

WETLANDS AND COPPER CONCENTRATIONS ACROSS A HEADWATER
CATCHMENT IMPACTED BY ACID ROCK DRAINAGE

by

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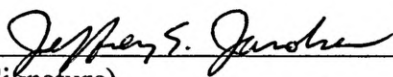
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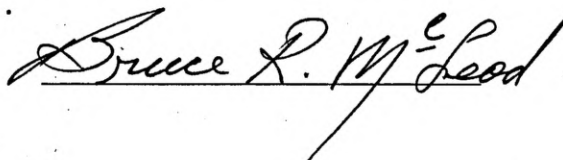
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ABSTRACT

Water quality improvement is a primary goal in degraded watersheds, such as those affected by historic mining activities. Natural wetlands have been shown to improve water quality from areas affected by acid mine / acid rock drainage. Failures have also occurred, and more research is needed to fully understand water quality improvements associated with wetland systems.

The overall goal of this research was to assess wetland water quality improvement by characterizing copper concentrations and related physical and chemical factors in riparian wetlands impacted by acid rock or acid mine drainage in Upper Fisher Creek of the New World Mining District, near Cooke City, Montana. Wetland soils within a 2.5 mile (4.0 km) reach were surveyed and sampled to describe general trends of pH, EC, and exchangeable copper concentrations. Total copper analyses by sequential extraction were performed on five wetland types to evaluate relative potential mobility of copper. Associations between exchangeable copper concentrations and landscape position and wetland characteristics were evaluated to provide clues to controls of copper.

Riparian wetlands in Upper Fisher Creek apparently have improved water quality by sequestering copper. Roughly half (46%) of the total copper measured was held in the relatively immobile organic matter + sulfides + residuals fraction. One to 4% was held in the relatively mobile exchangeable fraction.

Landscape factors such as lateral slope position and incoming water source (chemistry and geology) and wetland characteristics such as wetland type and water regime exhibited the greatest differences of exchangeable copper among categories. The highest median exchangeable copper concentrations were found in the streambank (1-, 5- and 10-ft.) slope position, one herbaceous fen saprist pothole, and in the semipermanently flooded sites. Exchangeable copper concentrations were higher in the right bank samples (surface and groundwaters from Fisher and Henderson Mountains) than the left bank (surface and groundwaters from Scotch Bonnet and Sheep Mountain) samples. Collectively, these findings indicate that landscape factors appear to be as important in controlling copper concentrations in these slope wetlands as saturated conditions or soil type.

INTRODUCTION

Natural wetlands perform a variety of functions within a given drainage basin. These functions can be broadly categorized as habitat, hydrologic and water quality (Novitski et al. 1996). Wetland areas have been shown to improve water quality and protect ground and surface water quality in a variety of natural and constructed settings, and for a variety of pollutants (Kadlec and Kadlec 1978, Gambrell 1994, Keller et al. 1998). Wetland or riparian areas have been used as streamside buffer zones to filter sediment and pollutants (Gilliam and Skaggs 1988, Castelle et al. 1994, Hill 1996), and constructed wetland treatment systems have been developed to treat a variety of industrial and agricultural wastes (Kadlec and Knight 1995), including acid mine drainage (Brodie 1990, Perry and Kleinmann 1991, Brodie et al. 1996).

Maintaining or improving water quality within a drainage basin is of utmost importance to land managers. Water quality improvement is a primary goal in degraded watersheds, such as those affected by historic mining activities, acid mine drainage, excessive grazing, logging, recreation and road building (Johnston and Brown 1979). Mining districts with near-surface, highly sulfidic ore also produce natural acid rock drainage, primarily through natural weathering and oxidation processes (Furniss et al. 1999).

Interest in the use of wetlands to treat acid mine/rock drainage, in both active and abandoned mine areas, has risen among mining industry and government agency land managers. Degradation of rivers and streams by acid mine drainage is a persistent problem in the United States. According to a 1990 survey, over 6450 kilometers (4000

miles) of rivers and streams in the United States are adversely affected by acid mine drainage (Kleinmann 1990). Fortunately, natural wetlands have been shown to improve water quality (to varying degrees) from areas affected by acid mine drainage (Emerick 1988, Eger and Lapakko 1988, Dollhopf et al. 1988, Sobolewski 1997 and 1999). However, failures have also occurred, and more research is needed to fully understand mechanisms and controls of wetland systems and associated water quality improvements.

Natural Wetlands and Water Quality

Wetland and riparian areas can filter sediments and contaminants from the landscape (Gilliam and Skaggs 1988, Gambrell 1994, Daniels and Gilliam 1996). Wetlands can trap, precipitate, transform, recycle and export many waterborne contaminants (Mitsch and Gosselink 1993). Because of their unique chemical and physical properties, wetlands can be both sinks and sources for contaminants. Wetlands can mobilize or immobilize various elements or compounds, depending upon the pH, redox state, hydrology, substrate, microbiology, vegetation and chemical forms present. Understanding these controls aid in the understanding how and if a wetland is improving water quality by influencing the relative amounts of constituents held in immobile versus mobile soil fractions. Knowing if and where wetlands serve as sinks or as sources is important for evaluating the role these wetlands play in water quality, and also can aid in reclamation or restoration design.

Hydrology plays a key role in wetland water quality functions (Carter et al. 1978, Novitski 1978, Kadlec 1988). Hydrologic processes control the persistence, size and

function of wetlands in the watershed (Carter 1996). Water is the primary medium of material transfer into and out of wetlands (Johnston 1994). The relative amounts and quality water entering and leaving a wetland by different pathways and the residence time of water (i.e. the water budget or balance) are very important in determining effluent water quality. However, identifying and quantifying all possible inputs, outputs and storages and their seasonal variation makes it very difficult to construct hydrologic and chemical budgets.

Wetland effects on water quantity and quality are related to their physical settings and are controlled by the following factors (Carter 1996):

- Landscape position, including elevation in the drainage basin relative to other wetlands, lakes and streams
- Topographic positions (depressions, flood plains, slopes)
- Presence or absence of vegetation
- Type of vegetation
- Type of soil
- Relative amounts of water flowing in and water flowing out of the wetland (water sources and water budgets)
- Local climate
- Hydrogeologic framework
- Geochemistry of surface and ground water

Water quality in wetlands is primarily a result of geologic setting, water balance, quality of inflowing water, type of soils and vegetation, and human activity within or near the wetland. For example, wetlands dominated by surface-water inflow and outflow reflect the chemistry of the associated stream or river. In contrast, wetlands that receive water primarily from precipitation and groundwater and lose water to surface water outflows and or seepage to groundwater discharge have water chemistries similar to the

groundwater. In most cases, wetlands receive water from more than one source, so the resultant water chemistry is a composite of the various sources.

Wetland functional assessment methodologies are currently being developed to help land managers evaluate what roles wetlands play in the landscape, and how these roles may be altered through proposed impacts (Brinson 1993, Novitski et al. 1994, Adamus et al. 1987). Evaluating wetland water quality function is necessary for two primary reasons. First, to understand watershed water quality relationships as a whole, one must understand the functions of its parts. Second, functional assessments are used in regulatory settings where land managers must evaluate how proposed impacts to wetlands could affect downgradient surface and groundwater quality. Clean Water Act Section 404 permits for projects involving substantial wetland modification typically cannot be issued unless a wetland functions and values assessment has been performed. The identification of important variables that predict function typically comes from laboratory and field experiments or case studies such as this.

Research Goals and Objectives

The overall goal of this research was to characterize copper concentrations and related physical and chemical factors in riparian wetlands impacted by acid rock or acid mine drainage in upper Fisher Creek of the New World Mining District. Copper was chosen because it is the most toxic element in the minespoils, waters and sediments in the New World District (Amacher 1998). To identify spatial patterns of copper and related parameters, I grouped landscape position and wetland characteristics into categories and

quantified relative copper concentrations in each. These associations between copper concentrations and landscape and wetland characteristics provide clues about the relationship between these riparian wetlands and water quality, and may aid land managers in reclamation efforts.

Mobility of copper through the riparian wetlands is also a concern. This study evaluated the relative amounts of mobile and immobile copper fractions found within five dominant wetland types. Understanding copper partitioning and the related physical and chemical properties associated with each, land managers can evaluate potential mobility changes accordingly.

The specific research objectives were:

1. Sample wetland soils to identify general trends of pH, specific electrical conductance and exchangeable copper concentrations across the riparian wetlands.
2. Qualitatively assess the relative importance of surface and groundwater inputs to wetlands by surveying the riparian wetlands and assessing site topography, water table gradients and flow directions.
3. Evaluate landscape position factors and wetland characteristics associated with copper and related water quality improvements in these wetlands.
4. Sample soils in five wetland types and analyze total copper by sequential extraction to determine relative amounts of mobile and immobile fractions.

Findings will assist scientists in understanding landscape position and wetland characteristics that influence wetland/water quality relationships in a headwater catchment impacted by acid mine or acid rock drainage. This study will also assist land managers to focus or direct reclamation efforts accordingly. The development of predictors (or indices) of wetland water quality function in slope wetlands is currently

underway for the Rocky Mountain West. This study may serve as a case study for the development of appropriate variables to assess wetland water quality functions.

NEW WORLD MINING DISTRICT

The New World Mining District (District) near Cooke City, Montana is a historic mining district (Figure 1). Deposits of gold, silver, lead, copper and zinc were explored and subsequently mined sporadically between approximately 1860 and 1953 (URS 1998, Maxim 1999). The District contains headwater drainages impacted by acid rock and acid mine drainage. Relatively large, diverse and persistent riparian wetland communities border these affected streams (WESTECH 1993, USDI 1997)(Figure 2). This site is currently being reclaimed under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). The United States Forest Service administers the clean-up effort. Water quality improvement is one of the primary goals of the reclamation effort (Maxim 1999).

The District is a mountainous, high elevation setting (7,900 to 10,400 ft [2408 to 3170 m] above sea level) with over 35 different wetland plant communities bordering streams in all drainages (CBMI 1990, WESTECH 1993, NRC 1994, USDA 1996, Brown et al. 1996, URS 1998). Three headwater drainages originate here, Miller Creek (tributary to Soda Butte Creek), Fisher Creek (tributary to the Clark's Fork of the Yellowstone River), and Daisy Creek (Tributary to the Stillwater River). All of these eventually flow into the Yellowstone River.

Fisher and Daisy Creeks in particular have been severely degraded by both natural acid rock drainage and acid mine drainage (CBMI 1992, WESTECH 1992, Furniss 1996). Chemical analysis of ferricrete deposits provides evidence that natural, metal-rich acid rock drainage has been occurring in this mineralized region for thousands of years as

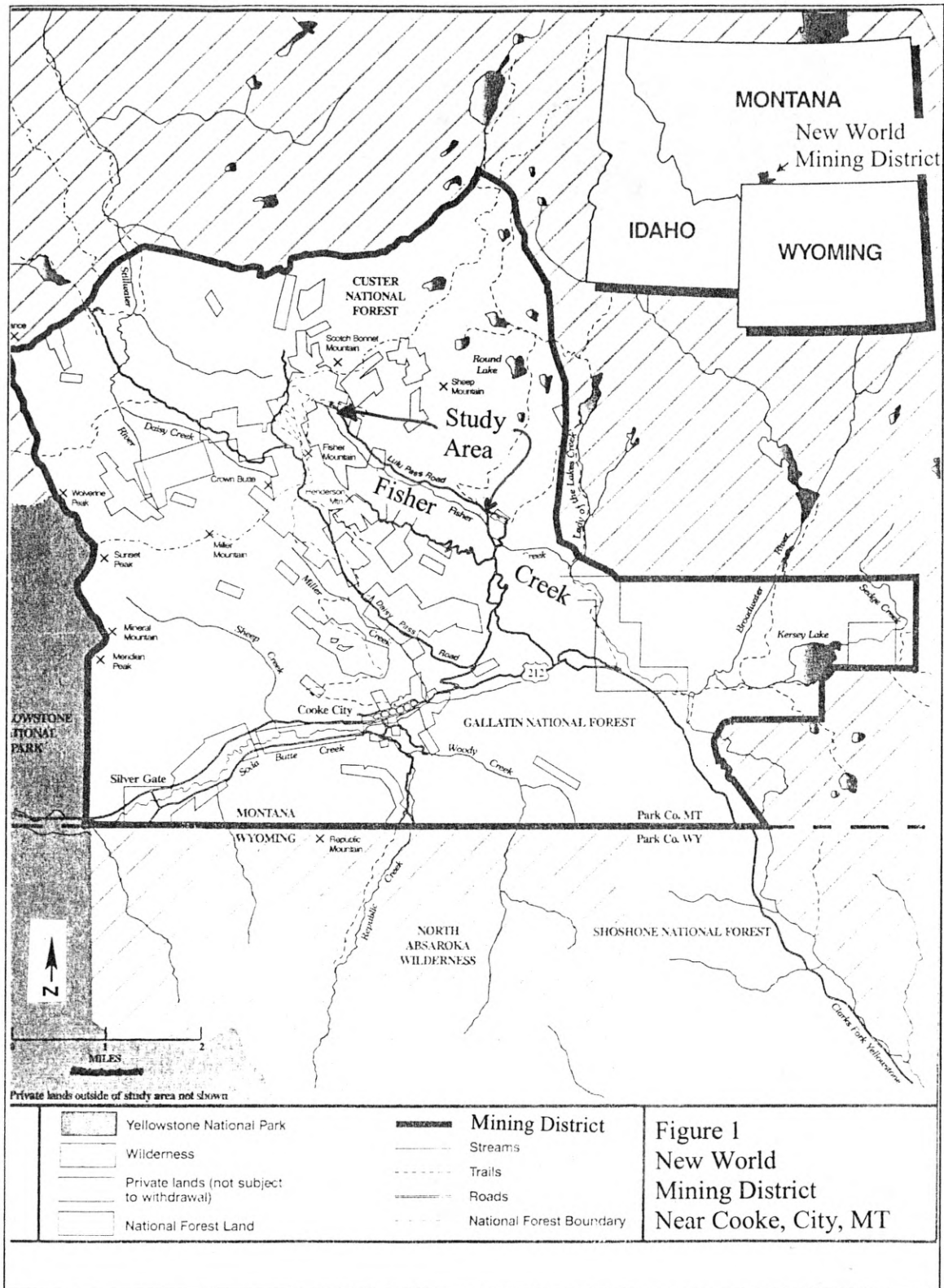


Figure 1. New World Mining District location map.

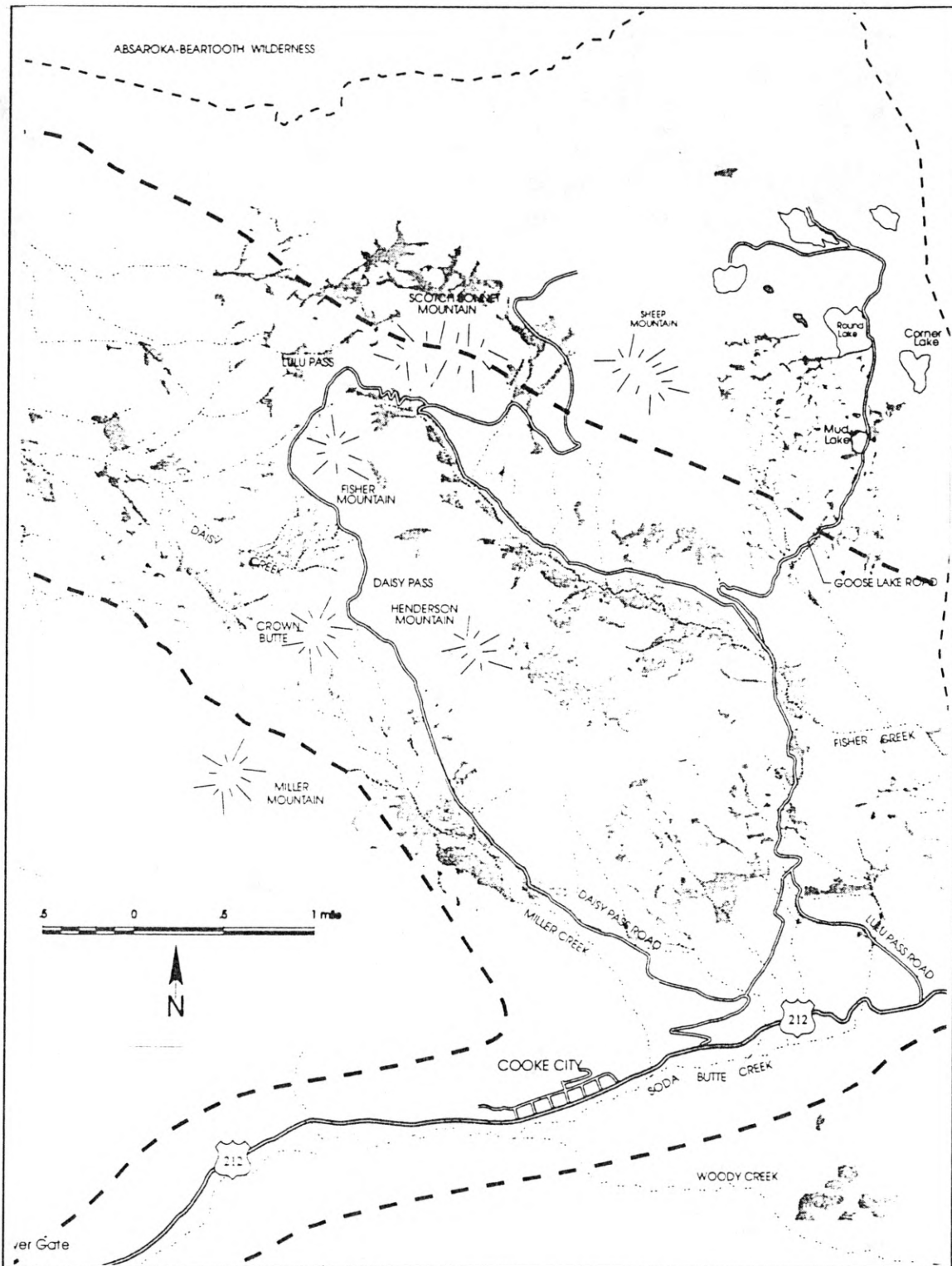


Figure 2. Wetlands and Waters of the United States in the New World Mine District, near Cooke City, Montana.

a result of weathering and oxidation of exposed or near-surface massive sulfide ore deposits (Furniss 1996). The riparian wetlands bordering these streams have co-existed and evolved with relatively high levels of metals and pyritic acid materials.

