereas only 12 hours were required to reach 90% mortality in the May 2011 experiment. Due to harsh conditions during the 2010-2011 winter it is assumed that the mussels in San Justo Reservoir were under stress at the time when the May 2011 experiment was completed. This may have contributed to the higher mortalities observed. During the October 2011 experiment, the mussels would have had several months to recover from the stressful winter and may have been more able to withstand the elevated pH conditions. Although mortalities in October 2011 were less than those seen in the May 2011 experiment in both experiments the mussels did show swelling and disintegration of body tissues at very high pH indicating they were adversely affected.

4.3 Impact of elevated pH on materials of construction

When examining elevated pH as a possible control measure for dreissenid mussels, it is important to determine the impact that different pH levels may have on different materials commonly used for systems in contact with water. In both the lower Colorado River and San

Justo Reservoir experiments, corrosion rates were tested on Stainless Steel, Carbon Steel and Copper.

The water of the lower Colorado River is known to be very aggressive on a variety of metals under normal conditions. In the test tanks for the lower Colorado River, elevated pH was found to have little effect on the corrosion rates for carbon steel and copper, compared to the control. However, the pH adjustment with sodium hydroxide was found to significantly increase the corrosion penetration for stainless steel although in absolute terms the increase was small. At San Justo Reservoir, a decrease in corrosion rates was noted on all materials. Carbon steel and copper corrosion rates were less than the control at all test pH levels. For stainless steel, corrosion rates were the lowest at a pH of 9.2 and they were comparable to the control at pH 9.4 and pH 9.6.

These results suggest that water systems designed with carbon steel or copper pipes will be better able to withstand elevated pH treatments for dreissenid control. Stainless steel systems, however, may be at a greater risk for corrosion in some locations. Given the variation in corrosion results for the Colorado River and San Justo Reservoir sites, though, it may be important to carry out site specific testing to more carefully determine the impact of elevated pH on materials of construction.

4.4 Regulations surrounding the use of sodium hydroxide as a pesticide

In our experiments the pH was adjusted using sodium hydroxide. Sodium hydroxide is managed by the Antimicrobials Division of the U.S. Environmental Protection Agency's (EPA) Office of Pesticide Programs. Sodium hydroxide is registered by the EPA for use as a herbicide, fungicide, algaecide, and indoor disinfectant (US EPA 1992). All pesticides sold or used in the United States must be registered by the EPA, based on scientific studies showing that they can be used without posing unreasonable risks to people or the environment. Sodium hydroxide was initially registered in 1951 (US EPA 1992). To ensure registered pesticides meet current standards which have been updated as a result of advances in scientific knowledge, they are occasionally required to be reregistered. The reregistration for sodium hydroxide was completed in March 2009 (US EPA 2009a).

During the reregistration process for sodium hydroxide, the EPA waived all generic data requirements except basic product identity and chemistry information (US EPA 2009a). Sodium hydroxide has low toxicity, it does not contaminate water or soil, and it does not bioaccumulate (US EPA 2009a). Sodium hydroxide dissociates to sodium cations and hydroxide anions immediately in water, and these components do not pose a risk to aquatic organisms (US EPA 2009a).

At present, the EPA has registered two indoor pesticide products that have sodium hydroxide as their active ingredient, both manufactured by The Proctor and Gamble Company. These cleaning agents, Mr. Clean (#3573-63) and Ultra Mr. Clean (#3573-65), each have less than 0.5% sodium hydroxide as their active ingredient (US EPA 2009b). At such low concentrations of sodium hydroxide, and because of they are diluted in water, these agents are considered safe for public use without additional study or labeling (US EPA 2009a). Sodium hydroxide is also regulated for outdoor use as a herbicide in the removal of tree roots in sewage systems. However, effluent from treating sewers with sodium hydroxide may not be discharged to natural or public waters without a National Pollution Discharge Elimination System (NPDES) permit (US EPA 1992).

Given that pesticides containing sodium hydroxide as the active ingredient have received EPA registration in the past, it may be possible that sodium hydroxide could receive registration for mussel control. To amend sodium hydroxide's current registration, an application for a new use would be required (US EPA 2011b), the result of which would be the addition of mussel control to approved uses for sodium hydroxide (US EPA 2011a). If the U.S. Bureau of Reclamation (USBR) wishes to use elevated pH as means of mussel control, an application for a new use change will have to be submitted by USBR directly. Alternatively, USBR could partner with the manufacturer of an existing pesticide (e.g. The Proctor and Gamble Company) to apply for an amended label for their product.

5 Conclusions

The experiments carried out in this study produced new findings not previously recorded in the literature. Elevated pH was shown to inhibit settlement of dreissenid veligers and to cause tissue damage and increased mortality in adult mussels. The quick mortality observed when adult dreissenids were exposed to very high pH (i.e. pH 12) is a new finding which offers the possibility of a novel end of season treatment for dreissenid mussel control. Also profound was the impact the chemistry of raw water had at elevated pH levels. Under certain conditions, elevated pH may result in the formation of calcium carbonate precipitate that may hinder the use of high pH as a control measure for mussels. Determination of the calcium carbonate saturation index may help identify systems that are more likely to be affected by calcium carbonate precipitate. Additionally, site specific testing is recommended to determine to which pH the system can be elevated without the formation of a precipitate.

Sodium hydroxide is currently registered as a pesticide with the US EPA. It is possible that registration of sodium hydroxide may be amended for use as a mussel control.

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Appendix I

Experimental data for the high pH experiment at the lower Colorado River.

