THE EFFECTS OF DREDGING ON DISSOLVED OXYGEN IN AGRICULTURAL WATERWAYS IN KING COUNTY, WASHINGTON

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of ELIZABETH ANNE MILBURN find it satisfactory and recommend that it be accepted.

Chair

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THE EFFECTS OF DREDGING ON DISSOLVED OXYGEN

IN AGRICULTURAL WATERWAYS IN

KING COUNTY, WASHINGTON

Abstract

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Oxygen levels in streams, rivers, and lakes play an important role in habitat availability and are a good indicator of overall water system health. The purpose of this experimental study was to investigate the alterations to dissolved oxygen levels in agricultural waterways as a result of vegetation removal. This was part of a comprehensive water quality study in a series of low-flow low-gradient agricultural drainage ditches in King County, Washington.

This investigation was accomplished through water quality monitoring and modeling. The monitoring portion of the study involved routine stab readings and lab analysis including diel measurements with data sondes. The EPA water quality model Qual2kw was used to model dissolved oxygen in the study reaches. In conjunction with the modeling process several parameters hypothesized to be altered as a result of dredging operations were examined in detail including channel roughness, energy gradients, sediment oxygen demand, reaeration, sedimentation, and photosynthesis. Hydraulic parameters such as channel roughness, wetted perimeter, and energy gradients were modeled using HEC-RAS software. Sediment oxygen demand was measured ex-situ in the Washington State University lab using sealed Plexiglas chambers and dissolved oxygen probes. The water system's dependence on reaeration, sediment oxygen demand, and photosynthesis was investigated by a sensitivity analysis in Qual2kw.

The study results indicated that there are significant differences in key channel characteristics as a result of maintenance activities. Manning's roughness was found to be between 0.41 and 1.9 in pre-dredged and 0.08 in post-dredged reaches respectively. The energy grade slopes in pre- and post-dredged segments were found to be approximately .0029 and .000021. Dissolved oxygen levels rose approximately 3.4 mg/l (over 250%) following vegetation removal. Sediment oxygen demand rose after maintenance activities from approximately 0.67 to 3.17 $g/m^2/d$. The vegetation removal was performed by hand which left a large amount of loose, highly organic decaying matter on the channel floor. Instead, the primary contributor to increased dissolved oxygen was found to be increased reaeration and photosynthesis as a result of vegetation removal.

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Dedication

This thesis is dedicated to my sisters.

You are my inspiration, strength, and comfort.

1.0 CHAPTER ONE THESIS INTRODUCTION

Dissolved oxygen (DO) levels in streams, rivers, and lakes play an important role in habitat availability and are a good indicator of overall water system health. A number of variables affect DO concentrations including algal activity, vegetation concentration, water temperature, flow velocity, reaeration, photosynthesis, biological oxygen demand, and sediment oxygen demand (SOD) (Pelletier et al, 2006). These natural processes must be in balance with each other for healthy levels of DO to be present. When one or more becomes dominant, oxygen can be consumed in disproportionate amounts that lead to low DO and results in impaired waterways. According to the Washington Department of Ecology (DOE (Ecology, 2007)) DO must be between 6.5 and 9.5 mg/l for healthy fish population habitat and rearing conditions. In King County, Washington a series of drainage channels have been demonstrating DO levels much lower than Ecology's recommendations. As a result, King County has undertaken a five-year water quality study to address the waterway's level of impairment and design strategies to ameliorate the low DO and improve fish habitat. This investigation was undertaken as a part of that study and spanned two years from 2005 to 2007. The objective of this investigation was to increase knowledge of factors affecting DO and drainage capabilities in agricultural waterways in order to provide a tool to aid landowners and legislators in developing effective best management strategies. A secondary goal designed to complement the first was to undertake a detailed study of how sediment oxygen demand interacts with other components of the DO cycle as a result of maintenance activities.

Over time the county ditches have become inhabited by fish including salmon species found on the EPA's endangered species list. When maintenance activities are prevented the channels become choked with thick vegetation including Reed canary grass (RCG). This effectively blocks the channels to the point of flooding the agricultural fields they were designed to drain. This reduced ability to drain is hypothesized to be due to restricted flow and decreased velocities in un-maintained channels. The vegetation also affects fish populations which have been shown to decrease or disappear altogether when the grasses are left untouched. This is in part due to the anaerobic conditions which occur in un-maintained reaches. This is thought to be in part due to high sediment oxygen levels under the grass mats as detritus and decaying organic matter increases as a result of natural growth and death cycles of the RCG. This occurs when the decaying matter settles out of the water column and rests on the channel floor where it contributes to a DO deficit by becoming a source of nutrients for oxygen-consuming microorganisms. The grasses are also thought to reduce reaeration by preventing wind and precipitation from reaching the water surface. A third contribution to low DO is the shade provided by the grasses, which decreases algal photosynthesis by restricting solar radiation penetration at the water's surface. Finally, thick vegetation reduces channel flow velocity which effectively increases residence time and reduces the opportunity for reaeration-inducing turbulence. Increased residence time causes oxygen-consuming processes in the water column (biological oxygen demand (BOD)) to have more opportunity to degrade DO within a reach segment. Reduced velocity is hypothesized to be due to elevated roughness coefficients and energy slopes due to the uneven and varied channel bottom in un-maintained channels.

Relatively little research has been performed on the components of the DO mass balance equation in heavily vegetated low-flow, low-gradient channels such as those found in King County. To date DO investigations have been for large-scale rivers and lakes (Jones and Stokes, 2005, Litton et al., 2003) which differ from smaller water bodies in numerous ways including temperature, depth, flow rate, vegetation, sediments, nutrient concentration, reaeration rates, and microbial populations. There is especially a knowledge deficit concerning how specific components of the DO balance are affected by human activity. Therefore the purpose of this research was to investigate the effects of maintenance practices on dissolved oxygen levels in agricultural waterways and provide relevant information on their unique characteristics. This thesis seeks to address these components of the DO mass balance equation by documenting monitoring and measurement results of the channels prior to and following vegetation removal and by modeling these variables to observe their individual contributions to the DO budget.

This report has been divided into four chapters, with the first being an introduction to the study, the second and third detailing the water quality investigation, and the fourth providing a summary of the study's findings. Specifically, chapter two addresses changes to channel roughness coefficients and drainage capabilities in maintained channels. These issues were addressed by a combination of field surveying, first-hand observations, and modeling.

The third chapter documents a DO model that includes a detailed investigation into the contributions of sediment oxygen demand, reaeration, and photosynthesis. The SOD study was performed on sites undergoing various stages of maintenance or the lack thereof and used in conjunction with the modeling efforts to provide a reliable means of predicting water quality behavior as a result of vegetation removal. The literature on SOD has until now, been primarily focused on large rivers and lakes, much like the DO research (Matlock et al., 2003; Caldwell and Doyle, 1995). The effects of SOD on aquatic systems are proportional to the depth of flow above the sediments, therefore playing a much larger role in DO degradation in shallow waterways than the well-documented large systems. As a result of this study, documentation on the behavior of SOD in shallow channels undergoing vegetation removal will be improved. The third chapter also details the development of a calibrated water quality model for low-flow agricultural channels before and after vegetation removal. The results of this study will be included in a comprehensive report for King County. Because of this report format, both chapters two and three were designed as stand-alone investigative reports and detail site selection, study methods, results, analysis, and conclusions. As such, some material is repeated in chapters two and three including project descriptions and explanations. The references used in each chapter have been combined into one section at the conclusion of chapter four. Since the author anticipates submitting the chapters to scientific journals, the data included is a summary of relevant information. Detailed model input/output tables and graphs can be found in the appendices as well as site maps, state water quality standards, experiment results data and calculations.

2.0 CHAPTER TWO

2.1 INTRODUCTION TO CHARACTERISTIC INDICATORS OF IMPROVED DRAINAGE AFTER EXCAVATION

Preserving the agricultural function of existing farmland while improving habitat conditions for endangered species is of vital importance to many of King County's residents. An important component to preserving these low-lying farmlands is the maintenance of agricultural waterways for drainage as most of the ditches' flow characteristics directly impact the drainage of adjacent lands. When maintenance practices are neglected, vegetation tends to increase to a level that both raises the water surface elevation and restricts flow. This in turn causes flooding throughout the surrounding areas. Furthermore, without vegetation removal, the flooded portions do not fully drain, resulting in ponding which restricts or removes the land's agricultural viability.

King County's goal has been to develop a methodology to help predict water levels after excavation of Reed canary grass and sediment. With the assistance of KCDNRP staff, the following research hypotheses were posed in relation to this study component:

Hypothesis 1: Maintaining select channel segments will not alter drainage of adjacent agricultural lands as indicated by statistically significant decreases in water surface elevation within the channel, compared to baseline conditions.

Hypothesis 2: Maintaining select channel segments will not alter agricultural channel drainage in terms of hydraulic parameters (e.g., wetted-perimeter, bed slope, and channel roughness) compared to baseline conditions.

As a result of these hypotheses, the purpose of Goal 12 is two-fold: The first is to investigate the effects of dredging clogged waterways on adjacent agricultural lands. The second is to measure and report the changes said dredging has on hydraulic parameters within the cleaned waterways.

In order to address the first purpose, samplers monitored maintenance operations and documented their effects on adjacent lands. The operation involved removing vegetation and sediment from a ditch in order to increase flow and decrease water surface elevations and channel roughness. The cleaners operated under the theory that the subsequently improved drainage capability would dry out surrounding ponded regions leaving the land usable for agricultural use. Documenting improvements to adjacent lands included first-hand accounts by landowners and WSU staff who observed changes in land use practices. Measurements of pre- and post- dredged water surface elevations, channel characteristics and flow velocities also illustrated enhanced drainage since management practices were resumed.

The second purpose was analyzed using a combination of site surveys, data collection, and calculations. Sites under various stages of maintenance were surveyed and their geomorphology and flow characteristics measured. Using the collected data the values were then analyzed with a computer model called HEC-RAS that reported selected hydraulic parameters. In this way pre- and post maintenance conditions were reported for use in subsequent drainage, flood, and management calculations and decisions.

2.2 SUMMARY OF RELEVANT RESEARCH

Depending on flow and channel characteristics, free-surface open channel flows can be theoretically classified as (Chaudhry 1993):

1. Steady Uniform Flow
2. Steady Nonuniform (Varied) Flow
    a. Gradually Varied
    b. Rapidly Varied
3. Unsteady Uniform Flow
4. Unsteady Nonuniform (Varied) Flow
    a. Gradually Varied
    b. Rapidly Varied

The terms steady vs. unsteady refer to whether or not the flow velocity at a point changes with time. In steady flow situations, the velocity (and therefore the discharge) is assumed to be nearly constant. In unsteady flow cases, the velocity at a point changes with respect to time. Uniform versus nonuniform refers to whether or not the flow rate changes with respect to longitudinal distance. For uniform flow, there is no change in flow with respect to the longitudinal flow direction along the channel. For nonuniform flow, the flow is assumed to change with distance.

Flow is referred to as “gradually varied flow” if the rate of depth variation is small with respect to distance. Conversely, they are referred to as “rapidly varied flow” if the rate of depth variation is large with respect to distance.

Natural open channel flow conditions may be represented either by steady uniform flow (Case 1), steady nonuniform flow (Case 2) or unsteady nonuniform flow (Case 4). While theoretically possible, the occurrence of unsteady uniform flow (Case 3) does not occur in nature.

To be truly uniform, the channel must be 1) straight, 2) have constant slope, and 3) have constant cross-sectional area. Because of these three constraints, few natural channels actually qualify as uniform although approximations that allow for this simplified solution are often made. Steady uniform flow (Case 1) can be expressed using the well-known Manning's Equation. In English units, this equation can be expressed as:

$$Q = \frac{1.49}{n} A R^{2/3} S_o^{1/2} \tag{2-1}$$

Where A is cross-sectional area [ft^2], n is the Manning's roughness coefficient, R is the hydraulic radius [ft], and S_o is the bed slope [ft/ft].

Hydraulic roughness parameters for varying types of channels have been well documented. Typical roughness values were covered in detail by Chow (1959). Chow recommends maximum Manning's n values for un-maintained excavated channels of 0.08 to 0.14 depending on the levels of vegetation present. For maintained excavated channels, he recommends Manning's n not exceed 0.06 to 0.08. However, these values were developed for engineered flow conveyance channels and natural streams, not for the level of vegetation present in some of the agricultural drainage channels within King County.

For relatively short sections of drainage canals typically involved in maintenance activities, the assumption of steady gradually varied nonuniform flow (Case 2 a) may be more appropriate than steady uniform flow because channel bottom slopes are unlikely to be constant. In this case, an iterative approach to solving the following expression is used:

$$\Delta x = \frac{\left[\frac{\left(V_1^2 - V_2^2\right)}{2g}\right] + y_1 - y_2 - h_L}{S_o - S_f} \quad (2\text{-}2)$$

Where V is the average cross-sectional velocity [ft/s], g is gravity [ft/s^2], y is flow depth [ft], h_L is head loss due to expansion, contractions, and bridge piers [ft], S_o is the bed slope [ft/ft], and S_f is the friction slope (slope of the energy grade line) [ft/ft]. The subscripts in Equation 2-2 refer to upstream and downstream cross-sections along the agricultural waterway.

Unlike steady uniform flow where the bed slope is assumed equal to the slope of the energy grade line, in steady nonuniform flow, the two terms in the denominator must be different to avoid dividing by zero. With the bed slope known from field measurements, the friction slope is typically estimated by rearranging Manning's Equation as:

$$S_f = \left(\frac{n\,Q}{1.49\,A\,R^{2/3}}\right)^2 \quad (2\text{-}3)$$

Using this approximation, Equation 13-2 can be solved. It should be noted that for the mild slope conditions existing in agricultural waterways, this expression is controlled by a known downstream flow level and is solved by progressing upstream.

A thorough discussion of one-dimensional flow calculations is beyond the scope of this document. Readers wishing to learn more about the specific procedures are referred to the Hydraulics Reference Manual produced by the US Army Corps of Engineers (2002a).

The unsteady gradually varied flow scenario (Case 4) requires time dependent flow conditions and complex simulation that were not considered feasible for this task.

2.3 METHODS

2.3.1 Site Selection

Three sites were chosen for conducting sampling and surveys. Each one was selected based on characteristics that were representative of conditions found throughout all the King County APDs. In addition, the chosen sites were appropriate due to the advanced nature of their flow restrictions and pending scheduled cleaning operations.

The first was the portion of Mullen Slough owned by Smith Brother's Dairy in Kent, Washington. An additional segment of the Slough owned by the Boscolo family was also used. Both Mullen and Boscolo are located in the Lower Green River APD. Mullen Slough afforded a unique location from which to observe the effects of cleaning operations on site drainage. During the course of the study, maintenance activities were scheduled at Smith Brother's Dairy resulting in the site's selection for survey data collection. Prior to cleaning operations, Mullen Slough was severely clogged with Reed canary grass that was restricting channel flow and causing local ponding in surrounding agricultural lands. During the sampling at Mullen Slough, hand-cleaning operations were underway. This offered a unique opportunity for direct comparison between un-cleaned and cleaned channel characteristics. The Boscolo portion of the Slough was located upstream from the dairy and both segments joined under a bridge over 277th in Kent, Washington. The Boscolo's performed maintenance activities after survey data was obtained, so the reaches included in analysis were still heavily vegetated. Figure 2-1 depicts pre-maintained conditions along a section of the Mullen Slough drainage. Alternately, Figure 2-2 shows a typical channel just after maintenance.

The third and final site was a segment of Big Spring Creek in Enumclaw, Washington at 236th Ave SE between SE 424th and SE 436th streets at the Engburg family residence. This site was selected because its un-maintained status gave researchers an excellent opportunity to survey and analyze pre-dredge channel characteristics. The Engburg portion of Big Spring Creek flowed through a portion of agricultural land inhabited by a small cattle herd. Other segments were unused at the time of sampling and vegetated primarily by grass species. Figure 2-3 shows a typical section of Big Spring Creek with its high levels of vegetation.

Figure 2-1 Pre-maintained Mullen Slough agricultural waterway

Figure 2-2 Typical post-maintained channel prior to mitigation

Figure 2-3 RCG vegetation growing in Big Spring Creek on June 21, 2005

2.3.2 Field Measurements

For collecting the survey data, a Total Station EDM device was used along with an extendable 8.5 ft target rod with a mounted prism. Measurements were taken at various points along the ditch edge or bed. Typical cross-sections were surveyed in heavily vegetated reaches of Big Spring Creek and Mullen Slough. Additionally, survey data was taken at recently hand-cleaned portions of Mullen Slough to compare to the un-maintained regions. Sufficient data was collected to provide a characteristic representation of a cleaned ditch.

The longitudinal and elevation data was acquired using a hand-held GPS device at the base of the EDM at both the Big Spring Creek and Mullen Slough locations. The accuracy of the GPS unit was approximately ± 23 ft making the absolute elevations calculated somewhat approximate. Because of this, the GPS points were used as a general reference to location, but longitudinal data and channel geometry were taken with the more precise EDM and their relative positions were then used in calculations. Flow was calculated using traditional stream-gauging techniques and devices. Elizabeth Milburn, Tom Cichosz, and Dr. Michael Barber collected this data on June 21-22, 2005.

2.3.3 Observations

Land use observations were collected throughout the study duration. Most recently, observations were made at two hand-cleaned sites: Mullen Slough at both Smith Brother's and Boscolo's properties in Kent, Washington in the Lower Green River APD. Additionally, pre-dredge observations and measurements were conducted at both Mullen Slough (Smith Brothers Dairy) and Big Spring Creek (Engburg family) located in the Enumclaw APD. Changes to surrounding agricultural landscape were observed visually and recorded throughout the study duration. WSU staff and Smith Brothers' Dairy staff both contributed by noting drainage trends and land usability at various stages of channel maintenance. Smith Brother's site manager Jack Woods monitored changes to Mullen Slough and adjacent fields and his comments are in the results section.

2.3.4 Numerical Analysis

The initial goal of WSU researchers was to create a simple spreadsheet capable of solving for water surface elevations in a channel with gradually varied flow. While such a task is relatively simple for prismatic channels with two cross-sections and relatively simple channel geometry, the complexity of handling multiple segments, variable cross-section geometries, and multiple segments along the reach led us to pursue a slightly more sophisticated numerical approach. Balancing cost and complexity with need, the HEC-RAS simulation model was selected as the most appropriate model. This model is widely used and available free of charge from:

http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html

Improvements to drainage were quantified using the HEC-RAS model. The model was used in conjunction with the survey data to evaluate changes to wetted perimeter, channel roughness, and bed slope. The collected survey and flow data was entered into the program which calculated flow depths based on the variables collected in this study by iterating between different known parameters such as velocity, water surface elevations, and channel geometry. When the modeled water depths matched those observed in the field, the roughness input from the calibrated model was recorded. In this way a representative roughness value was chosen for both cleaned and vegetated scenarios. The resulting roughness values can then be used in future flood prediction calculations and evaluations of drainage potential as well as a mechanism for estimating flow velocities in water quality models. A typical HEC RAS geometric data entry window is displayed in Figure 2-4.

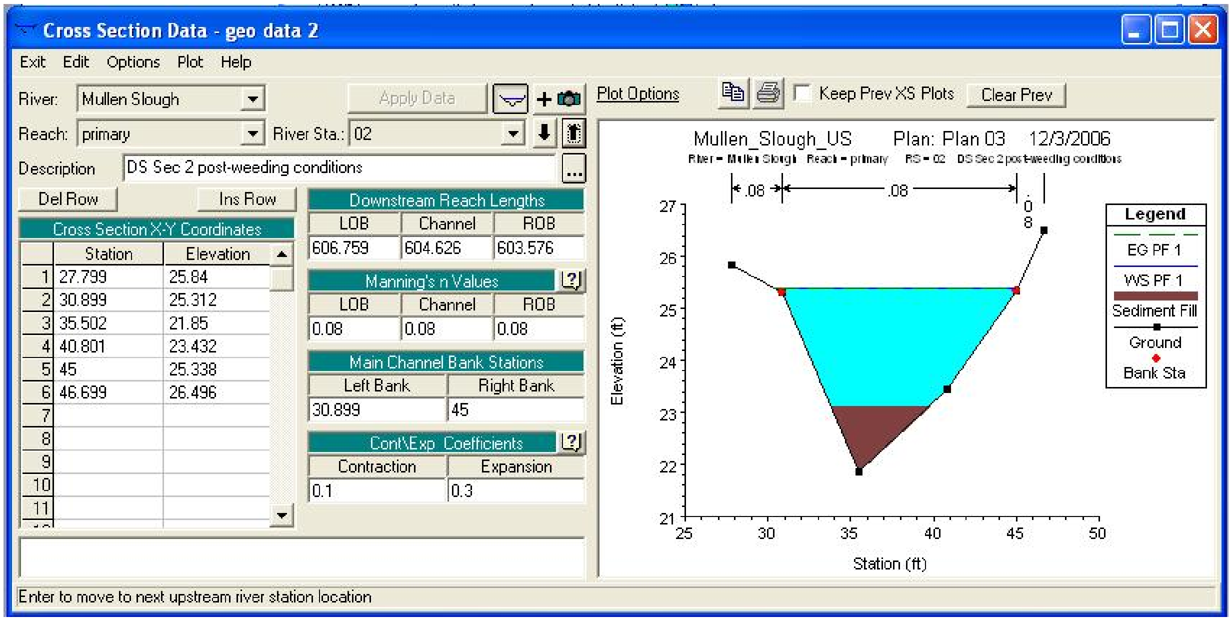

Figure 2-4 Typical HEC-RAS data frame window

In addition to the HEC-RAS simulation, Manning's roughness values were also calculated using a spreadsheet in Excel. The channel trapezoidal geometry values were entered into Manning's equation along with known water surfaces. Manning's n was then determined by iterating between different roughness values until the known discharge was obtained. Due to the amount of variables HEC-RAS accounts for, including sediment depth and impacts from adjacent reach segments, the Excel and HEC-RAS values were anticipated to differ somewhat with the HEC-RAS results being more accurate. This discrepancy is to be expected in a natural system with a high number of variables. The Excel values should confirm the HEC-RAS outputs by illustrating a general trend agreement and will be discussed accordingly in the Results section of this report.

2.4 RESULTS

2.4.1 Surveying

Some small discrepancies in water surface elevations across cross-sections were found during survey conduction. This was due to the difficulty in measuring a true perpendicular cross-section. As a result, the water surface elevation on one side of the stream differed from the water surface elevation at the same cross section on the opposite side of the stream. The difficulty arose when dense vegetation prevented adequate visual lines from one stream side to the other and caused mobility challenges to the samplers as well. An average between the two measured elevations was used during modeling calculations.

2.4.1.1 Big Spring Creek

The reach surveyed for Big Spring Creek included a 683 ft long section with the survey equipment situated at GPS station N47.13.032 W122.1.511 at elevation 599 ft above sea level. Typical reach conditions are shown in Figure 2-5. The water surface elevation change from the far upstream point to the far downstream point was approximately 1.64 ft for a slope of 0.29 % over the entire 683 ft reach. A typical cross section in the upstream direction can be seen in Figure 2-5 as plotted by HEC-RAS 3.1 modeling software. Similarly, Figure 2-6 shows a typical downstream cross-section.

The creek depth varied from approximately 3.0 ft to 1.4 ft upstream to downstream with an average flow depth of 2.1 ft over the entire survey length.