In more recent geologic history, man's historic mining activities have released a significant amount of metals and associated acid mine drainage into Fisher and Daisy Creeks (CBMI 1992, URS 1998). Fisher and Daisy Creeks exhibit relatively low pH and high metals near the headwaters that gradually improve downstream. Water quality in Fisher and Daisy Creeks do not meet applicable water quality standards for a variety of constituents (Maxim 1999).

New World Mining District Response and Restoration Project

The site is currently regulated under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). CERCLA regulation is due to the human health and environmental issues related to elevated levels of heavy metals present in mine waste piles, open pits, acidic water discharging from mine openings, and stream sediments.

The United States Forest Service (USFS) directs and administers the clean-up effort with considerable assistance from the Environmental Protection Agency and the United States Geological Survey. The initial stages of clean up began in 1998, as documented in the Overall Project Work Plan, New World Response and Restoration Project (Maxim 1999).

Water quality is one of the two primary objectives of the New World Mining District Response and Restoration Project. The primary goals of the New World response and restoration project are:

1. *"To assure the achievement of the highest and best water quality practicably attainable on District Property, considering the natural geology, hydrology and background conditions in the District (Agreement, Appendix C, ¶ 6).*
2. *To mitigate environmental impacts that are a result of historic mining, ...taking into consideration the desirability of preserving the existing undeveloped character of the District and the surrounding area (Decree, Part II, ¶ F)" (Maxim 1999).*

Fisher Creek

The study area included the riparian areas along the uppermost 2.5 miles (4.0 km) of Fisher Creek (Figure 1). Fisher Creek originates below Lulu Pass, as two headwater tributaries on either side of Glengarry Adit that converge below the adit and the Glengarry waste rock pile. Fisher Creek flows southeasterly, and eventually joins the Clark's Fork of the Yellowstone River. Stream widths in the study reach range from <1 ft. (0.3 m) in the upper tributaries to 30 ft. (9.1 m) at the lower end. Hydrographs available for a station within this study reach (SW-4) show that Fisher Creek flows are very low for 8 months of the year and peak in May and June (USDA 1996). Average stream discharge for this segment ranges from approximately 3.3 cfs low flow to 24.9 cfs high flow based on available information contained in the preliminary draft environmental impact study (USDA 1996).

Two metal loading studies were performed on Fisher Creek by Kimball et al. (1999) and Amacher (1998). These studies indicate that about 75% of the Fisher Creek

metal load is from sources such as tributaries, adits and waste rock areas, and that a significant portion (25 to 33%) of the metal load is from groundwater non-point sources. Loads from Glengarry Adit are more significant in baseflow periods when the contribution is roughly 30%. Site reclamation is primarily focused on reducing or eliminating point source toxicants.

Amacher (1998) also found that in the upper, acidic reaches of Fisher Creek most of the total copper in the water column is in the $<0.4 \mu\text{m}$ fraction ("dissolved" + "colloidal"). In the lower reaches where the pH increases above 5, the highest concentrations of copper are in the particulate fraction. This particulate copper is sorbed to the iron oxide fraction of the streambed sediments when the pH is greater than 5. This iron oxide fraction may exist as discrete particles that settled out of the water column in pools and edgewater areas or as coatings on sand and gravel grains. Copper associated with the streambed sediments is introduced to adjacent wetlands by overbank flooding.

Riparian wetlands are fed primarily by groundwater, which may be metal laden, and in some areas by overbank flooding from Fisher Creek. The 25 - 33% non-point source metal load to Fisher Creek flows over and through these riparian wetlands, giving these wetlands the opportunity to improve water quality.

Research in the District reveals complex geologic structure with extensive faulting, heterogeneous mineralogy, and zones of localized groundwater flow (USDA 1996). Consequently, metal loadings to individual wetlands may be highly variable.

The wetland inventory performed by WESTECH grouped the wetlands into 4 types — herbaceous, shrub, forested and fen (CMBI 1992, WESTECH 1993). The dominant herbaceous vegetation consists primarily of various species of *Carex*,

Calamagrostis, *Caltha*, and *Danthonia*. The dominant shrubs include a few species of *Salix*. Approximately 75% of the riparian wetland area within this study reach are willow wetlands. The dominant trees include species of *Abies* and *Picea*. Relatively small dead patches of vegetation are found near the headwater area just below Glengarry Adit and sporadically throughout the study reach.

The fens identified are very small patches, 0.1 to 3.0 acres (0.04 to 1.2 ha) in size, and are found primarily in the lower reaches of the study area. The usage of the term fen is problematic because there has not been one standardized approach to classifying peatlands (Bridgham et al. 1996). For this investigation, a fen, in its most simple definition, is a type of peatland that receives significant inputs of water and dissolved solids from a mineral source, such as runoff from mineral soil or ground water discharge (Chadde et al. 1998).

There has not been a formal identification of mosses in Fisher Creek Drainage (J. Elliot, Ecological Consultant, pers. comm., 2000). However, Kastning-Culp et al. (1992) sampled mosses and other vegetation in Daisy Creek (Figure 1). Her findings revealed a variety of moss species present, and that two species of mosses, *Pohlia annotina* and *Pohlia wahlenbergii*, accumulated significant amounts of copper.

The riparian wetland zone and Fisher Creek drainageway are very steep and narrow in the upper reaches of this study area. In the lower reach they are relatively wide — characteristic of typical U-shaped glacial valleys. The riparian wetlands range in width from <10 ft. (3.1 m) at the headwaters to approximately 800 ft. (244 m) at the widest point. Steep slopes, climbing ultimately to mountainous peaks and narrow ridges lie upgradient of the riparian wetlands.

Amacher (1998) investigated metals in 11 wetland soils along Fisher Creek, and found that there is considerable spatial variability in the chemical form and amount of metals and sulfur in these wetland soils. Results from his investigation indicate that wetlands are both contributors to the metal load as well as a sink for metals and sulfur. Amacher recommended a more intensive sampling and analysis program to adequately define the spatial variability in terms of those wetlands that contain high metals concentrations and those that do not.

METHODS

Cross-Section Surveys of the Riparian Wetlands

Six transects across the riparian wetlands were selected that represented varied landscape positions and wetland characteristics (Figure 3). Transects were established perpendicular to Fisher Creek. Transect 1, the most upstream transect, was located just below the waste rock disturbance below Glengarry Adit. The most downstream transect, #6, was located approximately 2 miles (3.2 km) downstream from Transect 1. The others were spaced between these two, approximately 2,000 to 3,000 feet (610 to 914 m) apart. Transects were surveyed in late September 1999 using a Sokia auto-level package for elevation and stadia for distance.

Wetland Soil Sampling

Soil samples were collected along each transect. The stream's edge was considered 0-ft. The first soil pit was on the streambank at 1-ft. distance away from Fisher Creek. Successive pits were dug at 5-ft., 10-ft., 50-ft., 100-ft., and 250-ft. (1.5-, 3.1-, 15.2-, 30.1-, and 76.2-m) away from Fisher Creek, on both sides of the creek. Soil samples were from riparian wetlands, except for two upland soil pits on transect 6 (one each side) and one on transect 1. Transect lengths varied due to the width of riparian wetlands on each transect (Table 2). Typically, the 1-ft., 5-ft., 10-ft., and 50-ft.

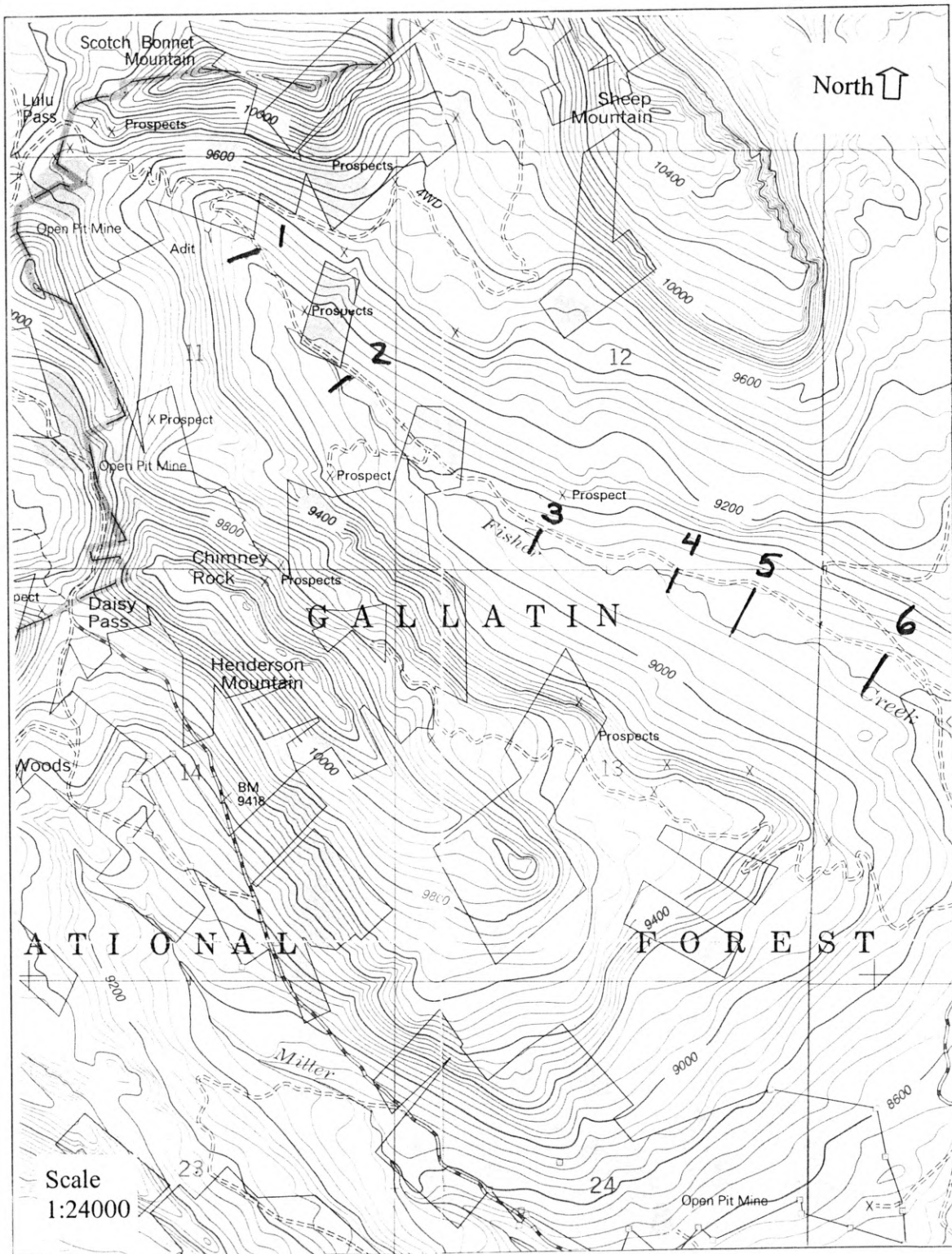


Figure 3. Cross-section and soil sampling transect locations across the riparian wetlands of Upper Fisher Creek, New World Mining District.

(0.31-, 1.5-, 3.1-, 15.2-m) samples were collected on most transects. Transect 6 had the most soil pits at 13, while Transect 2 had only 4 (Table 1).

Samples were collected from depths of 0 to 6 in. (0 to 15 cm) and 6 to 12 in. (15 to 30.5 cm) in September and October 1999. A total of 102 soil samples were collected from 51 pits. Vegetation type, soil type and depth of saturation were noted for each soil pit.

Table 1. Lengths, vertical relief, wetland surface slopes and number of soil pits for each transect sampled.

Transect ¹	Length (ft.)	Vertical Relief (ft.)	Percent Surface slopes of Wetlands	No. of Soil Pits
Transect 1 (upstream)	325	95	near vertical to 5 %	9
Transect 2	400	141	10.5 to 7 %	4
Transect 3	350	95	5.5 to 4 %	6
Transect 4	425	25	4 to 1.5 %	10
Transect 5	700	130	10 to 1 %	9
Transect 6 (downstream)	700	40	1.5 %	13
Total:				51

¹ See also cross-section drawings, Appendix A1 through A6.

Laboratory Analysis of Wetland Soil Samples

Laboratory analyses of saturated paste pH and solution extract specific electrical conductance (Rhoades 1992) were performed on all 102 soil samples. Exchangeable copper (Amacher 1999) was analyzed for only the surface 0 to 6 in. (0 to 15 cm) sample.

Table 2 lists the methods used to analyze wetland soils.

Table 2. Methods used to analyze the wetland soil samples.

Parameter	Method	Reference
pH	Saturated paste	Rhoades 1982
EC	Solution extract	Rhoades 1982
Exchangeable metals	1 M NH_4CL	Amacher 1999
Noncrystalline iron oxides and associated metals	0.2 M NH_4 oxalate + 0.2 M oxalic acid in dark	Amacher 1999
Total free iron oxides and associated metals	0.2 M NH_4 oxalate + 0.2 M oxalic acid + 0.1 M ascorbic acid	Amacher 1999
Metals bound to organic matter + metal sulfides + residual metals	conc. HNO_3 + conc. HCl + 30 % H_2O_2	Amacher 1999

Total copper concentrations of the surface 0 to 6 in. (0 to 15 cm) were determined by sequential extraction for five samples representing different wetland types. These wetland types represent the dominant wetland types present, as well as different soil and water regime characteristics (Table 3).

Samples for total copper analysis were air dried at room temperature and sieved through a 2-mm stainless steel sieve. The <2-mm size fraction for each sample was analyzed sequentially by the methods listed in Table 2. The resultant digests were analyzed using inductively-coupled plasma emission spectrophotometry.

Sequential extraction is useful for assessing the relative mobility of copper associated with different soil fractions. The fractions or species of copper analyzed were (1) exchangeable copper, (2) copper associated with manganese oxides, (3) copper

Table 3. Summary of wetland characteristics for samples used for total copper analyses by sequential extraction.

Wetland Type	Dominant Vegetation	Soil Type	Water Regime ¹	Landscape Position	Perpendicular Distance from Fisher Creek	Bank	Trans. No.	pH (su)	Dominant Water Inputs ²
Herbaceous fen saprist pothole	<i>Carex spp.</i>	Organic Saprist	Saturated year round	Midslope	100 ft.	Right	4	5.1	GW+ Seasonal Overbank flooding
Willow	<i>Salix spp.</i>	Mineral Sand/Gravel	varies - mostly semi-perm. flooded	Midslope	50 ft.	Left	6	4.2	GW + Seasonal Overland flow
Seep/spring	<i>Carex spp.</i>	Organic Saprist	Saturated year round	Midslope	50 ft.	Left	2	4.4	GW + Seasonal Overland flow
Herbaceous fen Saprist	<i>Carex spp.</i>	Organic Saprist	Saturated year round	Upperslope	250 ft.	Left	5	3.9	GW + Seasonal Overland flow
Herbaceous fen Fibrist	<i>Carex spp.</i>	Organic Fibrist	Saturated year round	Upperslope	300 ft.	Right	3	4.1	GW + Seasonal Overland flow

¹ The Cowardin water regime is used (Cowardin et al. 1979)

² Dominant water inputs: GW = groundwater

associated with noncrystalline iron oxides, (4) copper associated with crystalline iron oxides and (5) copper associated with organic matter, sulfides and residuals.

Exchangeable copper is the most weakly held, and is relatively more mobile and available to downgradient environments. The 1 M NH_4Cl extractant removes exchangeable metals from soil minerals and organic matter. The amount extracted depends on the amount of metal bound to the permanent charge sites on clay minerals and the pH of the soil (Amacher 1998).

Copper associated with the manganese and iron oxide fractions is intermediate in relative mobility – less mobile than exchangeable but more mobile than copper associated with the organic matter + sulfides + residual fraction. Copper sorbed to manganese and iron oxides is very pH dependent – the lower the pH, the less sorption and vice versa.

Copper bound to organic matter and sulfides is relatively immobile. This fraction accounts for the ability of a wetland to act as a “sink”. The concentrated HNO_3 + concentrated HCl (aqua regia) + 30% H_2O_2 extractant digests organic matter and dissolves metal sulfides. Also, residual phases (e.g., silicates) may be extracted with this strong digestion reagent, although amounts are expected to be minor (Amacher 1998).

Copper bound to the organic matter + sulfides + residuals fractions is very redox dependent. Oxidation of this reduced fraction will cause an increase in copper mobility. Oxidation of this fraction could also cause an increase in acidity if pyrite (FeS_2) is present in this reduced fraction.

Landscape Position and Wetland Factor Descriptions

The association between copper concentrations and various landscape position and wetland factors was evaluated to provide information on possible controls of copper distribution and mobility in this system.

Landscape Position Factors

Four factors related to location or position in the landscape were evaluated. These were: (1) lateral slope position, (2) left bank versus right bank, (3) distance from Fisher Creek and (4) transect or longitudinal position.

Lateral slope position refers to the wetland's position along the slope perpendicular to Fisher Creek, from streambanks to upland sites. General categories represent differences in potential hydrologic interaction between Fisher Creek and upslope surface overland flow or groundwater sources. The upland position was non-wetland. The upperslope wetlands were typically herbaceous fens, 250-ft. (76.2 m) away from Fisher Creek. The midslope wetlands were usually 50- to 100-ft. (15.2- to 30.5-m) away from Fisher Creek, and included all wetland types. Streambank samples included the 1-, 5- and 10-ft. (0.3-, 1.5- and 3.1-m) samples, and also were any type of wetland.

Effects of the differences in the quality of incoming water chemistry, influenced highly by geology, can be evaluated indirectly by comparing left bank samples to right bank samples. Fisher and Henderson Mountains are located on the right bank side, while Scotch Bonnet and Sheep Mountains are on the left bank side (Figure 2). Most of the ore deposits and mining disturbances are on Fisher and Henderson Mountains.