		Ph 8.9					Ph 9.0					Ph 9.1				
Date	pH raw water	Tank C meas.	Tank C hand	C 1	C 2	C 3	Tank B meas.	Tank B hand	B 1	B 2	B 3	Tank A meas.	Tank A hand	A 1	A2	A3
12-Mar	8.36	8.92	8.92	8.87	8.89	8.88	9.32	9.39	8.87	9.35	9.34	9.1	9.34	8.98	9.25	9.28
12-Mar	8.31	8.89	8.89	8.89	8.89	8.91	9.01	9.01	8.9	9	8.9	9.1	9.22	9.12	8.76	9.1
13-Mar	8.29	8.93	8.9	8.9	8.89	8.88	9	9.22	9.1	9.1	9					
15-Mar		8.89	8.87	8.86	8.86	8.85	9	9.06	9.03	9.02	8.88					
16-Mar	8.3	8.88	8.88	8.85	8.86	8.86	8.99	9.3	9.25	9.24	9.26	9.4	9.2	9.13	9.15	9.2
17-Mar	8.32	8.93	9.05	8.83	8.83	8.82	8.99	9.05	8.97	8.95	8.95	9.1	9.05	9.01	8.73	9
18-Mar	8.19	8.95	8.7	8.65	8.65	8.66	8.99	9.06	9	9	8.97	9.15	9.06	9	9.02	8.8
19-Mar	8.17	8.96	8.84	8.8	8.8	8.8	8.99	8.9	8.88	8.8	8.88	9.18	9.35	8.93	9.28	9.24
20-Mar	8.17	8.93	8.83	8.82	8.83	8.82	9.03	8.99	8.94	8.94	8.94	9.19	9.14	8.82	9.09	9.08
21-Mar	8.12	8.96	8.85	8.83	8.88	8.83	9.02	9.17	9.1	9.09	9.1	9.23	9.38	9.28	9.28	9.24
21-Mar				8.88	8.88	8.88			8.9	8.9	8.9			9.08	9.08	9.05
22-Mar	8.23	8.97	8.99	8.93	8.94	8.93	8.98	9.03	8.94	8.93	8.93	9.26	9.41	9.22	9.24	9.16
22-Mar	8.21	9.03	8.89	8.82	8.83	8.82	8.98	9.03	9.03	8.94	8.94	9.23	9.1	9.04	8.5	8.97
23-Mar	8.16	8.97	8.81	8.75	8.77	8.77	9.03	9.1		8.95	8.97	9.2	9.4	9.19	9.22	9.16
23-Mar	8.21	8.97	8.85	8.77	8.79	8.77	9.02	9.04	8.98	8.98	8.99	9.28	9.16	9.06	9.07	9.04
24-Mar	8.15	8.89	8.72	8.77	8.75	8.77	8.98	9.15	9.07	9.07	9.08	9.14	9.36	9.2	9.22	9.17
24-Mar	8.19	8.96	8.82	8.76	8.78	8.78	8.98	8.95	8.89	8.89	8.89	9.23	9.14	9.36	9.34	9.31
25-Mar	8.16	8.97	8.81	8.74	8.75	8.75						9.2	9.27	9.22	9.24	9.2
25-Mar							9.02	8.93		8.86	8.4					
25-Mar	8.2	8.9	8.78	8.79	8.8	8.8	8.99	8.96	8.95	8.91	8.9	9.19	9.11	9.07	9.09	9.08
26-Mar	8.16	8.91	8.72	8.8	8.8	8.8					9	9.2	9.23	9.29	9.29	9.24
26-Mar							9	8.99	8.97	9.03	9.01					
27-Mar	8.2	8.94	8.89	8.85	8.84	8.84	9.01	9.2	8.86	9.14	9.14					
28-Mar	8.16	8.9	8.9	8.88	8.87	8.87	8.99	9.02	8.92	8.89	8.91	9.18	9.18	9.14	9.3	9.18
29-Mar	8.16	8.9	8.82	8.79	8.8	8.8						9.2	9.2	9.1	8.96	9.1
30-Mar																
31-Mar																
1-Apr	8.17	8.9	8.8	8.78	8.78	8.77	9.02	9.02	8.94	8	8.67	9.26	9.32	9.01	7.73	8.82
1-Apr		8.97	8.85				9.02	9	8.93	8	8.72	9.19	9.25	9.01	7.73	8.81
2-Apr																
2-Apr																
2-Apr	8.21	8.97	8.84	8.7	8.73	8.66	9.05	9	12.4	9.75	12.18	9.18	9.14	9.03	9.07	8.91
3-Apr	8.17	8.95	8.86	8.65	8.8	8.3	9.03	9.12	9.97	9.16	9.02	9.21	9.14	8.89	8.96	8.5
4-Apr	8.17	8.91	8.9	8.86	8.75	8.87	9.07	9.37	9.12	9.17	9.18	9.24	9.3	9.01	9.11	8.88
5-Apr	8.18	8.93	8.79	8.72	8.39	8.5	9.04	9.09	8.86	9	8.99					
5-Apr	8.17	8.91	8.78	8.73	8.64	8.71	9.01	9.1	8.95	9.02	9.01	9.18	9.2	9.13	9.06	9.13
6-Apr	8.16	8.95	8.79	8.72	8.63	8.43	8.98	8.95	8.86	8.91	8.98	9.19	9.24	9.15	9.08	9.16
6-Apr	8.16	8.9	8.72	8.67	8.66	8.68	9.98	8.97	8.83	8.9	8.83	9.18	9.11	9.02	8.97	9.04
7-Apr	8.31	8.9	8.9	8.82	8.76	8.83	8.99	9.21	9	9.7	9.1	9.22	9.64	9.44	9.45	9.44
7-Apr	8.33	8.95	8.9	8.83	8.8	8.86	9.01	9.14	9	9.08	9.03	9.19	9.19	9.13	9.13	9.12
8-Apr	8.33	8.89	8.91	8.84	8.81	8.85	9	9.15	9	9.1	8.96	9.18	9.29	9.17	9.21	9.18
8-Apr	8.29	8.89	8.96	8.86	8.9	8.88	8.99	9.12	9.02	9.03	9.03	9.18	9.31	9.15	9.21	9.2
9-Apr	8.37	8.92	9.03	8.82	8.95	8.83	8.98	9.21	9	9.13	9.03	9.22	9.57	8.83	9.49	9.07
10-Apr	8.39	8.9	9.14	8.73	9.02	8.61	8.99	9.17	9.1	9.14	9.11	9.19	9.57	8.84	8.85	9.34
11-Apr	8.4	8.91	9.03	8.6	8.99	8.51	8.99	9.16	8.9	9.08	8.97	9.18	9.49	9.24	9.04	9.27
11-Apr	8.42	8.89	9.09	9.02	8.99	8.85	8.99	9.22	8.94	9.11	8.97	9.19	9.4	9.23	9.03	9.2
12-Apr	8.37	8.9	9.15	9.03	8.98	8.88	8.99	9.29	8.91	9.15	8.93	9.2	9.57	9.25	8.73	9.26
13-Apr	8.36	8.9	9.33	9.15	8.96	8.69	8.98	9.44	8.8	9.2	8.97	9.06	9.38	9.28	8.76	9.26
14-Apr	8.38	8.89	9.1	9.03	8.89	9.03	9.05	9.34	9.18	9.07	9.22	9.21	9.52	9.44	9.3	9.45
15-Apr	8.3	8.82	9	8.89	8.8	8.9	8.6	8.68	8.63	8.1	8.63	9.1	9.29	9.05	9.13	9.22
15-Apr	8.27	8.88	8.88	8.87	8.83	8.87	8.91	8.98	8.9	8.86	8.93	9.14	9.23	8.89	8.99	8.91
16-Apr	8.28	8.97	9.07	8.99	8.85	8.99	8.89	9	8.88	8.87	8.93	9.09	9.25	9.21	9.06	9.18
17-Apr	8.29	8.92	9.01	8.91	8.9	8.89	8.89	8.89	8.88	8.88	8.9	9.1	9.27	9.21	9.12	9.19
18-Apr	8.27	8.89	8.9	8.84	8.87	8.62	8.9	8.92	8.84	8.88	8.81	9.09	9.33	8.81	9.13	9.72
19-Apr	8.27	8.89	8.91	8.75	8.88	8.81	8.9	8.93	8.84	8.89	8.84	9.21	9.21	10.42	9.37	10.08
19-Apr	8.28	8.89	8.92	8.67	8.98	8.8	8.9	8.94	8.86	8.9	8.86	9.1	9.31	9.17	9.2	9.24
20-Apr	8.28	8.87	8.98	8.67	8.89	8.92	8.96	8.98	8.9	8.94	8.89	9.03	9.1	9.07	9.02	9.05
21-Apr	8.27	8.86	9.2	8.72	9	9.02	9	9.04	8.95	8.98	8.92	9.08	9.3	9.15	8.98	9.15
Average	8.24	8.92	8.89	8.81	8.82	8.77	8.99	9.06	8.95	8.83	8.93	9.17	9.26	9.09	8.79	9.10