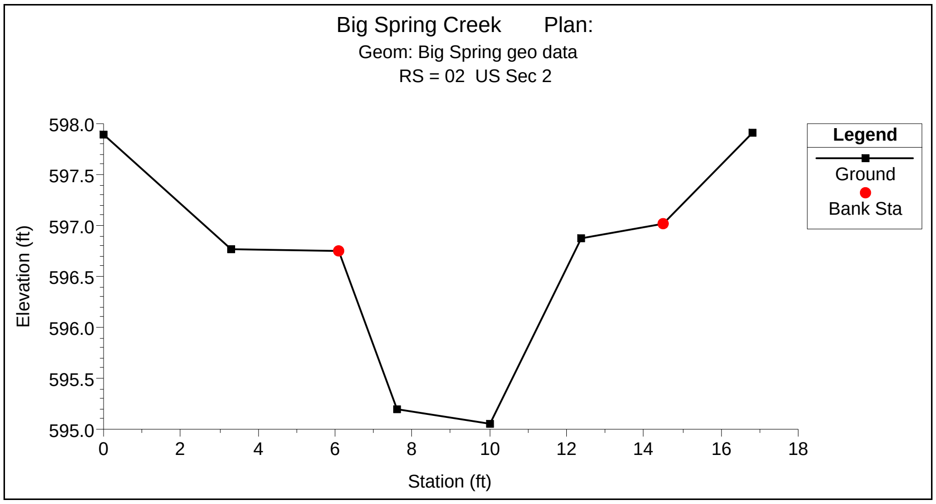

Figure 2-5 Characteristic upstream cross-section of Big Spring Creek

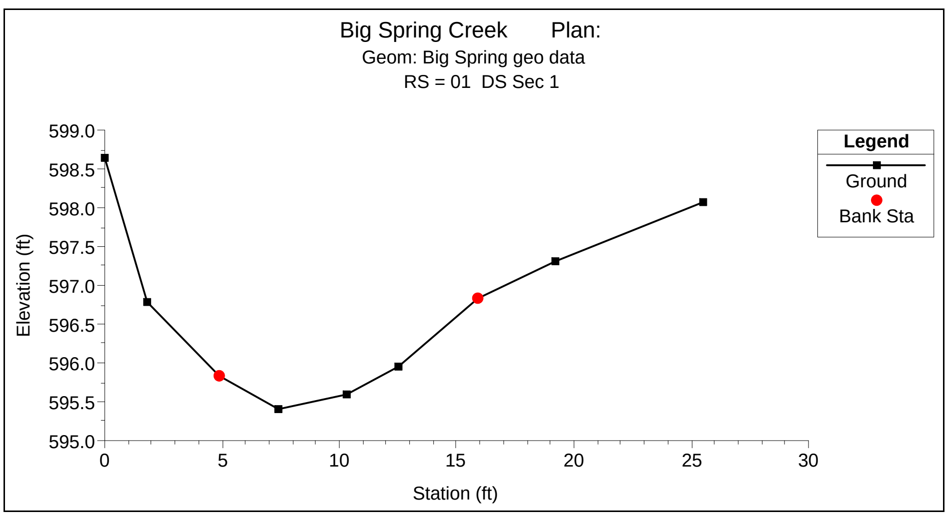

Figure 2-6 Characteristic downstream cross-section of Big Spring Creek

2.4.1.2 Mullen Slough

The reach surveyed for Mullen Slough was a relatively straight, flat section 1,594 ft long with the survey equipment situated at GPS station N47.27.648 W122.15.663 (Mullen_5) at elevation 31.0 ft above sea level. Figure 2-1 illustrates pre-maintained conditions in the lower segment of Mullen Slough between Mullen_5 and Mullen_4 at the Smith Brothers Dairy. Figure 2-7 shows the same location after being cleaned.

Figure 2-7 Typical post-cleaned conditions at Mullen Slough from Mullen_5 to Mullen

Approximately 604.9 ft between Mullen_5 and Mullen_4 (the most downstream segment) was devoid of vegetation due to ongoing hand cleaning. The remaining 989.1 ft between Smith_Brothers_4 and Mullen_5 was clogged with Reed canary grass (RCG). The water surface elevation change of the vegetated portion from the far upstream point to the far downstream point was approximately 1.4 ft for a slope of 0.14 % over the entire 989 ft reach. The weeded portion had a water surface elevation change of approximately 0.004 ft over the 605 ft length giving a slope of 0.00066 %. Typical cross sections for upstream and downstream directions can be seen in Figure 2-8 and Figure 2-9 respectively.

Mullen Slough's creek depth varied from approximately 3.4 ft upstream to 3.6 ft downstream with an average flow depth of 3.4 ft over the entire survey length.

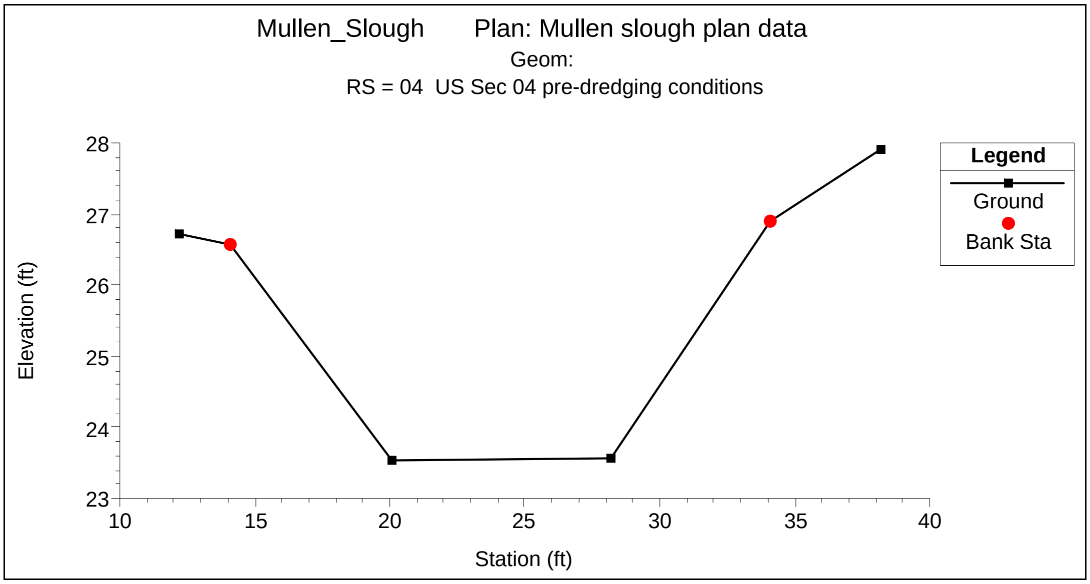

Figure 2-8 Characteristic pre-cleaned upstream cross-section of Mullen Slough

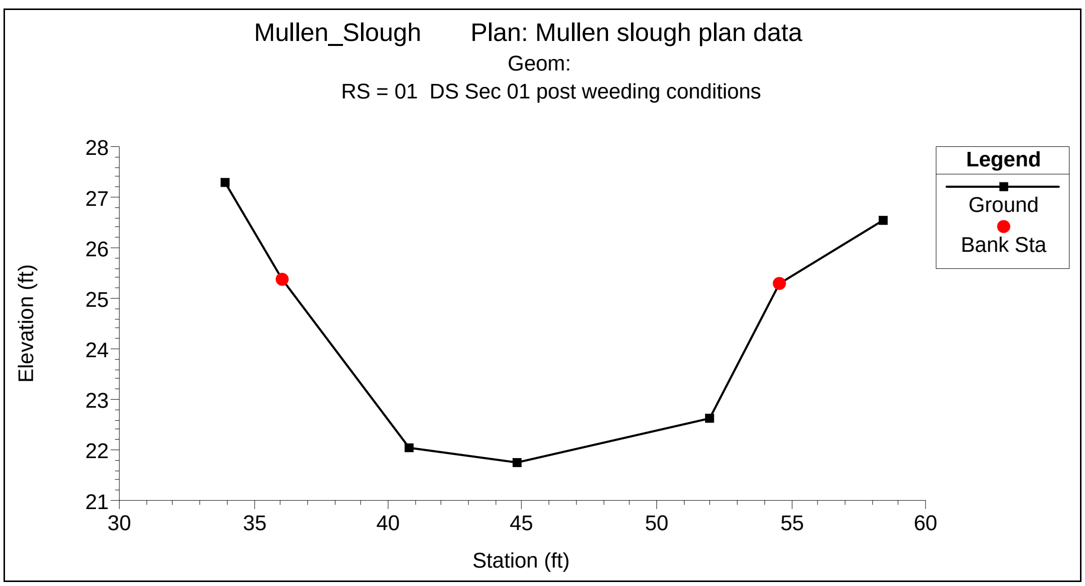

Figure 2-9 Characteristic post-cleaned downstream cross section of Mullen Slough

2.4.2 Flow Data

2.4.2.1 Big Spring Creek

In most areas the creek was clogged with thick vegetation consisting primarily of Reed canary grass. As illustrated in Figure 2-10, local livestock appear to have cleared the vegetation from an area downstream from a small bridge. This was the location chosen for flow measurements. Discharge was determined to be 2.05 cfs and the maximum velocity was 0.81 ft/sec.

Figure 2-10 Stream gauging location on Big Spring Creek

2.4.2.2 Mullen Slough

Due to thick vegetation in Mullen Slough, the flow was not able to be measured using traditional stream gauging techniques. Employees of the Smith Brother's. Dairy had weeded the reach portion downstream from the survey equipment, making flow observation more feasible. However, the flow downstream was not measured due to an approximately 4 ft deep layer of silty sediment that caused the stream gauging equipment to jam. Flow was therefore estimated by taking the cross sectional area and one stream gauge data point. Discharge was determined to be approximately 0.5 cfs at a maximum velocity of 0.11 ft/s at the channel center. Sampling teams in July measured flow in the maintained reaches at 1.5 cfs downstream from an inflow source (Smith_Brothers_2 to Smith_Brothers _3). They also attempted to measure in the un-maintained reaches but were unable to observe enough discernible flow for an accurate reading. This difficulty in measuring reliable values was taken into account, therefore flow inputs were considered approximate when Manning's n was being calculated. A summary of these values for both Mullen Slough and Big Spring Creek can be found in Table 2-1.

2.4.3 HEC-RAS ANALYSIS

Manning's n values were determined from HEC-RAS simulations. Energy grade slopes were also calculated in HEC-RAS. See Table 2-1 for a summary of these results.

Table 2-1 Results summary for Manning's n and energy grade slopes

Site Name	Maintained Status	Length (ft)	Energy Grade Slope (ft/ft)	Discharge (cfs)	Manning's n
Mullen Slough	Cleaned	604.9	0.000021	1.52	0.08
	Un-cleaned	989.0	0.0029	0.5	1.9
Big Spring Creek	Un-cleaned	683.0	0.011	2.05	0.41

The difference in slopes for both sites can best be illustrated by a longitudinal profile of the reach system. In Figure 2-11 the highly variable slope of the un-maintained Big Spring Creek site is shown. By contrast, in Figure 2-12 the cleaned portion of Mullen Slough has a much lower slope gradient beginning at River Station 03. Note the varied gradient upstream between stations 03 and 07 where cleaning operations had not yet begun.

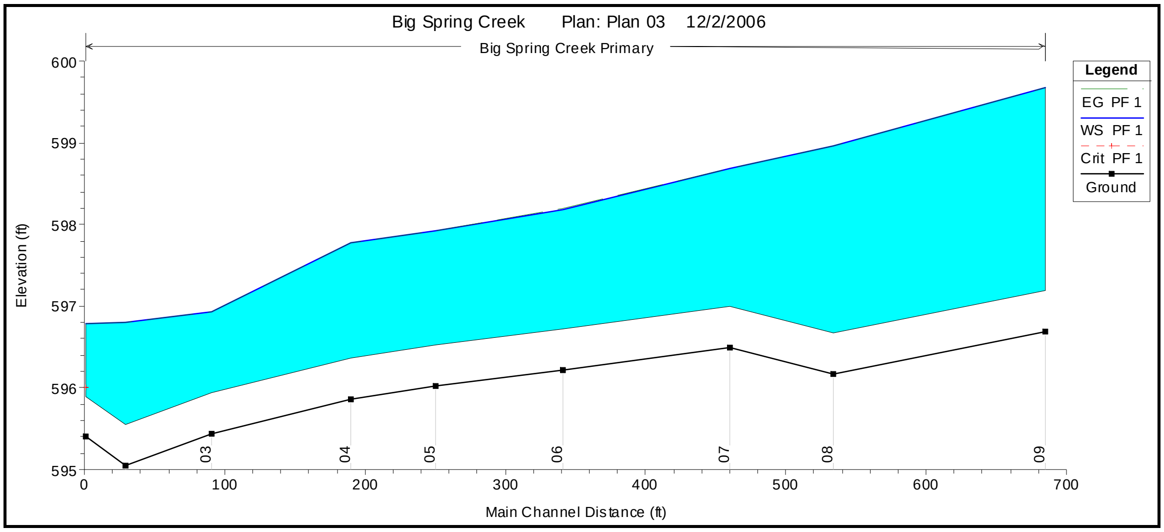

Figure 2-11 Longitudinal profile of Big Spring Creek showing a highly variable flow gradient throughout the un-maintained reach

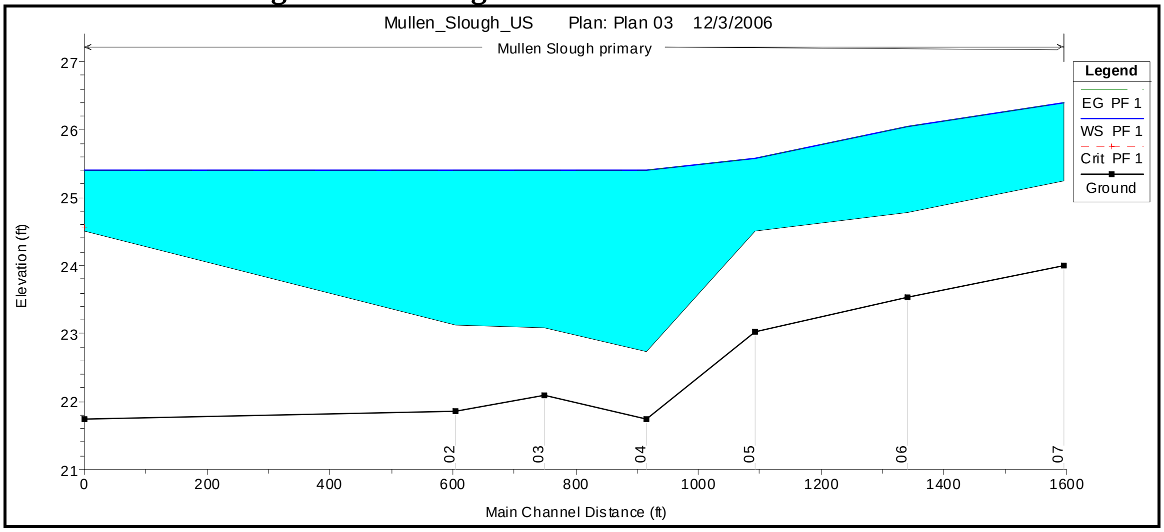

Figure 2-12 Longitudinal profile of Mullen Slough illustrating altered flow gradient as a result of cleaning operations

Note that the simulations are based on known sediment elevations which appear as a white space between the ground level and the water /sediment interface. The nature of the maintained reach sediment was that of a low-density silty medium with a high degree of decaying matter. Due to these characteristics, the surveying prism protruded through the sediments resulting in a measurement of the firm ditch bottom below.

2.4.4 Observations

Throughout the course of the study, various alterations to channels and adjacent lands have been observed. The Smith Brother's site provides a particularly applicable scenario on the effects of maintenance operations. Hand cleaning was undertaken on Mullen Slough in early summer of 2005 and took 5.5 months to complete. As a result, according to Jack Woods, Smith Brother's site manager, the surrounding land became useable for agricultural purposes almost immediately and they were able to harvest crops for the first time in thirteen years. The first growing season following vegetation removal, Smith Brother's harvested livestock feed from their property and a neighbor planted pumpkins. Mr. Woods also noted the improvements to accessibility that the cleaning efforts provided, including the ability to reach parts of the property by motorized vehicle that previously had been too saturated to drive across. He also has not seen ponded or standing water on the property since cleaning commenced, whereas previously there had been significant portions of the property rendered unusable by standing water. Mr. Woods was also impressed when after a recent flood event in King County (November, 2006), Mullen Slough drained out within two days while Mill Creek (an uncleaned reach in the same vicinity), was still at bank-full depth in late December. Additionally, since cleaning operations commenced, the Dairy has been able to generate income off the land by leasing parcels to local growers who have continued harvesting pumpkins and hay where prior to ditch maintenance activities the land was saturated.

WSU staff has noted changes as well, including an increased ability to gain access to certain reaches due to decreased saturation. Formerly ponded regions have since drained sufficiently to enable potential agricultural practices.

2.5 DISCUSSION

The Manning's n values obtained in this study differ significantly from typically reported industry standards. Chow (1959) recommends a maximum roughness value of 0.120 for un-maintained excavated channels with dense weeds. By contrast, the channels in this study were demonstrating a range of 0.41 to 1.9 for Manning's n. These values, which are much greater than those used under standard conditions, illustrate the inability to apply typical equations to the agricultural waterways. The uniqueness of the hydraulic characteristics of an un-maintained agricultural channel dictates a higher level of measurement and analysis than similar non-agricultural waterways might. Before modeling these reaches, a detailed survey should be conducted and used for roughness calculations as well as other relevant hydraulic parameters. Once the channels undergo maintenance they begin demonstrating roughness characteristics in accordance with Chow's recommendations. He lists a maximum n value of 0.08 for excavated channels with clean bottoms and dense brush on the banks (Chow, 1959). The maintained portions of Mullen Slough possessed an average Manning's n of 0.08. This value is toward the high end of Chow's values, but considering the variability of measuring a channel undergoing drastic alterations, it shows a remarkable fit.

The difference in water surface elevation, slope, and energy gradient for maintained channels suggests an increased drainage capability. The lowered uniform slope of the maintained reach will specifically provide greater flood drainage capabilities and improved fish passage. Similarly, a reach with a lowered surface elevation should be cooler than its vegetated counterpart leading to improved fish habitat.

Observed agricultural improvements at the Smith Brother's site indicate increased drainage due to hand cleaning operations. This restoration of the land's agricultural purpose serves both the landowner and the surrounding community who have demonstrated an interest in maintaining agricultural activities in the valley.

2.6 CONCLUSIONS AND RECOMMENDATIONS

Periodic cleaning of agricultural waterways has been quantitatively and qualitatively shown to significantly reduce the negative aspects of farmland flooding and improve the economics of agriculture in King County. Numerical modeling with HEC-RAS and roughness coefficients much greater than typical reported values has been shown to produce results that accurately match measured water surface elevations. This methodology can be used in the future to predict the post-dredge water surfaces. The exact roughness value to use will depend on the level of RCG and sediment clogging the channel. There was insufficient information to develop a reliable means of estimating this as a function of RCG density or other metric.

A quick estimate of the drop in elevation may be obtained simply by examining the slope of the water surface. As shown at both sites, RCG and sediment are such impediments to the movement of water that a considerable head builds up in the system. Post-maintenance water surface elevations are much milder in slope. As was illustrated in Table 2-1, the slope is significantly reduced even after hand cleaning. Mechanical cleaning would likely improve the drainage even further (at least until upstream sediment moved into the excavated area).

Hypothesis 2 was effectively disproved by the results of the HEC-RAS modeling which demonstrate significant changes in hydraulic parameters as a result of dredging. The hydraulic and energy grade line slopes were shown to be reduced dramatically by a factor of more than 100 as the result of a significant decrease in head loss. Correspondingly, the roughness value (n) was reduced by a factor of over 20. Higher head loss under pre-maintained conditions result in greater flooding potential as the resistance to flow moving through the channel will force the water level to rapidly rise upstream and find its way out of the channel. Increased roughness due to excessive RCG also contributes to flooding problems by decreasing the cross-sectional flow area which raises the surface elevation even further and causes additional flooding. As the water surface rises the wetted perimeter also increases which, when paired with a lowered cross-sectional area reduces the hydraulic radius thereby decreasing the available flow path. Maintaining the channel regularly eliminates these negatives and improves channel hydraulics.

3.0 CHAPTER THREE

3.1 INTRODUCTION TO DISSOLVED OXYGEN LEVELS IN AGRICULTURAL AND NON-AGRICULTURAL WATERWAYS

Oxygen levels in streams, rivers, and lakes play an important role in habitat availability and are a good indicator of overall water system health. Although little information exists on the role of agricultural waterways in providing habitat, data suggests that over time such waterways in King County have become inhabited with fish, including salmon species found on the EPA's endangered species list. Preliminary measurements have shown that un-maintained reaches may have dissolved oxygen conditions much lower than EPA allows for fish-inhabited streams. The premise is that prior to cleaning efforts most of the targeted waterways are colonized by a high percentage of vegetation and partially filled with anaerobic sediments. As the vegetation dies, falls into the water, and begins to decay, the bacteria decomposing the vegetation consume dissolved oxygen. This component of the dissolved oxygen balance, called the sediment oxygen demand (SOD), can effectively deplete oxygen in water systems to uninhabitable levels thereby impacting the quality of the habitat.

Currently landowners are not permitted to dredge vegetation such as Reed canary grass (RCG) or other invasive species from the reaches due to concerns about migrating salmon and other fish habitat. In an effort to determine the impact of maintenance activities on salmonids, the agricultural waterways in King County have been undergoing a five-year study that included a water quality component aimed at scientifically determining dissolved oxygen levels before and after dredging. This chapter of the report details the results of a comprehensive water quality study in a series of low-flow low-gradient agricultural drainage ditches in King County, Washington. This is expected to assist King County staff and farmers in submitting their planned best management strategies based on the ability to accurately predict water quality parameters affected by these management practices.

With the assistance of KCDNRP staff, the following initial research hypotheses were posed in relation to this study component:

Hypothesis 1: Dissolved oxygen levels in agricultural waterways do not differ from those in adjacent natural streams.

Hypothesis 2: Dissolved oxygen levels in agricultural waterways do not change as a result of maintenance activities.

These research questions will be answered through a combination of water quality monitoring and modeling. Monitoring efforts were focused on reaches that would contribute typical conditions of sites throughout the study region. Researchers sampled at both agricultural and adjacent non-agricultural points at both pre-maintained and post-maintained conditions. This measurement strategy allowed researchers to draw comparisons between DO levels in maintained vs. un-maintained locations as well as note any differences between reaches flowing through agricultural land vs. those flowing through similar un-farmed areas.

Washington State University researchers tailored an existing Washington Department of Ecology (DOE) water quality model (Qual2Kw) to fit the project's unique characteristics. This model will facilitate the County's development of management strategies for the targeted waterways. King County specifically requested dissolved oxygen predictions, therefore the results discussed in this report will be restricted to DO levels and a limited number of other significant variables which were collected along with DO data and can subsequently be used for model calibration verification.

Sediment oxygen demand and reaeration restrictions are thought to play a large role in the degradation of oxygen levels in the King County agricultural watercourses. These man-made ditches typically run the length of an agriculturally zoned flood plain and assist in draining the fields to a farmable saturation level. In conjunction with this study, SOD was monitored and analyzed as an important variable in understanding the DO balance and to facilitate in model calibration. In addition, reaeration rates were used as a key calibration variable for the model and were evaluated for both pre and post-maintenance scenarios.

3.2 PHYSICAL SYSTEM

3.2.1 Overview

The system chosen for the initial model simulation is a low-flow, low gradient agricultural ditch network called Mullen Slough in Kent Washington; global positioning system (GPS) coordinates (47.3609, -122.2611). The land is used primarily for small-scale private crops and the Smith Brother's Dairy, as is typical of many agricultural regions of King County. The dairy applies a diluted manure mixture to the property through a spraying device which serves to both irrigate and fertilize. The reach modeled was approximately 1.64 miles (2.65 km) long with a non-agriculture point-source inflow located approximately 0.8 km from the furthermost upstream (headwater) location. The non-agricultural inflow enters the valley after flowing through residential and undeveloped properties and was modeled as a point source to the main Mullen reach. Data was collected at the site on September 21, 2004 before any maintenance had been performed. The average flow in the primary system was approximately 0.5 cfs (.01 cms) with an average depth of 3.3 ft (1.0 m) and width of 16.5 ft (5.0 m). Average temperature for the reach in September 2004 was 60°F (15.4 °C). Extremely dense RCG clogged most of the reach as shown in Figure 3-1 Pre-dredge Mullen Slough showing.

Figure 3-1 Pre-dredge Mullen Slough showing dense RCG and restricted flow path

3.2.2 Dissolved Oxygen

Sites throughout the target area were selected based on their perceived contribution to the study's goals. This was accomplished by focusing on points which were either typical of agricultural or non-agricultural conditions or where maintenance operations were scheduled and subsequently performed. Samples were taken at enough points to obtain reasonable representation of reach conditions for each stage of maintenance. Samplers also recognized key inflows and outflows and took care to document corresponding upstream and downstream alterations.

Non-agricultural sites were chosen based on their proximity to their agricultural counterparts. In Kent, WA an inflow to Mullen Slough located at the Smith Brothers dairy was selected as a representative non-agricultural site (see

Figure B.1). This reach, labeled "Smith_Brothers_1" flows through a forested slope adjacent to the Smith Brother's agricultural land before joining Mullen Slough. The geomorphology of the non-agricultural reach and the main Slough differed in depth, sediment composition, shade, and flow velocity. Pre-dredged Mullen Slough was about 3.5 ft deep on average while the non-agricultural inflow averaged 0.5-1.5 ft in depth. The area around Smith_Brothers_1 is more forested and shaded than the man-made slough, which results in a more diverse flow path and cooler temperatures. The natural shape of the flow also provides increased aeration over natural obstacles and through pools. During the study period beavers dammed up the inflow at least once causing significant upstream flooding. The flow exiting the beaver dam exhibited a high rate of aeration and increased velocity.