Distance from Fisher Creek is similar to lateral slope position, but with actual distances instead of general distance groupings. Several distinct distances to Fisher Creek were sampled on all six transects, on both sides of the stream. These distances were 1-, 5-, 10-, 50-, 100-, and 250-ft. (0.3-, 1.5-, 3.1-, 15.2-, 30.5-, 76.2-m). These samples were located in wetland areas. An upland sample was taken on both sides of the lowest transect (#6), and on the left bank of the highest transect (#1). The upland samples provided a non-wetland comparison.

Transect locations represent the distance from a primary point source, Glengarry Adit, and how it is related to copper concentrations. The use of 6 transects and several lateral distances provided good spatial coverage of the 2.5 mile (4.0 km) study reach.

Wetland Characteristics

Relations between five wetland characteristics and copper concentrations were evaluated. These wetland characteristics were: (1) wetland type I, which included different fen types, (2) water regime, using the Cowardin et al. (1979) classification system, (3) wetland type II, using a simplified grouping which included primarily fens versus willows, (4) soil type, and (5) pH.

It is likely that different wetland types will attenuate copper differently (Amacher 1998 and Sobolewski 1997). Wetland types were identified primarily by dominant vegetation, soil and water regime characteristics. The first set of wetland types evaluated all unique wetland types, including different fen types. These wetland types were: (a) herbaceous fen saprist pothole, (b) herbaceous wet meadow, (c) willow, (d) seep/spring, (e) herbaceous fen saprist, (f) herbaceous fen fibrist, and (g) upland. The second wetland

grouping was similar to the first, except that all fens were grouped into one category. These wetland types were: (a) herbaceous wet meadow, (b) fen, (c) willow, and (d) upland.

The Cowardin nontidal water regime classification system (Cowardin et al. 1979) was used to group wetlands of similar hydrologic regime. The possible classes included: (1) permanently flooded, (2) intermittently exposed, (3) semipermanently flooded, (4) seasonally flooded, (5) saturated, (6) temporarily flooded, (7) intermittently flooded, and (8) artificially flooded.

The remaining two factors were soil type and pH. Soil types were grouped into either organic or mineral soils. Soil saturated paste pH was taken at each soil sample location, and grouped into ranges centering around 4 and 5.

Since the lower transects (4, 5 and 6) were likely to have more overbank flooding, the above characteristics were also evaluated for those transects separately.

Statistical Analysis

Exchangeable copper results were analyzed using nonparametric Kruskal-Wallis (Gibbons 1976) procedures to evaluate associations between copper concentrations and landscape position and wetland characteristic factors. Median exchangeable copper values for each factor level are presented in descending order to describe variation in relative copper concentrations between levels.

Nonparametric Kruskal-Wallis tests were used to determine significance of differences among categories because (1) sample sizes varied widely among categories,

(2) medians represent central tendency better than means because of the high number of values below detection (28% in this dataset) and the presence of outliers, (3) non-normal distributions, and (4) heterogeneity of variances among groups. A specific significance level was not chosen due to the observational study design. However, p-values are reported and ordered to show the relative strength of association between copper and different factors.

To be conservative, values below detection were replaced with the detection limit value of 1 mg/kg for data analysis. In this study, exchangeable copper values ranged from below detection (<1mg/kg) to 95 mg/kg, with 28% of the values below detection. Four standard approaches for estimating statistical parameters are commonly used when below-detection values are present: (1) replace the detection limit value for below detection values, (2) replace with zero, (3) replace with one-half the detection limit, or (4) ignore all below detection values (Gilbert 1987). Trace level analysis in this study is not needed and therefore, zero values or one-half the detection level values are not meaningful. It is not reasonable to ignore 28 percent of the dataset because the values are below detection. Values near the method detection level are unreliable (Taylor 1987) making <1 mg/kg essentially indistinguishable from 1 mg/kg. Therefore, to be conservative and represent the higher possible parameter value, below detection limit values were replaced with the detection limit value of 1 mg/kg.

RESULTS AND DISCUSSION

Cross-Section Surveys of the Riparian Wetlands

Cross-section surveys and topographic maps indicate that Upper Fisher Creek is a gaining reach throughout the 2.5 mile (4.0 km) study reach (Figure 4 and Appendix A1-A6). The flow direction for water sources is over and through the riparian wetlands and into Fisher Creek. The surface slopes of the riparian wetlands range from near vertical banks to 10.5 percent slopes in the upper transects and from 4 to 1 percent slopes in the lower transects. Susceptibility to frequent and extensive overbank flooding from Fisher Creek is greater on the lower transects (4, 5 and 6) where the adjacent topography flattens.

Topography and resultant limited surface water inputs indicate that groundwater is the dominant year-round water source feeding these wetlands and Fisher Creek, with a strong surface water runoff and precipitation input during spring (USDA 1996, Kimball et al. 1999). Groundwater depths for this one-time sampling event in September and October varied by location throughout the study reach. The pothole samples had approximately 2 ft. (61 cm) of standing water and the seep/spring and herbaceous fen saprist samples were saturated to the ground surface. Groundwater depths varied for the willow wetlands, but the majority of sites were semipermanently flooded and groundwater depths ranged from 8 to 14 inches (20 to 36 cm) below ground surface. The groundwater depths in the temporarily flooded herbaceous wet meadow were greater than 18 inches (46 cm).

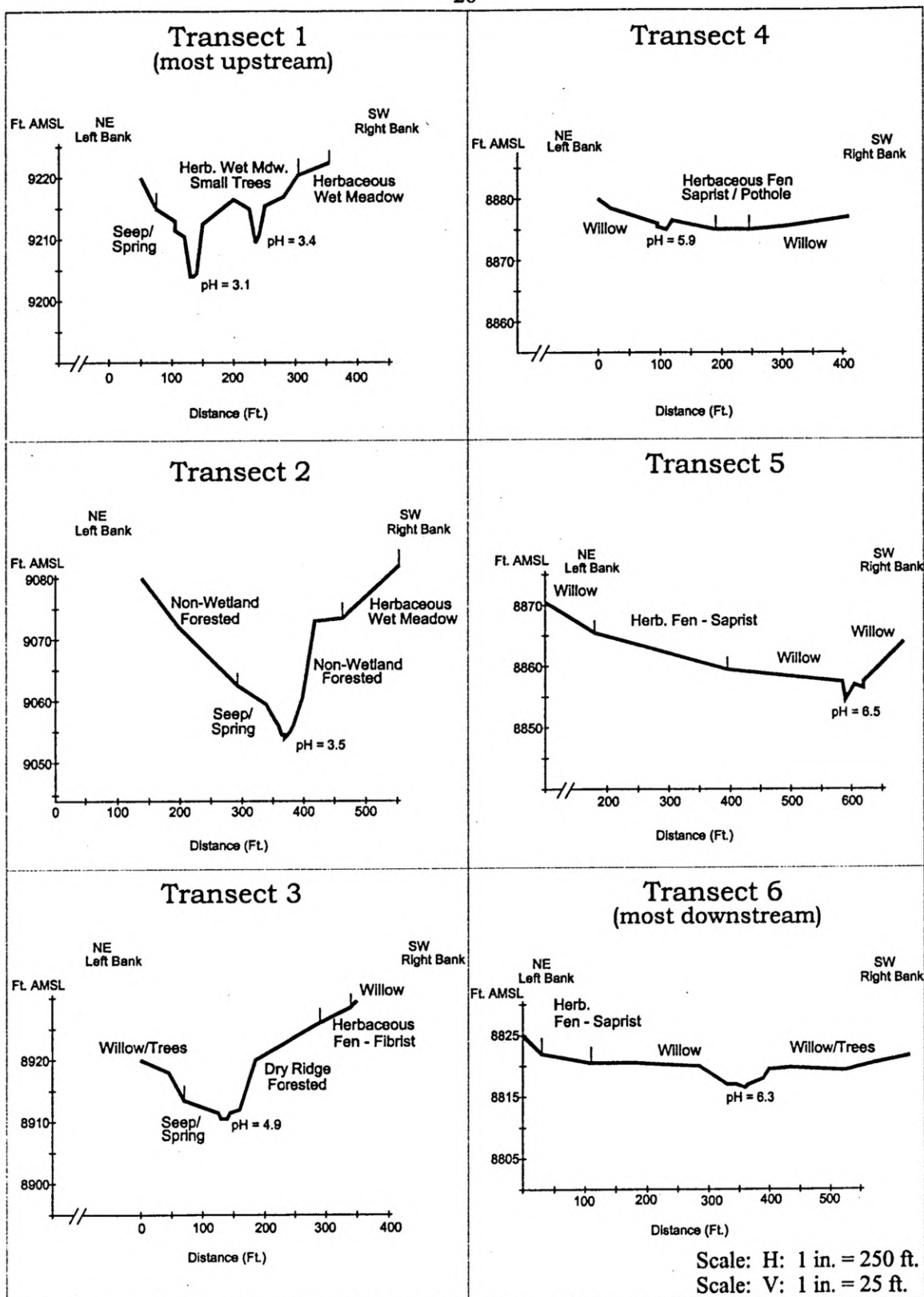


Figure 4. Cross-section topography and wetland types of Upper Fisher Creek. Vertical lines denote a vegetation change. pH values are for Fisher Creek. Double slanted line on x-axis indicates a shift in horizontal scale.

Groundwater depth for the herbaceous fen fibrist was 10 inches (25.4 cm) below ground surface.

Based on cross-sectional surveys and evaluation of water flow, these riparian wetlands are classified as “slope” wetlands using the Hydrogeomorphic Approach to Assessing Wetland Function (Brinson 1993) and as “palustrine emergent or scrub-shrub” using Cowardin et al. (1979).

Wetland Soil pH, EC and Exchangeable Copper

Upper Fisher Creek wetland soils are moderately acidic to acidic and have highly variable EC and exchangeable copper concentrations (Table 4) with some values high enough to be a concern for contamination. Appendix C tabulates summary statistics by transect.

Table 4. Summary statistics for pH, EC, and exchangeable copper concentrations.

Summary Statistics	pH (su)	EC (uS/cm)	Exch. Cu (mg/kg)
Mean	4.4	80	19
Standard Dev.	± 0.5	± 39	± 24
Median	4.3	70	6
Range	2.9 to 5.5	12 to 266	<1 to 95
N =	102	102	51

Data for EC and exchangeable copper were not normally distributed, but skewed to the left (Figure 5). The skewed exchangeable copper data distribution was due to the

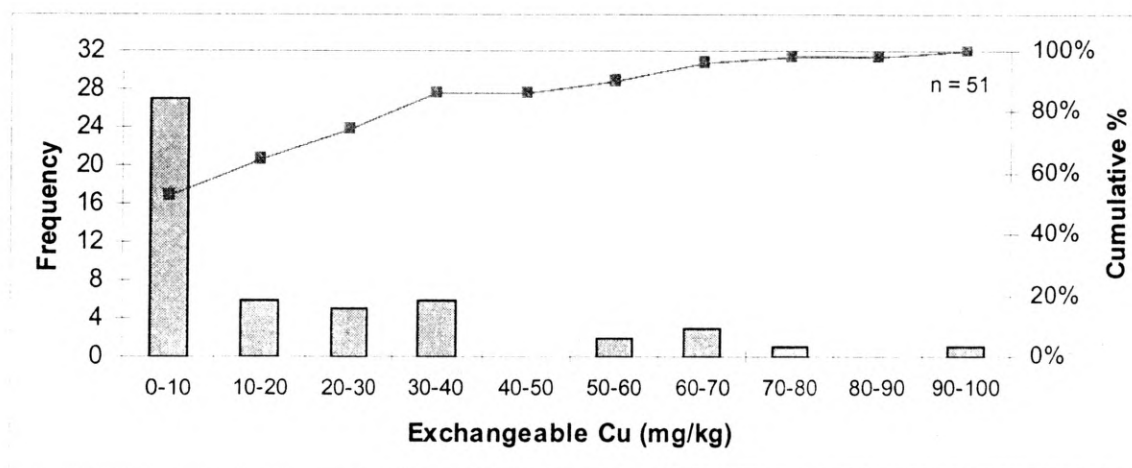
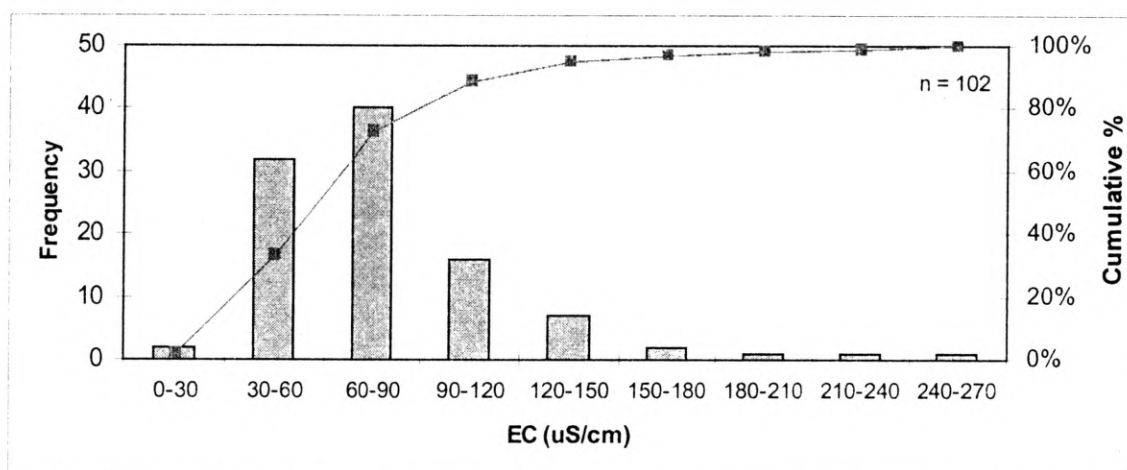
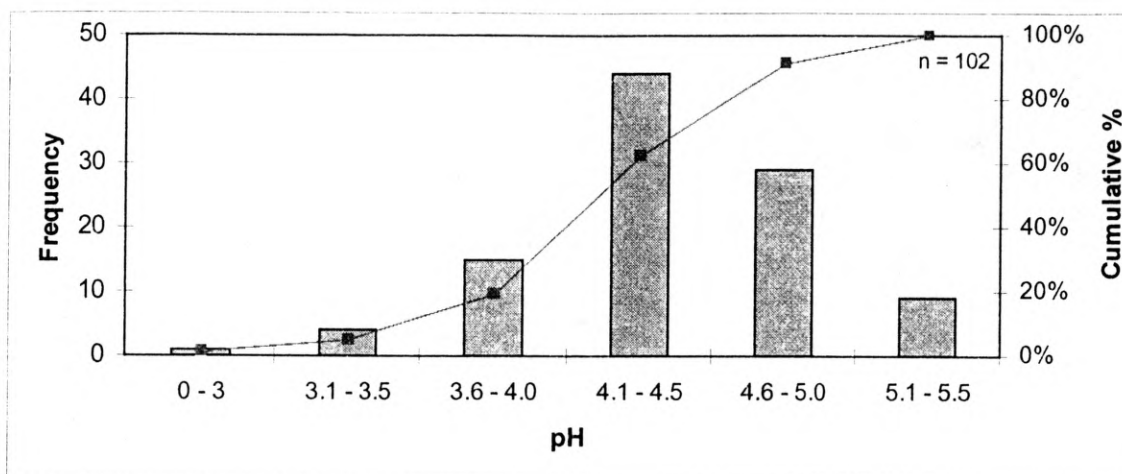


Figure 5. Histograms of wetland soil pH, EC and exchangeable copper.

fact that 28 percent of the values were below detection and most values were < 10 mg/kg. For this reason, median values and ranges are presented, as well as means (Table 4). Ninety-one percent of the EC values were less than $120 \mu\text{S}/\text{cm}$ and 86% of exchangeable copper values were less than 40 mg/kg. Detailed cross-sections are found in Appendix A1 through A6 and include pH, EC and exchangeable Cu results, as well as wetland types, topography, gradients and groundwater observations. Detailed graphs of pH, EC and exchangeable copper are found in Appendix B1 through B6.

Upper Fisher Creek wetland soils are moderately acidic to acidic with pH values from 2.9 to 5.5 (mean = 4.4, median = 4.3, Table 4). The lowest pH values are found on transect 1 (mean = 3.8) and the highest are found on transect 4 (mean = 4.9)(Appendix C). Acid soils in this study reach are the result of erosion of parent materials with relatively high amounts of quartz, feldspar and iron- and magnesium-rich minerals and low calcareous substrates. Acidic conditions typically mobilize copper. Generally, as pH decreases, the solubility of copper oxides, hydroxides, and sulfides increases (Stumm and Morgan 1996), mobilizing copper. In addition, the adsorption of copper to oxides and hydroxides and sulfides increases with increasing pH (Stumm and Morgan 1996 and Amacher 1998). Wetland soil pH is typically 1 unit below the pH of Fisher Creek for all transects (Appendix A1 through A6).

Specific electrical conductance values ranged from $12 \mu\text{S}/\text{cm}$ to $266 \mu\text{S}/\text{cm}$ (Table 4). The lowest EC samples are found on transect 1 ($12 \mu\text{S}/\text{cm}$) and the lowest transect average is transect 6 ($65 \mu\text{S}/\text{cm}$)(Appendix C). The highest EC value is found on transect 5 ($266 \mu\text{S}/\text{cm}$ for the 1-ft. 6 to 12 inch sample) and the highest transect averages are transects 3 and 4 ($93 \mu\text{S}/\text{cm}$). There were not significant pH or EC differences

between the two depth samples. However, the greatest differences between the two depth samples were in the streambank samples (1-, 5- and 10-ft.).

Exchangeable copper values ranged from <1 mg/kg to 95 mg/kg (Table 4). Transect 4 had the highest average exchangeable copper, with most of that attributed to the herbaceous fen saprist pothole samples on the right bank (28 mg/kg) (Appendix C). The highest exchangeable copper concentration (95 mg/kg) was found on transect 1 between the two tributaries of Fisher Creek (Appendix A1). Very low exchangeable copper concentrations were found on either side of this particular sample, which could be a remnant from a copper-laden sediment deposit off of the waste rock pile. Transect 5 also had a relatively high exchangeable copper concentration of 78 mg/kg at the 5-ft. right bank streambank sample (Appendix A5). Some of these sporadic high concentrations did not fall into any discernible pattern, but they can indicate areas for potential further evaluation.