Experimental data for the high pH experiment at San Justo Reservoir

		pH 9.2					pH 9.4					pH 9.6				
Date (dd/mm)	pH Raw Water	Tank A monitor	Tank A Handheld	A1	A2	A3	Tank B monitor	Tank B handheld	B1	B2	B3	Tank C monitor	Tank C handheld	C1	C2	C3
22-May	8.91	9.21	9.22	9.22	9.23	9.23	8.89	8.93	8.85	8.85	9.11	9.59	9.63	9.63	9.64	9.64
22-May	8.98	9.2	9.22	9.21	9.22	9.22	9.4	9.42	9.42	9.42	9.42	9.56	9.62	9.61	9.6	9.6
23-May	8.87	9.2	9.22	9.21	9.22	9.22	9.39	9.41	9.42	9.42	9.42	9.58	9.63	9.61	9.56	9.61
23-May	8.92	9.2	9.21	9.19	9.2	9.2	9.38	9.41	9.4	9.4	9.4	9.59	9.62	9.61	9.59	9.61
24-May	8.86	9.17	9.22	9.21	9.22	9.22	9.37	9.42	9.41	9.41	9.4	9.58	9.65	9.61	9.59	9.62
24-May	8.95	9.19	9.23	9.19	9.2	9.2	9.38	9.42	9.42	9.41	9.41	9.57	9.64	9.62	9.62	9.62
25-May	8.89	9.19	9.22	9.2	9.21	9.21	9.37	9.41	9.4	9.4	9.4	9.57	9.62	9.61	9.61	9.61
25-May	8.94	9.19	9.21	9.19	9.19	9.2	9.37	9.42	9.41	9.41	9.41	9.58	9.65	9.61	9.62	9.62
26-May	8.86	9.17	9.27	9.22	9.23	9.24	9.38	9.41	9.42	9.41	9.41	8.85	8.91	9.4	8.9	8.89
26-May	8.95	9.19	9.24	9.2	9.2	9.21	9.37	9.44	9.42	9.41	9.41	9.58	9.66	9.61	9.62	9.63
27-May	8.92	9.19	9.22	9.2	9.21	9.22	9.37	9.42	9.41	9.41	9.4	9.53	9.64	9.6	9.62	9.6
27-May	8.74	9.19	9.24	9.21	9.21	9.21	9.37	9.45	9.44	9.44	9.44	9.51	10.31	9.85	10.06	9.74
27-May	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	9.56	9.65	9.62	9.65	9.64
28-May	8.85	9.19	9.2	9.17	9.18	9.18	9.37	9.42	9.4	9.4	9.38	9.54	9.61	9.57	9.56	9.56
28-May	8.86	9.2	9.22	9.19	9.19	9.19	9.37	9.4	9.4	9.39	9.58	9.6	9.59	9.6	9.6	9.6
29-May	8.79	9.2	9.19	9.18	9.19	9.19	9.38	9.4	9.39	9.38	9.38	9.58	9.62	9.59	9.59	9.59
29-May	8.78	9.2	9.19	9.18	9.19	9.19	9.37	9.39	9.38	9.38	9.38	9.59	9.6	9.58	9.58	9.58
30-May	8.72	9.2	9.19	9.19	9.19	9.2	9.39	9.41	9.4	9.4	9.39	9.6	9.61	9.6	9.6	9.6
30-May	n/a	9.2	n/a	n/a	n/a	n/a	9.4	n/a	n/a	n/a	n/a	9.6	n/a	n/a	n/a	n/a
31-May	8.67	9.2	9.21	9.2	9.21	9.21	9.4	9.41	9.42	9.41	9.41	9.59	9.65	9.63	9.64	9.63
31-May	8.67	9.21	9.2	9.18	9.19	9.19	9.4	9.39	9.39	9.39	9.39	9.59	9.62	9.61	9.61	9.61
1-Jun	8.69	9.21	9.21	9.19	9.21	9.21	9.4	9.39	9.41	9.42	9.41	9.59	9.62	9.63	9.63	9.63
1-Jun	8.7	9.2	9.2	9.2	9.22	9.22	9.39	9.39	9.4	9.4	9.41	9.61	9.64	9.63	9.64	9.64
2-Jun	8.65	9.2	9.19	9.19	9.21	9.22	9.4	9.4	9.41	9.4	9.41	9.61	9.65	9.64	9.65	9.64
2-Jun	8.68	9.2	9.2	9.19	9.2	9.2	9.4	9.38	9.38	9.38	9.38	9.59	9.62	9.63	9.63	9.63
3-Jun	8.59	9.22	9.21	9.2	9.2	9.2	9.4	9.4	9.39	9.39	9.39	9.58	9.61	9.63	9.69	9.63
3-Jun	8.67	9.23	9.22	9.18	9.21	9.21	9.38	9.42	9.4	9.4	9.39	9.57	9.61	9.63	9.63	9.62
4-Jun	8.56	9.2	9.19	9.19	9.2	9.2	9.39	9.37	9.39	9.39	9.38	9.59	9.62	9.6	9.6	9.6
4-Jun	8.52	9.21	9.21	9.17	9.18	9.19	9.39	9.4	9.4	9.4	9.39	9.58	9.61	9.61	9.61	9.61
5-Jun	8.42	9.22	9.18	9.18	9.19	9.19	9.38	9.38	9.38	9.37	9.37	9.57	9.59	9.58	9.59	9.58
5-Jun	8.5	9.23	9.18	9.19	9.2	9.2	9.42	9.41	9.42	9.42	9.41	9.56	9.63	9.62	9.62	9.62
6-Jun	8.45	9.23	9.18	9.19	9.2	9.41	9.4	9.4	9.39	9.55	9.6	9.59	9.6	9.59	9.59	9.6
6-Jun	8.62	9.22	9.21	9.2	9.21	9.22	9.41	9.43	9.43	9.43	9.42	9.58	9.63	9.63	9.63	9.63
7-Jun	8.54	9.22	9.2	9.18	9.19	9.19	9.4	9.38	9.38	9.37	9.55	9.55	9.59	9.59	9.59	9.6
7-Jun	8.69	9.22	9.2	9.19	9.2	9.19	9.41	9.41	9.41	9.41	9.41	9.55	9.63	9.61	9.62	9.62
8-Jun	8.58	9.22	9.21	9.19	9.2	9.2	9.42	9.41	9.4	9.39	9.4	9.55	9.6	9.59	9.6	9.59
8-Jun	8.66	9.2	9.19	9.18	9.18	9.17	9.39	9.39	9.38	9.39	9.4	9.57	9.59	9.59	9.59	9.59
9-Jun	8.62	9.22	9.23	9.22	9.22	9.09	9.4	9.42	9.41	9.42	9.42	9.56	9.61	9.61	9.61	9.61
9-Jun	8.69	9.2	9.23	9.2	9.2	9.19	9.39	9.42	9.41	9.41	9.42	9.58	9.64	9.63	9.62	9.59
10-Jun	8.62	9.21	9.21	9.21	9.21	9.2	9.39	9.39	9.4	9.39	9.4	9.57	9.62	9.61	9.61	9.61
10-Jun	8.71	9.21	9.2	9.2	9.19	9.18	9.4	9.42	9.4	9.39	9.58	9.61	9.6	9.59	9.59	9.59
11-Jun	8.66	9.21	9.22	9.2	9.2	9.2	8.57	8.62	9.6	9.56	9.15	9.59	9.63	9.61	9.6	9.61
11-Jun	8.74	9.2	9.23	9.21	9.2	9.2	9.39	9.42	9.4	9.39	9.41	9.58	9.64	9.63	9.62	9.62
12-Jun	8.64	9.21	9.2	9.2	9.2	9.2	9.4	9.41	9.39	9.38	9.38	9.56	9.61	9.6	9.59	9.59
12-Jun	8.21	9.2	9.21	9.22	9.21	9.22	9.41	9.41	9.39	9.39	9.4	9.56	9.61	9.6	9.59	9.59
13-Jun	8.64	9.2	9.19	9.19	9.18	9.4	9.39	9.39	9.38	9.37	9.38	9.56	9.58	9.57	9.58	9.58
13-Jun	8.72	9.22	9.21	9.2	9.18	9.2	9.41	9.42	9.4	9.4	9.4	9.57	9.62	9.61	9.6	9.6
14-Jun	8.67	9.19	9.22	9.2	9.2	9.2	9.4	9.41	9.39	9.38	9.39	9.55	9.59	9.58	9.59	9.59
14-Jun	8.71	9.21	9.24	9.21	9.21	9.22	9.39	9.41	9.38	9.38	9.37	9.55	9.6	9.59	9.59	9.6
15-Jun	8.66	9.2	9.21	9.19	9.19	9.19	9.4	9.39	9.37	9.37	9.36	9.56	9.59	9.57	9.57	9.57
15-Jun	8.78	9.22	9.21	9.2	9.21	9.2	9.41	9.4	9.59	9.4	9.39	9.58	9.6	9.61	9.6	9.61
16-Jun	8.69	9.21	9.2	9.19	9.2	9.2	9.41	9.4	9.39	9.39	9.4	9.57	9.6	9.59	9.6	9.6
16-Jun	8.7	9.21	9.19	9.18	9.18	9.17	9.4	9.44	9.42	9.41	9.43	9.57	9.6	9.59	9.59	9.59
17-Jun	8.65	9.22	9.23	9.22	9.22	9.21	9.4	9.44	9.43	9.44	9.44	9.58	9.58	9.58	9.57	9.58
17-Jun	8.75	9.21	9.23	9.22	9.21	9.21	9.38	9.44	9.43	9.43	9.43	9.6	9.63	9.62	9.62	9.62
18-Jun	8.59	no flow	8.64	9.02	8.93	8.9	no flow	8.72	9.03	8.99	9.12	9.59	9.61	9.61	9.61	9.6
18-Jun	8.77	9.19	9.21	9.19	9.2	9.19	9.39	9.42	9.41	9.41	9.42	9.6	9.62	9.62	9.62	9.6
19-Jun	8.63	9.18	9.19	9.18	9.19	9.18	9.39	9.41	9.4	9.41	9.4	9.6	9.6	9.6	9.6	9.59
19-Jun	8.71	9.19	9.22	9.21	9.21	9.21	9.4	9.41	9.39	9.39	9.4	9.59	9.62	9.6	9.6	9.59
20-Jun	8.68	9.2	9.19	9.2	9.2	9.2	9.39	9.42	9.4	9.4	9.41	9.6	9.62	9.6	9.6	9.6