Before Mullen Slough reaches the dairy it flows through the Boscolo family's property (see Figure B.2) which is also zoned agriculturally and is used mainly for small-scale gardening when it is drained sufficiently. After Boscolo's, the slough passes under 277th and flows into Smith Brother's territory. Throughout the study Smith Brother's' land was too saturated to be used for significant agricultural applications but was still being fertilized with diluted manure and hosted a small cattle herd. Smith Brother's began hand-cleaning their channel around July of 2005 resulting in significant changes to the channel vegetation. The cleaning operations removed RCG and other vegetation by hand or small power tools. Plant spoils were deposited on the bank and sediment spoils allowed to settle to the channel floor. The hand dredging operations exposed most of the channel and removed essentially all vegetated shade for the reach. Flow depth after the dredge was approximately 1.0 ft deep.

A second non-agricultural site was chosen at the Duvall site at 124th Street (see Figure B.3). The selected reach was Deer Creek and labeled Deer_1 for this study. Deer_1 intersects with the Pickering/Olney ditch between Pickering_2 and Pickering_1 upstream to downstream respectively. Deer_1 flows down a heavily shaded shallow slope out of a partially residential partially undeveloped region. It should be noted that although Deer_1 was selected as a non-agricultural comparison to the Pickering/Olney ditch its geomorphology differs in several key areas including velocity, temperature, sediment composition, shade, and depth. Deer_1 sediment has a higher concentration of gravels and sands than the adjacent agricultural ditch, is shallower, more shaded, and swifter. The adjoining agricultural land is used for small-scale gardening, minimal livestock, or left fallow with a high degree of grass and other vegetation. Several representative sites and their sampling locations and GPS (Global Positioning System) points are listed alphabetically in Table 3-1 and Table 3-2.

Table 3-1 Duvall Sampling Sites

Site Name	Latitude (decimal deg)	Longitude (decimal deg)	Type of Site	Date of Dredge/Clean
Deer _1	47.7117	-121.9852	Non-Agricultural	
Olney_1	47.7158	-121.9891	Agricultural	Summer 2004
Olney_2	47.7156	-121.9864	Agricultural	Summer 2004
Olney_3	47.7141	-121.9858	Agricultural	Summer 2004
Pickering_1	47.7119	-121.9854	Agricultural	Summer 2004
Pickering_2	47.7115	-121.9855	Agricultural	Summer 2004
Pickering_3	47.7103	-121.9862	Agricultural	Summer 2004
Pickering_4	47.7091	-121.9862	Agricultural	Summer 2004

Table 3-2 Mullen Slough Sampling Sites

Site Name	Latitude (decimal deg)	Longitude (decimal deg)	Type of Site	Date of Dredge/Clean
Boscolo_1	47.3535	-122.2588	Agricultural	Summer 2005
Boscolo_2	47.3531	-122.2600	Agricultural	Summer 2005
Boscolo_3	47.3509	-122.2601	Agricultural	Summer 2005
Boscolo_4	47.3492	-122.2602	Agricultural	Summer 2005
Boscolo_5	47.3468	-122.2602	Agricultural	Summer 2005
Mullen_1	47.3751	-122.2660	Agricultural	Summer 2005
Mullen_2	47.3713	-122.2651	Agricultural	Summer 2005
Mullen_3	47.3647	-122.2622	Agricultural	Summer 2005
Mullen_4	47.3637	-122.2620	Agricultural	Summer 2005
Mullen_5	47.3609	-122.2611	Agricultural	Summer 2005
Mullen_6	47.3578	-122.2602	Agricultural	Summer 2005
Mullen_7	47.3538	-122.2583	Agricultural	Summer 2005
Smith_Brothers_1	47.3580	-122.2635	Non-Agricultural	
Smith_Brothers_2	47.3607	-122.2642	Agricultural	Summer 2005
Smith_Brothers_3	47.3551	-122.2587	Agricultural	Summer 2005

3.2.3 SOD

Four sites were chosen for detailed SOD studies based on their vegetation and maintenance status. The two sites selected to represent the dredged portion of the study were on Mullen Slough. Cleaning efforts removed the bulk of growing vegetation while leaving behind a large amount of sediment and decaying spoils. This sediment layer ranges in depth from approximately 2.0 feet to 5.0 feet and consists of a silty material mixed thoroughly with decaying vegetation. An example of the post-hand dredged waterway is shown in Figure 3-2.

Figure 3-2 Slough post hand-cleaned conditions showing thick sediment layer

A site in Enumclaw, WA owned by the Engburg family was selected as a representative reach for un-dredged waterways. This reach called Big Spring Creek (BSC) flows through pastureland currently inhabited by a small cattle herd and discharges to the Green River. The reach is primarily clogged (see Figure 3-3) with Reed canary grass with patches of clearing possibly due to livestock activity. Beneath the vegetation mat the sediment consists primarily of sand and fine gravels.

Figure 3-3 Example of Big Spring Creek vegetation

The final sampling location was on Deer Creek in Duvall (See Figure B.3). The site was chosen as a comparison between agricultural and non-agricultural waterway sediments. The sediment characteristics closely resemble the Big Spring Creek site and consist of sandy materials. A picture of the study area is shown in Figure 3-4.

Figure 3-4 Creek inflow into Pickering/Olney drainage ditch

All four sites offer unique opportunities to observe the sedimentary component of water quality in scenarios representative of conditions throughout the King County targeted APDs.

3.3 METHODS

3.3.1 Dissolved Oxygen (DO) Data Collection

The methods used for water quality monitoring were three-fold: taking and sending samples to the WSU lab, taking stab readings with hand-held monitoring devices, and measuring diurnal fluxes using deployed logging devices (YSI Sondes).

Data at specific points along the reach were collected at both diel intervals and stab measurements over the course of three years from 2003 to 2005 with a concentration on summer months (April through September). Stab readings were collected on approximately bi-monthly schedules during that time. Diel data was collected less frequently with the majority being measured in the summer of 2004 and 2005. Diel measurements were conducted using YSI Sondes which were deployed for approximately weekly intervals. Sondes measured dissolved oxygen, water temperature, pH, and conductivity at 0.25-hour intervals. Grab samples were collected and sent to the Biosystems Water Quality Laboratory at Washington State University for analysis of DO, conductivity, total phosphorous (TP), total suspended solids (TSS), nitrite (NO_2^-), nitrate (NO_3^-), biological oxygen demand (BOD), and ammonia (NH_3). The four points selected on Mullen Slough included three in the primary reach and the non-agricultural inflow (Smith_Brothers_1) which Qual2kw treated as a point source. At the Duvall site data was sampled at six sites including upstream and downstream from Deer Creek and within Deer Creek itself.

Latitude and longitude data were determined by aerial photographs within a GIS-ArcView format. Segment geometry and lengths were calculated using standard surveying equipment. Meteorological data was obtained for the Boeing Field weather station (located just to the north of the Kent study site) from the NOAA National Climate Data Center web site http://cdo.ncdc.noaa.gov/ulcd/ULCD and the University of Washington site http://www-k12.atmos.washington.edu/k12/grayskies/nw_weather.html. The data provided includes air temperature, dew-point temperature, wind direction and speed, cloud cover, relative humidity, solar radiation, and precipitation all measured at hourly intervals.

3.3.2 Sediment Oxygen Demand (SOD) Data Collection

SOD sampling was performed in July 2006. Care was taken to avoid disturbing the sediments as shown in Figure 3-5. Sediment cores were collected by inserting Plexiglas cylindrical chambers into the sediment at the water interface and carefully capping the bottom of them before removal. Figure 3-6 illustrates a typical sample prior to capping.

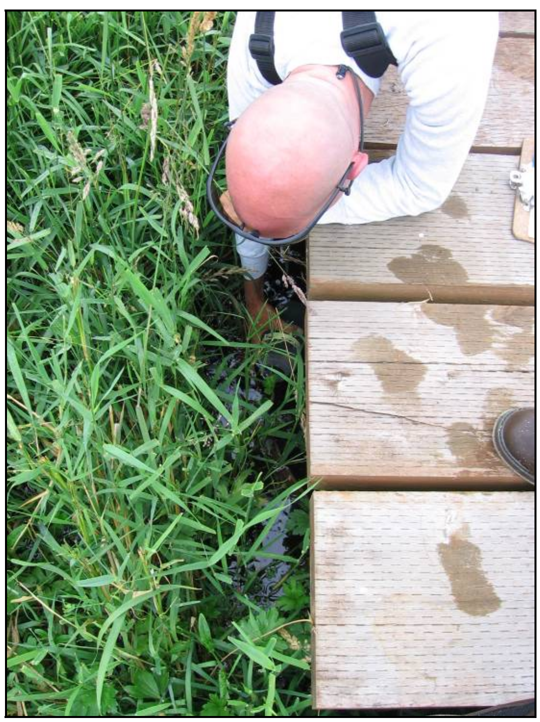

Figure 3-5 Sediment sampling at BSC site

Figure 3-6 Sediment sampling chamber inserted into sediment-water interface prior to capping

The chambers measured 15 cm tall by 9.5 cm inner diameter. They had a Plexiglas top cap and bottom base connected to threaded bolts that held both ends to the cylinder with wing nuts as shown in Figure 3-7. Seepage was in part prevented by rubber gaskets between the sediment and bottom caps.

Figure 3-7 Freshly sampled sediment cores with their caps in place

The Mullen samples were collected in taller chambers due to limited availability of the smaller chambers. The chambers were 25 cm in height although the inside diameters were the same as the shorter ones. This discrepancy in cylinder height does not affect final SOD values due to the inclusion of water column height in the SOD calculations (see key equations in section 2.4.2.2). Sediment samples ranged from approximately 6.4 to 14.5 cm in depth with the remaining portion of the chamber being filled with stream water. This sampling technique preserves the sediment-water interface with a minimal amount of agitation. Two samples were taken at each site for the purpose of replication for a total of eight samples. The samples were kept in a cooler filled with crushed ice and transported back to the lab the day after sampling.

There was some leakage experienced in samples with more sandy sediments. This was due to the sand interfering with the chamber gaskets and preventing an adequate seal from forming. This situation was remedied by sealing the chambers externally with a line of aquarium silicone.

3.4 DATA ANALYSIS

In addition to the collected variables covered in previous sections Qual2kw requires specified roughness values for use in Manning's equation. Manning's roughness (n) values were calculated using software called HEC-RAS which utilized an iterative approach to obtain the roughness values which corresponded to known inputs such as flow depth, sediment depth, flow rate, and channel geomorphology. Field survey data from Mullen Slough was input into the HEC-RAS model along with flow and reach characteristics for both pre- and post-maintained reaches to obtain accurate results for each scenario. The model results indicated average Manning's roughness values of 0.08 for recently hand-cleaned segments and 1.9 for un-cleaned segments. These values were then used in the Qual2kw model for the post and pre-dredged scenarios respectively.

3.4.1 Dissolved Oxygen (DO)

DO data collected from the sondes and stab readings were compiled and analyzed by WSU staff. This data, combined with the lab results, was organized and used to develop the Qual2kw model for agricultural waterways in King County.

3.4.1.1 Model Description

The model used was the Washington Department of Ecology's version of Qual2kw, a one-dimensional water quality model that uses Microsoft Excel as its graphical user interface and Microsoft Excel VBA and FORTRAN 95 as its program languages (Pelletier et al, 2006). Steve Chapra and Greg Pelletier are the primary authors of Qual2kw, which builds on the previous USEPA model Qual2E. The model has been recommended by the Environmental Protection Agency (EPA) as one of the preferred methods of predicting water quality in impaired waterways and can be found at http://www.ecy.wa.gov/programs/eap/models.html.

The model uses reach data from existing water systems to calculate various water quality parameters in each specified segment. The model assumes steady state hydraulics (e.g. constant inflows at all boundary conditions) and non-uniform steady flow is simulated. Qual2kw calculates temperature on a diurnal time scale as a function of meteorology. Organic carbon concentration is represented twofold, with fast and slow CBOD (carbonaceous biochemical oxygen demand), where fast and slow refer to the rate of oxidation for each form. Remaining non-living particulate is simulated as detritus, consisting of particulate carbon, nitrogen, and phosphorous. Oxygen levels are further simulated by Qual2kw's ability to calculate denitrification rates which allows the model to predict anoxia in regions where dissolved oxygen approaches or reaches zero. The interface between sediment and water is calculated within the model as a function of organic particulate settling rates, intra-sediment chemical reactions, and concentrations of overlying soluble forms. These calculated variables include sediment oxygen demand (SOD) and nutrient fluxes. The amount of light reaching each depth in the reach is calculated based on algae concentrations, detritus, and inorganic solids. Solar radiation is calculated based on the specified time of simulation and data collection. pH is based on alkalinity and total inorganic carbon. Units for the model are metric.

3.4.1.2 Dissolved Oxygen Equations

Qual2kw uses both user-defined inputs and internal assumptions and defaults when calculating water quality predictions. These calculated and given values are used to produce output predictions for a specified time duration and time step. The predicted results are then paired against known data versus distance in output graphs to illustrate the degree of fitness between the two.

Qual2kw incorporates numerous variables and parameters to calculate a general mass-balance of constituents. Dissolved oxygen sources and sinks are calculated using the following equation:

$$\begin{aligned} S_o = r_{oa}\,\text{PhytoPhoto} + r_{od}\,\text{BotAlgPhoto} - r_{oc}\,\text{FastCOxid} - r_{oc}\,\text{SlowCOxid} - r_{on}\,\text{NH4Nitr} \\ - r_{oa}\,\text{PhytoResp} - r_{od}\,\text{BotAlgResp} + \text{OxReaer} - \text{CODoxid} - \text{SOD/H} \end{aligned} \tag{2.1}$$

Where S_o is the dissolved oxygen source/sink term [mg O_2/L/day], PhytoPhoto is the Phytoplankton photosynthesis rate, BotAlgPhot is the bottom algal photosynthesis rates, FastCOxid is the fast reacting CBOD, SlowCOxid is the slow reacting CBOD, NH_4Nitr is the ammonia nitrification rate, PhytoResp is the phytoplankton respiration rate, BotAlgResp is the bottom algae respiration rate, OxRear is the rate of oxidation reaeration, CODoxid is the COD oxidation, and SOD is the sediment oxygen demand divided by the water column depth H. R_{xy} =

stoichiometric coefficients for organic matter ie. $r_{xy} = \frac{gX}{gY}$ where gX = mass of element X [grams] and gY = mass of element Y [mg] and the coefficients a, d, c, and n refer to chlorophyll *a*, dry weight, carbon, and nitrogen respectively (Pelletier, et al 2006).

WSU researchers hypothesized that the variables with the most considerable changes between pre- and post-dredged reaches would be SOD and reaeration rates. This was in part due to the limited range of accepted stoichiometric coefficients of other variables such as algal and phytoplankton growth, respiration, and mortality rates. These ranges indicated that changes within accepted parameters to any one of these rates would not result in a drastic change in simulated DO levels. COD was another consideration and therefore altered for each maintenance scenario in accordance with observed changes in collected BOD but still was not significant enough to result in the observed DO increases. The remaining unknown variables were SOD and reaeration and each were investigated in detail as a result.

SOD is an integral part of the DO equation because DO depletion occurs when oxygen-dependant microorganisms and chemical processes decay organic sediments and vegetation at the sediment-water interface in bodies of water. The ensuing processes exhaust the oxygen in the sedimentary level and subsequently become a significant DO sink in overlying water layers. The process for investigating this important parameter is covered in detail in Section 3.3.2.

Reaeration is the process by which oxygen is introduced into a water surface from the atmosphere. Most methods of measuring reaeration coefficients involve releasing a type of dye or tracer into the water and tracking its travel in units of $time^{-1}$. This would be difficult in pre-dredge waterways in King County due to the inability to access the water surface through thick vegetation. This is also why reaeration is hypothesized to be considerably limited in vegetated channels. A previous study involving vegetation removal and subsequent DO increases determined that reaeration and photosynthesis were the primary contributing factors (Perna, 2005). Calculating the reaeration coefficients is accomplished using equations dependant on channel morphology and flow velocity. In Qual2kw the reaeration rate can either be specified by the user or calculated internally by Qual2kw using a variety of prescribed methods. For the King County calibration, the temperature-dependant oxygen reaeration coefficient was determined to be best represented by the O'Connor-Dobbins method (a mean temperature of 20°C was assumed):

$$\boxed{k_a(20) = 3.93\frac{U^{0.5}}{H^{1.5}}} \qquad (3.2)$$

Where $k_a(20)$ is the reaeration rate at 20°C [1/day], U is the flow velocity [m/s], and H is the flow depth [m].

In Qual2kw, flow rates can be calculated using weirs, rating curves, or Manning's equation. Manning's equation was selected for these simulations. Manning's roughness was calculated using HEC-RAS and known downstream water surface elevations from pre- and post-dredge site surveys as is detailed in Chapter 2.

3.4.1.3 Calibration Method

Qual2kw offers two methods of calibration; by hand and an internal genetic algorithm which calibrates the model automatically based on a number of specified stoichiometric rates and constants. Due to the extensive amount of measured and known stoichiometric rates required for the auto calibration feature WSU researchers determined hand-calibration served King County better in this case. Calibration was therefore performed by hand by running the model multiple times while changing unknown parameters slightly until the model results for DO and temperature matched known values. The model plots its predictions against known values as additional points on calculated output graphs in order to facilitate this comparison. Qual2k uses the root mean square error method for determining the fit of known to predicted values. This fit is calculated on the “Fitness” sheet within the model by using user-defined equations for known versus predicted differences. The known variables for the model included temperature, DO, NO_3^-, NO_2^-, pH, and conductivity. Both pre and post dredge conditions were calibrated and simulated. The input data set for post-dredge conditions was from September 2005 and the pre-dredge data was from September 2004 except for a few variables measured in September 2003. Both sets included data derived from lab, in-situ stab readings and diel measurements. Unless otherwise specified model default variables were used for stoichiometric rates and were confirmed by values in the EPA rates and Kinetics manual (Bowie et al., 1985). Several unknown parameters were estimated initially using the Rates and Kinetics Manual and then altered slightly with each model run to achieve calibration. These calibration variables include reaeration, detritus, phytoplankton concentration, algal concentration, and nitrification. The effect of vegetation removal on these rates and concentrations was difficult to measure, hence their application as unknown calibration variables instead of known inputs.

3.4.2 Sediment Oxygen Demand (SOD)

3.4.2.1 Lab Set-up

Once in the lab the samples were kept in a dark 4° C refrigerator before being transferred to an intermediate cooler and then to room temperature. They were then mounted on a Phipps and Bird PB-700 Jar Tester with six rotating paddles. The experimental set-up is shown in Figure 3-8. A paddle was inserted into each chamber about 1.5 -2.0 cm above the sediment surface. The velocity of the paddles was determined using Beutel’s method (Beutel, 2006) for the Phipps and Bird tester paddle size:

$$V = 0.265 * RPM \qquad (3.3)$$

Where V is the velocity [cm/s] and RPM is revolution per minute. The tester was set at a revolution of 10 RPM which equates to a velocity of 2.65 cm/s. This velocity simulated flow patterns in the chambers; a method which has been shown to produce more stable DO measurements by homogenizing the water. This is accomplished with a velocity low enough to produce the desired results but not swift enough to cause sediment agitation.

Figure 3-8 Lab set-up with probes, paddles, and aerating tubes installed

The samples were then aerated with aquarium pumps and tubing in darkness until they reached saturation (approximately 8.0 mg/L of oxygen). Oxygen levels were measured using DO probes inserted into the top of the chambers and sealed off. The probes were luminescent probes (see Figure 3-9) which according to Beutel (Beutel et al, 2006) have an advantage over traditional membrane DO probes for their inability to absorb oxygen and their pre-calibration status. Before initiating DO measurements each chamber was topped off with deionized water and sealed with rubber stoppers to prevent any external introduction of oxygen.

A total of four measurements were run for Boscolo and BSC, five for Deer Creek, and two for Mullen Slough. Mullen Slough had fewer measurements due to limited availability of the DO probes. All samples were mounted on the Phipps and Bird PB-700 Jar Tester except for Mullen Slough because the Mullen samples were collected in chambers too tall for the apparatus.

Figure 3-9 Luminescent DO probe

2.4.2.2 Key Equations

According to Nakamura (1994), consumption at the sediment/water interface can be effectively modeled by assuming a two-layer condition exists consisting of an oxygen-rich upper water layer and a lower, high SOD diffusive boundary layer. For his model he also assumes a steady state system with constant horizontal velocity and smooth streambed and walls. Previously Walker and Snodgrass (1986) represented SOD as:

$$SOD = \mu_\beta \frac{C_\infty}{K_{0_2} + C_\infty} + k_c C_\infty \tag{3.4}$$

Where the first term represents the biological SOD (BSOD) and the second the chemical SOD (CSOD) component. The biological term represents the biological oxidation of organic matter occurring in the aerobic portion of the sediment while CSOD refers to the oxidation of reduced compounds diffusing upwards from deeper anaerobic soils (Beutel, 2006). Additionally, μ_β is the BSOD aerobic oxidation rate ($g/m^2/d$), C_∞ equals the bulk DO concentration in the water directly above the sediment (g/m^3), K_{02} is the half saturation constant for DO (g/m^3), and k_c is the CSOD first-order rate constant (m/d). It is worth noting that $K_{02,}$ k_c, and μ_β are also dependant on the aerobic zone depth, δ_s.

Due to his assumption that velocity was the prevailing variable in SOD concentrations, Nakamura (1994) determined that the two parameters μ_β and k_c were not appropriate independent parameters for SOD. Further assuming that "the chemical reaction is a first-order reaction of DO concentration" the author was able to derive an equation for the volumetric rate of O_2 consumption in sediments as follows:

$$R = \mu \frac{C_w}{K_{0_2} + C_w} + k' C_w \tag{3.5}$$

Where μ is the maximum aerobic oxidation rate, k' the first order rate constant, and Cw equals the dissolved O2 concentration at the sediment-water interface [mg/L].

For ease of differentiating between chemical and biological sediment oxygen demand Walker and Snodgrass' equation was determined to be best suited for this study. Their model also provided the simplest method of calculation given that it is dependent on the bulk concentration of overlying dissolved oxygen which is easily measurable. Beutel further simplified this equation by setting the half-saturation coefficient (K_{02}) to zero since compared to typical SOD levels it is small, on the order of ≈0.5 g/m^3 (Beutel et al, 2006). This simplification results in the following equation:

$$SOD(C_w) = \mu_\beta + k_c \cdot C_w \tag{3.6}$$

These variables are found by plotting DO as it degrades with time. SOD can then be calculated as the linear regression of DO versus time (g/m^3/d) at hourly intervals multiplied by the water column height in each chamber. These SOD values are then plotted against DO values from the midpoint of each hour interval. From this graph the remaining variables necessary can be determined, with BSOD (μ_β) equaling the intercept and CSOD (k_c) the slope of a linear line through the data points.

To account for different temperatures during the SOD measurements a simple equation can be used to standardize the results according to Truax et al (1995):

$$SOD(t_1) = SOD(t_2) \cdot 1.065^{(t_1 - t_2)} \tag{3.7}$$

For the purpose of comparison, all SOD values were standardized to 20° C in this report.

3.5 RESULTS

3.5.1 DO Monitoring

Monitoring efforts resulted in two key findings. The first is that maintenance activities altered the DO considerably. The second is that there is a significant difference between DO levels in agricultural and non-agricultural waterways. In order to illustrate the maintenance-induced alterations plots were made of average DO levels for summer months (June through September) at the same Mullen Slough site for 2003, 2004, and 2005. The post-dredged 2005

DO data was on average 3.4 mg/l higher than the pre-dredged levels of the two prior years, as is illustrated in Figure 3-10.