Similar pH, EC and exchangeable copper trends were found across the riparian wetlands. Generally, pH, EC and exchangeable copper values tended to increase towards Fisher Creek, with the highest concentrations on either side of the stream found in the streambank zone (1- to 10-ft.samples) (Figure 6). This pattern of increased pH, EC and exchangeable copper may suggest the zone of overbank flooding to be to be approximately 10 feet away from Fisher Creek (Appendix B1 through B6). Elevated pH, EC and copper levels in the streambanks may reflect the slope topography towards Fisher Creek, but also likely indicate additional inputs of acidity, salts, and copper from Fisher Creek overtopping its banks. Also, in general, EC and exchangeable copper values were higher in the right bank samples than the left bank samples.

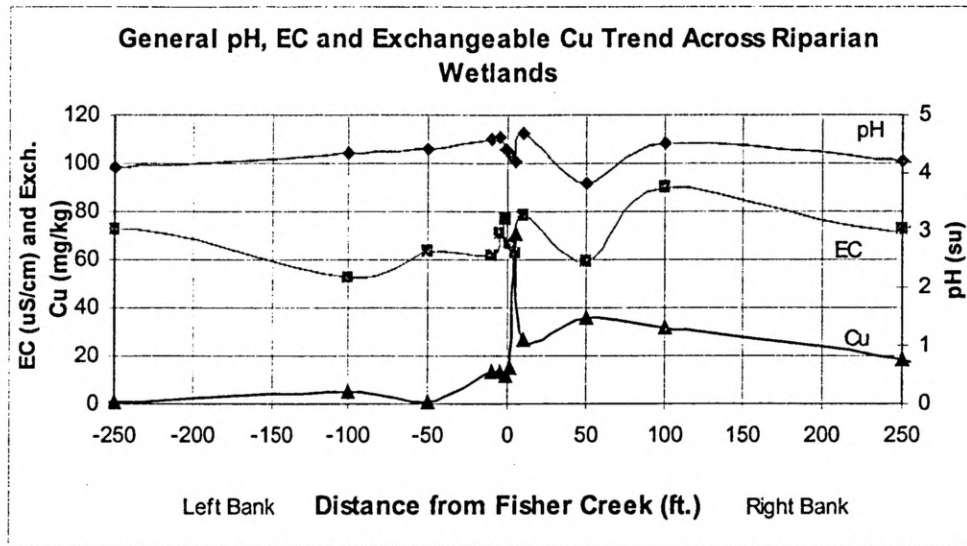


Figure 6. General pH, EC and exchangeable copper trends across the riparian wetlands. The plotted values are the averaged median concentrations for all samples at a given distance from Fisher Creek. Certain locations (primarily the >100-ft.) have relatively few data points and are strongly influenced by potential outliers or below detection results. See Appendix B1-B6 for more detailed trends by transect.

In addition to general trends across the riparian wetlands, other generalizations can be made based upon median copper values. Transects 1, 2 and 3 have different wetlands types and hydrology than transects 4, 5 and 6. Because transects 1, 2 and 3 are steeper, there is more overland surface water flow, dominant during spring runoff, and less saturation. Consequently, drier, herbaceous wet meadows are found on these transects, well above the stream elevation and further away. High (i.e. above the median) exchangeable copper concentrations are found in herbaceous wet meadows. On transects 4-6, high values are from various wetland types, with willow sites being most numerous, but are at elevations and (usually) distances closer to the stream than on transects 1-3. In general, the seep/spring samples had low exchangeable copper, except for those found on the left bank of transect 3. However, these samples are also included in the streambank

category; higher copper concentrations in the streambanks is discussed in more detail below. Some of these generalizations are expanded upon as results of the analysis discussed in the following sections.

Landscape Position and Wetland Factors Associated with Copper

The strongest differences of exchangeable copper concentrations were found among categories of lateral slope position, wetland type, and water regime ($p = 0.031$, 0.032 , and 0.05 respectively)(Table 5). The highest median copper concentrations were found in the streambanks, in the herbaceous fen saprist pothole wetland type, and in the semipermanently flooded sites. Characteristics such as transect location, pH, and soil type had the weakest differences of copper concentrations between levels ($p = 0.72$, 0.93 and 0.16 respectively).

Copper concentrations in the right bank samples were higher than the left bank samples and copper concentrations in mineral soils were higher than the organic soils ($p = 0.09$ and 0.16 , respectively)(Table 5). A summary of all characteristics considered with resultant p-values, median copper concentrations, and number of samples is listed in Table 5.

Landscape Position Factors

Watershed-scale characteristics such as landscape position, water regime and incoming water chemistry and geology accounted for the highest differences in copper concentrations (Table 5 and Figure 7). Streambanks had higher median

Table 5. Variation in exchangeable copper associated with landscape and wetland factors.

Factor	P-value	Category	Exch.Cu (mg/kg)	No. of Samples
<i>A. Location or Position in the Landscape Factors</i>			<u>Median</u>	
1. Lateral Slope Position	0.031 *	Streambanks (1-10-ft.)	15	27
		Mid-Slope (50 & 100-ft.)	3.5	16
		Upper-Slope (250-ft.)	1	5
		Upland	1	3
2. Left Bank vs. Right Bank (In-coming water chemistry and geology)	0.094	Right bank	22.5	29
		Left bank	4	22
3. Distance from Fisher Creek	0.098 *	5-ft.	21.5	6
		10-ft.	14	8
		1-ft.	12	13
		100-ft.	4	7
		50-ft.	3.5	10
		250-ft.	1	4
4. Transect No. (longitudinal gradient and distance from adit point source)	0.716 *	350-ft.	1	3
		Transect 4	27	10
		Transect 3	12.5	6
		Transect 5	12	9
		Transect 6	5	13
		Transect 1	4	9
<i>B. Wetland Characteristics</i>	0.032 *	Transect 2	1.5	4
		Herb. fen sap. pothole	49	2
		Herb. wet meadow	21	6
		Willow	15	26
		Seep/spring	4	11
		Herb. fen saprist	1	2
		Herb. fen fibrist	1	1
		Upland	1	3
6. Water Regime (Cowardin)	0.052	Semi-perm. flooded	26	10
		Seasonally flooded	15	13
		Temporarily flooded	2	13
		Saturated (year round)	2	15
7. Wetland Type II (fens vs. willows primarily)	0.069 *	Herb. wet meadow	21	6
		Willow	15	26
		Fen	3	16
		Upland	1	3
8. Soil Type	0.164	Mineral	12	37
		Organic	3	14
9. pH	0.931	4.5 to 5.3 (~5)	12	20
		3.2 to 4.4 (~4)	5	31

* Note: One or more categories had fewer than 3 samples.

exchangeable copper concentrations (15 mg/kg) than the midslope, upperslope, and upland positions (3.5, 1 and 1 mg/kg). Similarly, the 5-ft. location had the highest median copper concentration (21.5 mg/kg) and the 250-ft. and upland positions had the lowest (both 1 mg/kg).

Exchangeable copper concentrations from right bank samples, representative of water originating from Henderson and Fisher Mountain, were higher ($p = 0.09$) than left bank samples, representing copper concentrations originating from Scotch Bonnet and Sheep Mountains (22.5 mg/kg versus 4 mg/kg). Distance from the adit point source was not correlated with copper concentrations, and median copper concentrations did not differ strongly among transects.

Because more areas on transects 4, 5 and 6 have the potential to receive overbank flooding inputs from Fisher Creek in addition to groundwater inputs, analysis was performed on these transects separately to evaluate the importance of floodplain riparian wetland zones, and the width of that zone in attenuating metals. The results indicate that the streambank zone (0- to 10-ft.) had higher concentrations of copper than the other positions (Table 6, Figure 8). The other factors were less significant, with p -values > 0.2 .

Focusing again on sites most susceptible to flooding from Fisher Creek, the right and left bank samples were compared separately for streambank, willow wetland samples, which were all from transects 4-6. This narrower analysis removed the confounding effects of different wetland types and slope positions but sacrificed sample size ($n = 17$). Median exchangeable copper concentrations tended to be higher in right bank streambank willow samples than left streambank willow samples (40 versus 22

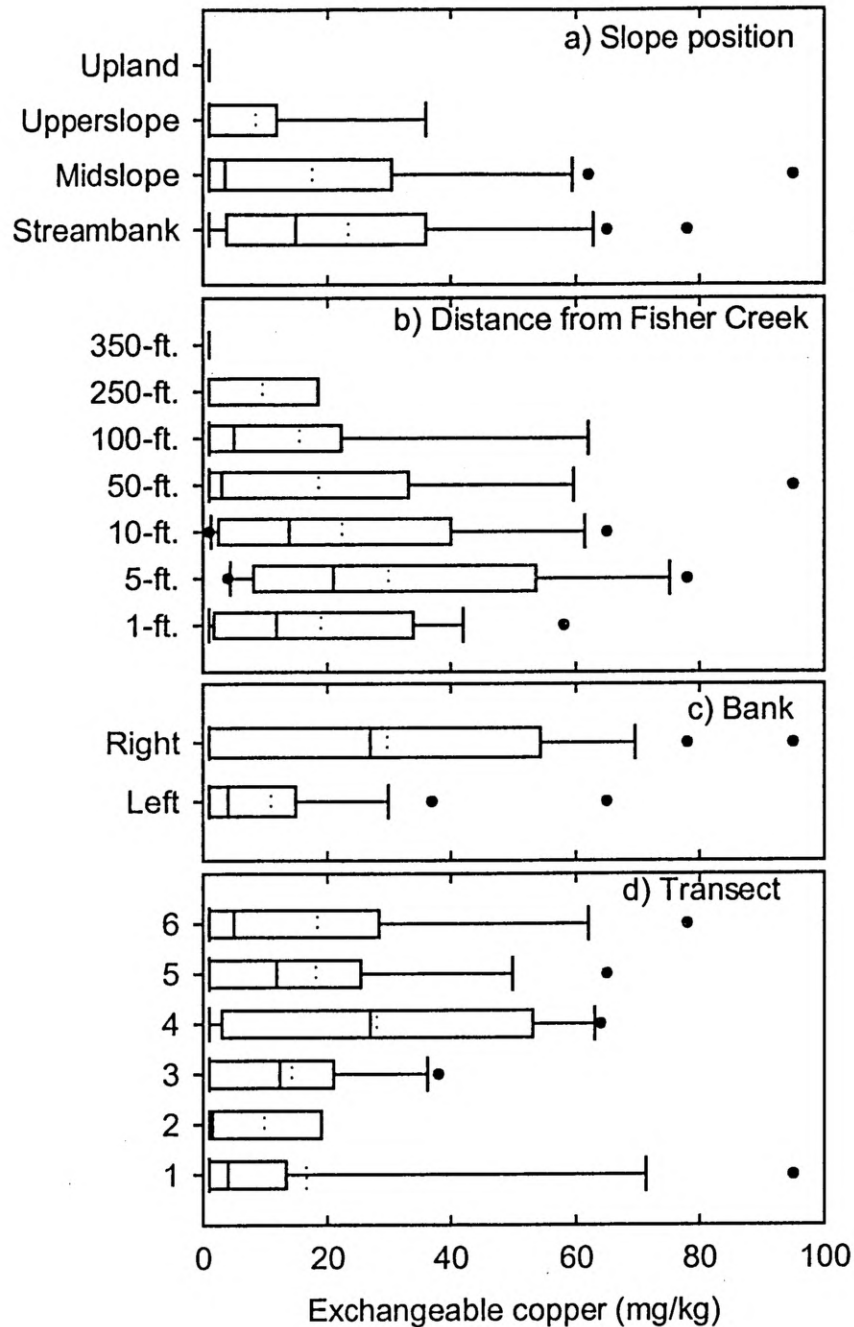


Figure 7. Exchangeable copper concentrations by landscape position factors. The solid line in the box represents the median, the dotted line represents the mean. Boxes represent the 25th and 75th percentiles. Bars represent the 10th and 90th percentiles. Dots represent values outside the 10th and 90th percentiles.

Table 6. Variation in exchangeable copper associated with landscape and wetland factors, transects 4, 5 and 6 only.

Factor	P-value	Factor Level	Exch.Cu (mg/kg)	No. of Samples
<i>A. Location or Position in the Landscape Characteristics</i>			<u>Median</u>	
Lower Transects (4 – 6)	0.051	Streambanks (1-10-ft.)	27	17
Lateral Slope Position		Mid-Slope (50 & 100-ft.)	3	11
		Upper-Slope (250-ft.)	1	2
		Upland	1	2

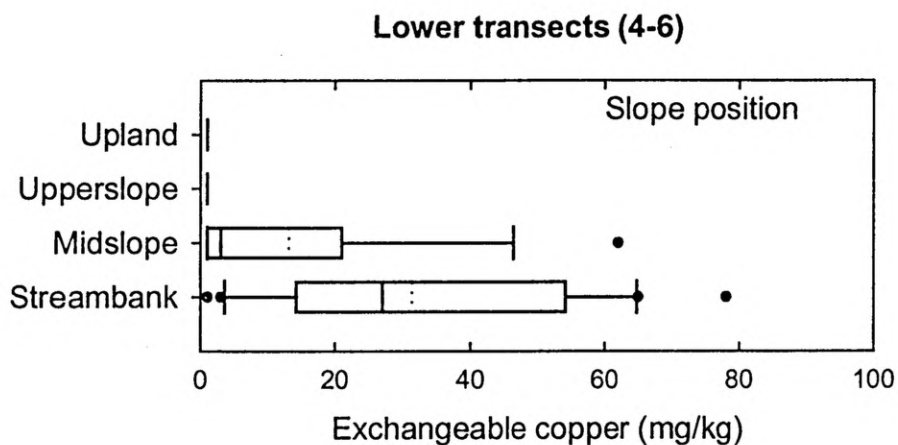


Figure 8. Exchangeable copper concentrations by slope position for transects 4, 5 and 6. The solid line in the box represents the median, the dotted line represents the mean. Boxes represent the 25th and 75th percentiles. Bars represent the 10th and 90th percentiles. Dots represent values outside the 10th and 90th percentiles.

mg/kg, $p = 0.24$), suggesting that differences in water source geochemistry are important to copper accumulation even in the area most likely to be affected by water and sediment from Fisher Creek.

Wetland Characteristics

Different wetland types and wetland water regimes exhibited significant differences in copper concentrations ($p=0.03$ and 0.05)(Table 5 and Figure 10). The herbaceous fen saprist pothole had the highest median exchangeable copper concentrations at 49 mg/kg and the herbaceous fen saprist, herbaceous fen fibrist and upland sites had the lowest at 1 mg/kg. However, only two samples were taken from the herbaceous fen saprist pothole. The herbaceous wet meadow and willow wetlands were intermediate at 21 and 15 mg/kg respectively. However, when all fen types were grouped together, analysis indicated that the wet meadow and willow wetland types, which are typically drier, had the highest exchangeable copper at 21 and 15 mg/kg. The largest number of samples with high exchangeable copper concentrations were from the willow sites.

Semipermanently flooded sites had the highest median exchangeable copper concentrations at 26 mg/kg, and saturated sites had the lowest at 2 mg/kg. “Semipermanently flooded” means that surface water persists throughout the growing season in most years, and when surface water is absent, the water table is usually at or very near the land surface (Cowardin et al. 1979). “Seasonally flooded” means that surface water is present for extended periods especially early in the growing season, but is absent by the end of the season in most years. “Temporarily flooded” means that surface water is present for brief periods during the growing season, but the water table usually lies well below the soil surface for most of the season. Plants that grow both in uplands and wetlands are characteristic of the temporarily flooded regime.

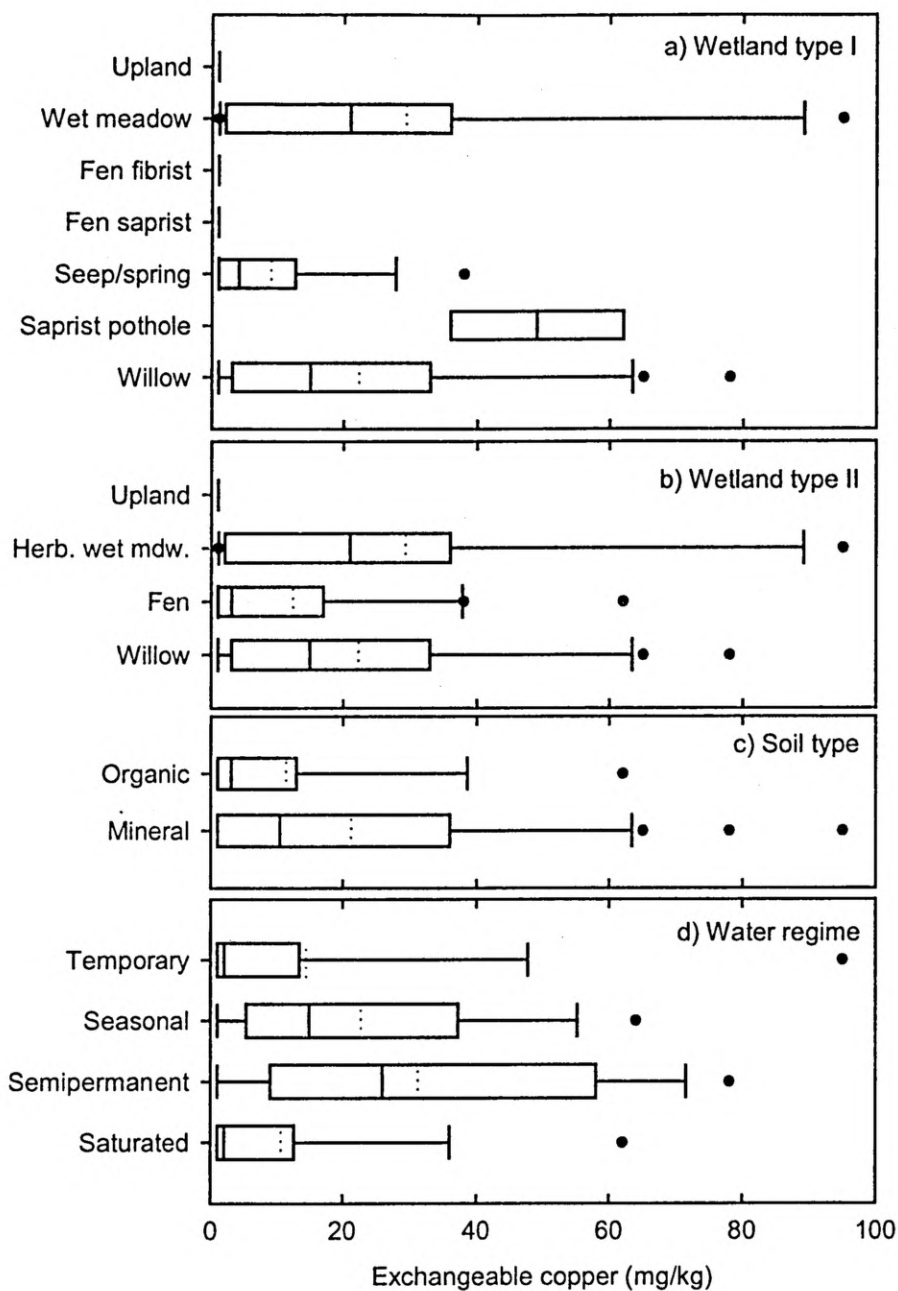


Figure 9. Exchangeable copper concentrations by wetland characteristics. The solid line in the box represents the median, the dotted line represents the mean. Boxes represent the 25th and 75th percentiles. Bars represent the 10th and 90th percentiles. Dots represent values outside the 10th and 90th percentiles.