Experimental data for the high pH experiment at San Justo Reservoir continued

		pH 9.2					pH 9.4					pH 9.6				
Date (dd/mm)	pH Raw Water	Tank A monitor	Tank A Handheld	A1	A2	A3	Tank B monitor	Tank B handheld	B1	B2	B3	Tank C monitor	Tank C handheld	C1	C2	C3
20-Jun	8.79	9.19	9.2	9.19	9.19	9.19	9.4	9.42	9.4	9.41	9.41	9.6	9.62	9.61	9.6	9.6
21-Jun	8.66	9.19	9.2	9.18	9.18	9.18	9.39	9.42	9.4	9.39	9.4	9.6	9.6	9.59	9.59	9.59
21-Jun	8.77	9.19	9.22	9.21	9.2	9.21	9.4	9.41	9.42	9.4	9.42	9.6	9.62	9.61	9.61	9.59
22-Jun	8.62	9.2	9.18	9.19	9.2	9.2	9.4	9.39	9.41	9.42	9.42	9.61	9.62	9.6	9.6	9.58
22-Jun	8.79	9.19	9.2	9.19	9.2	9.19	9.39	9.42	9.42	9.41	9.42	9.59	9.62	9.61	9.6	9.58
23-Jun	8.65	9.2	9.19	9.19	9.18	9.18	9.39	9.41	9.4	9.39	9.4	9.59	9.61	9.59	9.59	9.58
24-Jun	8.63	9.2	9.19	9.19	9.2	9.2	9.4	9.4	9.4	9.39	9.4	9.6	9.61	9.57	9.57	9.58
24-Jun	8.71	9.21	9.2	9.19	9.2	9.2	9.41	9.41	9.39	9.39	9.4	9.59	9.61	9.58	9.59	9.59
25-Jun	8.58	9.19	9.19	9.19	9.2	9.19	9.39	9.41	9.39	9.38	9.39	9.59	9.6	9.58	9.59	9.58
25-Jun	8.7	9.19	9.21	9.2	9.2	9.19	9.4	9.41	9.4	9.39	9.41	9.6	9.61	9.59	9.59	9.58
26-Jun	8.56	9.2	9.19	9.19	9.18	9.18	9.4	9.41	9.41	9.4	9.41	9.6	9.6	9.61	9.6	9.6
26-Jun	8.51	9.22	9.21	9.18	9.17	9.17	9.39	9.39	9.35	9.35	9.37	9.6	9.6	9.58	9.56	9.57
27-Jun	8.54	9.23	9.21	9.2	9.19	9.18	9.42	9.4	9.4	9.4	9.41	9.63	9.61	9.61	9.6	9.6
27-Jun	8.73	9.22	9.21	9.2	9.19	9.19	9.41	9.44	9.42	9.42	9.43	9.62	9.64	9.63	9.63	9.63
28-Jun	8.6	9.22	9.2	9.2	9.19	9.19	9.4	9.4	9.39	9.39	9.4	9.6	9.59	9.59	9.59	9.59
28-Jun	8.71	9.2	9.2	9.2	9.19	9.19	9.41	9.4	9.39	9.39	9.4	9.6	9.62	9.61	9.6	9.59
29-Jun	8.58	9.22	9.22	9.21	9.2	9.2	9.4	9.42	9.39	9.39	9.4	9.61	9.62	9.6	9.6	9.59
29-Jun	8.7	9.22	9.23	9.21	9.2	9.2	9.39	9.42	9.39	9.4	9.4	9.6	9.62	9.61	9.6	9.59
30-Jun	8.64	9.22	9.21	9.21	9.2	9.19	9.4	9.4	9.39	9.39	9.4	9.61	9.62	9.61	9.59	9.6
30-Jun	8.82	9.23	9.25	9.23	9.22	9.23	9.41	9.43	9.42	9.41	9.43	9.61	9.64	9.65	9.65	9.65
1-Jul	8.75	9.22	9.23	9.21	9.2	9.2	9.4	9.42	9.4	9.4	9.41	9.61	9.62	9.62	9.61	9.62
2-Jul	8.81	9.2	9.19	9.19	9.2	9.18	9.4	9.4	9.38	9.37	9.38	9.59	9.59	9.59	9.59	9.59
2-Jul	8.88	9.2	9.23	9.21	9.2	9.21	9.4	9.41	9.39	9.38	9.39	9.6	9.62	9.61	9.6	9.6
3-Jul	8.83	9.2	9.24	9.22	9.22	9.21	9.39	9.41	9.4	9.4	9.41	9.6	9.62	9.61	9.6	9.61
3-Jul	8.89	9.2	9.23	9.21	9.2	9.2	9.4	9.42	9.4	9.4	9.41	9.6	9.62	9.61	9.6	9.59
4-Jul	8.89	9.22	9.21	9.21	9.22	9.22	9.4	9.41	9.41	9.4	9.41	9.6	9.63	9.62	9.59	9.62
4-Jul	n/a	9.21	n/a	n/a	n/a	n/a	9.39	n/a	n/a	n/a	n/a	9.6	n/a	n/a	n/a	n/a
5-Jul	8.82	9.2	9.22	9.21	9.2	9.21	9.4	9.41	9.41	9.4	9.4	9.6	9.61	9.61	9.17	9.6