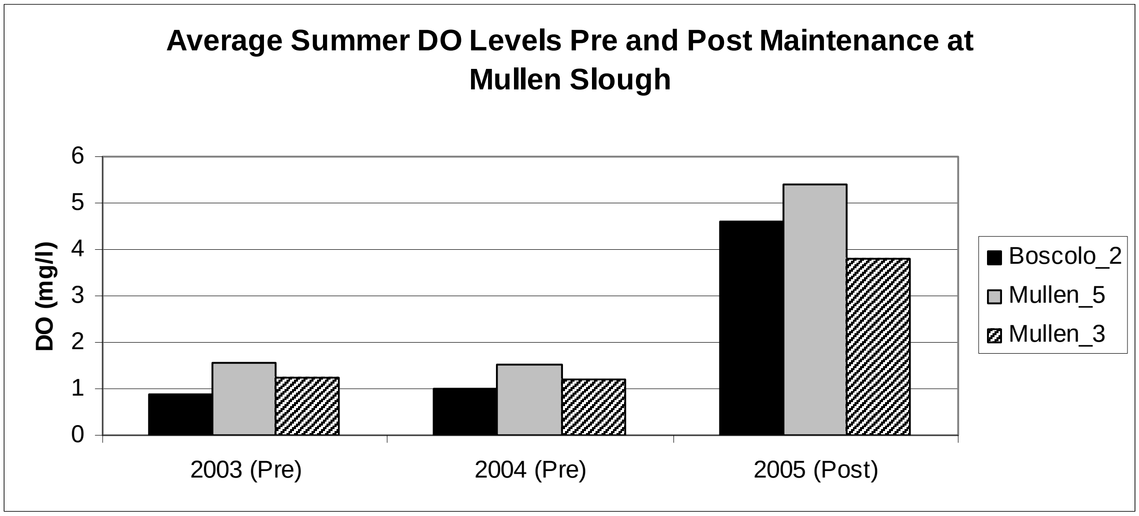

Figure 3-10 Pre- and Post- Dredge DO levels in Mullen Slough

An observation of the diel outputs shows that DO levels in the slough are also maintaining higher levels throughout the night. Pre-dredge DO diel patterns can be seen in Figure 3-11 where the diel temperature is also shown to illustrate the relationship between the two. By contrast, Figure 3-12 shows the DO levels after the bulk of the vegetation was removed upstream. Note how DO peaks around noon when the temperature is at its lowest and drops off after sunset when the temperature peaks. This inverse relationship is likely due to the increase and decrease of photosynthetic processes in the water column with a corresponding amount of solar radiation penetrating the water's surface. Similarly, prior to vegetation removal, the diel flux is much less pronounced due in part to the limited amount of photosynthesis occurring in the clogged, shaded waterway.

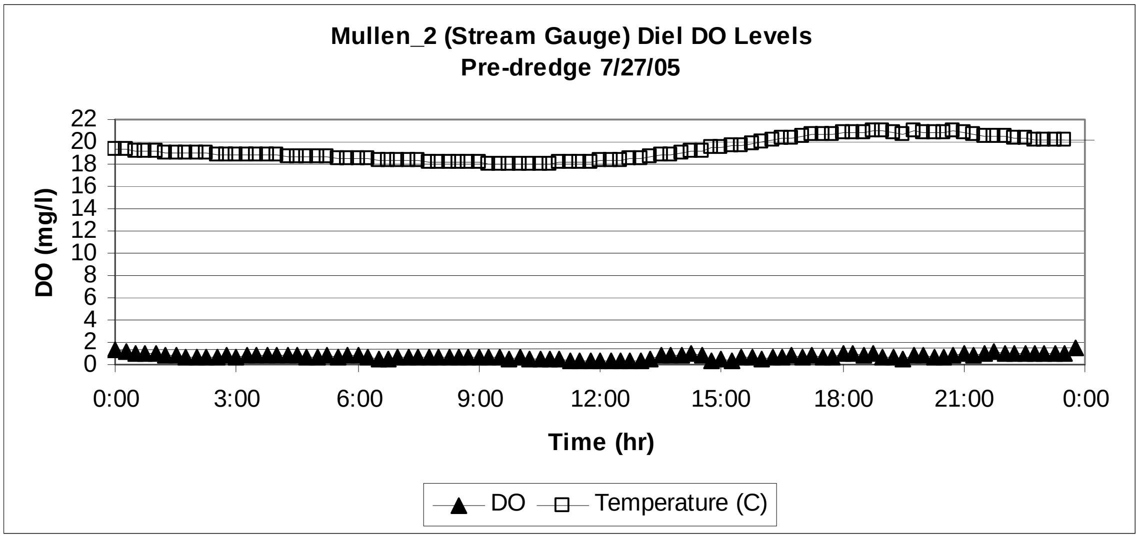

Figure 3-11 DO levels prior to upstream dredge operation's completion

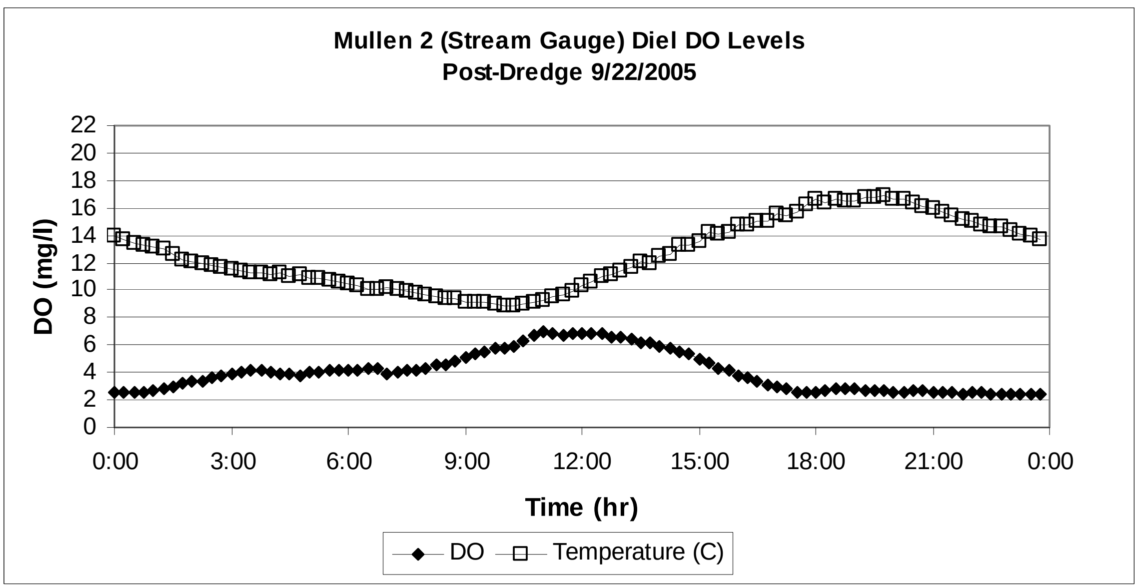

Figure 3-12 DO levels following upstream dredging operation's completion

Additionally, there was a marked difference in measured DO levels between agricultural reaches and their non-agricultural counterparts. At the Duvall site, where Sondes were deployed in the non-agricultural inflow as well as at points directly upstream and downstream, the DO showed an average increase of approximately 2.25 mg/l in the downstream portion. The diel trend at the Duvall site can be seen in Figure 3-13 which is a 24 hour sampling from September 2005. The summer stab readings (June through September) for two years at the Duvall site were averaged and graphed in Figure 3-14 to show the difference in DO levels downstream from the non-agricultural inflow (Deer_1).

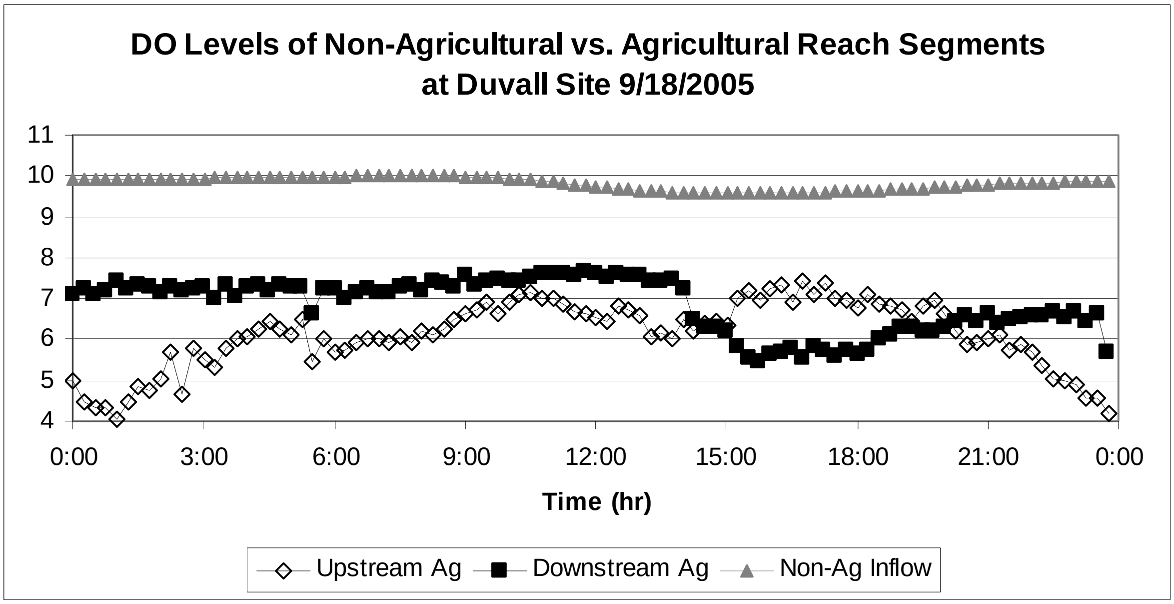

Figure 3-13 Diel DO levels upstream and downstream from a non-agricultural inflow

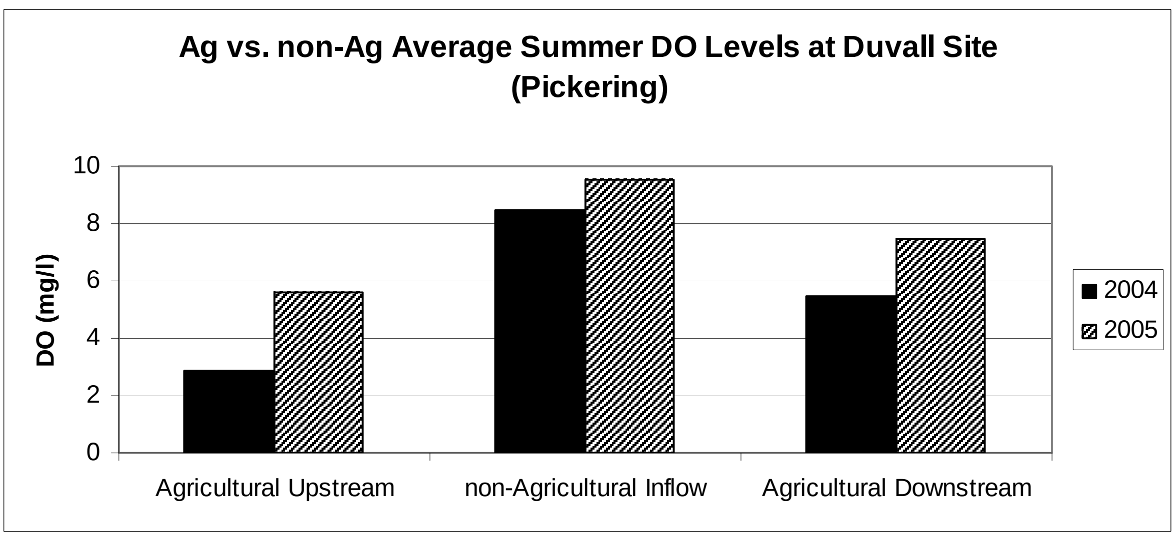

Figure 3-14 Summer stab readings at three points at Duvall site averaged to illustrate elevated DO levels in non-agricultural adjacent reaches

The Duvall data was compiled into the graph shown in Figure 3-15 to illustrate that the elevation of DO levels in non-agricultural reaches vs. adjacent agricultural reaches was constant across all monthly stab measurements. These same values are plotted as % of DO saturation in Figure 3-16 to further illustrate this scenario. A similar trend was observed at the Mullen Slough site where the flow immediately downstream from a non-agricultural inflow (Smith_Brothers_1) raises an average of 250% (Figure 3-17). The non-agricultural inflow DO levels averaged about 5.25 mg/l higher than the adjacent agricultural segments. This trend had some variation throughout the day when the downstream section occasionally reached higher concentrations than the non-agricultural site (see Figure 3-18).

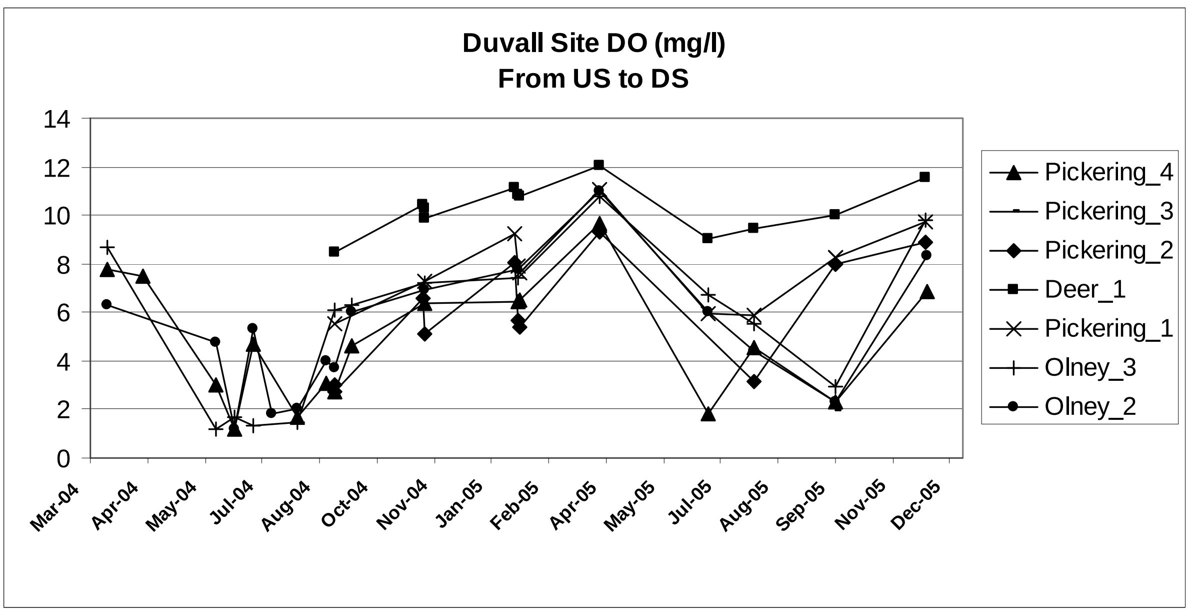

Figure 3-15 Stab DO measurements for seven Duvall sampling sites listed upstream to downstream respectively, illustrating difference between non-agricultural inflow and agricultural DO levels

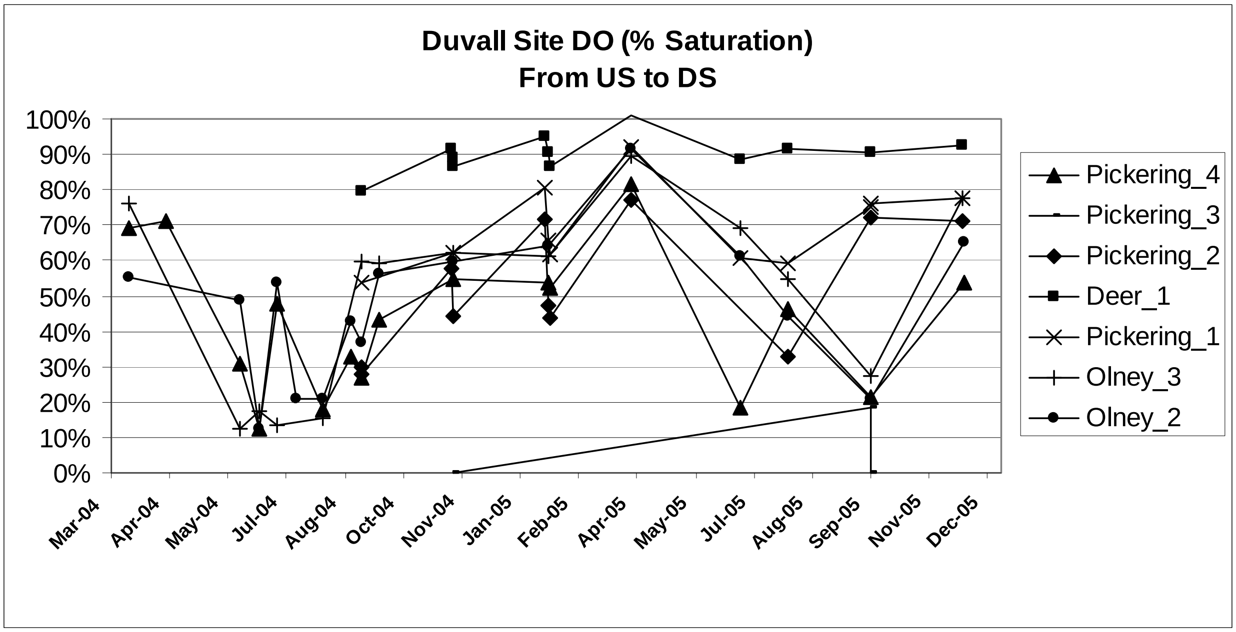

Figure 3-16 Percentage of DO Saturation of measurements for seven Duvall sampling sites listed upstream to downstream respectively, illustrating difference between non-agricultural inflow and agricultural DO levels

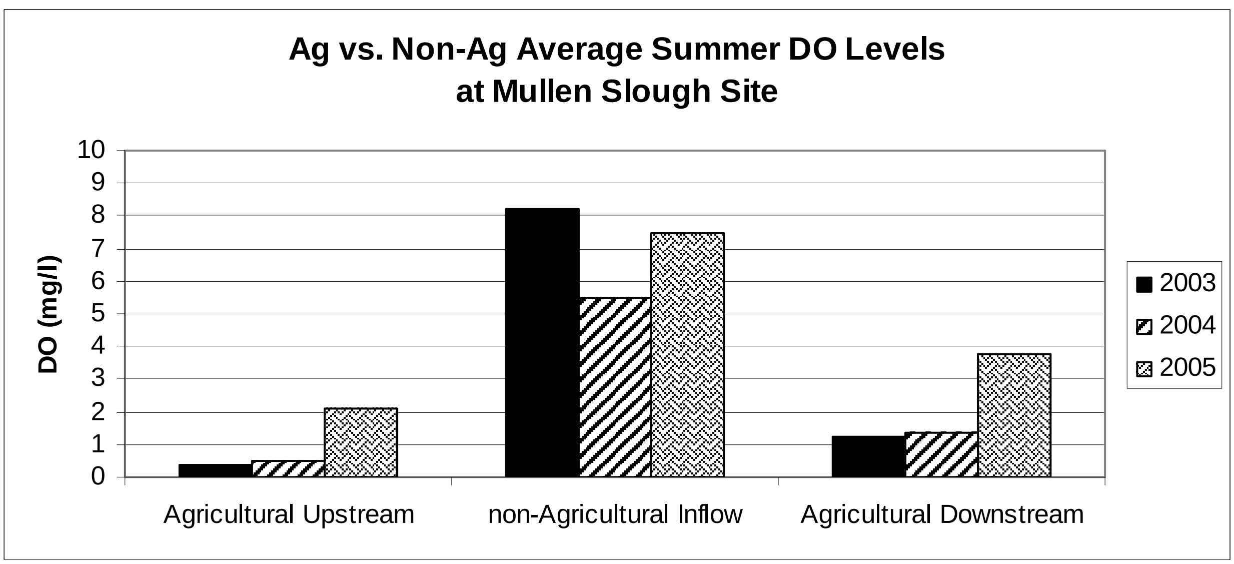

Figure 3-17 Summer stab readings at three points at Mullen Slough site averaged to illustrate elevated DO levels in non-agricultural adjacent reaches

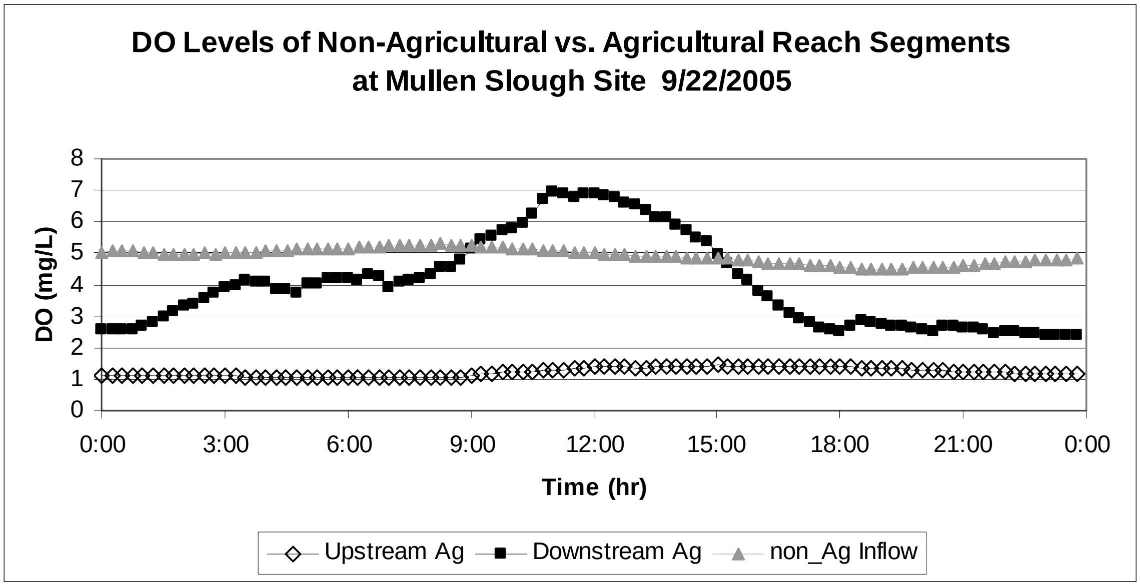

Figure 3-18 Diel plot of DO at points upstream and downstream from a non-agricultural inflow at the Mullen Slough site

3.5.2 Model Calibration Results

In order to represent pre- and post- maintenance conditions, two scenarios were calibrated in Qual2kw. Calibration of the pre-dredged condition resulted in a total root mean squared error of 3.1 calculated for four variables (temperature, DO, pH, and conductivity) with each having an equal weight factor of 1. The individual temperature value was 1/.04 or 27.6 and the DO error was 1/.76 or 1.3. The output graph for simulated vs. known DO data from the calibrated pre-dredge run is shown in Figure 3-19. Calibration of the post-dredged condition produced a total root mean squared error of 5.0 for the same four variables as the pre-dredged scenario. Its individual temperature and DO errors were 1/.25 or 4.0 and 1/.38 or 2.6 respectively. The fit of predicted to known DO data for post-dredge calibration is illustrated in Figure 3-20. Qual2kw predicted post-dredge DO values to be approximately 4.0 mg/l which was a 2.2 mg/l (over 120 %) increase over the pre-dredge predictions.