Mineral soil samples had higher median exchangeable copper than the organic soils (12 mg/kg versus 3 mg/kg); however this difference was not strong ($p = 0.16$). This result is somewhat unconventional in that saturated organic soils typically have a higher capacity (i.e. cation exchange capacity) to attenuate metals than drier, mineral soils (Mitsch and Gosselink 1993).

Collectively, these results indicate that wetland properties conventionally used to evaluate water quality function do not seem to apply well in this particular study area, or potentially for slope wetlands in general. Conventionally, wetland properties used to evaluate a wetland's functional capacity to attenuate metals are (1) soil organic matter content, (2) soil sorptive properties or high cation exchange capacities, and (3) degree of saturation or frequency of surface or sub-surface flooding (Brinson 1993). Typically, wetlands with organic soils, saturated conditions and healthy microbes can attenuate more metals than drier, mineral soils. In contrast, this study demonstrates that landscape-scale factors such as incoming water chemistry and landscape position appeared to influence copper concentrations more than soil organic matter, soil development or degree of saturation. Collectively, the right bank samples had higher copper concentrations than the left bank samples and similarly, the right bank willow streambank samples had higher concentrations than the left bank willow streambank samples. The wet meadow and willow wetlands, which were drier, had higher copper than the fens, which were wetter. The semi-permanently flooded sites had higher copper concentrations than those saturated year round. The mineral soils had higher copper concentrations than the organic soils. These results suggest that care needs to be taken when applying functional assessment methodologies to a particular project area, and that

characterizing site hydrology and water chemistry is an important first step in water quality functional assessments. Further research on hydrogeology and geochemistry of source areas is needed to better understand the movement and accumulation of copper in the landscape and the factors that control it.

All of the evaluations above involved the exchangeable copper fraction only. It could be misinterpreted that high exchangeable values indicate low copper attenuation and less importance for improving water quality. However, as presented in the total copper and sequential analyses results, higher exchangeable copper also means proportionately higher copper attenuated in the immobile fractions. Therefore, high exchangeable copper values indicate relatively more copper attenuation and potential for water quality improvement.

Wetland Soils Total Copper and Mobile Versus Immobile Fractions

Total copper concentrations ranged from <1 mg/kg to 1407 mg/kg in the five wetlands sampled (Figure 10 and Table 7). The herbaceous fen saprist pothole on the right bank of transect 4 had the highest total copper concentration at 1407 mg/kg. The willow sample had the next highest total copper at 240 mg/kg. The remaining three wetland type samples had relatively low amounts of total copper, ranging from 27 to 79 mg/kg.

How do these values compare to copper levels found in the mine waste or natural background levels? Typical total copper concentrations of soils range from 2 to 100 mg/kg, with an average of 20 to 30 mg/kg (Alloway 1995). Preliminary results from a

Total Copper and Mobile versus Immobile Fractions of Wetland Soils

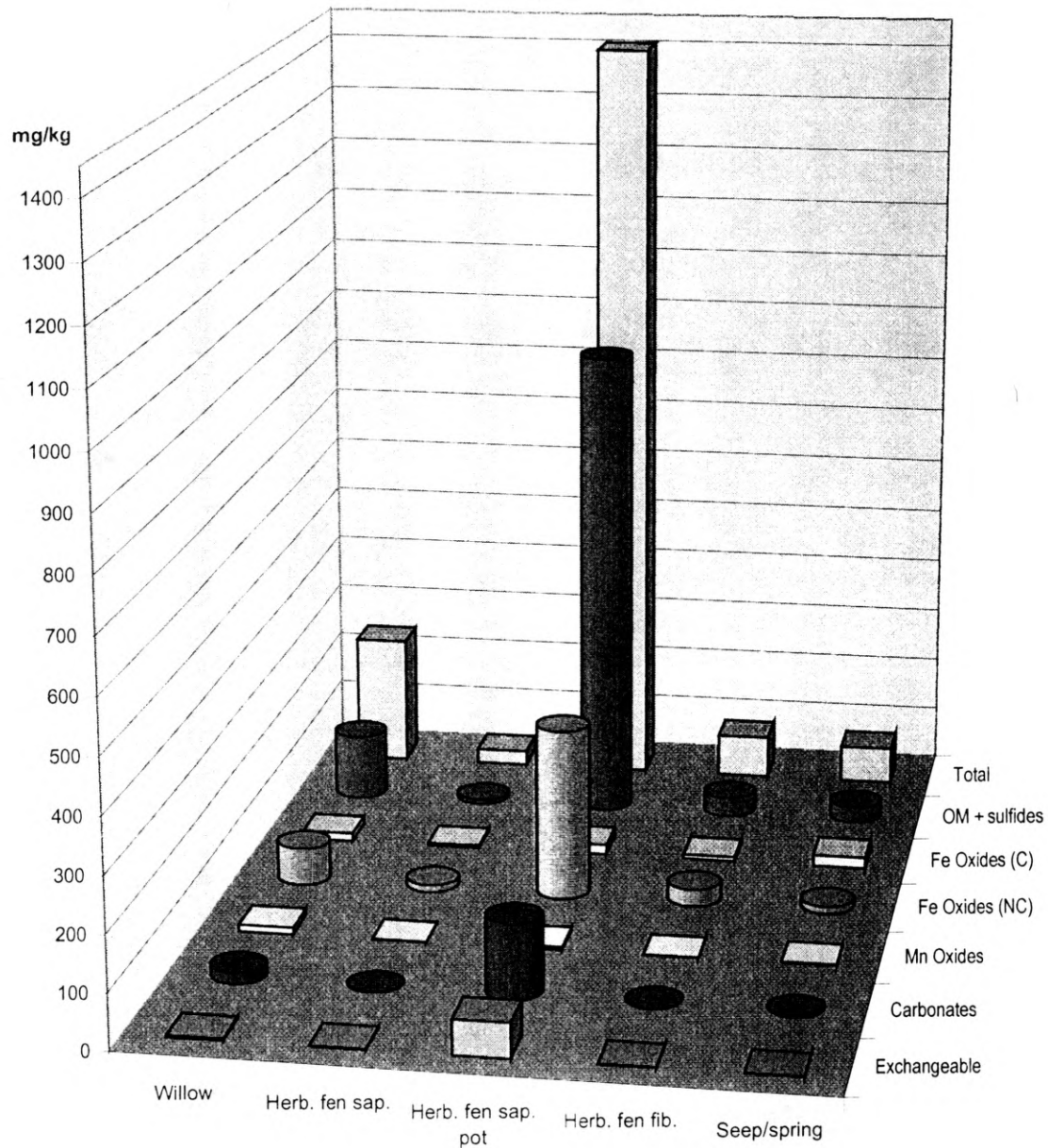


Figure 10. Total copper and mobile versus immobile fractions of wetland soils. Wetland types include willow, herbaceous fen saprist, herbaceous fen saprist pothole, herbaceous fen fibrist and seep/spring. Fractionation abbreviations are: NC = noncrystalline, C = crystalline and OM = organic matter.

Table 7. Total copper concentrations and copper associated with various soil fractions by wetland type.

Wetland type	Exchangeable		Carbonates		Mn Oxides		Noncrystalline		Crystalline		Organic Matter		Total EPA Method 3050 ⁴
	Extraction NH ₄ CL	ug/g	Extraction 1M NH ₄ OAc	ug/g	Extraction 1M NH ₂ OH-HCL	ug/g	Iron Oxides Extraction ¹	ug/g	Iron Oxides Extraction ²	ug/g	plus Sulfides plus residual ³	ug/g	
	(% of total)		(% of total)		(% of total)		(% of total)		(% of total)		(% of total)		
Willow	3	1%	20.1	8%	12.3	5%	68.2	28%	15	6%	121	51%	240
Herb. fen saprist	1	4%	0.5	2%	0.5	2%	12.9	48%	4	15%	8	30%	27
Herb. fen sap. pothole	62	4%	136	10%	4.9	0%	312	22%	18	1%	874	62%	1407
Herb. fen fibrist	1	1%	2.1	3%	0.5	1%	31.2	40%	8	10%	36	46%	79
Seep/spring	1	1%	1.6	2%	2	3%	13.2	19%	20	29%	30	44%	68
Mean		2%		5%		2%		32%		12%		46%	

Bold values indicate $\geq 10\%$.

1) - 0.2 M Ammonium oxalate + 0.2 M oxalic acid

2) - 0.3 M Ammonium oxalate + 0.3 M oxalic acid

3) - Total metals extraction was performed on the sample portion that had

been subjected to the previous extractions and includes only

the residual, non-extractable metals (i.e. metals bound to the organic matter, sulfides plus residual).

4) - The total of all extractions added together.

District-wide mine waste metal sampling indicate that total copper in mine wastes range from 11 to 17600 mg/kg (Maxim 2000), with an average of 963 mg/kg. The total copper found in the herbaceous fen saprist pothole was well above this average, while the other four sites were well below. Data from sites un-affected by mining indicate natural background levels to be between 11 and 56 mg/kg, with an average of 63 mg/kg (Maxim 2000). The herbaceous fen saprist pothole and the willow wetland were well above natural background levels, whereas the other three wetland types were close to that range.

The forms in which copper is bound in the soil is of interest when evaluating wetland sink or source functions and associated effects on water quality. Is copper freely moving through these systems or is it held in relatively immobile forms? Also, when evaluating potential impacts to specific wetlands, it's useful to know the quantity of metals that would be re-mobilized if the organic matter + sulfide fraction was disturbed (i.e. oxidized).

Copper is bound in varying degrees by different soil fractions. The sequential extraction relatively quantified copper in the loosely bound (relatively mobile) soil fraction to the most tightly bound (relatively immobile) soil fraction. Results indicated that all of these wetlands are likely both sinks and contributors of copper to varying degrees, with the immobile (sink) copper being a much larger percentage than the mobile copper. Most of the copper in these five selected samples is found in the relatively immobile organic matter + sulfides + residual fraction (Figure 10 and Table 7). In the sites with the highest total copper, the herbaceous fen saprist pothole sample and the willow wetland, 62 and 51 percent of the total copper, respectively, was found in the organic matter + sulfides + residual fraction. In the other samples, this fraction

accounted for between 30 and 46 percent of the total. Copper associated with the intermediate mobility, noncrystalline iron oxides comprised the next highest percentage of the total (19 to 48 percent), followed by crystalline iron oxides (1 to 29 percent). The relatively mobile exchangeable copper fraction, discussed in previous section, was only 1 to 4 percent of the total.

Even though the relatively mobile exchangeable copper fraction is a much lower percentage than the other soil fractions, its importance as a potential copper source to downgradient environments should not be overlooked. The term “source” is used to reflect copper that is moving through the wetland — not necessarily the copper the wetland produced through chemical transformations. The amount of copper that is moving through the wetland system (i.e. dissolved and exchangeable) from upgradient sources is dependent upon the water balance for the particular wetland as well as copper transformations. Water balance investigations were not included in this study, but it is likely that the water balances vary greatly between specific wetlands. If the hydrology results in large copper inputs, both continually or seasonally, this mobile or source copper fraction could pose a concern for downgradient environments. It is also possible that exchange sites are saturated, prohibiting adsorption. Site specific water balance and copper budget investigations would be required to more adequately assess the water quality effects from this relatively mobile or source copper fraction and the proportion of copper retained by wetlands. Adsorption isotherm experiments and geochemical studies would also be needed to evaluate adsorption capacity, saturation, and mechanisms of copper retention.

Current functional assessment methodologies do not account for the fact that wetlands can be contributors to the metal load as well as sinks. Granted, the exchangeable fraction is usually a much smaller percentage than the amount retained in less mobile fractions. However, if the total concentrations are high enough, or the saturation capacity of the soil is reached, or the wetland-specific water balance includes high water and copper inputs and outputs, the contribution could be significant. Potentially, a wetland can contribute relatively high concentrations to the downgradient environment while at the same time sequestering significant concentrations from the upgradient environment. Assessments of wetland water quality function should perhaps include the dual sink and source roles of wetlands.

The willow wetlands cover the most area in this study reach, especially in the wider, flatter area of transects 4, 5 and 6. No quantitative data exists, but estimated from a map, the relative percentage of willow wetland area is roughly 75 percent, with the other wetland types comprising the remaining 25 percent. Herbaceous fen sapist potholes, on the right bank, with the highest concentrations of copper measured, comprise a very small area. There are other herbaceous fen sapist potholes in this study reach, including potholes on the other side of Fisher Creek (left bank). However, in general, left bank samples did not have elevated copper levels.

Results in the previous section revealed that willow and herbaceous wet meadow wetland types (i.e. drier, mineral soil) had higher average exchangeable copper (and thus potentially higher total copper as seen in Figure 10) than the fens (wetter, organic soil). Though not a strong difference ($p = 0.16$), mineral soils had higher copper concentrations

than organic soils. This result is supported somewhat by the total copper analyses. The willow sample was much higher in both exchangeable and total copper than the three fen organic soil wetlands, but not the herbaceous fen saprist pothole. A reasonable interpretation for this is based on results from the previous section. The incoming water chemistry on the right bank (from Henderson and Fisher Mountains) probably has higher copper concentrations than the water chemistry on the left bank (Scotch Bonnet and Sheep Mountains). The quality of incoming waters apparently plays a larger role in wetland metal attenuation, and hence wetland water quality improvement, than the amount of organic matter, soil development, or degree of saturation.

There are other factors that likely influence elevated copper concentrations in the herbaceous fen saprist pothole. This pothole was a depression, with elevations below that of Fisher Creek. Water (ground and surface) is collected from both the floodplain and the mountain slope upgradient, and surface water is contributed from Fisher Creek when discharges reach a critical level. This particular pothole was between 50 and 100 feet away from Fisher Creek. Alluvial sands and gravels are between Fisher Creek and this pothole. Both ground and surface water sources have elevated levels of copper (USDA 1996), which apparently collects naturally in these potholes.

Soil pH may play a role here as well. When evaluating only the five wetland types used in the total copper analysis (i.e. one sample from each wetland type), pH differences were found. The pH of this pothole was 5.1 - roughly a full unit higher than the other wetland types (Table 3). Amacher's (1998) work in Fisher Creek found that when pH increases above 5, copper concentrations appear to be controlled by sorption of

hydrous Fe oxide (ferrihydrite) as predicted by the diffuse-layer adsorption model coupled to MINTEQA2.

The complimentary findings from the mobility analysis (above) and the landscape position and wetland characteristics analysis (previous section) point to the fact that a wetland's potential capacity to attenuate metals can be much different than the wetland realized functional role. This is because the realized metal attenuation is both of function of capacity and opportunity. In this particular setting, a wetland that receives water from copper-laden sources (i.e. Fisher and Henderson mountains) will attenuate more copper than a wetland that is exposed to much lower levels of soluble copper (Scotch Bonnet and Sheep mountains). Also, both oxidized and reduced soil compounds adsorb metals. The semipermanently flooded, mineral soil, willow wetlands have iron and manganese oxides (scavengers for copper) as well as some organic matter to attenuate copper. Yet because these willow wetlands have both the capacity to attenuate metals and are exposed to copper-laden water, they attenuate more copper overall.

Changes in soil physical or chemical characteristics can cause changes in mobility with all of these soil fractions. Changes in mobility can be caused by changes in soil physical properties, pH or redox potential from direct disturbance or from changes in upgradient water chemistry. Understanding copper partitioning and the related physical and chemical properties associated with each, land managers can evaluate potential mobility changes accordingly.

MANAGEMENT IMPLICATIONS

Disturbance Impacts

Wetlands can accumulate high levels of copper in both water and sediments. This is beneficial to the downgradient aquatic environment in that these wetlands are accumulating copper and releasing water with reduced copper concentrations. However, metal attenuation processes are reversible with changes in pH, oxygenation or physical structure. Consequently, these wetlands can also be a potential liability if natural or man-induced events change the biogeochemical or physical characteristics of the wetland (Owen et al. 1992). Natural disturbances such as threshold runoff or flood events can move large amounts of sediment, physically scouring the substrate and re-depositing the copper-laden sediments somewhere downgradient. Human-caused disturbances such as changes in the water table or water supply, road building or the institution of inadequate erosion measures for disturbed sites upgradient can also cause physical and chemical changes to the wetlands. Changes that oxidize wetland sediments, alter pH, alter wetland hydrology, or compact soil can potentially re-release copper to the downgradient aquatic habitat.

Knowing where copper is found in these riparian wetlands can assist land managers plan reclamation designs accordingly. This research identifies the streambank zone (10-ft. wide), the herbaceous fen saprist pothole area on transect 4, and the entire right bank as having elevated copper concentrations when various landscape position and

wetland characteristics are compared. Various individual hotspots of elevated copper were also identified, and others likely exist.

These wetlands apparently both contribute to the copper load in Fisher Creek and serve as a sink for copper. The largest proportion (average 46%) of the copper is bound to the relatively immobile fractions with a significant portion also bound to the intermediate noncrystalline iron oxides fraction (average 31%). The most mobile copper is only 1 to 4% of the total copper bound to the soil. Wetlands can export exchangeable and dissolved copper. The amount exported is contingent upon wetland-specific water balance conditions, and may be significant in certain areas.