5-Jul	n/a	9.21	n/a	n/a	n/a	n/a	9.4	n/a	n/a	n/a	n/a	9.59	n/a	n/a	n/a	n/a
6-Jul	8.77	9.21	9.2	9.19	9.19	9.19	8.78	8.76	8.81	8.94	9.12	9.6	9.59	9.59	9.59	9.58
6-Jul	8.81	9.2	9.2	9.19	9.19	9.18	9.41	9.41	9.39	9.34	9.41	9.6	9.62	9.62	9.62	9.59
7-Jul	8.73	9.19	9.2	9.19	9.19	9.2	9.4	9.39	9.39	9.4	9.39	9.6	9.59	9.59	9.59	9.59
7-Jul	8.8	9.2	9.21	9.19	9.19	9.19	9.39	9.4	9.4	9.4	9.4	9.6	9.6	9.59	9.59	9.59
8-Jul	8.71	9.2	9.21	9.21	9.19	9.2	9.4	9.39	9.37	9.37	9.39	9.36	9.59	9.59	9.57	9.58
8-Jul	8.79	9.2	9.2	9.2	9.19	9.2	9.4	9.39	9.39	9.4	9.4	9.6	9.6	9.6	9.59	9.58
9-Jul	8.66	9.2	9.2	9.21	9.2	9.21	9.41	9.4	9.41	9.41	9.42	9.6	9.59	9.61	9.61	9.1
9-Jul	8.78	9.2	9.21	9.21	9.2	9.2	9.41	9.41	9.4	9.4	9.4	9.6	9.6	9.1	9.59	9.59
10-Jul	8.63	9.2	9.2	9.2	9.19	9.19	9.4	9.4	9.39	9.4	9.4	9.6	9.6	9.6	9.6	9.6
10-Jul	8.75	9.2	9.2	9.2	9.19	9.19	9.4	9.4	9.39	9.4	9.4	9.6	9.6	9.6	9.6	9.59
11-Jul	8.64	9.2	9.2	9.2	9.19	9.19	9.41	9.42	9.4	9.39	9.41	9.61	9.62	9.61	9.6	9.6
12-Jul	8.65	9.19	9.21	9.2	9.2	9.2	9.4	9.39	9.4	9.4	9.41	9.59	9.62	9.6	9.6	9.6
13-Jul	8.59	9.2	9.2	9.2	9.2	9.2	9.41	9.42	9.41	9.41	9.41	9.6	9.61	9.61	9.61	9.61
13-Jul	8.64	9.19	9.2	9.2	9.19	9.2	9.4	9.41	9.4	9.41	9.41	9.59	9.62	9.61	9.61	9.6
14-Jul	8.55	9.2	9.21	9.2	9.19	9.19	9.39	9.39	9.4	9.39	9.4	9.6	9.61	9.61	9.6	9.6
14-Jul	8.61	9.21	9.2	9.2	9.2	9.19	9.4	9.39	9.4	9.4	9.4	9.6	9.61	9.61	9.6	9.6
15-Jul	8.53	9.21	9.2	9.2	9.2	9.2	9.39	9.38	9.4	9.4	9.39	9.6	9.61	9.61	9.61	9.6
16-Jul	8.51	9.22	9.21	9.2	9.21	9.21	9.41	9.4	9.41	9.41	9.41	9.61	9.61	9.61	9.61	9.61
16-Jul	8.62	9.19	9.2	9.2	9.19	9.19	9.4	9.42	9.4	9.4	9.41	9.6	9.62	9.61	9.61	9.6
17-Jul	8.48	9.21	9.21	9.2	9.2	9.2	9.39	9.4	9.4	9.4	9.41	9.61	9.62	9.62	9.62	9.61
18-Jul	8.43	9.2	9.22	9.21	9.21	9.21	9.41	9.41	9.41	9.4	9.41	9.61	9.62	9.62	9.61	9.62
19-Jul	8.45	9.21	9.21	9.21	9.21	9.21	9.39	9.41	9.42	9.42	9.42	9.61	9.63	9.63	9.62	9.62
20-Jul	8.52	9.2	9.19	9.19	9.2	9.2	9.4	9.39	9.39	9.38	9.39	9.61	9.6	9.59	9.6	9.59
21-Jul	8.69	9.2	9.2	9.2	9.19	9.2	9.4	9.39	9.39	9.39	9.4	9.59	9.6	9.61	9.61	9.6
22-Jul	8.53	9.2	9.2	9.2	9.19	9.19	9.39	9.38	9.39	9.39	9.38	9.6	9.59	9.6	9.6	9.59
24-Jul	8.54	9.2	9.2	9.2	9.2	9.19	9.41	9.39	9.38	9.38	9.38	9.59	9.59	9.58	9.58	9.58
28-Jul	8.55	9.19	9.19	9.19	9.19	9.2	9.38	9.39	9.37	n/a	9.39	9.61	9.61	9.59	9.6	9.6
29-Jul	8.54	9.19	9.23	9.22	9.23	9.2	9.4	9.42	9.41	9.41	9.42	9.61	9.67	9.64	9.63	9.63
30-Jul	8.46	9.2	9.19	9.18	9.17	9.1	9.39	9.33	9.32	9.34	9.34	9.59	9.56	9.53	9.49	9.53
31-Jul	8.41	9.19	9.23	9.22	9.23	9.21	9.39	9.4	9.44	9.45	9.45	9.61	9.62	9.64	9.65	9.61
1-Aug	n/a	9.2	9.2	9.23	9.16	9.19	9.4	9.39	9.45	9.46	9.44	9.61	9.64	9.65	9.65	9.65