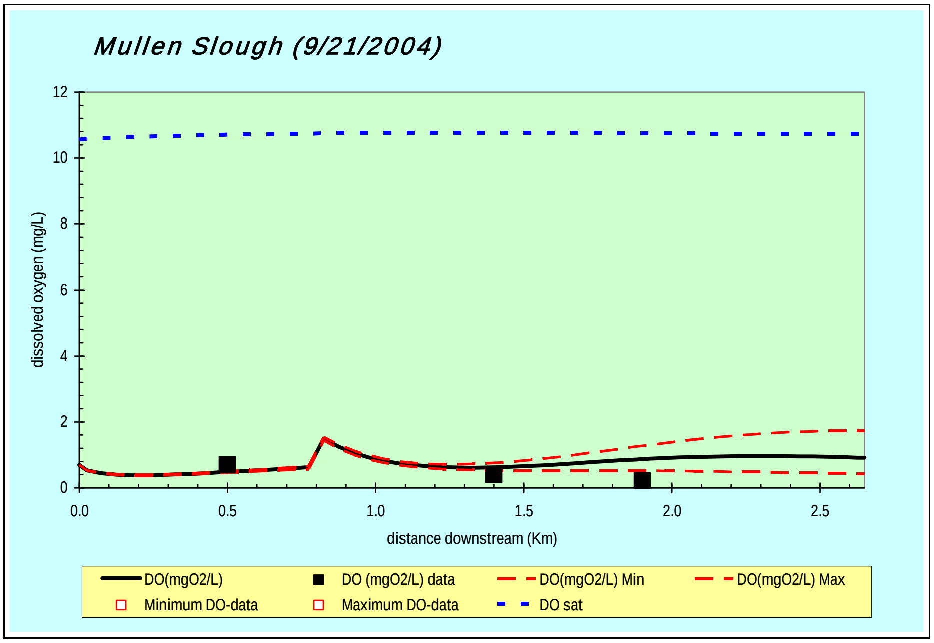

Figure 3-19 Qual2kw output graph of DO for calibrated pre-dredged conditions. Lines represent simulated results while blocks represent known values

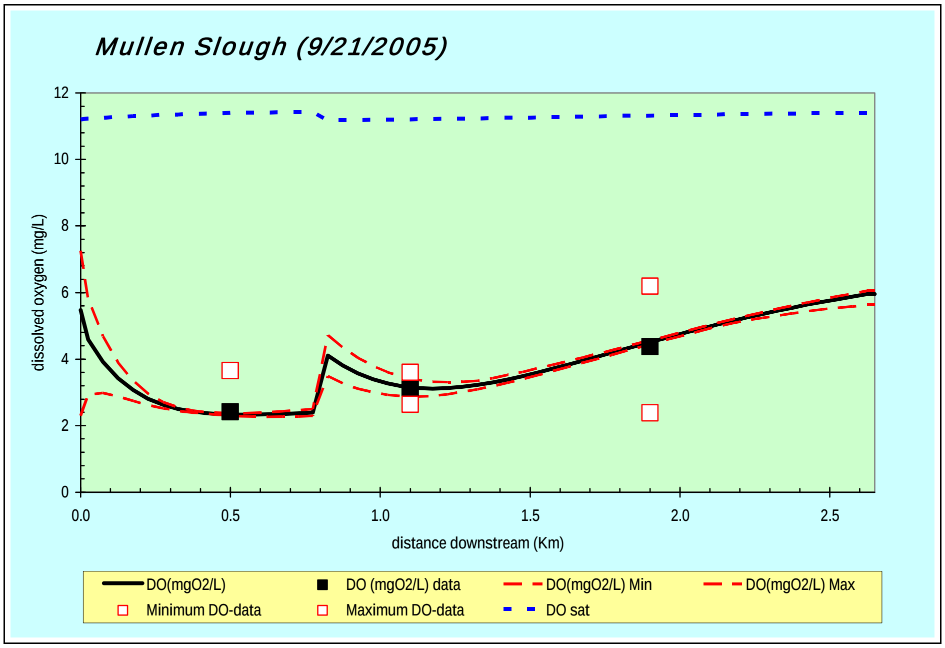

Figure 3-20 Qual2kw output graph of DO for calibrated post-dredged conditions. Lines represent simulated results while blocks represent known values

Sensitivity analyses on SOD and reaeration rates were performed and the model's corresponding errors evaluated. SOD and reaeration were assumed to be the two most sensitive parameters because of their relative uncertainty compared to other model inputs. The analysis was performed on the post-dredged calibrated model with only the specified parameter being altered by values of ten and fifty percent. The fitness values were then recorded for both temperature and DO, the two target parameters of the study. The results were tabulated in Table 3-3 and demonstrate similar patterns between reaeration rate alteration and that of the SOD. Note that the final calibration resulted in the fitness values in the last row of the table.

Table 3-3 Calibration fitness outputs from using the root mean squared error method for temperature and DO Qual2kw predicted values vs. known inputs with changes in reaeration and SOD input values of ± 10 and 50 % respectively

	Reaeration		SOD	
Variation	Temperature Fitness	DO Fitness	Temperature Fitness	DO Fitness
+10%	4.0	2.2	4.0	2.9
-10%	4.0	2.9	4.0	2.3
+50%	4.0	2.3	4.0	2.7
-50%	4.0	0.7	4.0	1.2
Calibrated	**4.0**	**2.6**	**4.0**	**2.6**

When the reaeration rate was increased by 10 percent, the DO fitness decreased by approximately 15 percent. When the reaeration rate was decreased by 10 percent, the DO fitness increased by approximately 11 percent. An alteration in the reaeration rate of plus or minus fifty percent caused a DO fitness decrease of 11 percent and 73 percent, respectively. In contrast, the temperature fitness did not change at all which indicates DO is a much more sensitive parameter to model than temperature. For SOD deviation a change of plus or minus ten percent caused a DO fitness increase and decrease of 11 percent. An increase or decrease of 50 percent resulted in a DO fitness increase of 4 percent and decrease of 54 percent, respectively. Again, by altering the SOD inputs, temperature maintained a consistent fitness of 4.0. The changes in inputs that resulted in increased fitness values do not necessarily represent a better overall fit. The root mean square error method removes any limitations caused by some variables being above or below the accepted mean and instead combines any deviation into one squared value. A combination of visual inspections of predicted versus known values and the fitness method was employed to obtain the best calibration possible.

A second analysis of Qual2kw was performed to determine how the model's temperature predictions compared to the Heat Source model submitted to King County in conjunction with the study. Both diel and longitudinal results were plotted on the same axis for both models to facilitate this objective. Both demonstrated acceptable fitness between the models as is shown in Figure 3-21 and Figure 3-22.

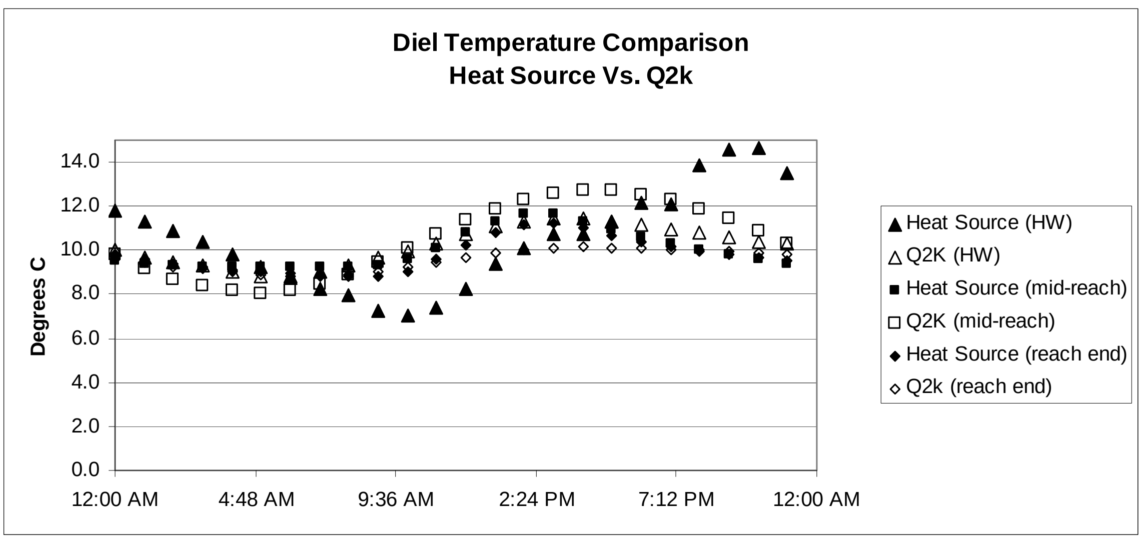

Figure 3-21 Predicted diel temperature comparison between Heat Source model and QUAL2kw

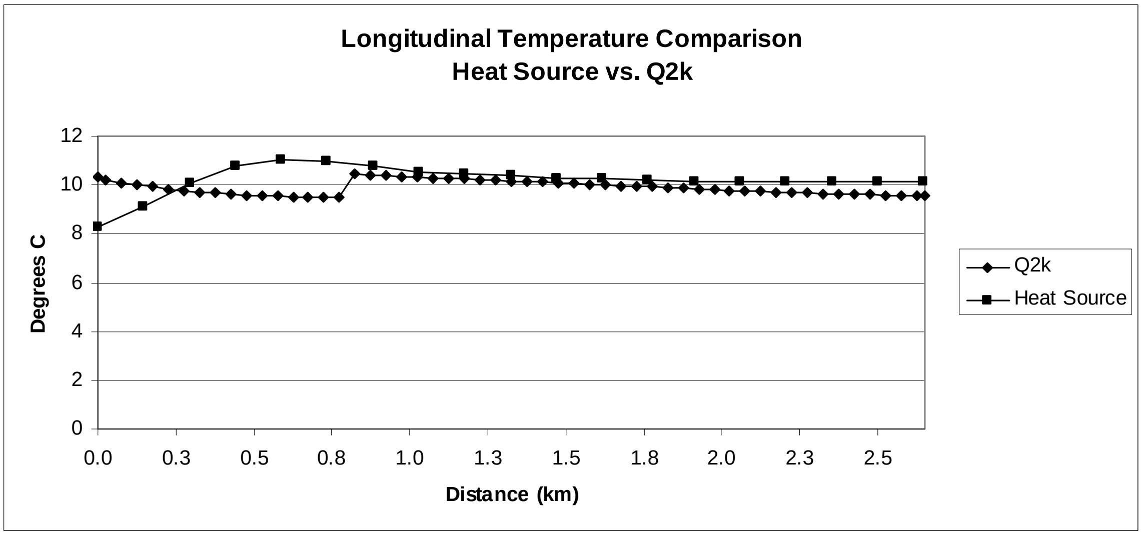

Figure 3-22 Predicted longitudinal temperature comparison between Heat Source model and QUAL2kw

3.5.3 Sediment Oxygen Demand (SOD)

An evaluation of the sediment cores' moisture content resulted in Table 3-4. Dredged sites Mullen and Boscolo had the lowest moisture content while those undredged or non-agricultural had moistures of approximately 28% higher. These samples were taken from the top 1.5 inches (3.8 cm) of the sediment/water interface from the cylinders used in the SOD calculations.

Table 3-4 Average moisture content of sediment cores taken from four sites

Site	Avg Moisture Content (%)
BSC	62.6%
Mullen	31.5%
Deer Creek	51.4%
Boscolo	26.7%

The time it took for the dissolved oxygen to reach zero from saturation levels ranged from approximately 3.5 hours to 35 hours. Figure 3-23 illustrates the process of DO degradation over time. A difference in time required to degrade the DO was observed between the runs. The last run in particular, demonstrated a longer duration to reach zero from saturation than the other three runs. This is most likely due to a decrease in biological and chemical oxygen demand over time in the sealed chambers which had no source of inflowing fresh nutrients. Figure 3-24 shows a representative plot of calculated sediment oxygen demand at hourly intervals versus dissolved oxygen at the midpoint of the hour segments. From this and similar plots, the BSOD and CSOD values were calculated using the intercept and slope of best-fit linear lines. These lines were limited to between 1.0 and 7.0 g/m^3 DO due to increased scatter below and above those values. In some cases, values slightly higher or lower were included where a limitation of measurement points required it.

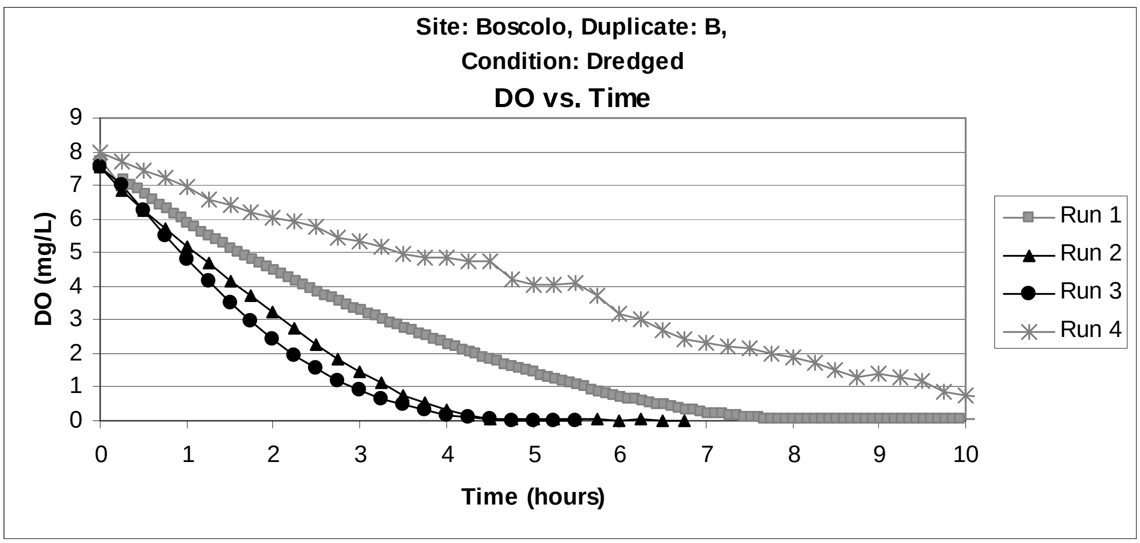

Figure 3-23 DO decreasing with time in a sealed SOD chamber with sediment from a dredged site, SOD measurements were performed four times

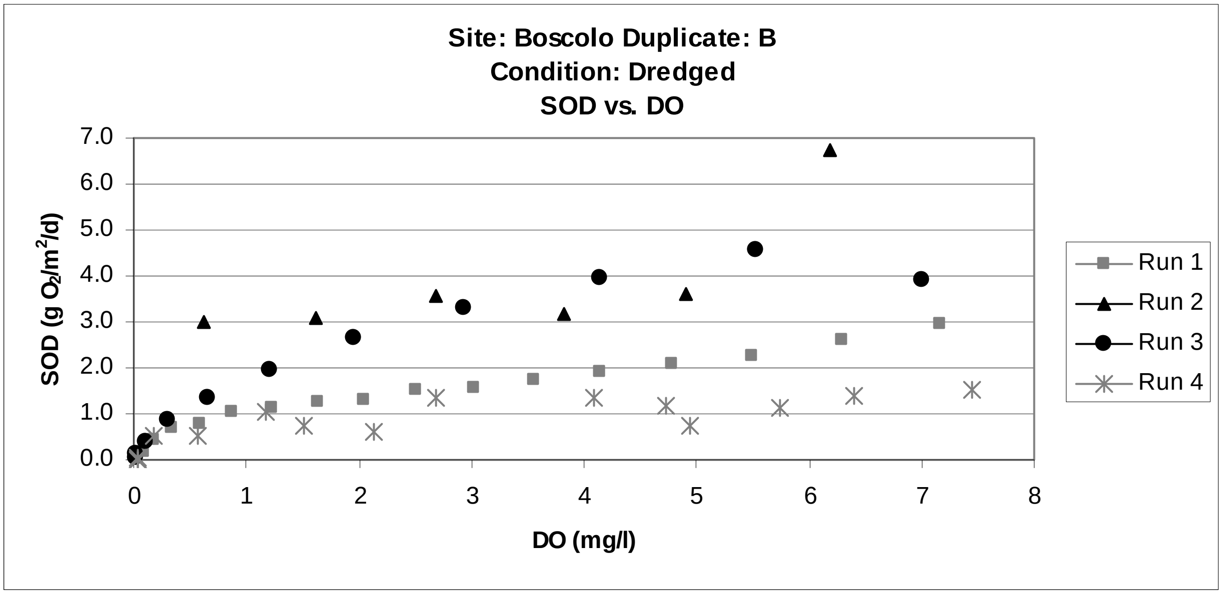

Figure 3-24 Total Sediment oxygen demand at a dredged site plotted against hourly DO intervals

Total SOD_5 values at 20°C differed for each site with the largest value at the hand-cleaned Boscolo site (2.90 $g/m^2/d$) and the smallest occurring at the un-maintained BSC site (0.46 $g/m^2/d$). The SOD_5 results for all four sites (each tested twice) are shown in Figure 3-25.

The chemical component (first-order rate coefficient) of the SOD (CBOD) dominated the process for each site with values ranging from 0.41 to 2.21 $g/m^2/d$. In contrast, the biological component (BSOD) ranged from 0.16 to 2.03 g $O_2/m^2/d$. Figure 3-26 illustrates the collective contributions of BSOD and CSOD to the total SOD values.

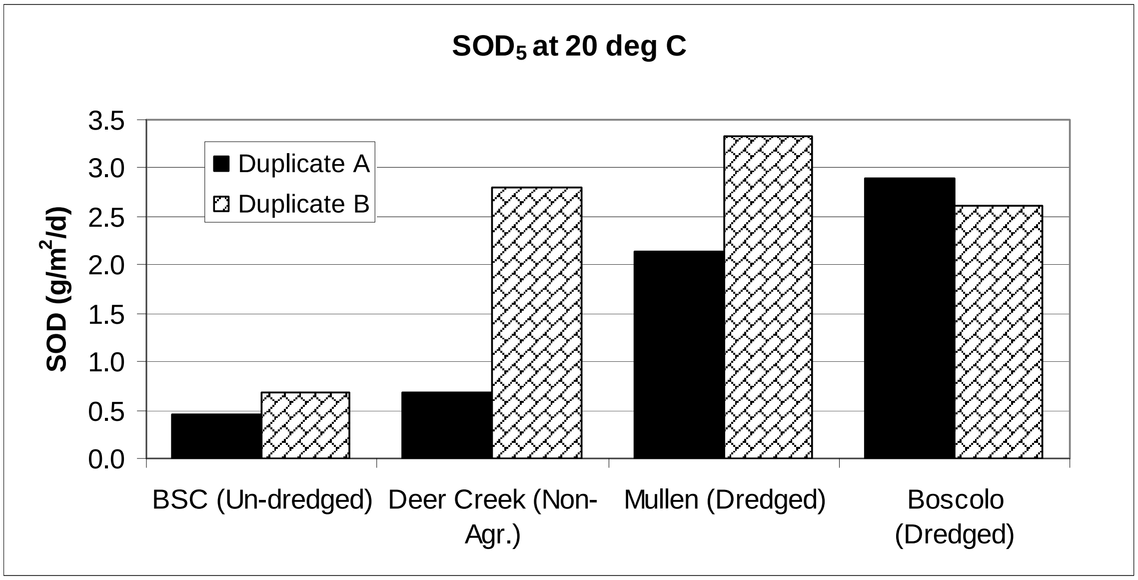

Figure 3-25 Averaged total SOD at a DO of 5 mg/l for four sites with two duplicates per site

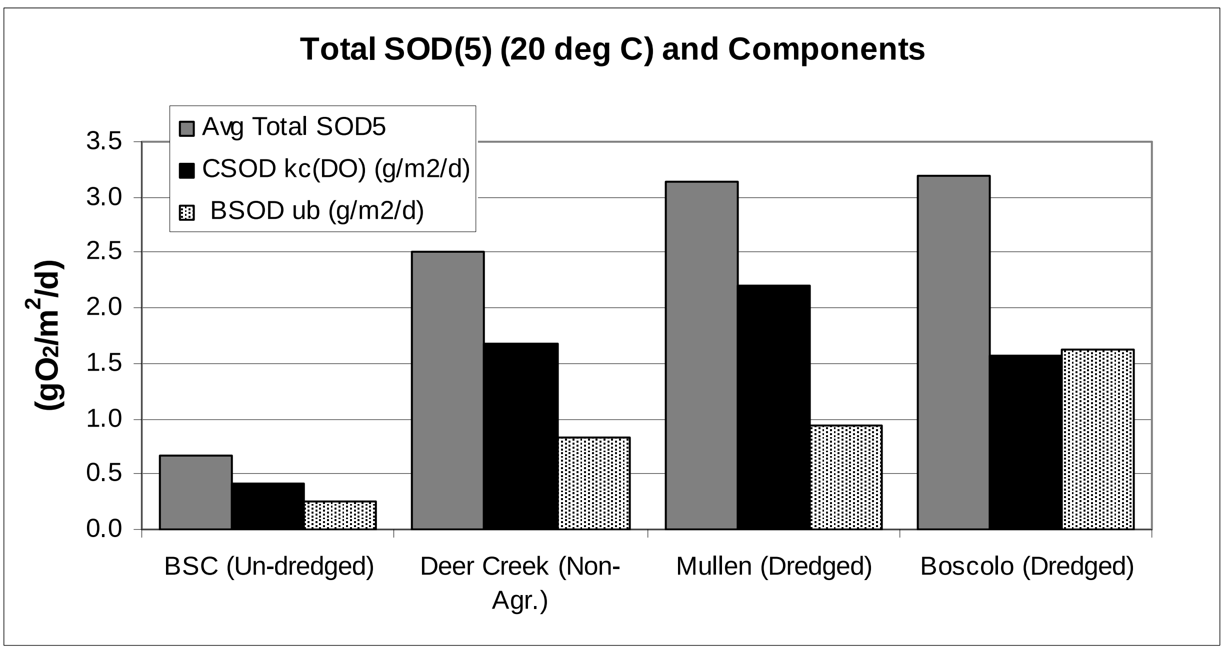

Figure 3-26 Individual contributions of biological and chemical sediment oxygen demand processes to total SOD

R^2 values were taken across the data sets used to derive SOD values (like those in Figure 3-26) to analyze scatter and averaged from 0.16 to 0.97. SOD values were calculated for three different DO values, 2, 5, and 10 mg/l using the chemical and biological coefficients found by using methods described in Section 3.4.2.2. See Table 3-5 for individual calculated values and Figure 3-27 for the graphed results for each sampling site.

Table 3-5 Summary of lab measurement results for four sites with two sets of duplicates each run two to four times

Site	Dup	Date	K_c (m/d)	μ_b (g/m^2/d)	R^2	SOD_2 (20°) (g/m2/d)	SOD_5 (20° (g/m2/d))	SOD_{10} (20°) (g/m2/d)
BSC (Undredged)	A	**Average**	**0.08**	**0.16**	**0.97**	**0.26**	**0.46**	**0.78**
		Std Dev	0.03	0.19		0.12	0.06	0.10
	B	**Average**	**0.09**	**0.37**	**0.90**	**0.46**	**0.67**	**1.04**
		Std Dev	0.04	0.13		0.14	0.23	0.40
Deer Creek (Non-Agricultural)	A	**Average**	**0.23**	**0.39**	**0.63**	**0.70**	**1.25**	**2.19**
		Std Dev	0.17	0.09		0.26	0.66	1.33
	B	**Average**	**0.44**	**1.26**	**0.78**	**1.74**	**2.80**	**4.58**
		Std Dev	0.37	0.73		1.04	1.85	3.27
Mullen Slough (Recently Dredged)	A	**Average**	**0.24**	**1.27**	**0.16**	**1.51**	**2.13**	**3.16**
	B	**9.07**	**0.65**	**0.61**	**0.21**	**1.65**	**3.33**	**6.13**
Boscolo (Recently Dredged)	A	**Average**	**0.27**	**2.03**	**0.78**	**2.21**	**2.90**	**4.06**
		Std Dev	0.11	0.38		0.45	0.70	1.15
	B	**Average**	**0.36**	**1.22**	**0.68**	**1.68**	**2.62**	**4.17**
		Std Dev	0.24	0.63		0.85	1.40	2.39

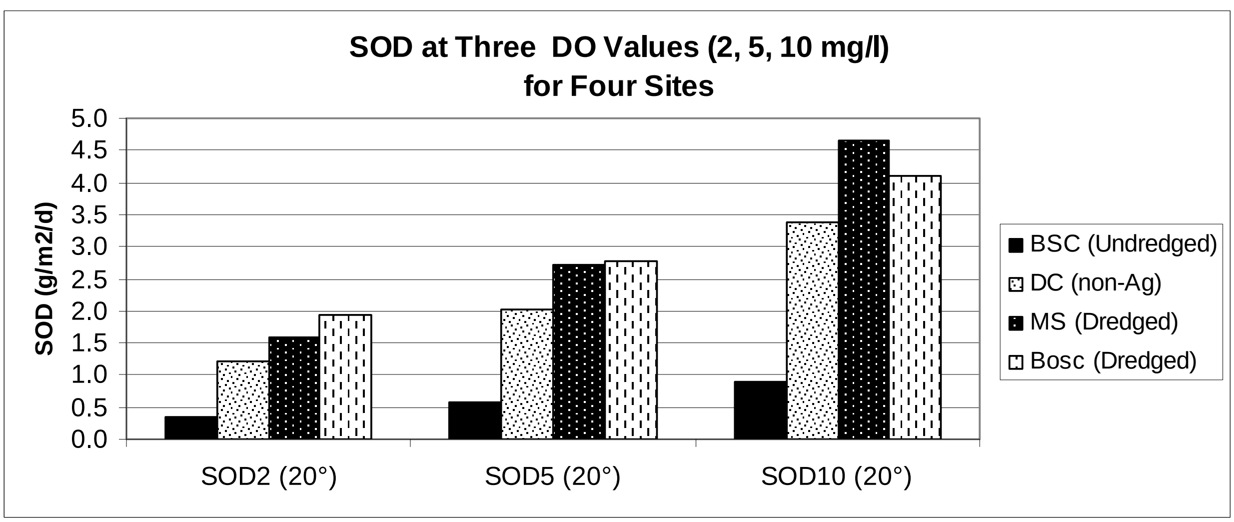

Figure 3-27 SOD at selected DO values (2, 5, 10, mg/l) for each site

3.6 DISCUSSION/CONCLUSIONS

3.6.1 SOD Accuracy

R^2 values for SOD vs. DO plots varied from 0.16 to 0.97. This value demonstrates the amount of scatter occurring during testing. The lowest R^2 values were in the unmixed Mullen Slough cylinders, however their averaged overall SOD agreement was the best of the study. The high degree of scatter found on the Mullen plots follows the model that Beutel (Beutel et al, 2006) developed which demonstrates that even the slightest mixing during measurement results in a much more linear plot due to a more uniform oxygen level crossing the DO probes. In order to avoid low R^2 values and obtain more symmetrical plots, a minimum mixing velocity apparatus is typically recommended for SOD measurements of this method.