Physical or chemical changes to any of these fractions could re-release copper downgradient. If road building or other disturbances are needed for reclamation purposes, the design should try to avoid or minimize direct and indirect effects in wetland areas if possible. If copper concentrations are high enough in wetlands to be impacted, side-cast materials should be hauled to a repository with other waste materials.

Removal of wetland copper sediments during clean up is not recommended (Amacher 1998). The many benefits of these unique and functioning wetlands to the ecosystem, not fully explored in this paper, including the water quality benefits described here, far outweigh the risk to the already degraded aquatic environment in this reach.

Water Quality Functional Assessment Methodologies

Methodologies to evaluate a wetland's ability to remove or sequester imported elements or compounds are currently being developed for hydrogeomorphic methodology

slope wetlands (M. Gilbert, U.S. Army Corps of Engineers, pers. comm., 2000). This research suggests that in addition to wetland characteristics, landscape characteristics such as incoming water chemistry and geology may be important to wetland water quality improvements in headwater or slope wetland areas. Additional findings suggest that the opportunity for water quality improvement may be just as important as wetland capacity when evaluating wetland water quality functions. Current methodologies do not account for the fact that wetlands can be contributors to, or a conduit for, the metal load as well as sinks. These findings suggest that the potential for wetland copper exports exists, and is likely dependent upon the site-specific water balance and biogeochemistry.

SUMMARY

Results from this study suggest that the riparian wetlands found in the upper reaches of Fisher Creek have improved water quality to some degree by sequestering copper from acid rock and acid mine drainage sources, and that landscape factors may be equally (if not more) important in controlling copper concentration and distribution as wetland characteristics.

In the wetland types sampled, roughly half (46%) of the total copper measured was held in the relatively immobile organic matter + sulfides + residuals soil fraction. Another 32% was held in the relative intermediate mobility noncrystalline iron oxides. These findings are favorable for wetland water quality improvements given the acidic nature of the soils present (average pH 4.4), the relative abundance of copper and acidic inputs from natural rock and acid mine drainage sources, and the relative abundance of natural wetlands bordering District streams. Wetlands can also be contributors to the copper load, as 1 to 4% of the copper is in the relatively mobile exchangeable fraction. This export contribution potentially can be quite high in certain locations where copper and water inputs of the wetland-specific water balance are relatively high.

This research also shows that there is a high spatial variability to copper removal that is associated with landscape position and wetland characteristics. As expected, a host of landscape factors and wetland characteristics explain differences in copper concentrations within these slope wetlands. In this study, landscape factors such as lateral slope position and incoming water chemistry and geology exhibited the highest differences of exchangeable copper among categories ($p = 0.03$ and 0.09 , respectively).

Wetland characteristics such as wetland type and water regime exhibited the highest differences in copper concentrations ($p = 0.03$ and 0.05 , respectively). The highest median copper concentrations were found in the streambank (1- to 10-ft.) slope position, one herbaceous fen saprist pothole, and in the semipermanently flooded sites.

Characteristics such as transect location, soil type, and pH had the lowest differences of copper concentrations among categories. Copper concentrations in the right bank samples (Fisher and Henderson Mountain) were higher than the left bank (Scotch Bonnet and Sheep Mountain) samples ($p = 0.09$). Copper concentrations in the mineral soils tended to be higher than the organic soils, but the difference was not strong. The drier wet meadow and willow wetlands had higher copper concentrations than the fens. Presumably this is due partially to the fact that the incoming water chemistry and geology from Fisher and Henderson Mountains, which feeds right bank wetlands, differs in copper concentration and hydrology from the water from Scotch Bonnet and Sheep Mountains, which feed the left bank wetlands.

The water regime and soil type results were notable in that the semipermanently flooded sites and mineral soils have higher median exchangeable copper concentrations (and thus have attenuated more copper) than the saturated sites and organic soil types. This contradicts the assumption that saturated, organic soils attenuate more copper because they generally have more organic matter and higher cation exchange capacities.

Collectively, these findings indicate that landscape factors such as slope position and incoming water chemistry and geology may be more important in controlling wetland copper concentrations in this headwater catchment or slope wetlands in general than saturated conditions or type of soil, the more conventional characteristics assumed to

control copper accumulation. Wetland functional assessment methodologies for slope wetlands may need to account for opportunity as well as capacity and dual sink/source roles when evaluating wetland water quality functions, and include landscape variables in the assessment of water quality functions. Additionally, potential effectiveness of wetlands needs to be assessed at a landscape or watershed scale. In this case, for example, an estimated 25-33% of Fisher Creek's copper load is from groundwater non-point sources (Amacher 1998 and Kimball et al. 1999) that may pass through wetlands.

Management and reclamation can benefit from knowing where high copper concentrations exist, in what form they exist, and what landscape and wetland characteristics are associated with high copper concentrations. Because wetland areas evaluated in this stretch of upper Fisher Creek generally improve water quality, protection of these riparian wetlands and associated water quality should be included in the long-term strategies for site reclamation. Strategies such as avoidance or minimization of direct and indirect disturbance to these wetlands and management of the dredged materials appropriately (if avoidance weren't possible) would be prudent.

Supplementary investigation of wetland-specific water balances, hydrogeology, and source area geochemistry, and soil processes involved in copper retention would provide additional insight into the water quality functions of these wetlands.

LITERATURE CITED

- Alloway, B.J. (ed.). 1995. Heavy Metals in Soils. 2nd Edition. Blackie Academic and Professional, Glasgow, UK.
- Adamus, P.R., E.J. Clairain, R.D. Smith, and R.E. Young. 1987. Wetland Evaluation Technique (WET), v. 2 of Methodology: Operational Draft Technical Report, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, USA.
- Amacher, M.C. 1998. Metal loadings and metals in sediments and wetland soils in the Fisher Creek and Daisy Creek catchments in the New World Mining District, Montana. A draft assessment report prepared for USDA-FS Region 1 and the USEPA. Forestry Sciences Laboratory, USDA-FS-RMRS, Logan, UT, USA.
- Amacher, M.C. 1999. Manual of Methods - Open File Report. USDA Forest Service Intermountain Research Station Forestry Sciences Laboratory, Logan, UT, USA.
- Bridgham, S.D., J. Pastor, J.A. Janssens, C. Chapin, and T.J. Malterer. 1996. Multiple limiting gradients in peatlands: A call for a new paradigm. *Wetlands*. 16:45-65.
- Brinson, M.M. 1993. A hydrogeomorphic classification for wetlands. U.S. Army Engineers, Vicksburg, MS, USA. Wetland Research Program Technical Report WRP-DE-4.
- Brodie, G.A. 1990. Treatment of acid drainage using constructed wetlands – Experiences of the Tennessee Valley Authority. p. 77-83. *In* D.H. Graves (ed.) National Symposium on Mining. University of Kentucky, Lexington, KY, USA.
- Brodie, G.A., D.A. Hammer, and D.A. Tomljanovich. 1996. Man-made wetlands for acid mine drainage control. p. 87-103. *In* Proceedings of the 5th Annual National Abandoned Mine Lands Conference. Billings, MT, USA.
- Brown, R.W., M. C. Amacher, B.D. Williams, W.F. Mueggler, and J. Kotuby-Amacher. 1996. Reclamation research in the New World: 1995 Report of Research. USDA Forest Service, Intermountain Research Station Forestry Sciences Laboratory, Logan, UT, USA.
- Carter, V. 1996. Wetland hydrology, water quality and associated functions. p. 35-48. *In* J.D. Fretwell, J.S. Williams and P.J. Redman (compilers) National Water Summary on Wetland Resources. U.S. Department of the Interior, U.S. Geological Survey, Washington, D.C. USA. Water-Supply Paper 2425.

- Carter, V., M.S. Bedinger, R.P. Novitzki, and W.O. Wilen. 1978. Water resources and wetlands. p. 344-377. *In* Wetland Functions and Values: The State of Our Understanding. American Water Resources Association. Denver, CO, USA.
- Castelle, A.J., A.W. Johnson and C. Conolly. 1994. Wetland and stream buffer size requirements – A review. *J. Environ. Qual.* 23:878-882.
- CBMI (Crown Butte Mines, Inc). 1992. Application for a Hard Rock Mine Operating Permit and Proposed Plan of Operations. Submitted to U.S. Forest Service Region 1 and the Montana Bureau of State Lands. USDA Forest Service Region 1, Missoula, MT, USA.
- Chadde, S.W., J.S. Shelly, R.J. Bursik, R.K. Moseley, A.G. Evenden, M. Mantas, F. Rabe and B. Heidel. 1998. Peatlands on national forests of the Northern Rocky Mountains: Ecology and conservation. USDA Forest Service Rocky Mountain Research Station General Technical Report (RMRS-GTR-11). Ogden, UT, USA.
- Chambers, J.C., M.C. Amacher and R.W. Brown. 1991. Effect of acid mine drainage on a riparian area: Element concentrations in soils and plants. p. 183-191. *In* Proceedings of the American Association of Surface Mining and Reclamation Annual Meeting. Durango, CO, USA.
- Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoe. 1979. Classifications of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service, Department of the Interior, Washington, D.C., USA. FWS/OBS-79/31.
- Daniels, R.B. and J.W. Gilliam. 1996. Sediment and chemical load reduction by grass and riparian filters. *Soil Sci. Soc. Am. J.* 60:246-261.
- Dollhopf, D.J., J.D. Goering, R.B. Rennick, R.B. Morton, W.K. Gauger, J.B. Guckert, P.M. Jones, K.C. Cooksey, K.E. Bucklin, R. Weed, and M.M. Lheman. 1988. Hydrochemical, vegetational and microbiological effects of a natural and constructed wetland on the control of acid mine drainage. Reclamation Research Unit Publication 88-04, Montana State University, Bozeman, MT, USA.
- Eger, P. and K. Lapakko. 1988. Nickel and copper removal from mine drainage by a natural wetland. Paper presented at the Mine Drainage and Surface Mine Reclamation Conference, sponsored by the USDI Bureau of Mines and Surface Mining Reclamation and Enforcement. Pittsburgh, PA, USA.
- Emerick, J.C. 1988. The restoration potential for wetlands impacted by acid mine drainage in the Colorado Rocky Mountains. *In* Restoration, Creation and Management of Wetland and Riparian Ecosystems in the American West. Proceedings from the Symposium of the Rocky Mountain Chapter of the Society of Wetland Scientists. Denver, CO, USA.

- Furniss, G. 1996. Age relationships of acid drainage water quality at the New World Mining District, Park County, Montana. p. 191-194. *In* Extended Abstracts, Montana Geological Society 1996 Rocky Mountain Section Meeting, American Association of Petroleum Geologists. Billings, MT, USA.
- Furniss, G., N.W. Hinman, G.A. Doyle and D.D. Runnells. 1999. Radiocarbon-dated ferricrete provides a record of natural acid rock drainage and paleoclimatic changes. *Environmental Geology* 37:102-106.
- Gambrell, R.P. 1994. Trace and toxic metals in wetlands – A review. *J. Environ. Qual.* 23:883-891.
- Gibbons, J.D. 1976. *Nonparametric Methods for Quantitative Analysis*. 2nd Edition. American Sciences Press, Inc. Columbus, OH, USA.
- Gilbert, R.O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. Van Nostrand Reinhold, New York, NY, USA.
- Gilliam, J.W. and R.W. Skaggs. 1988. Nutrient and sediment removal in wetland buffers. p 174-178. *In* Proceedings of the National Wetland Symposium on Wetland Hydrology. Chicago, IL, USA.
- Hill, A.R. 1996. Nitrate removal in stream riparian zones. *J. Environ. Qual.* 25:743-755.
- Johnston, C.A. 1991. Sediment and nutrient retention by freshwater wetlands: Effects on surface water quality. *Critical Reviews in Environmental Control* 21(5,6):491-565.
- Johnston, R.S. and R.W. Brown. 1979. Hydrologic aspects related to the management of alpine lands. p. 65-75. *In* D.A. Johnson (ed.) *Special Management Needs of Alpine Ecosystems*. Society for Range Management, Range Sciences Series No. 5. Denver, CO, USA.
- Kadlec, R.H. and J.A. Kadlec. 1978. Wetlands and water quality. p. 436-456. *In* *Wetland Functions and Values: The State of Our Understanding*. American Water Resources Association. Denver, CO, USA.
- Kadlec, R.H. and R.L. Knight. 1995. *Treatment Wetlands*. CRC Press, Inc. Lewis Publishers, Boca Raton, FL, USA.
- Kadlec, R.H. 1988. Wetland hydrology and water pollution control functions. p. 168-173. *In* Proceedings of the National Wetland Symposium on Wetland Hydrology. Chicago, IL, USA.

- Kastning-Culp, N., L. DeBrey and J. Lockwood. 1992. Year end report: On mitigation systems for hardrock mine effluent in the Gallatin National Forest. University of Wyoming, Laramie, WY, USA.
- Keller, B.E.M., K. Lajtha, and S. Cristofor. 1998. Trace metal concentrations in the sediments and plants of the Danube Delta, Romania. *Wetlands* 18(1):42-50.
- Kimball, B.A., D.A. Nimick, L.J. Gerner, and R.L. Runkel. 1999. Quantification of metal loading in Fisher Creek by tracer-injection and synoptic sampling, Park County, Montana, August 1997. U.S. Geological Survey Water-Resources Investigations Report 99-4119. Salt Lake City, UT, USA.
- Kleinmann, R.L.P. 1990. Acid mine drainage in the United States. p. 1-8. *In* Proceedings of the First Midwestern Region Reclamation Conference. Southern Illinois University. Carbondale, IL, USA.
- Maxim (Maxim Technologies, Inc.). 1999. New World Mining District Response and Restoration Project Overall Project Work Plan. USDA Forest Service Region 1, Missoula, MT, USA.
- Maxim (Maxim Technologies, Inc.). 2000. New World Mining District Response and Restoration Project Engineering Evaluation / Cost Analysis. USDA Forest Service Region 1, Missoula MT, USA.
- Mitsch, W.J. and J.G. Gosselink. 1993. *Wetlands*. Van Nostrand Reinhold Company, New York, NY, USA.
- Novitski, R.P. 1978. Hydrologic characteristics of Wisconsin's wetlands and their influence on floods, stream flow, and sediment. p. 378-388. *In* *Wetland Functions and Values: The State of Our Understanding*. American Water Resources Association. Denver, CO, USA.
- Novitski, R.P., B.H. Rosen, L.S. McAllister, T.L. Ernst, B.E. Huntley, and K. Dwire. 1994. EMAP – Research strategy for the assessment of wetland condition: U.S. Environmental Protection Agency, Environmental Research Laboratory. Corvallis, OR, USA.
- Novitski, R.P., R.D. Smith, and J.D. Fretwell. 1996. Wetland Functions, Values, and Assessment. p. 79 - 86. *In* J.D. Fretwell, J.S. Williams and P.J. Redman (compilers) *National Water Summary on Wetland Resources*. U.S. Department of the Interior, U.S. Geological Survey, Washington, D.C. USA. Water-Supply Paper 2425.
- NRC (Northwest Resource Consultants). 1994. New World Project Proposed [Wetland] Mitigation Plan. USDA Forest Service Region 1, Missoula MT, USA.

- Owen, D.E., J.K. Otton, F.A. Hills, and R.R. Schumann. 1992. Uranium and other elements in a Colorado Rocky Mountain wetland – a reconnaissance study. U.S. Geological Survey Bulletin 1992, U.S. Geological Survey, Denver, CO, USA.
- Perry, A. and R.L.P. Kleinmann. 1991. The use of constructed wetlands in the treatment of acid mine drainage. *Natural Resources Forum* 15:178-184.
- Rhoades, J. 1982. Soluble salts. p. 167-179. *In* A.L. Page (ed.) *ASA-ASSA Methods of Soil Analysis – Part 2*. Madison, WI, USA.
- Sobolewski, A. 1997. The capacity of natural wetlands to ameliorate water quality: A review of case studies. p. 1549-1563. *In* *Proceedings of the Fourth International Conference on Acid Rock Drainage*. Vancouver, B.C., Canada.
- Sobolewski, A. 1999. A review of processes responsible for metal removal in wetlands treating contaminated mine drainage. *International Journal of Phytoremediation* 1:19-51.
- Stumm, W. and J.J. Morgan. 1996. *Aquatic Chemistry, Chemical Equilibria and Rates in Natural Waters*, 3rd Edition. John Wiley & Sons, Inc. New York, NY, USA.
- Taylor, J.K. 1987. *Quality Assurance of Chemical Measurements*. Lewis Publishers, Inc. Chelsea, MI, USA.
- URS (URS Operating Services, Inc.) and Superfund Technical Assessment and Response Team EPA Region VIII. 1998. *Site Assessment Summary and Sampling Activities Report*, New World Mine, Cooke City, MT. USDA Forest Service Region 1, Missoula MT, USA.
- USDA (U.S. Department of Agriculture) Forest Service Region 1. 1996. *Preliminary Draft Environmental Impact Statement of the New World Project* (unpublished). Missoula, MT, USA.
- USDI (U.S. Department of the Interior) Bureau of Land Management Montana State Office and U.S. Department of Agriculture (USDA) Forest Service Northern Region. 1997. *Environmental Impact Statement for the Proposed Cooke City Area Mineral Withdrawal*. Billings, MT, USA.
- WESTECH (Western Technology and Engineering, Inc.). 1992. *Baseline soils inventory New World Project Area Park County, Montana*. *In* *Application for a Hardrock Operating Permit and Proposed Plan of Operations New World Project Volume 6*. USDA Forest Service Region 1, Missoula, MT, USA.