Appendix II

Corrosion test results from the high pH experiment at the lower Colorado River

Job 133931

Material	Location	Coupon ID #	Penetration Rate mpy	Exposure Duration hours	Nature of Attack		Average mpy	Standard Dev mpy
304	A1	1	0.5135	1056	uniform etch	A1	0.4451	0.0968
304	A1	2	0.3766	1056	uniform etch			
304	A2	3	0.3423	1056	uniform etch	A2	0.3328	0.0134
304	A2	4	0.3233	1056	uniform etch			
304	A3	5	0.3975	1056	uniform etch	A3	0.3852	0.0175
304	A3	6	0.3728	1056	uniform etch			
304	B1	7	0.3538	1056	uniform etch	All A Coupons	0.3877	0.0670
304	B1	8	0.3557	1056	uniform etch			
304	B2	9	0.3423	1056	uniform etch	B1	0.3548	0.0013
304	B2	10	0.2948	1056	uniform etch			
304	B3	11	0.3461	1056	uniform etch	B2	0.3186	0.0336
304	B3	12	0.3499	1056	uniform etch			
304	C1	13	0.2957	1056	uniform etch	B3	0.3480	0.0027
304	C1	14	0.2920	1056	uniform etch			
304	C2	15	0.3533	1056	uniform etch	All B Coupons	0.3404	0.0229
304	C2	16	0.2343	1056	uniform etch			
304	C3	17	0.3292	1056	uniform etch	C1	0.2939	0.0026
304	C3	18	0.3459	1056	uniform etch			
304	D1	19	0.0000	1056	uniform etch	C2	0.2938	0.0841
304	D1	20	0.0019	1056	uniform etch			
304	D2	21	0.0019	1056	uniform etch	C3	0.3376	0.0118
304	D2	22	0.0000	1056	uniform etch			
304	D3	23	0.0019	1056	uniform etch	All C Coupons	0.3084	0.0442
304	D3	24	0.0000	1056	uniform etch			
						D1	0.0010	0.0013
						D2	0.0010	0.0013
						D3	0.0010	0.0013
						All D Coupons	0.0010	0.0010
						All 304 SS Coupons	0.2594	0.1599