Standard deviations of SOD_5 across the runs for each site ranged from .04 to 1.78 with an average of 0.69 g/m^2/d. This was in part due to differing slopes between the first and last measurement runs. Several samples demonstrated a similar trend to take longer durations to consume the oxygen than for previous or subsequent runs. This could be due to variations in the mechanical stirring device velocity or the introduction of small amounts of oxygen into the system between runs. Related studies resulted in similar differences of up to 20 hours between runs (Beutel). The longest difference in DO consumption for this study was 20 hours which was within acceptable ranges.

3.6.2 SOD Results

Pre-dredged SOD values were lower than post-maintained channels. These results were consistent across the replicates and duration of the study which gives a degree of confidence in the data and measurement procedure. The elevated SOD values in hand-cleaned waterways are possibly due to the amount of loose organic sediments and decaying vegetation remaining after the maintenance operations. The characteristics of the sediments indicate this since the two sites consisting of sandy sediments demonstrated the lowest SOD values. The highest values were found at locations where a silty material dominated. In contrast, the hand cleaning operations left a large quantity of easily agitated material in the streambed which presents a significant DO sink via SOD processes. The channels have sandy firm beds under the layer of silt and it could be argued that if the channels were dredged down to this original sand, they would demonstrate SOD values that would enhance already improved dissolved oxygen levels. To prove this theory, sediment cores should be sampled from mechanically dredged locations, and run through the SOD measurement procedure and compared to hand-cleaned ones such as Mullen and Boscolo. Mineralogy studies examining sediment composition would also assist in quantifying differences.

3.6.3 Case Study

In order to investigate whether complete vegetation removal would increase DO levels even further than hand-removal techniques, simulations of Qual2kw were run for scenarios with lowered SOD. These results indicate that if SOD levels of post-dredged sites were reduced by removal of loose, organic-rich sediments in addition to vegetation removal, DO will rise correspondingly. A 10% reduction in SOD resulted in a 10% increase in DO (see Figure 3-28). An even greater reduction of SOD by 50% increased DO by approximately 90% (Figure 3-29).

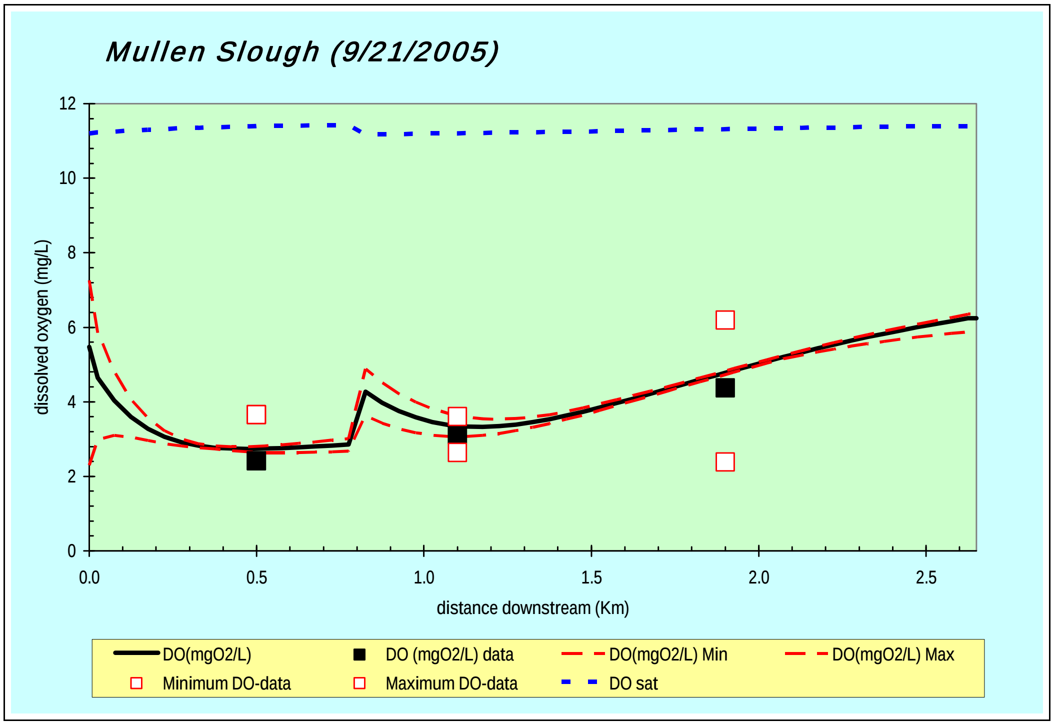

Figure 3-28 Qual2kw post-dredge results for a 10% reduction in SOD over current hand-cleaned levels

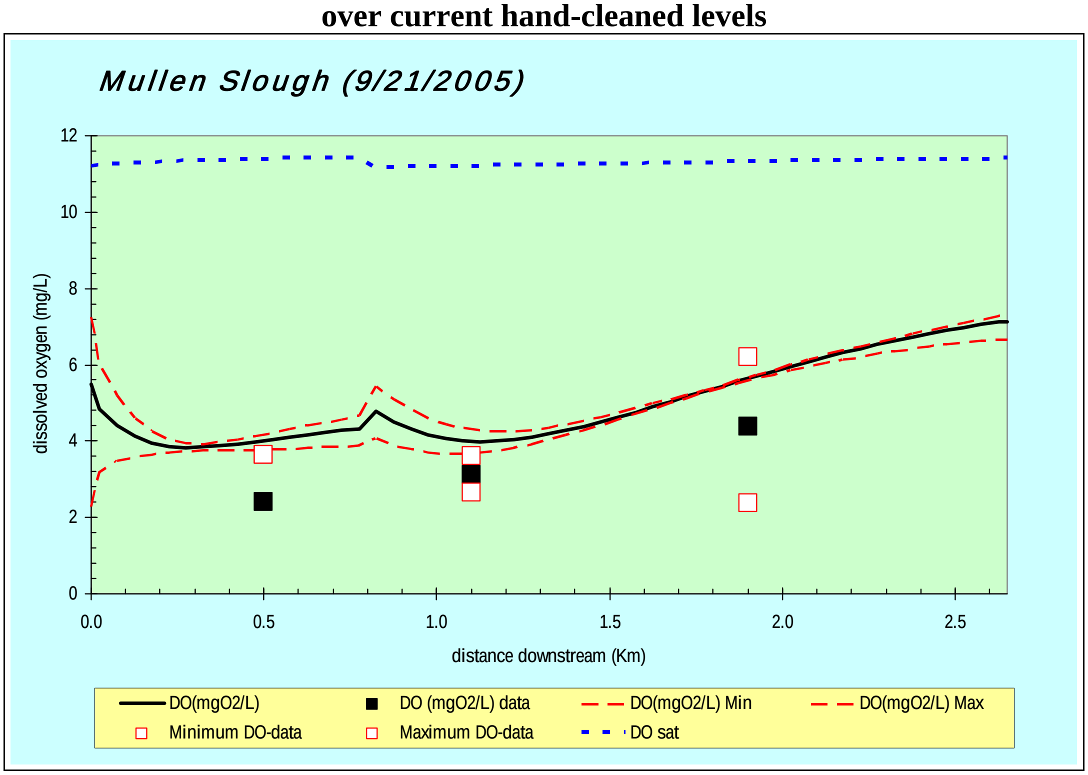

Figure 3-29 Qual2kw post-dredge results for a 50% reduction in SOD over current hand-cleaned levels

3.6.4 DO Results

Both monitoring and modeling indicate that DO levels raise significantly following vegetation removal in agricultural waterways. This increase was observed both at the Mullen Slough and Boscolo sites where DO increased on average 3.4 mg/l in post-dredged reaches. Qual2kw predicted an increase of approximately 4.0 mg/l due to vegetation removal. This demonstrates that dredging should potentially be beneficial to the water quality of the systems in question. According to nationally accepted reports, DO levels must be between 6.5 and 9.5 mg/L for most fish species to survive (Appendix C). Immediately after dredging, the oxygen levels were still not quite reaching acceptable levels. This deficit could be due to the amount of resuspended sediment in the channel following dredging as a result of the hand removal technique. Numerous studies have documented the contribution of resuspension to the SOD/BOD sink term in the DO equation (Matlock, 2003, Litton, 2003).

Both SOD and reaeration rates impacted modeled DO values. Qual2k calibration resulted in pre-dredge reaeration rates of approximately 1 /day and post-dredged rates of 8.5 /day. This indicates that vegetation removal facilitates increased oxygenation through the air-water interface by removing hindrances to flow and increasing surface area exposed to wind. While vegetation removal enhanced overall water quality, the SOD levels in dredged channels actually increased, becoming more of a DO sink. This could be due to the resuspension mentioned above and could be ameliorated by ensuring complete vegetation removal to decrease detritus and decomposition that have been documented as having an adverse effect on water systems' DO levels (Perna, 2005). Other factors contributing to the King County system's DO improvement include increased algal photosynthesis through enhanced solar radiation exposure, reduced residence time, and enhanced reaeration. Residence time is lowered when the velocity of the cleaned channels increases due to reduced obstructions, allowing a faster travel time from upstream to downstream. Decreased residence time limits the opportunity of BOD-generating processes to consume oxygen within a reach segment. A reduced residence time also contributes to better mixing, especially where non-agricultural inflow enters the reach. Vegetation removal allows the incoming flow to reach the main channel more rapidly, increasing its ability to introduce healthier oxygen levels. Reaeration is improved when the water surface is exposed to wind after thick vegetation has been removed. An enhanced exposure to rainfall has also been proven to increase reaeration rates (Belanger, 1991) that prior to cleaning, would have been restricted by the plants preventing precipitation from directly entering the water surface. The removal of plant stalks also facilitates wildlife mobility in the channels as noted by WSU researchers who observed renewed waterfowl activity immediately following and even during cleaning events. The reintroduction of animals in the channel contributes to reaeration through their swimming actions which agitate the water surface.

3.6.5 Final Recommendations

In conclusion, Hypothesis 1 was disproved by monitoring efforts which indicated with certainty that oxygen levels in agricultural waterways differ significantly from those in adjacent non-agricultural reaches. Hypothesis 2 was also rendered null by monitoring and modeling results, showing maintenance activities have been demonstrated to improve dissolved oxygen levels in the water column. However, high SOD as a result in remaining dredge spoils hampers further improvement of DO up to EPA standards. The length of this increased SOD was not investigated in this study so it is impossible to pronounce whether the SOD increase is temporary or a permanent result of maintenance activities. In order to augment the improvement to DO levels due to vegetation removal, a process for removing the loose sediment must be employed as well. If more mature soils were reached and left exposed to the overlying flow SOD values similar to the undredged sites would theoretically bring DO levels closer to accepted standards.

Pending further study it is this report's recommendation to continue with hand-removal of vegetation and to consider mechanical dredging to increase sustainable habitat and elevate dissolved oxygen concentrations to even higher levels. The downstream movement of sediment within ditch systems may reduce the benefit of mechanical dredging.

4.0 CHAPTER FOUR THESIS SUMMARY

Objectives revisited:

The objective of this investigation was to increase knowledge of factors affecting DO and drainage capabilities in agricultural waterways in order to provide a tool to aid landowners and legislators in developing effective best management strategies. A secondary goal designed to complement the first was to undertake a detailed study of how sediment oxygen demand (SOD) interacts with other components of the DO cycle as a result of maintenance activities.

4.2 Outcomes and Implications:

These thesis objectives were met through a combination of monitoring, measurements, modeling, and experimentation. This research provides a valuable contribution to the scientific community in the realm of how channel maintenance affects dissolved oxygen in agricultural settings. Prior to this study there was very little documentation on the parameters affected by complete vegetation removal in low-flow, low gradient agricultural waterways. This investigation found that sediment oxygen demand does not decrease in the short-term when vegetation is removed by hand, instead it becomes an even greater DO sink when the dredge spoils are left in the channels. Pre-dredge SOD_5 values at 20°C were found to be between 0.45 and 0.67 $g/m^2/d$ compared with values between 2.1 and 3.3 $g/m^2/d$ in hand-cleaned reaches. The SOD levels measured at dredged sites tend to fall between values found recently in the Tualatin and Willamette rivers in Oregon (Rounds and Doyle, 1997, Caldwell and Doyle, 1995). These two TMDL studies measured SOD ranges of 0.6 - 4.4 and 1.3 - 4.1 $g/m^2/d$ respectively. Both Oregon sites had silty sediments with a low to moderate amount of organic material. The lower SOD values found in undredged reaches were similar to values found in both lakes and rivers (Beutel, 2003, Truax, et al 1995) but the wide variety of water body characteristics in the literature makes direct comparison to other studies difficult. Overall, the SOD levels found in the King County study fell within a reasonable range when compared to relatively similar studies. Elevated SOD values in the hand-cleaned segments are possibly due to the amount of loose organic sediments and decaying vegetation remaining after the maintenance operations. The characteristics of the sediments indicate this since the two sites consisting of sandy sediments demonstrated the lowest SOD values. The highest values were found at locations where a silty material dominated. Age of sediments may also play a part in the SOD differences; however it was not possible to determine the duration sediments had been at each site.

Even though SOD levels rose following dredging, the improvements to overall DO levels were substantial, raising an average of 3.4 mg/l (over 250%) as a result of vegetation removal. This improvement indicates that a best management plan should include a scheduled vegetation removal procedure. This water quality improvement was determined to be due to increased reaeration, photosynthesis, and velocity. This deduction was made after examining key variables with the Qual2kw model and recording their sensitivity. Sensitivity analysis performed on the reaeration rate during the calibration of the Qual2kw model indicated that increases of 10 and 50% in reaeration resulted in significantly raised DO (10 and 73% higher, respectively). Reaeration was determined to be between 0.75 and 1.25 /d for pre-dredged conditions compared to 8.5 /d in cleaned reaches. Simulated velocity increased from .02 m/s (.06 ft/s) to .07 m/s (.23 ft/s) once the vegetation was removed. This increase in velocity reduces the travel time from 1.5 to 0.5 days. Decreased residence time affects DO quality by decreasing the duration BOD substances are exerting oxygen demand on a given channel segment (Jones and Stokes, 2005). Photosynthesis also increased following vegetation removal. Algal photosynthesis rate is important in the DO equation because it is an oxygen-producing process. In reaches with significant obstructions to solar radiation penetration this reaction is restricted resulting in lowered DO throughout the water column (Perna, 2005, Jones and Stokes, 2005).

These improvements to water quality were accompanied by an increased ability to drain agricultural fields and prevent flooding. This was mainly due to reduced Manning's roughness coefficients and channel energy gradients. Alterations to these hydraulic parameters were calculated by using the software HEC-RAS in conjunction with pre and post-dredge site surveys and flow measurements. Pre-dredge Manning's values were found to be 0.41 to 1.9, much higher than values suggested in the literature for undredged man-made channels. Chow suggests Manning's n to be between 0.08 and 0.14 (Chow, 1959) in undredged conditions. After cleaning the Manning's n values more closely resembled accepted values at 0.08 compared with Chow's 0.06 to 0.08 recommendation. Correspondingly, the hydraulic and energy grade line slopes were shown to be reduced dramatically by a factor of more than 100 as the result of a significant decrease in head loss. Higher head loss under pre-maintained conditions result in greater flooding potential as the resistance to flow moving through the channel will force the water level to rapidly rise upstream and find its way out of the channel. Increased roughness due to excessive RCG also contributes to flooding problems physically by decreasing the cross-sectional flow area which raises the surface elevation even further and causes additional flooding. As the water surface rises the wetted perimeter also increases which, when paired with a lowered cross-sectional area reduces the hydraulic radius thereby decreasing the available flow path. Maintaining the channel regularly eliminates these negatives and improves channel hydraulics.

Improved agricultural potential benefits landowners and farmers by providing needed income and cropland. As a result of this study and the Qual2kw model, landowners will be able to schedule maintenance plans that will increase fish and wildlife habitat and agricultural viability while reducing flooding. This report also provides future researchers investigating similar channels with relevant information on roughness coefficients, channel characteristics, energy grades slopes, sediment oxygen demand, and dissolved oxygen in both pre- and post-dredged scenarios

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APPENDIX A: EXTENDED LITERATURE REVIEW

Introduction

The purpose of this study was to investigate the effects of dredging on water quality in agricultural drainage ditches in King County, Washington. This was accomplished by a variety of methods including water quality monitoring and modeling. The water quality model chosen was the EPA recommended Qual2kw model which has been recently adjusted by Washington State Department of Ecology staff to specifically fit the low-flow short-reach scenarios found in the King County drainage ditches. During the modeling process several unknown variables were determined to be important factors in the King County water systems and investigated in detail to contribute to the modeling accuracy and understanding of similar systems undergoing maintenance activities. These included reaeration, sediment oxygen demand, channel roughness, and energy gradients.

Previous Research

Most current information on DO and water quality has been compiled as part of TMDL studies. TMDL stands for Total Maximum Daily Load and represents the maximum amount of pollutant a given water body can withstand without exceeding state and federally mandated water quality standards. The program is an extension of the Clean Water Act of 1972 and is primarily designed to ensure the Act's goals are met through a series of quantifiable parameters and water quality models. The TMDLs are designed after extensive research has been performed on a given water body and samples taken of existing conditions. In Washington State the Department of Ecology carries out TMDL mandates through cooperation from local stakeholders. Through the program many valuable water quality parameters have been monitored and recorded. In addition to TMDL research, several entities have investigated SOD, DO, and reaeration as part of independent studies. Their results and theories will also be briefly highlighted. This review focuses on scenarios most similar to those being simulated as part of the King County APD study.

Perna, 2005

An Australian water quality study involving vegetation removal in tropical river found that by removing dense weed mats DO levels increased substantially (Perna, 2005). Their situation is the most similar to the one found in King County in that fish populations were being adversely affected by low DO caused by stagnating aquatic vegetation which restricted solar radiation and reaeration. The decreased sunlight caused a reduction in algal photosynthesis and reduced any diel cycling in DO levels. Because of this the low DO remained constant throughout the day as opposed to cycling through a healthy, photosynthesis-induced increase in the afternoon. Although the study area had other factors besides the water hyacinth concentrations such as agricultural runoff the researchers felt the natural processes occurring as a result of the vegetation were the primary causes to DO degradation. After removing the vegetation by a mechanical weed harvester DO levels rose considerably and the duration the segments had DO below Australian standards decreased to a few hours per night instead of for a majority of the day. The researchers published their DO values as percent concentration instead of in mg/L and they were attempting to bring DO levels above 25% saturation for a majority of a 24-hour period. The study also specifies that the vegetation was not allowed to sink to the bottom of the channel due to decomposition concerns. Perna, et al felt that stab readings were an inaccurate method of investigating impaired DO conditions due to their tendency to be during daylight hours when DO is at its peak.

Prior to the vegetation removal the diel DO cycle accounted for an approximately 10% rise or fall whereas post-removal the diel flux increased to approximately 30%. This indicates that by increasing solar radiation and reaeration a water body will have a greater rise and fall in DO levels throughout the course of a day. This can facilitate healthier fish populations by allowing wind and other processes to reaerate the water's surface and encourage photosynthetic oxygen production. This was evident in subsequent studies in the cleaned reaches that had a marked increase in fish populations within a year of cleaning completion.

<u>DO in Depth</u>

Modeling DO

The models selected for investigation for the King County project were WASP and Qual2k. The EPA recommends both as effective water quality models. WASP can model in 1, 2, or 3 dimensions and includes BOD, DO, nutrients, eutrophcation, bacterial contamination, and organic chemical and heavy metal contamination considerations (Ambrose, 1988). The model can be downloaded from http://www.epa.gov/athens/wwqtsc/html/wasp.html. Qual2k is a one-dimensional water quality model that uses Microsoft Excel as its graphical user interface and Microsoft Excel VBA and FORTRAN 95 as its program languages (Pelletier et al, 2005). Some research has been performed on the accuracy of both models. A comparison between these two and a third probability model for the ability to predict chlorophyll a concentrations in estuaries found that there was little difference in accuracy between all three (Stow et al, 2003). In contrast, they found the models' accuracy to be lower than expected leading them to write: "our verification results underscore the realization that predicting ecosystem behavior is inexact" and "the utility of the models is to provide quantitative guidance rather than a definitive number."

Qual2kw Equation

Qual2kw uses the following equation for calculating DO sources and sinks for the model's general mass balance approach:

$$S_o = r_{oa}\,\text{PhytoPhoto} + r_{od}\,\text{BotAlgPhoto} - r_{oc}\,\text{FastCOxid} - r_{oc}\,\text{SlowCOxid} - r_{on}\,\text{NH4Nitr} - r_{oa}\,\text{PhytoResp} - r_{od}\,\text{BotAlgResp} + \text{OxReaer} - \text{CODoxid} - \text{SOD/H}$$

Equation A.1 DO source/sink equation

Where So is the dissolved oxygen source/sink term [mg O^2/L/day], PhytoPhoto is the Phytoplankton photosynthesis rate, BotAlgPhot is the bottom algal photosynthesis rate, FastCOxid is the fast reacting CBOD, SlowCOxid is the slow reacting CBOD, NH4Nitr is the ammonia nitrification rate, PhytoResp is the phytoplankton respiration rate, BotAlgResp is the bottom algae respiration rate, OxRear is the rate of oxidation reaeration, CODoxid is the COD oxidation, and SOD/H is the sediment oxygen demand divided by the water column depth. Rxy = stoichiometric coefficients for organic matter ie. $r_{xy} = \frac{gX}{gY}$ where gX = mass of element X [grams] and gY = mass of element Y [mg] and the coefficients a, d, c, and n refer to chlorophyll a, dry weight, carbon, and nitrogen respectively (Pelletier et al, 2005).

Factors affecting DO

There are a number of natural processes that affect DO concentrations in water bodies. These include biological oxygen demand (BOD), sediment oxygen demand (SOD), photosynthesis, aquatic plant respiration, growth, and mortality rates, residence time and reaeration.

Photosynthesis

Algal photosynthesis rates are important in the DO equation because it is an oxygen-producing process. In reaches with significant obstructions to solar radiation penetration this reaction is restricted resulting in lowered DO throughout the water column (Perna, 2005, Jones and Stokes, 2005). Decreased photosynthesis is also responsible for reducing diel cycling according to a Walla Walla River Basin TMDL: “The diel patterns of DO and pH indicate that these variables are strongly influenced by photosynthesis…” (Joy and Pelletier, 2007).

Reaeration

Reaeration plays a large role in stream quality health but it is not typically focused on in TMDL studies. One that mentions its effects is the San Joaquin River study which describes the tendency of stagnant waterways to have decreased reaeration: “Stratification can produce a shallow surface layer and limit reaeration of water below the surface layer” (Jones and Stokes). In the Australian vegetation removal project reaeration rates increased substantially once weed mats were harvested (Perna, 2005). This was considered a major contributor to increased DO levels that were observed almost immediately following cleaning operations. Rainfall was found to affect reaeration rates by causing surface turbulence (Belanger, 1991). This rainfall effect could be limited in highly vegetated reaches where direct precipitation is prevented from dropping onto the water surface by obstructing stems and leaves.

Dredging:

Very few studies investigated the effects of dredging on water quality. Even fewer discussed the differences between hand and mechanical dredging, or the impacts of leaving dredge spoils in the channel or depositing them elsewhere. The article most pertinent to this topic was the Australian removal of water hyacinth mats. The researchers found it important to remove all vegetation from the channel because “[they] felt that their decomposition would have resulted in significant consumption of the limited DO available in the lagoons” (Perna, 2005). They referenced a Mexican case where aquatic vegetation was removed from a reservoir by mechanical shredding and then allowed to sink. In that case the “water quality deteriorated severely including the development of hypoxia and toxic levels of ammonia, resulting in major impacts to biota, including the loss of all fish species" (Perna, on Mangas-Ramirez and Elias-Guterirrez (2004)). More on the Australian study can be found in the "Perna, 2005" section.