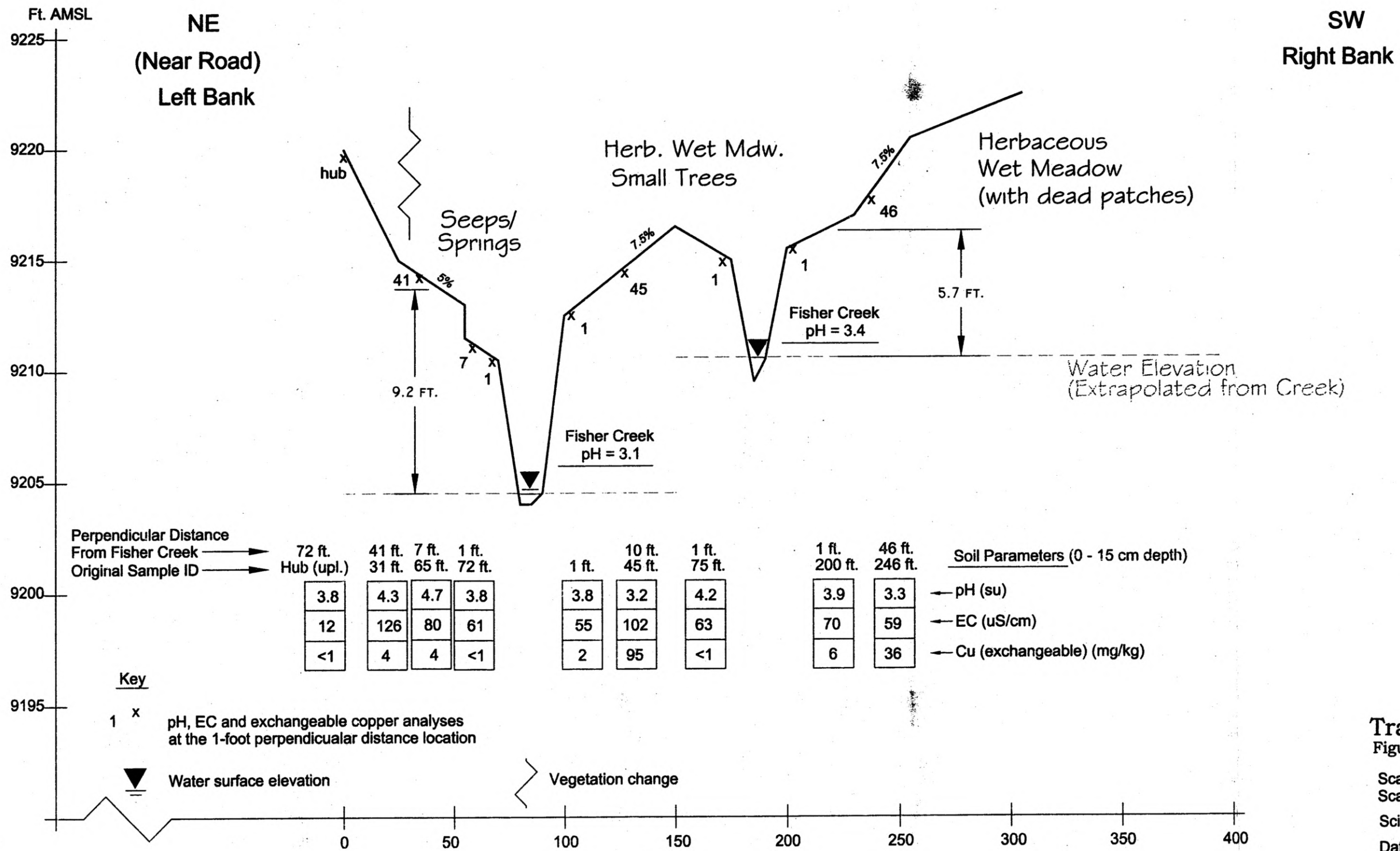
WESTECH (Western Technology and Engineering, Inc.). 1993. Wetlands inventory of the New World project area and tailing impoundment alternatives. USDA Forest Service Region 1, Missoula, MT, USA.

APPENDICES

APPENDIX A

CROSS-SECTIONS SURVEYS, VEGETATION TYPES, AND pH, EC, and
EXCHANGEABLE COPPER RESULTS

Transect 1



Transect 1
Figure A1.

Scale H: 1 inch = 50 feet
Scale V: 1 inch = 5 feet

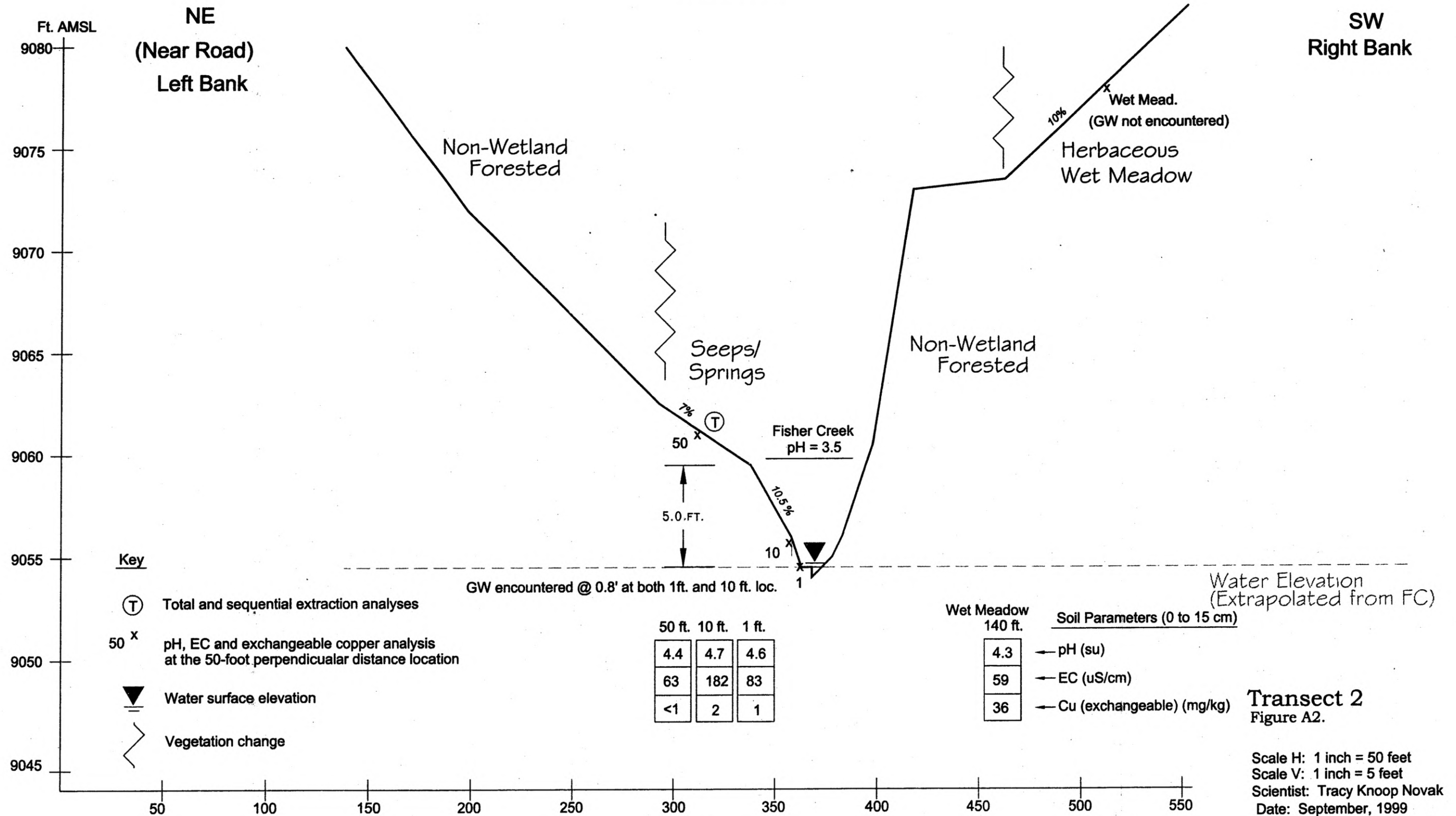
Scientist: Tracy Knoop Novak

Date: September, 1999

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Figure A1. Transect 1: Cross-section survey, wetland types, soil sample locations and pH, EC and exchangeable copper results.

Transect 2

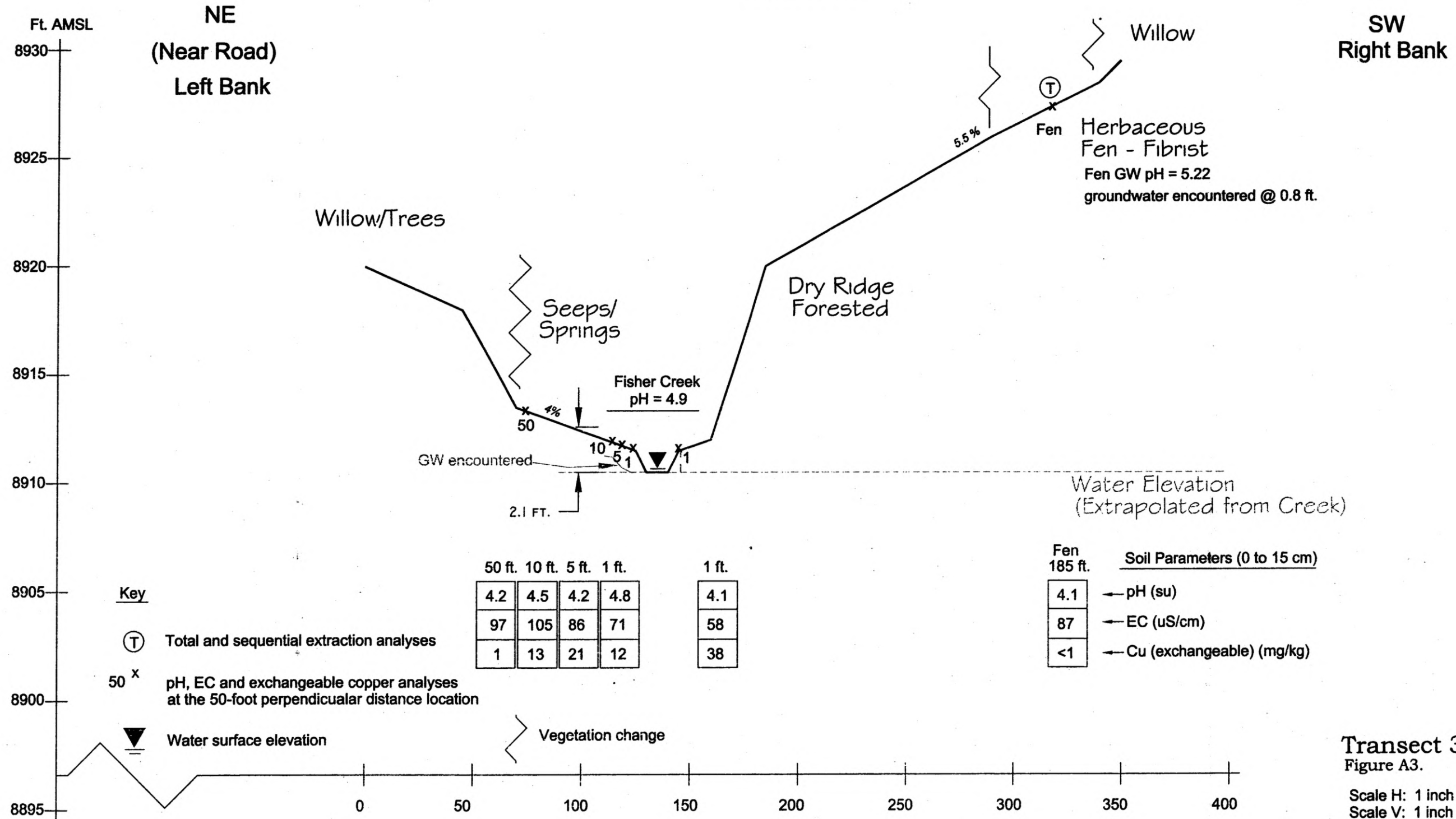


Transect 2
Figure A2.

Scale H: 1 inch = 50 feet
 Scale V: 1 inch = 5 feet
 Scientist: Tracy Knoop Novak
 Date: September, 1999
 File: D:\research\trans-2c.dwg

Figure A2. Transect 2: Cross-section survey, wetland types, soil sample locations and pH, EC and exchangeable copper results.

Transect 3



Transect 3
Figure A3.

Scale H: 1 inch = 50 feet
Scale V: 1 inch = 5 feet

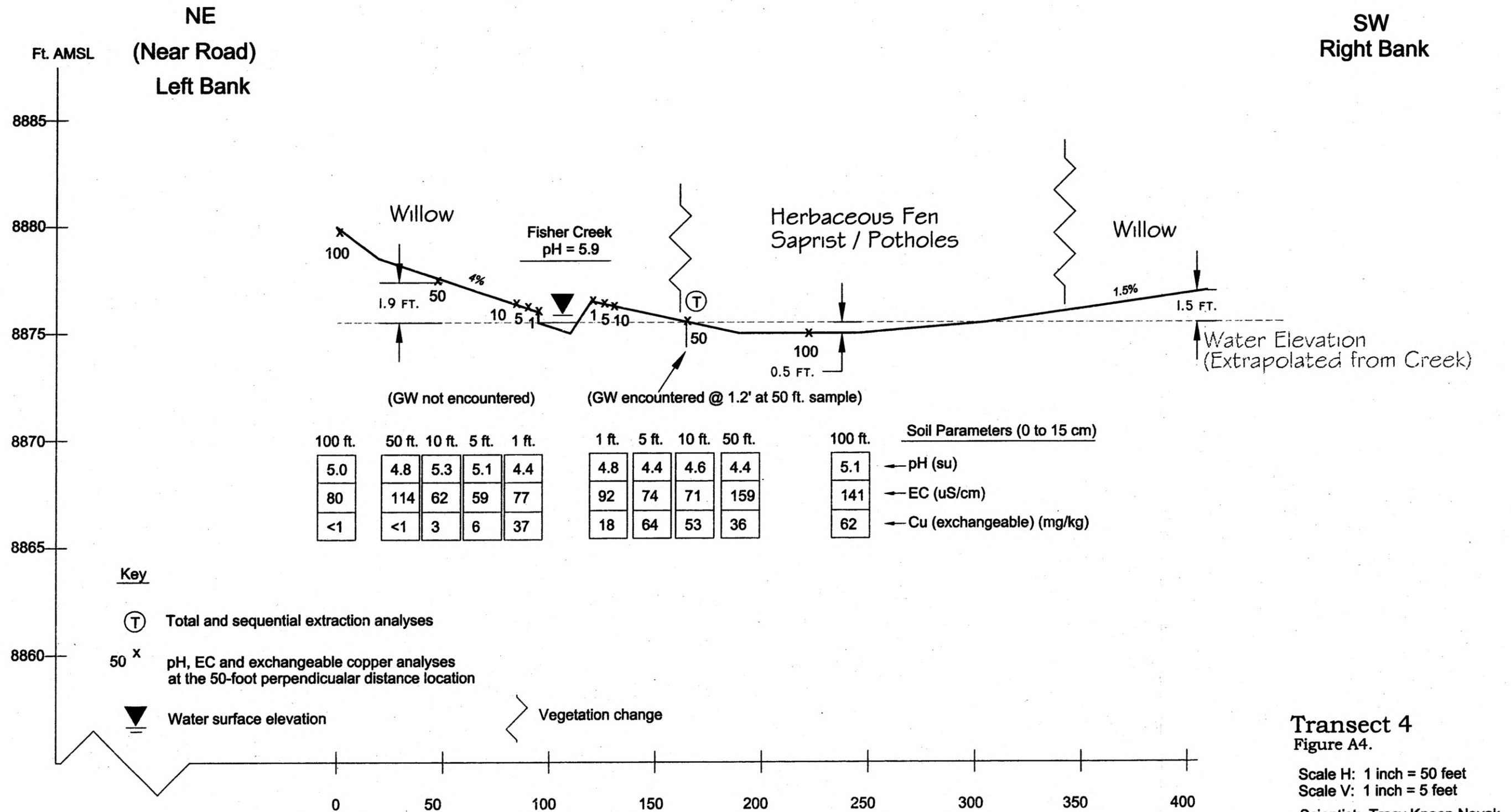
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Date: September, 1999

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Figure A3. Transect 3: Cross-section survey, wetland types, soil sample locations and pH, EC and exchangeable copper results.

Transect 4



Transect 4
Figure A4.

Scale H: 1 inch = 50 feet

Scale V: 1 inch = 5 feet

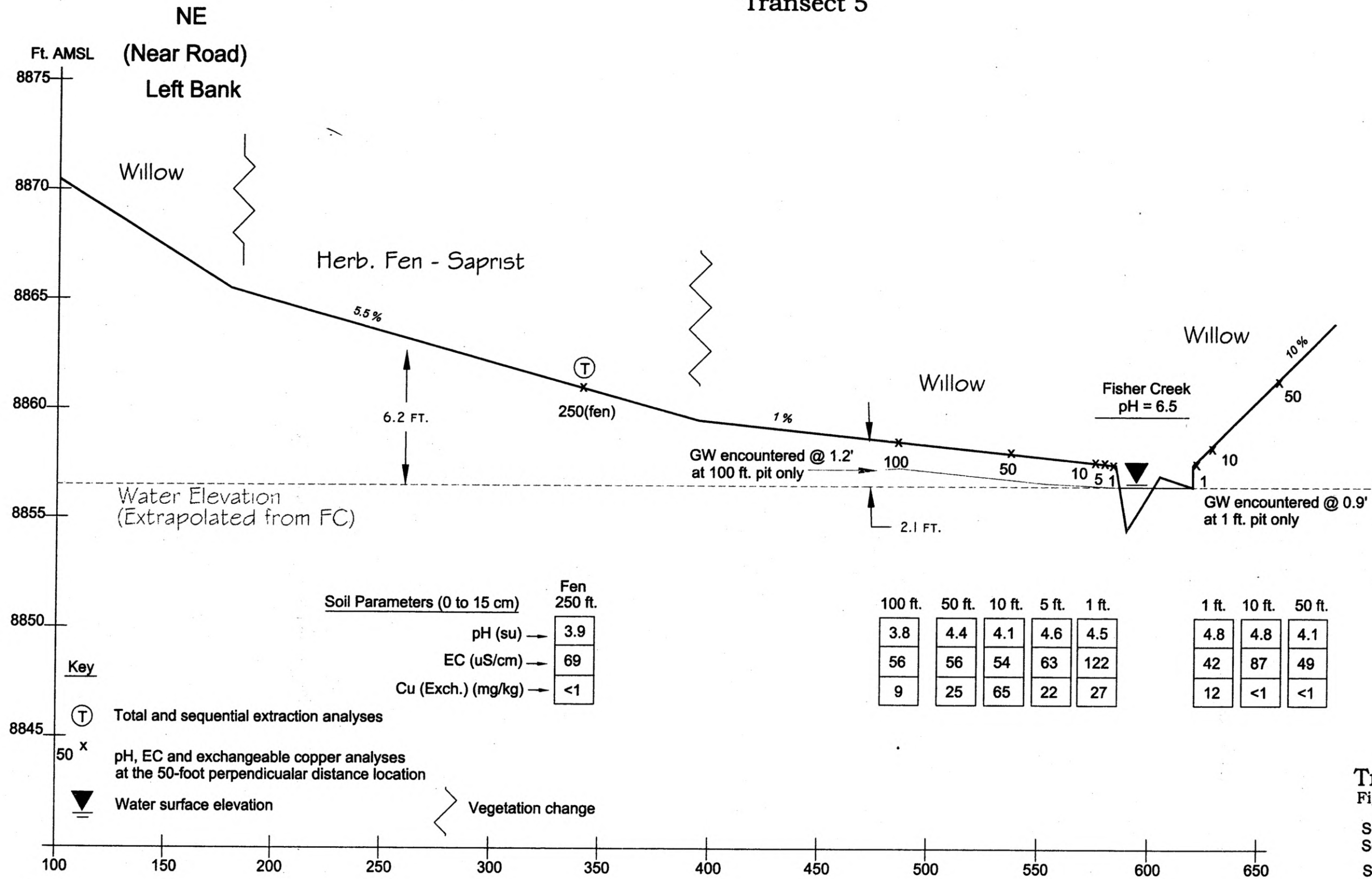
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Date: September, 1999

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Figure A4. Transect 4: Cross-section survey, wetland types, soil sample locations and pH, EC and exchangeable copper results.