Job 133931

Material	Location	Coupon ID #	Penetration Rate mpy	Exposure Duration hours	Nature of Attack		Average mpy	Standard Dev mpy
C1010	A1	B91117	2.3698	1056	general plus localized	A1	2.6255	0.3616
C1010	A1	B91118	2.8812	1056	general plus localized			
C1010	A2	B91119	3.0663	1056	general plus localized	A2	3.2218	0.2199
C1010	A2	B91120	3.3773	1056	general plus localized			
C1010	A3	B91121	3.3334	1056	general plus localized	A3	3.2390	0.1336
C1010	A3	B91122	3.1445	1056	general plus localized			
C1010	B1	B91123	3.3219	1056	general plus localized	All A Coupons	3.0288	0.3702
C1010	B1	B91124	3.0643	1056	general plus localized			
C1010	B2	B91125	3.6024	1056	general plus localized	B1	3.1931	0.1822
C1010	B2	B91126	3.3887	1056	general plus localized			
C1010	B3	B91127	2.9422	1056	general plus localized	B2	3.4956	0.1511
C1010	B3	B91128	3.4440	1056	general plus localized			
C1010	C1	B91129	3.7836	1056	general plus localized	B3	3.1931	0.3548
C1010	C1	B91130	3.5634	1056	general plus localized			
C1010	C2	B91131	3.5671	1056	general plus localized	All B Coupons	3.2939	0.2465
C1010	C2	B91132	3.3395	1056	general plus localized			
C1010	C3	B91133	2.9888	1056	general plus localized	C1	3.6735	0.1557
C1010	C3	B91134	3.0354	1056	general plus localized			
C1010	D1	B91135	2.8992	1056	general plus localized	C2	3.4533	0.1609
C1010	D1	B91136	3.3787	1056	general plus localized			
C1010	D2	B91137	3.3246	1056	general plus localized	C3	3.0121	0.0330
C1010	D2	B91138	3.4515	1056	general plus localized			
C1010	D3	B91139	3.0970	1056	general plus localized	All C Coupons	3.3796	0.3178
C1010	D3	B91140	2.8283	1056	general plus localized			
						D1	3.1390	0.3391
						D2	3.3881	0.0897
						D3	2.9627	0.1900
						All D Coupons	3.1632	0.2615
						All C1010 Coupons	3.2164	0.3135

Job 133931

Material	Location	Coupon ID #	Penetration Rate mpy	Exposure Duration hours	Nature of Attack		Average mpy	Standard Dev mpy
CDA110	A1	W5936	0.4029	1056	uniform etch	A1	0.4147	0.0167
CDA110	A1	W5937	0.4265	1056	uniform etch			
CDA110	A2	W5938	0.5024	1056	uniform etch	A2	0.4974	0.0071
CDA110	A2	W5939	0.4923	1056	uniform etch			
CDA110	A3	W5940	0.4147	1056	spotty etch	A3	0.4333	0.0262
CDA110	A3	W5941	0.4518	1056	spotty etch			
CDA110	B1	W5942	0.5142	1056	spotty etch	All A Coupons	0.4484	0.0413
CDA110	B1	W5943	0.6035	1056	spotty etch			
CDA110	B2	W5944	0.5176	1056	spotty etch	B1	0.5589	0.0631
CDA110	B2	W5945	0.3979	1056	spotty etch			
CDA110	B3	W5946	0.5142	1056	spotty etch	B2	0.4578	0.0846
CDA110	B3	W5947	0.4670	1056	spotty etch			
CDA110	C1	W5948	0.5160	1056	spotty etch	B3	0.4906	0.0334
CDA110	C1	W5949	0.6083	1056	spotty etch			
CDA110	C2	W5950	0.4517	1056	spotty etch	All B Coupons	0.5024	0.0677
CDA110	C2	W5951	0.5918	1056	spotty etch			
CDA110	C3	W5952	0.6000	1056	spotty etch	C1	0.5622	0.0653
CDA110	C3	W5953	0.5176	1056	spotty etch			
CDA110	D1	W5954	0.5704	1056	spotty etch	C2	0.5218	0.0991
CDA110	D1	W5955	0.5291	1056	spotty etch			
CDA110	D2	W5956	0.6116	1056	spotty etch	C3	0.5588	0.0583
CDA110	D2	W5957	0.6445	1056	spotty etch			
CDA110	D3	W5958	0.5918	1056	spotty etch	All C Coupons	0.5476	0.0624
CDA110	D3	W5959	0.5522	1056	spotty etch			
						D1	0.5498	0.0292
						D2	0.6281	0.0233
						D3	0.5720	0.0280
						All D Coupons	0.5833	0.0417
						All CDA110 Coupons	0.5204	0.0725

Appendix III

Corrosion test results from the high pH experiment at San Justo Reservoir.