SOD

Dissolved oxygen (DO) levels in the water column are directly related to the oxygen demand of underlying sediments. This component, called sediment oxygen demand (SOD) can effectively deplete water systems to uninhabitable levels of dissolved oxygen. This occurs when oxygen-dependant microorganisms and chemical processes decay organic sediments and vegetation at the bed level of water bodies. The ensuing processes exhaust the oxygen in the sedimentary level and subsequently become a significant DO sink in overlying water layers.

SOD in Depth

SOD has been studied in a wide variety of applications including lakes, streams, and large rivers. Information on SOD in agricultural settings is much more limited however, specifically in low-flow, low velocity channels.

Measuring SOD

Currently there is no one accepted method for SOD measurement and analysis. Some researchers prefer in-situ methods involving large cylinders inserted onto the sediment where it meets the water body floor (Truax et al.1995). These methods usually involve divers and a study time of less than two hours unless the area is shallow. Lab methods involve removing sediment cores carefully and transporting them to another location where techniques similar to the in-situ ones are employed. Still others measure SOD by employing BOD lab techniques by inserting a set amount of sediment into a BOD bottle and measuring the DO levels at regular intervals (Matlock et al., 2003).

Relevant Equations

According to Nakamura et al, the process of DO consumption at the sediment/water interface can be effectively modeled by assuming a two-layer condition exists consisting of an oxygen-rich upper water layer and a lower, high SOD diffusive boundary layer. For his model he also assumes a steady state system with constant horizontal velocity and smooth streambed and walls. Previously Walker and Snodgrass (1986) represented SOD as:

$$SOD = \mu_\beta \frac{C_\infty}{K_{0_2} + C_\infty} + k_c C_\infty$$ **Equation A.1**

Where the first term is the biological SOD and the second the chemical SOD component. μβ = aerobic oxidation rate constant, C∞ = dissolved O2 concentration in the bulk water K02 = half saturation constant for O2, and kc = first-order rate constant. Note that K_{02}, kc, and μβ are dependant on the aerobic zone depth, δs.

Due to his assumption that velocity was the prevailing variable in SOD concentrations, Nakamura determined that the two parameters μβ and kc were not appropriate independent parameters for SOD. Further assuming that "the chemical reaction is a first-order reaction of DO concentration" the author was able to derive an equation for the volumetric rate of O2 consumption in sediments as follows:

$$R = \mu \frac{C_w}{K_{0_2} + C_w} + k' C_w$$ **Equation A.2**

Where μ = the maximum aerobic oxidation rate, k' = first order rate constant, Cw = dissolved O2 concentration at the sediment-water interface. Additional pertinent equations included SOD flux at the sediment-water interface, and corresponding total SOD flux resulting in the equation:

$$SOD_* = \frac{-1 + \sqrt{1 + U^2{}_*}}{U_*}$$ **Equation A.3**

Where SOD* and U* are the dimensionless flux of O2 to sediment and the flow velocity respectively. This particular equation corresponds to k' and K_{02} values of zero, with other scenarios being represented by additional similar equations. The following figure shows this relationship, where biological SOD is the dominant oxygen-consumption process.

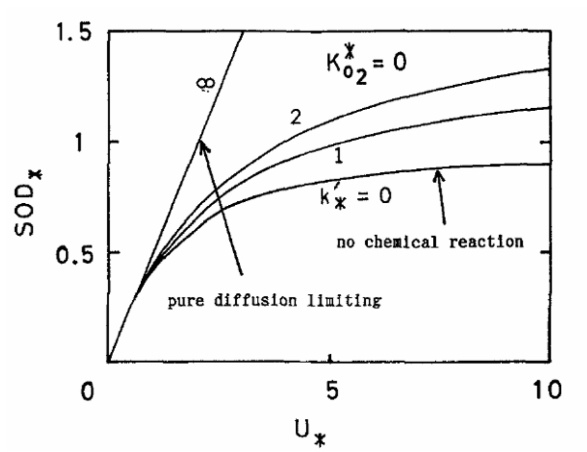

Figure A.1 Non-dimensional (SOD) as a function of non-dimensional velocity and first-order reaction rate constant k'$_*$ (Nakamura)

Additionally, Dimensioned SOD and velocities resulted in a similar graph:

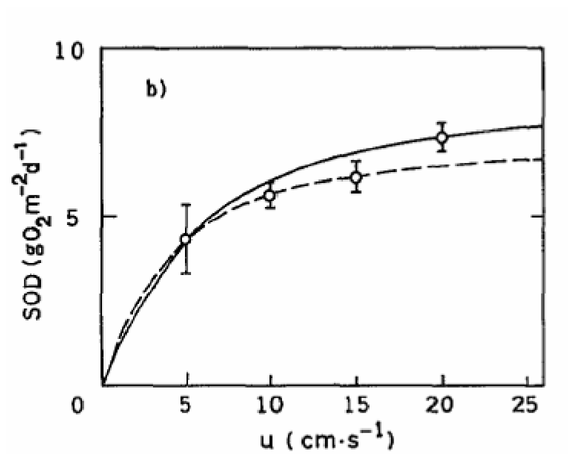

Figure A. 2 Comparison of observed and calculated results of SOD as a function of flow velocity in sandy mud. (Nakamura)

The SOD levels appear to increase with increasing velocity. This is explained by the author as a relationship between the diffusive boundary layer depth at the sediment-water interface and the velocity. As the velocity increases, the diffusive layer also decreases, allowing the DO concentration at the interface to correspondingly increase. Alternately, if the velocities are low the anaerobic zone depth increases causing a greater gap between oxygen-enriched flows and the oxygen-dependent sediments. This theory is further illustrated in the following figure:

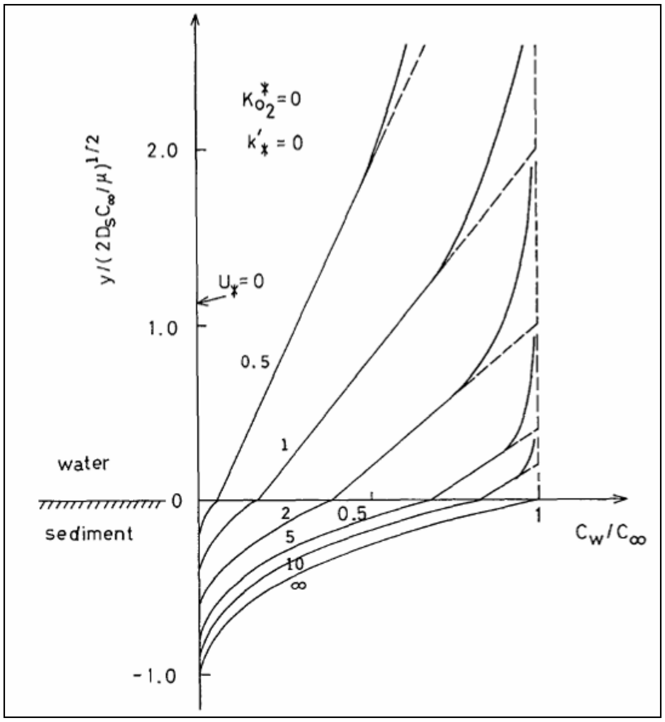

Figure A. 3 Vertical distribution of dissolved oxygen concentration as function of nondimensional velocity: K_{o2}. = 0 and k" = 0 (Nakamura)

Note that as the diffusive layer decreases the dissolved O2 concentration at the soil/water interface also increases. This is mirrored in the increasing dissolved O_2 concentration to non-dimensional velocity relationship.

The authors' conclusion in this study is that the dominant factor in low velocity-SOD relationships is flux through the diffusive boundary zone. This results in SOD being a function of flow velocity, DO concentration in the bulk water, and a friction factor at the sediment surface.

The scenario is slightly different for higher velocities however, with biological and chemical consumption of oxygen, DO concentration, and diffusion rates of O_2 in the sediment representing the primary variables. Transitional velocities posed a third set of dominant variables which will not be mentioned here. The combined variation in SOD levels with differing flow schemes poses a challenge to water system modelers and data collectors. SOD is a notoriously complex parameter to track and predict as has been demonstrated by Nakamura's study.

Factors affecting SOD rates

As Nakamura and others have demonstrated, SOD is related to several parameters including the velocity of the overlying flow, DO at the sediment/water interface, resuspension, sediment characteristics, and deposition patterns.

Resuspension

BOD represents the oxygen consumption occurring within the water column, SOD by contrast is limited in most studies to the interactions consuming DO at the sediment/water interface. There seems to be disagreement in whether resuspended sediments should be considered SOD or BOD (Matlock et al., 2003), but all researchers agree resuspension plays a large role in rapid oxygen consumption. In a TMDL oxygen demand study in the San Joaquin River researchers determined "significant resuspension events can result in elevated oxygen demands near the sediment-water interface" (Litton, et al.2003) and during an SOD study in the Arroyo Colorado River researchers documented "When the limits of diffusion no longer exist (as occurs during a resuspension event), very large oxygen consumption events can occur very rapidly" (Matlock et al., 2003). Matlock et al. also noted: "Sites with high sediment deposition potential had high SOD."

Sediment characteristics

Two studies sought to find relationships between sediment characteristics and SOD without success. In an SOD study in the Lower Willamette River in Oregon, the researchers investigated moisture content, percent sand and percent organics before concluding "no statistically significant correlations were found between these sediment characteristics and sediment oxygen demand" (Caldwell & Doyle, 1995). Of particular interest is that they found poor correlation between SOD and organic content of the sediments. However, they also acknowledged: "it is reasonable to assume…that the SOD associated with gravels and cobbles is less than the SOD where the chambers could be inserted" (soils with a higher percentage of silt and loose material). In the Tualatin River Basin report the authors assert that sediments with high sand and low organics typically will have the lowest SOD values whereas the highest SOD will be found in sites high in organic sludge (Rounds and Doyle, 1997). However when they attempted to find a correlation between chlorophyll concentration and SOD, there were unable to find any of significance. Instead, they determined that within-site heterogeneity contributed more to SOD differences than individual variables (Rounds and Doyle, 1997). As part of the same study they looked at the potential for an algal detritus/SOD connection and found that while algal detritus does indeed contribute to SOD, "most of the SOD is likely to originate from non-algal sources of organic matter" (Rounds and Doyle, 1997).

Residence time

According to a DO report on the San Joaquin River in California residence time affects DO quality by increasing the duration BOD substances are exerting oxygen demand on a given channel segment (Jones and Stokes, 2005). The report specifically states: "The larger the residence time, the more of the BOD will decay and the DO concentration will decline." This subsequently affects SOD by increasing the amount of decaying BOD particulates settling out of the water column onto the sediment below.

Effect of Flow Velocity on SOD

Sedimentation rates, deposition patterns, and resulting water qualities are all greatly affected by the velocity of the overlying flow. This is due in part to the size of the transported bed load, the lack of fresh oxygen-bearing inflow and the tendency for sediment accumulation in lower velocity regions. When flow velocities are low, a unique set of sedimentation characteristics arise. Deposition patterns contribute a challenge to developers, biologists, stream restoration experts and landowners. The USGS recognizes the unique characteristics of suspended sediment rates in lower velocity regimes, as they specify in their data collection recommendations, “When mean stream velocities are low [less than about 2 ft/s (0.6m/s)] and the flow is tranquil, generally fine silt- and clay-sized particles are in suspension, and sediment concentrations do not vary greatly either vertically or laterally.” Also, because of the deposition of finer particles vegetation growth rates can increase, making dredging and plant removal a consideration in long-term maintenance strategies (Haestad, 2006).

Typical SOD Values

Table A. 1 Reported SOD values for a variety of studies. (Note numbers 1 – 4 taken from Wood, 1999)

	Location	Description	SOD_{20} $g/m^2/d$	Reference
1	Willamette River, OR	silty sediment, moderate organic content (1-10% OC)	1.3 - 4.1	Caldwell and Doyle, 1995
2	Tualatin River, OR	slow-moving, reservoir reach, silty sediment, moderate OC	0.6 - 4.4	Rounds and Doyle, 1997
3	Tennessee-Tombigbee Waterway, Mississippi	measurements represent a range of bottom characteristics along the waterway	0.4 - 1.2	Truax, et al., 1995
4	Five South-western Lakes	trophic states varied from oligotrophic to eutrophic	0.3 - 9.0	Veenstra and Nolen, 1991
5	Upper Klamath and Agency Lakes, Oregon	mixed, including shallow, eutrophic lakes	1.6 - 1.7	Wood, 1999
6	California Drinking Water Reservoirs	Anoxic, moderately mixed chambers	0.3 - 0.6	Beutel, 2003
7	San Joaquin River, California		0.4 - 0.8	Litton et al., 2003
8	Upper Wisconsin River		0.02 - 0.92	Bowie et al., 1985 in Truax., et al 1995
9	Eastern U.S. Rivers		0.15 ± 0.04	Bowie et al., 1985 in Truax., et al 1995
10	Southeastern U.S. rivers		0.55 ± 0.22	Bowie et al., 1985 in Truax., et al 1995
11	Eastern Michigan rivers		0.10 - 5.3	Bowie et al., 1985 in Truax., et al 1995
12	Northern Illinois rivers		0.27 - 9.7	Bowie et al., 1985 in Truax., et al 1995
13	New Jersey rivers		1.1 - 12.8	Bowie et al., 1985 in Truax., et al 1995
14	Arroyo Colorado River	low DO river listed on 303(b) list	0.13 - 1.2	Matlock et al., 2003

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APPENDIX B: SITE MAPS

Figure B.1 Smith Brother site with Mullen Slough sampling points

Figure B.2 Boscolo property with sampling points

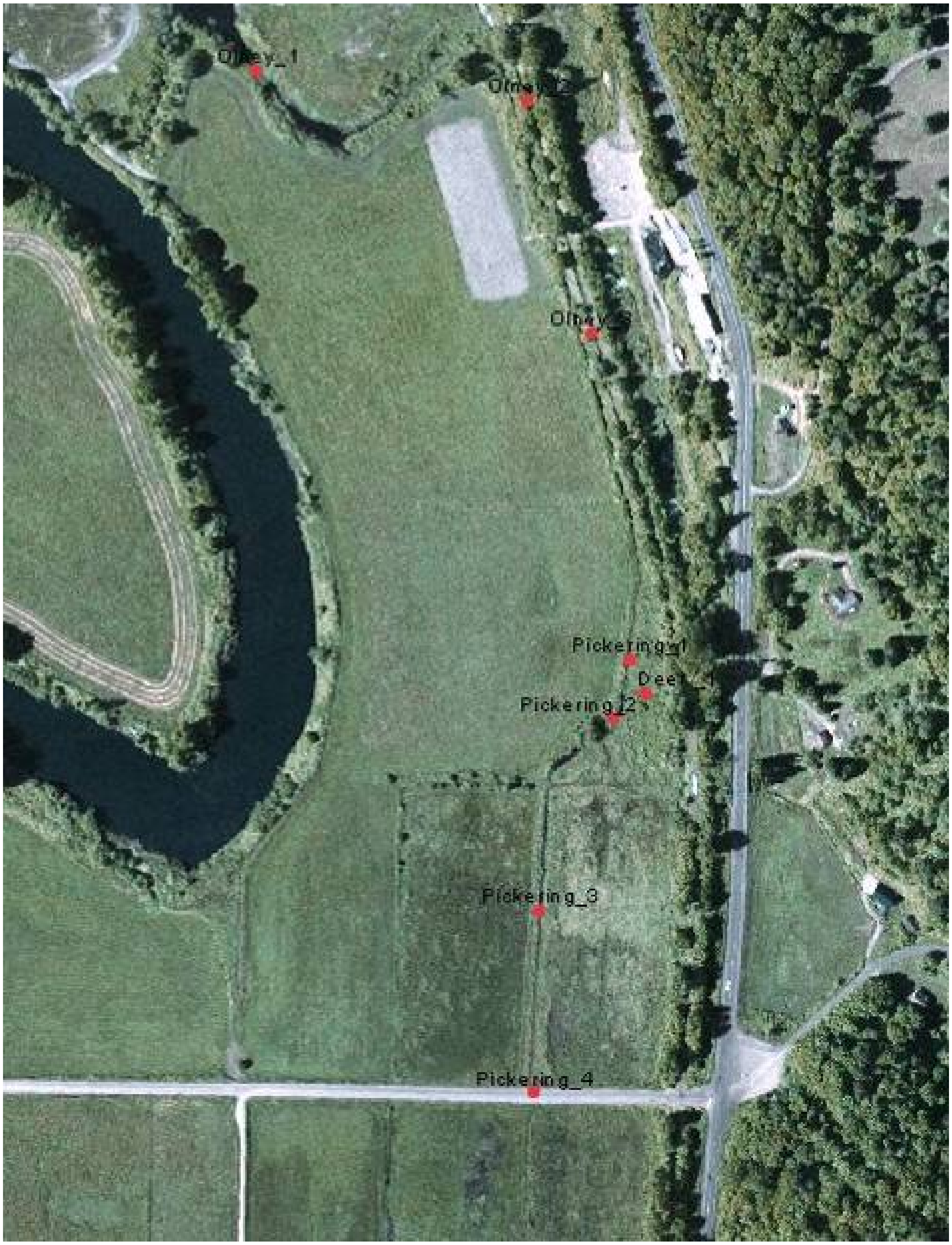

Figure B.3 Duvall site with Pickering/Olney sampling points

APPENDIX C: DOE WATER QUALITY STANDARDS

Table C. 1 DOE Water Quality Standards

Category	Lowest 1-Day Minimum
Char Spawning and Rearing	9.5 mg/L
Core Summer Salmonid Habitat	9.5 mg/L
Salmonid Spawning, Rearing, and Migration	8.0 mg/L
Salmonid Rearing and Migration **Only**	6.5 mg/L
Non-anadromous Interior Redband Trout	8.0 mg/L
Indigenous Warm Water Species	6.5 mg/L

*Table can be found in "Water Quality Standards for Surface Waters of the State of Washington" Chapter 173-201A WAC, Table 200(1)(d), page 12
http://www.ecy.wa.gov/pubs/0610091.pdf

APPENDIX D: SOD EXPERIMENT RESULTS

Table D.1 Results of individual SOD measurements

Site		Date	K_c (m/d)	μ_b ($g/m^2/d$)	R^2	avg DO	SOD	Avg T	SOD_2	SOD_5	SOD_{10}	SOD_2 (20°)	SOD_5 (20°)	SOD_{10} (20°)
BSC (Undredged)	A	9.17	0.11	0.00	0.97	2.99	0.30	23.05	0.22	0.54	1.08	0.18	0.45	0.89
		9.25	0.08	0.09	0.97	3.38	0.36	22.99	0.25	0.49	0.89	0.21	0.41	0.74
		10.03	0.04	0.37	0.96	3.10	0.51	21.98	0.46	0.59	0.81	0.41	0.52	0.71
		Average	**0.08**	**0.16**	**0.97**	**3.16**	**0.39**	**22.67**	**0.31**	**0.54**	**0.93**	**0.26**	**0.46**	**0.78**
		Std Dev	**0.03**	**0.19**	**0.01**	**0.20**	**0.11**	**0.61**	**0.13**	**0.05**	**0.14**	**0.12**	**0.06**	**0.10**
	B	9.07	0.07	0.49	0.86	3.50	0.73	23.49	0.63	0.83	1.16	0.50	0.66	0.93
		9.17	0.14	0.39	0.98	3.45	0.87	22.46	0.67	1.08	1.77	0.57	0.93	1.52
		9.25	0.09	0.41	0.98	3.70	0.75	22.54	0.59	0.87	1.33	0.50	0.74	1.14
		10.03	0.05	0.19	0.80	2.04	0.29	22.48	0.29	0.43	0.66	0.25	0.37	0.57
		Average	**0.09**	**0.37**	**0.90**	**3.17**	**0.66**	**22.74**	**0.54**	**0.80**	**1.23**	**0.46**	**0.67**	**1.04**
		Std Dev	**0.04**	**0.13**	**0.09**	**0.76**	**0.25**	**0.50**	**0.17**	**0.27**	**0.46**	**0.14**	**0.23**	**0.40**
Deer Creek (Non-Agricultural)	A	8.27	0.26	0.46	0.49	2.22	1.04	22.35	0.98	1.77	3.09	0.85	1.53	2.66
		9.07	0.51	0.35	0.85	2.25	2.05	23.75	1.36	2.88	5.41	1.07	2.27	4.27
		9.18	0.16	0.43	0.73	3.60	1.04	23.07	0.76	1.25	2.06	0.62	1.03	1.70
		9.25	0.15	0.25	0.78	3.49	0.79	23.23	0.56	1.02	1.79	0.46	0.84	1.46
		10.03	0.05	0.45	0.28	3.67	0.65	22.66	0.56	0.72	0.99	0.47	0.61	0.84
		Average	**0.23**	**0.39**	**0.63**	**3.05**	**1.11**	**23.01**	**0.84**	**1.53**	**2.67**	**0.70**	**1.25**	**2.19**
		Std Dev	**0.17**	**0.09**	**0.24**	**0.74**	**0.55**	**0.54**	**0.34**	**0.85**	**1.70**	**0.26**	**0.66**	**1.33**
	B	9.07	0.88	1.26	0.79	1.77	3.68	23.82	3.01	5.65	10.04	2.37	4.44	7.89
		9.18	0.62	2.30	0.75	3.05	4.91	23.32	3.54	5.40	8.50	2.87	4.38	6.90
		9.25	0.14	0.80	0.98	3.73	1.31	23.20	1.07	1.48	2.17	0.88	1.21	1.77
		10.03	0.14	0.70	0.61	2.97	1.29	22.47	0.97	1.38	2.07	0.83	1.18	1.77
		Average	**0.44**	**1.26**	**0.78**	**2.88**	**2.80**	**23.20**	**2.15**	**3.48**	**5.69**	**1.74**	**2.80**	**4.58**
		Std Dev	**0.37**	**0.73**	**0.15**	**0.81**	**1.80**	**0.56**	**1.32**	**2.36**	**4.18**	**1.04**	**1.85**	**3.27**

Table D-1 Continued

Site		Date	K_c (m/d)	μ_b ($g/m^2/d$)	R^2	avg DO	SOD	Avg T	SOD_2	SOD_5	SOD_{10}	SOD_2 (20°)	SOD_5 (20°)	SOD_{10} (20°)
A	Mullen Slough (Recently Dredged)	8.27	0.23	1.37	0.12	3.44	2.16	22.42	1.83	2.52	3.66	1.57	2.16	3.14
		9.07	0.24	1.17	0.21	3.78	2.09	22.02	1.66	2.39	3.60	1.46	2.10	3.17
		Average	**0.24**	**1.27**	**0.16**	**3.61**	**2.12**	**22.22**	**1.74**	**2.45**	**3.63**	**1.51**	**2.13**	**3.16**
B		**9.07**	**0.65**	**0.61**	**0.21**	**2.38**	**2.14**	**22.26**	**1.90**	**3.84**	**7.07**	**1.65**	**3.33**	**6.13**
A	Boscolo (Recently Dredged)	9.07	0.25	2.19	0.87	2.93	2.91	23.19	2.68	3.42	4.65	2.20	2.80	3.80
		9.13	0.36	1.93	0.83	3.14	3.06	22.18	2.65	3.73	5.54	2.31	3.25	4.82
		9.17	0.38	2.59	0.93	3.81	4.05	22.27	3.36	4.51	6.43	2.91	3.91	5.57
		9.25	0.12	1.85	0.61	3.76	2.31	22.38	2.10	2.46	3.06	1.80	2.12	2.64
		10.03	0.23	1.58	0.66	3.56	2.41	21.84	2.04	2.74	3.91	1.82	2.44	3.48
		Average	**0.27**	**2.03**	**0.78**	**3.44**	**2.95**	**22.37**	**2.57**	**3.37**	**4.72**	**2.21**	**2.90**	**4.06**
		Std Dev	**0.11**	**0.38**	**0.14**	**0.39**	**0.69**	**0.50**	**0.53**	**0.81**	**1.32**	**0.45**	**0.70**	**1.15**
B		9.13	0.30	0.72	0.99	3.81	1.85	22.08	1.31	2.21	3.70	1.15	1.94	3.25
		9.17	0.66	1.48	0.61	3.84	4.04	22.27	2.81	4.80	8.12	2.44	4.16	7.04
		9.25	0.37	1.98	0.75	3.80	3.39	22.24	2.73	3.84	5.71	2.37	3.34	4.96
		10.03	0.09	0.69	0.36	3.40	1.01	21.95	0.88	1.16	1.63	0.77	1.02	1.44
		Average	**0.36**	**1.22**	**0.68**	**3.71**	**2.57**	**22.13**	**1.93**	**3.00**	**4.79**	**1.68**	**2.62**	**4.17**
		Std Dev	**0.24**	**0.63**	**0.26**	**0.21**	**1.39**	**0.15**	**0.98**	**1.63**	**2.78**	**0.85**	**1.40**	**2.39**