Job 136181

Material	Location	Coupon ID #	Penetration Rate mpy	Exposure Duration hours	Nature of Attack
304	A1	1	0.0024	1680	uniform etch
304	A1	2	0.0000	1680	uniform etch
304	A2	3	0.0192	1680	uniform etch
304	A2	4	0.0240	1680	uniform etch
304	A3	5	0.0240	1680	uniform etch
304	A3	6	0.0288	1680	uniform etch
304	B1	7	0.0312	1680	uniform etch
304	B1	8	0.0252	1680	uniform etch
304	B2	9	0.0312	1680	uniform etch
304	B2	10	0.0192	1680	uniform etch
304	B3	11	0.0240	1680	uniform etch
304	B3	12	0.0228	1680	uniform etch
304	C1	13	0.0240	1680	uniform etch
304	C1	14	0.0288	1680	uniform etch
304	C2	15	0.0252	1680	uniform etch
304	C2	16	0.0324	1680	uniform etch
304	C3	17	0.0312	1680	uniform etch
304	C3	18	0.0312	1680	uniform etch
304	D1	19	0.0353	1656	uniform etch
304	D1	20	0.0329	1656	uniform etch
304	D2	21	0.0195	1656	uniform etch
304	D2	22	0.0207	1656	uniform etch
304	D3	23	0.0243	1656	uniform etch
304	D3	24	0.0231	1656	uniform etch

	Average mpy	Standard Dev mpy
A1	0.0012	0.0017
A2	0.0216	0.0034
A3	0.0264	0.0034
All A Coupons	0.0164	0.0122
B1	0.0282	0.0042
B2	0.0252	0.0085
B3	0.0234	0.0008
All B Coupons	0.0256	0.0048
C1	0.0264	0.0034
C2	0.0288	0.0051
C3	0.0312	0.0000
All C Coupons	0.0288	0.0035
D1	0.0341	0.0017
D2	0.0201	0.0008
D3	0.0237	0.0008
All D Coupons	0.0260	0.0066
All 304 SS Coupons	0.0242	0.0085

Job 136181

Material	Location	Coupon ID #	Penetration Rate mpy	Exposure Duration hours	Nature of Attack		Average mpy	Standard Dev mpy
C1010	A1	B94767	5.8857	1680	general plus localized	A1	5.5761	0.4378
C1010	A1	B94768	5.2665	1680	general plus localized			
C1010	A2	B94769	5.6144	1680	general plus localized	A2	5.5791	0.0499
C1010	A2	B94770	5.5438	1680	general plus localized			
C1010	A3	B94771	4.9569	1680	general plus localized	A3	5.3161	0.5080
C1010	A3	B94772	5.6753	1680	general plus localized			
C1010	B1	B94773	5.4363	1680	general plus localized	All A Coupons	5.4904	0.3297
C1010	B1	B94774	5.2032	1680	general plus localized			
C1010	B2	B94775	4.9737	1680	general plus localized	B1	5.3198	0.1648
C1010	B2	B94776	4.7298	1680	general plus localized			
C1010	B3	B94777	5.5988	1680	general plus localized	B2	4.8518	0.1725
C1010	B3	B94778	5.3251	1680	general plus localized			
C1010	C1	B94779	4.2673	1680	general plus localized	B3	5.4620	0.1935
C1010	C1	B94780	4.1298	1680	general plus localized			
C1010	C2	B94781	4.8374	1680	general plus localized	All B Coupons	5.2112	0.3169
C1010	C2	B94782	4.4597	1680	general plus localized			
C1010	C3	B94783	4.8087	1680	general plus localized	C1	4.1986	0.0972
C1010	C3	B94784	4.9820	1680	general plus localized			
C1010	D1	B94785	6.5955	1656	general plus localized	C2	4.6486	0.2671
C1010	D1	B94786	6.5033	1656	general plus localized			
C1010	D2	B94787	6.6392	1656	general plus localized	C3	4.8954	0.1225
C1010	D2	B94788	6.6804	1656	general plus localized			
C1010	D3	B94789	6.3627	1656	general plus localized	All C Coupons	4.5808	0.3450
C1010	D3	B94790	5.9116	1656	general plus localized			
						D1	6.5494	0.0652
						D2	6.6598	0.0291
						D3	6.1372	0.3190
						All D Coupons	6.4488	0.2865
						All C1010 Coupons	5.4328	0.7493

Job 136181

Material	Location	Coupon ID #	Penetration Rate mpy	Exposure Duration hours	Nature of Attack		Average mpy	Standard Dev mpy
CDA110	A1	0325	0.3210	1680	uniform etch	A1	0.3141	0.0098
CDA110	A1	0326	0.3072	1680	uniform etch			
CDA110	A2	0327	0.2774	1680	uniform etch	A2	0.2870	0.0136
CDA110	A2	0328	0.2966	1680	uniform etch			
CDA110	A3	0329	0.3455	1680	uniform etch	A3	0.3381	0.0105
CDA110	A3	0330	0.3306	1680	uniform etch			
CDA110	B1	0331	0.3338	1680	uniform etch	All A Coupons	0.3131	0.0245
CDA110	B1	0332	0.3232	1680	uniform etch			
CDA110	B2	0333	0.3465	1680	uniform etch	B1	0.3285	0.0075
CDA110	B2	0334	0.3487	1680	uniform etch			
CDA110	B3	0335	0.3317	1680	uniform etch	B2	0.3476	0.0016
CDA110	B3	0336	0.3168	1680	uniform etch			
CDA110	C1	0337	0.3136	1680	uniform etch	B3	0.3243	0.0105
CDA110	C1	0338	0.3338	1680	uniform etch			
CDA110	C2	0339	0.3434	1680	uniform etch	All B Coupons	0.3335	0.0126
CDA110	C2	0340	0.3083	1680	uniform etch			
CDA110	C3	0341	0.3232	1680	uniform etch	C1	0.3237	0.0143
CDA110	C3	0342	0.2955	1680	uniform etch			
CDA110	D1	0343	0.4260	1656	uniform etch	C2	0.3259	0.0248
CDA110	D1	0344	0.4454	1656	uniform etch			
CDA110	D2	0345	0.4292	1656	uniform etch	C3	0.3094	0.0196
CDA110	D2	0346	0.4314	1656	uniform etch			
CDA110	D3	0347	0.3839	1656	uniform etch	All C Coupons	0.3196	0.0175
CDA110	D3	0348	0.4130	1656	uniform etch			
						D1	0.4357	0.0137
						D2	0.4303	0.0016
						D3	0.3985	0.0206
						All D Coupons	0.4215	0.0211
						All CDA110 Coupons	0.3469	0.0482