Table D.2 Conversions for multiplication of SOD term by water column depth

conversions

Site name	Sed depth (in)	Sed depth (cm)	Water col depth (cm)	Water col depth (m)
Boscolo A	2.5	6.4	8.7	0.087
Boscolo B	3.4	8.6	6.4	0.064
BSC A	3.5	8.9	6.1	0.061
BSC B	3.2	8.1	6.9	0.069
Deer Ck A	2.2	5.6	9.4	0.094
Deer Ck B	2.7	6.9	8.1	0.081

Site name	Sed depth (cm)	Water col depth (cm)	Water col depth (m)	Total depth (cm)
Mullen A	13.75	11.25	0.113	25.0
Mullen B	14.5	10.5	0.105	25.0

SOD:

1. Walker and Snodgrass biochemical SOD model:
2. SOD = linear regression of DO vs. Time (g/m3/d)

multiplied by the water column height in the chamber

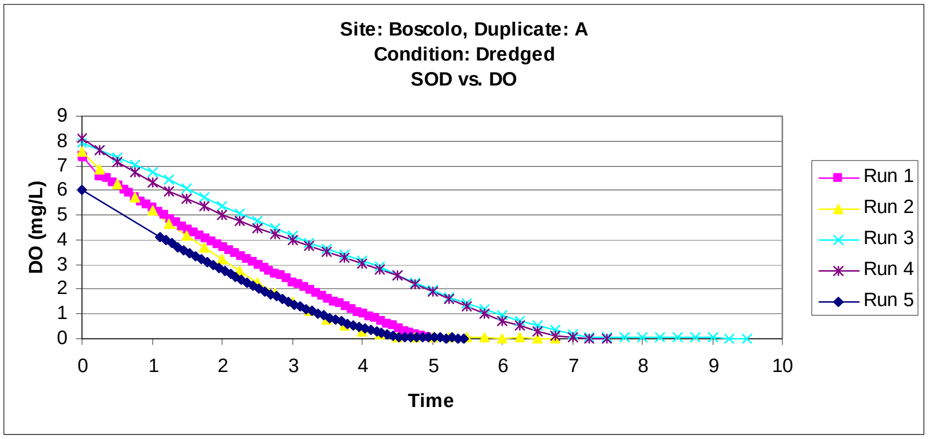

Figure D.1 Sediment-induced DO degradation over time in a sealed chamber run five times on a dredged core sample

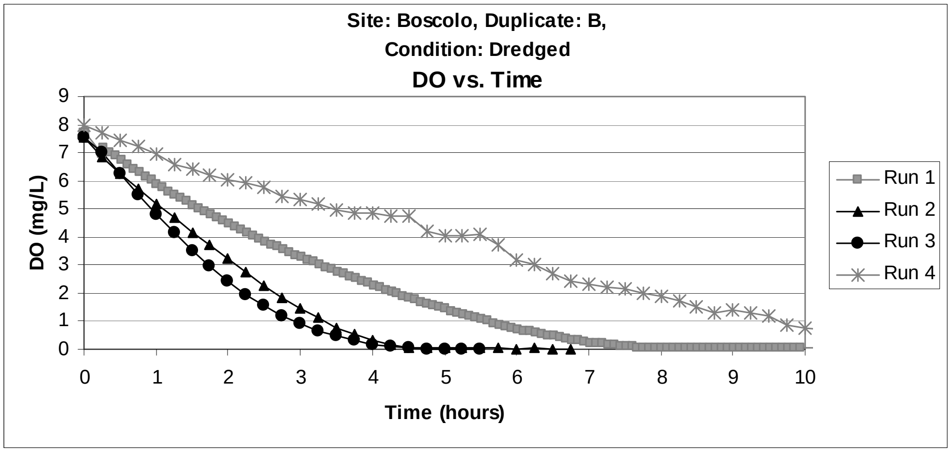

Figure D.2 Sediment-induced DO degradation over time in a sealed chamber run four times on a dredged core sample

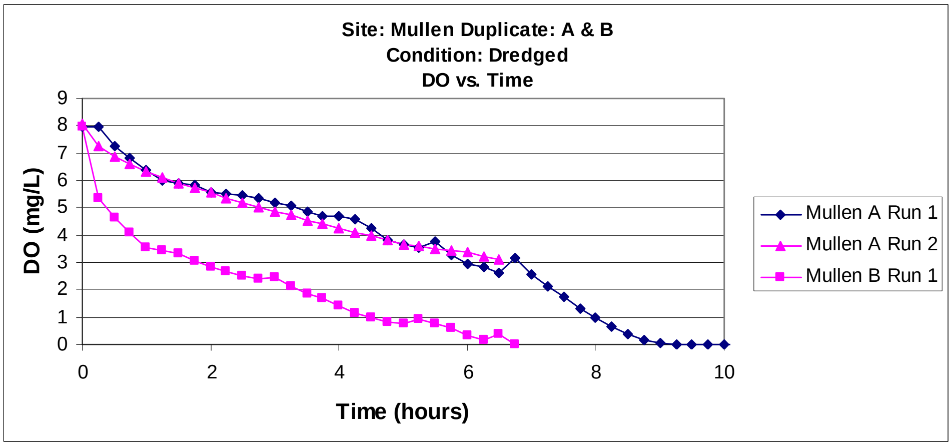

Figure D.3 Sediment-induced DO degradation over time in a sealed chamber run on two dredged core samples

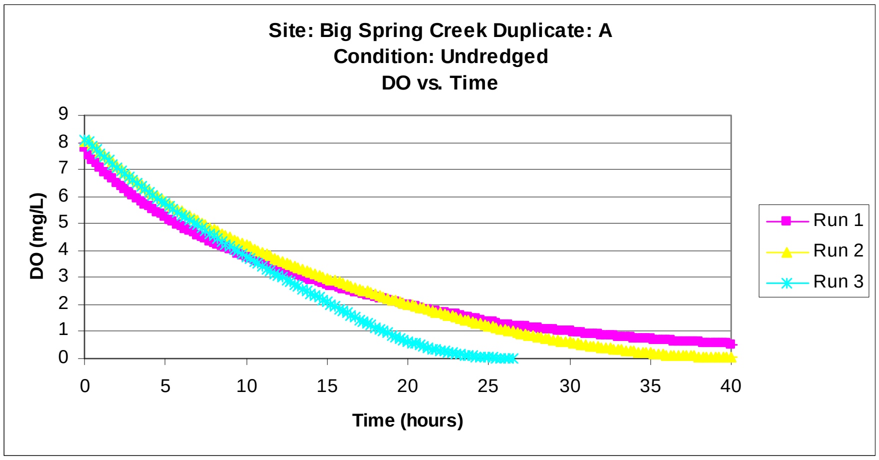

Figure D. 4 Sediment-induced DO degradation over time in a sealed chamber run three times on an un-dredged core sample

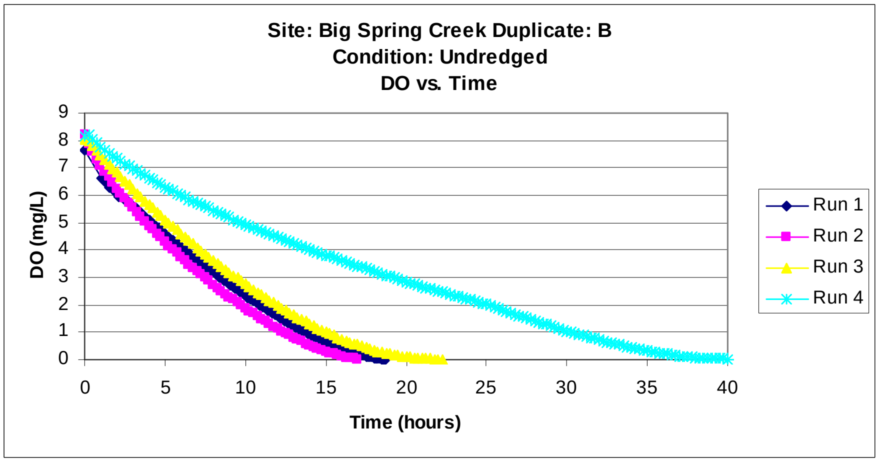

Figure D. 5 Sediment-induced DO degradation over time in a sealed chamber run four times on an un-dredged core sample

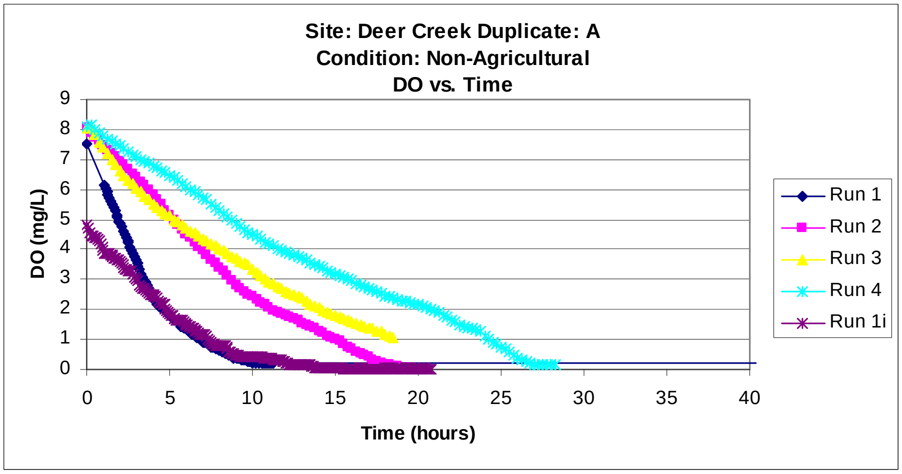

Figure D. 6 Sediment-induced DO degradation over time in a sealed chamber run five times on an un-dredged core sample

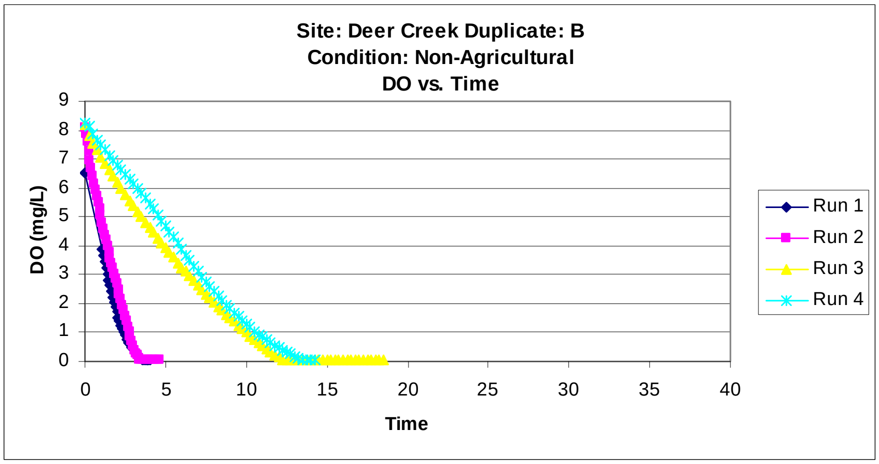

Figure D. 7 Sediment-induced DO degradation over time in a sealed chamber run four times on an un-dredged core sample

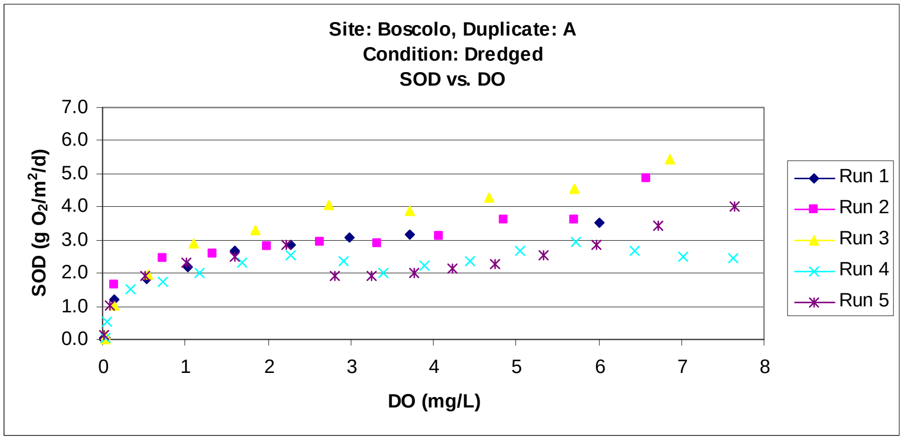

Figure D.8 Total sediment oxygen demand at a dredged site plotted against hourly DO intervals

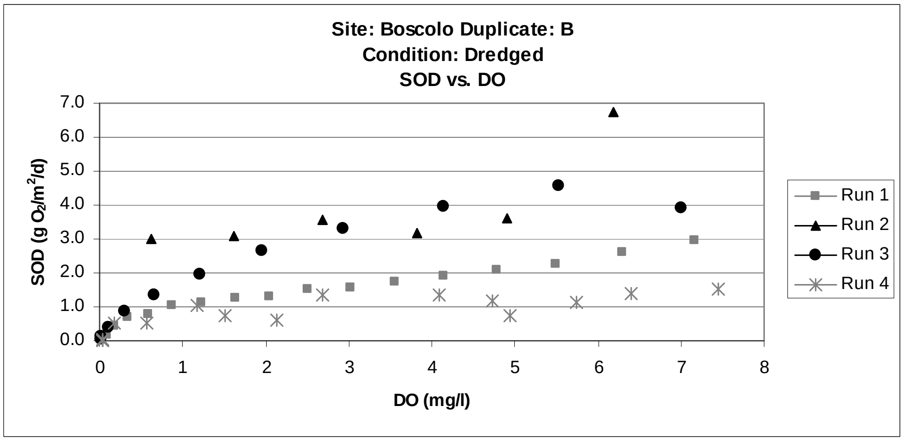

Figure D.9 Total sediment oxygen demand at a dredged site plotted against hourly DO intervals

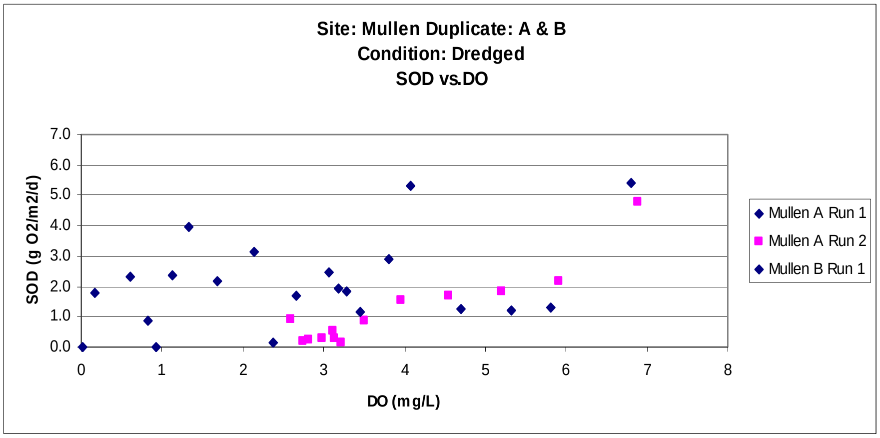

Figure D. 10 Total sediment oxygen demand at a dredged site plotted against hourly DO intervals

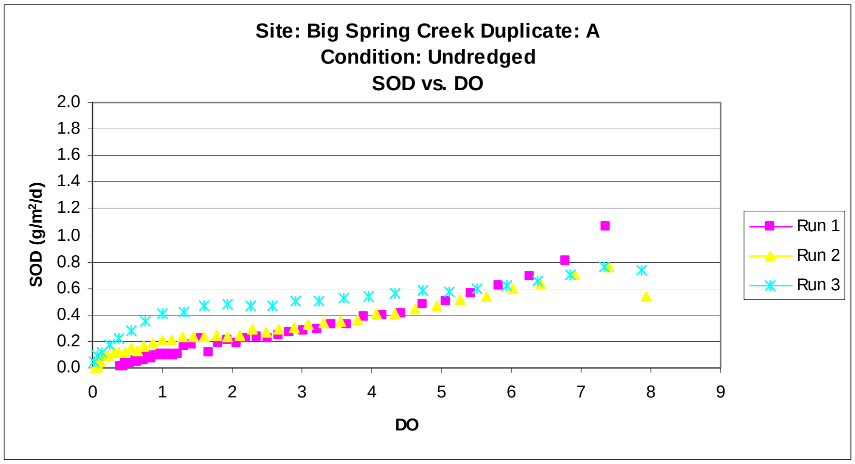

Figure D.11 Total sediment oxygen demand at au undredged site plotted against hourly DO intervals

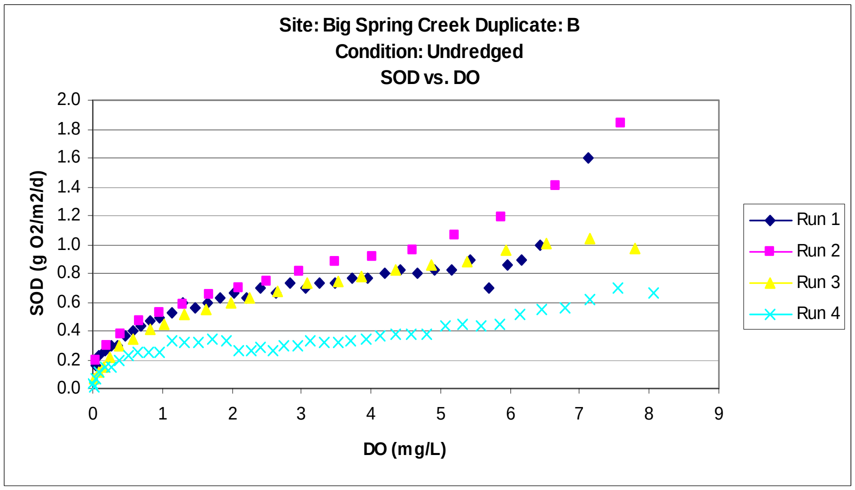

Figure D.12 Total sediment oxygen demand at an undredged site plotted against hourly DO intervals

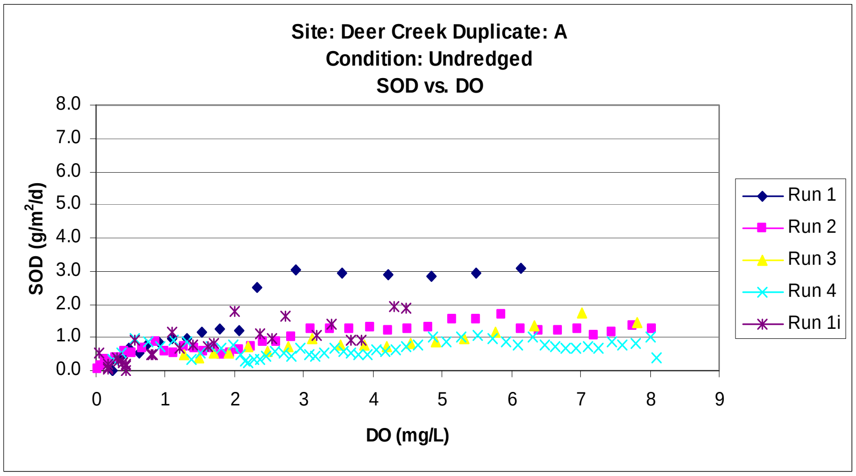

Figure D.13 Total sediment oxygen demand at an undredged site plotted against hourly DO intervals

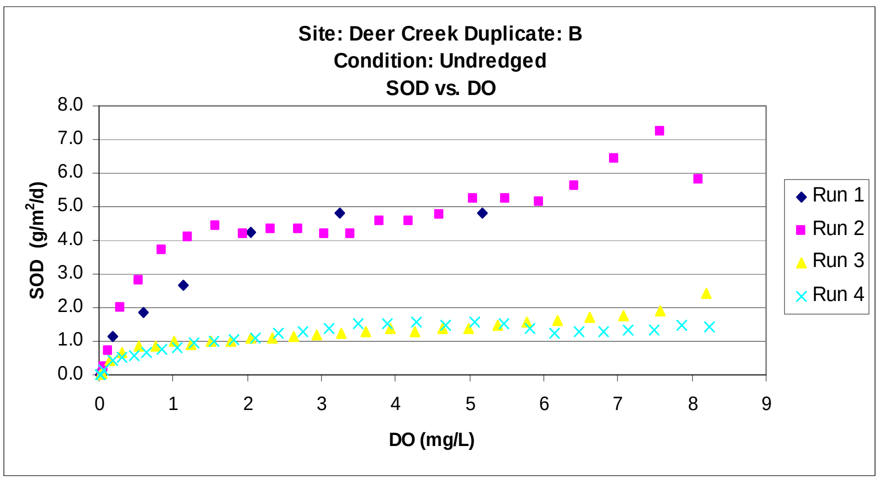

Figure D.14 Total sediment oxygen demand at an undredged site plotted against hourly DO intervals

APPENDIX E QUAL2KW INPUTS

Table E.1 Partial Qual2kw headwater inputs for pre-dredged scenario calibration

Headwater Flow	0.014	m3/s					
Prescribed downstream boundary?	No						
Headwater Water Quality	***Units***	***12:00 AM***	***2:00 AM***	***4:00 AM***	***6:00 AM***	***8:00 AM***	***10:00 AM***	***12:00 PM***
Temperature	C	12.94	12.87	12.74	12.61	12.68	12.71	12.81
Conductivity	umhos	148	148	148	148	148	148	148
Inorganic Solids	mgD/L	76	76	76	76	76	76	76
Dissolved Oxygen	mg/L	0.70	0.70	0.70	0.70	0.70	0.70	0.70
CBODslow	mgO2/L	3.08	3.08	3.08	3.08	3.08	3.08	3.08
CBODfast	mgO2/L	1.54	1.54	1.54	1.54	1.54	1.54	1.54
Organic Nitrogen	ugN/L	15	15	15	15	15	15	15
NH4-Nitrogen	ugN/L	390	390	390	390	390	390	390
NO3-Nitrogen	ugN/L	150	150	150	150	150	150	150
Organic Phosphorus	ugP/L	75	75	75	75	75	75	75
Inorganic Phosphorus (SRP)	ugP/L	75	75	75	75	75	75	75
Phytoplankton	ugA/L	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Detritus (POM)	mgD/L	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Pathogen	cfu/100 mL	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Generic constituent	user defined	8.43	8.43	8.43	8.43	8.43	8.43	8.43
Alkalinity	mgCaCO3/L	74.35	74.35	74.35	74.35	74.35	74.35	74.35
pH	s.u.	6.51	6.51	6.51	6.51	6.51	6.51	6.51

Table E.2 Partial Qual2kw headwater inputs for post-dredged scenario calibration

Headwater Flow	0.014	m3/s						
Prescribed downstream boundary?	No							
Headwater Water Quality	*Units*	*12:00 AM*	*2:00 AM*	*4:00 AM*	*6:00 AM*	*8:00 AM*	*10:00 AM*	*12:00 PM*
Temperature	C	10.36	9.68	9.08	8.54	8.93	9.70	10.36
Conductivity	umhos	152.	154.	153.	147.	147.	147.	146.
Inorganic Solids	mgD/L	105.	105.	105.	105.	105.	105.	105.
Dissolved Oxygen	mg/L	4.88	5.07	5.15	5.30	5.24	5.20	5.83
CBODslow	mgO2/L	0.98	0.98	0.98	0.98	0.98	0.98	0.98
CBODfast	mgO2/L	0.48	0.48	0.48	0.48	0.48	0.48	0.48
Organic Nitrogen	ugN/L	230.	230.	230.	230.	230.	230.	230.
NH4-Nitrogen	ugN/L	150.	150.	150.	150.	150.	150.	150.
NO3-Nitrogen	ugN/L	10.	10.	10.	10.	10.	10.	10.
Organic Phosphorus	ugP/L	1100	1100	1100	1100	1100	1100	1100
Inorganic Phosphorus (SRP)	ugP/L	1100	1100	1100	1100	1100	1100	1100
Phytoplankton	ugA/L	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Detritus (POM)	mgD/L	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Pathogen	cfu/100 mL	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Generic constituent	user defined	2.65	2.65	2.65	2.65	2.65	2.65	2.65
Alkalinity	mgCaCO3 /L	74.35	74.35	74.35	74.35	74.35	74.35	74.35
pH	s.u.	6.96	6.92	6.90	6.92	6.93	6.93	6.90