Transect 5



Transect 5
Figure A5.

Scale H: 1 inch = 50 feet
Scale V: 1 inch = 5 feet

Scientist: Tracy Knoop Novak

Date: September, 1999

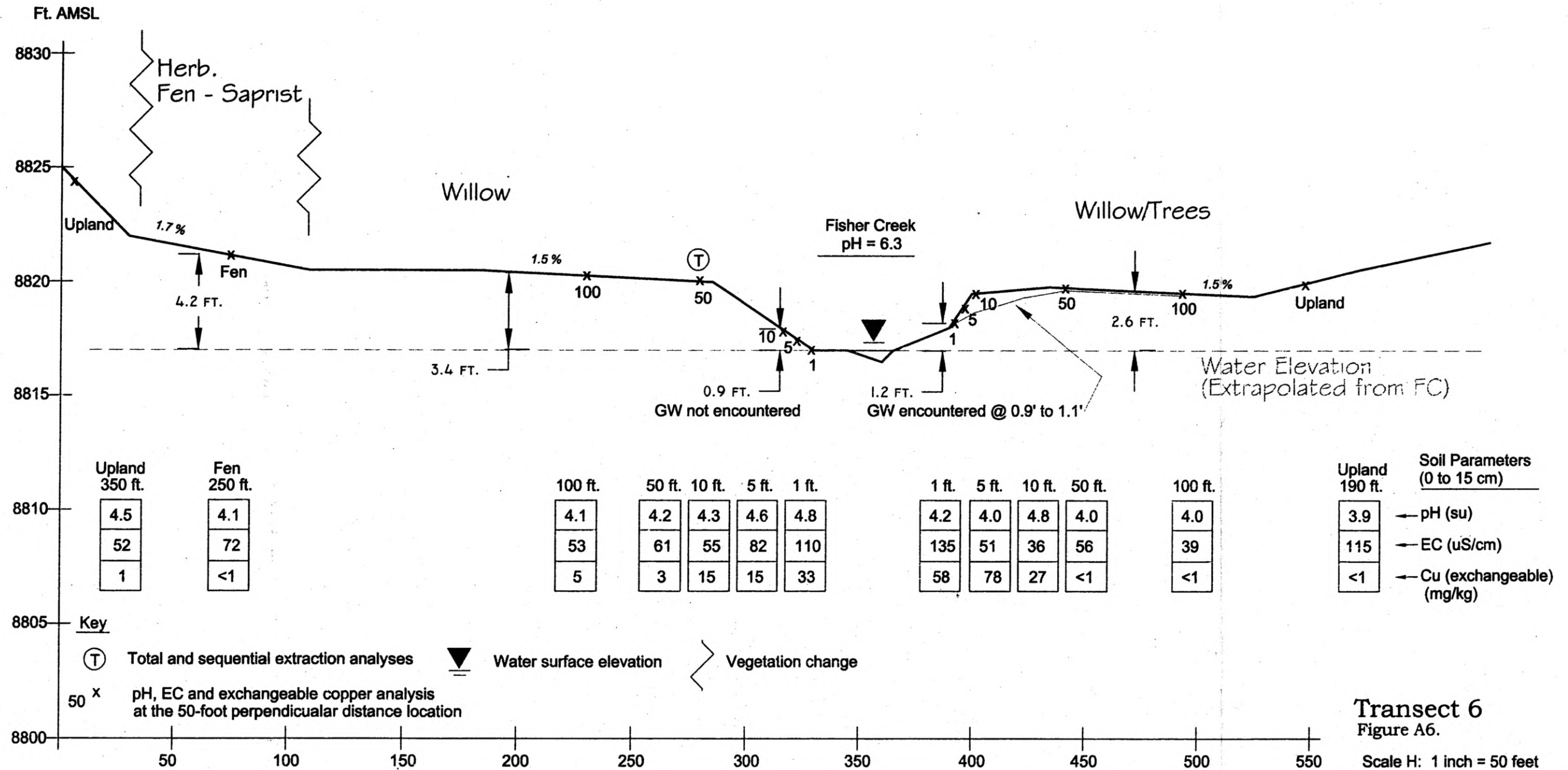
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Figure A5. Transect 5: Cross-section survey, wetland types, soil sample locations and pH, EC and exchangeable copper results.

Transect 6

NE
(Near Road)
Left Bank

SW
Right Bank



Transect 6
Figure A6.

Scale H: 1 inch = 50 feet
Scale V: 1 inch = 5 feet

Scientist: Tracy Knoop Novak

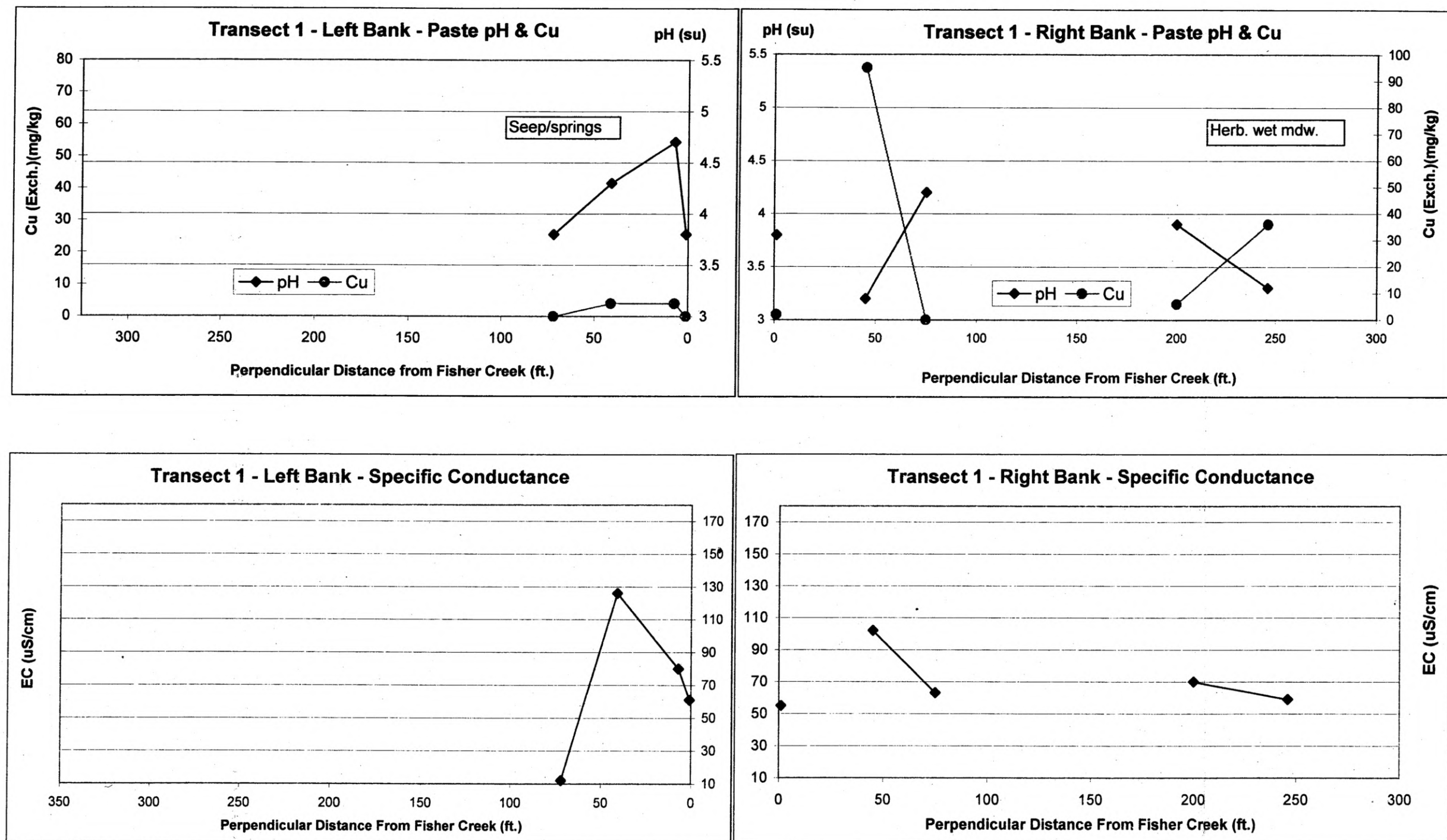
Date: September, 1999

File: D:\research\trans-6g.dwg

Figure A6. Transect 6: Cross-section survey, wetland types, soil sample locations and pH, EC and exchangeable copper results.

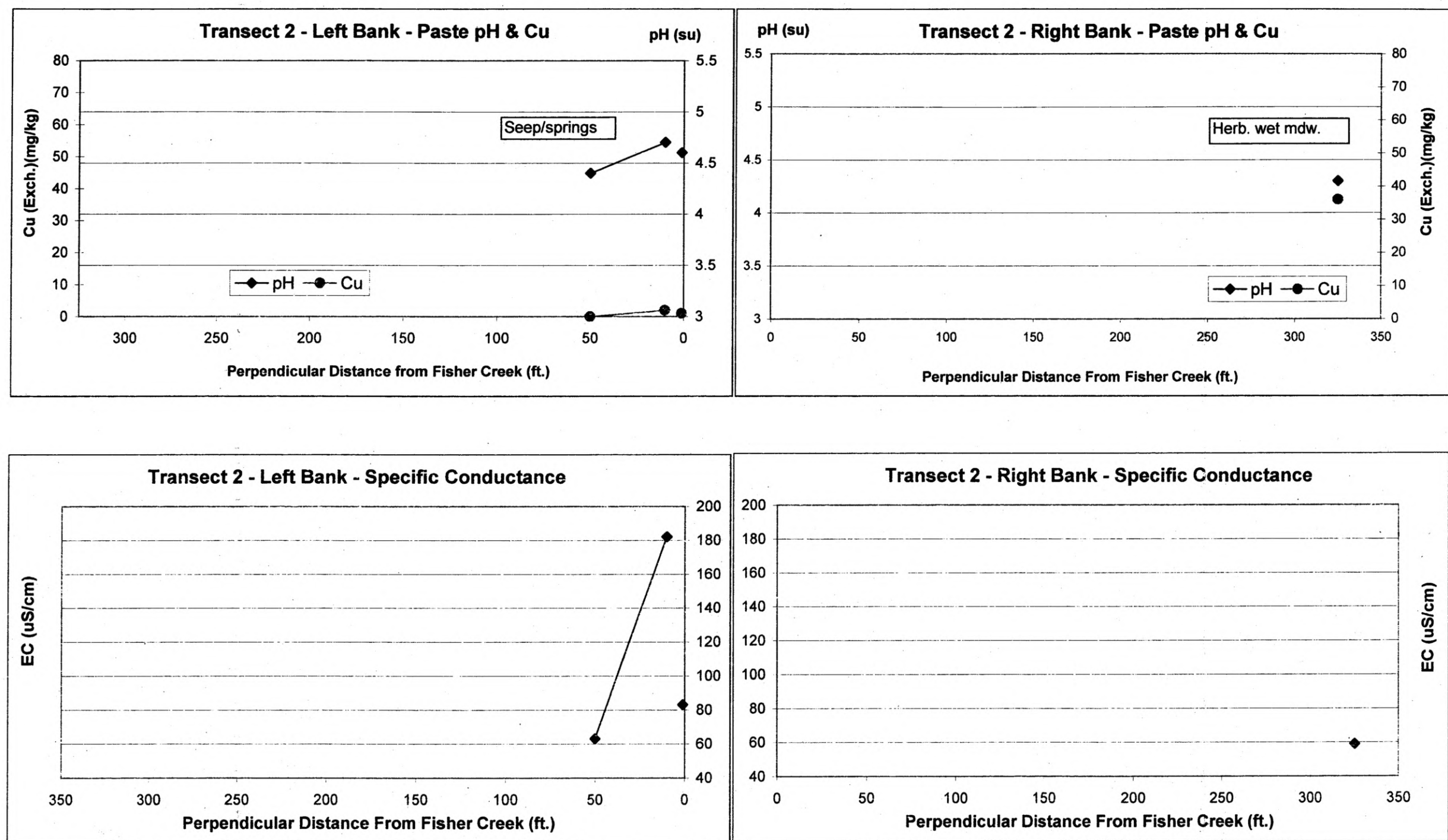
APPENDIX B

pH, EC and EXCHANGEABLE CU TRENDS ACROSS the RIPARIAN WETLANDS



File: D:\research\11x17pH-ECgraphs\sb1.xls

Figure B1. Transect 1: Paste pH, exchangeable copper and EC of wetland floodplain soils.



File: D:\research\11x17pH-ECgraphs\1.xls

Figure B2. Transect 2: Paste pH, exchangeable copper and EC of wetland floodplain soils.

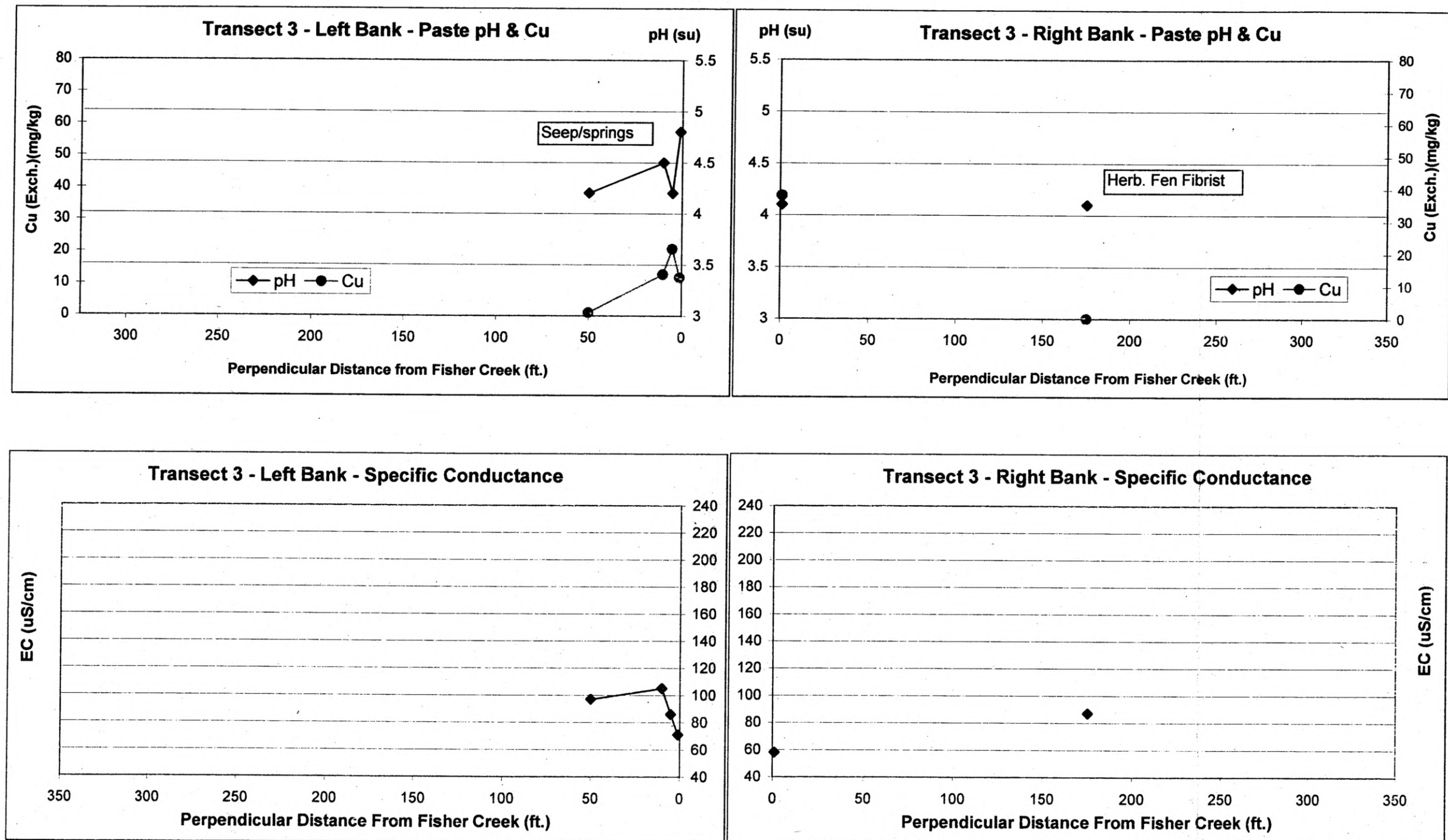
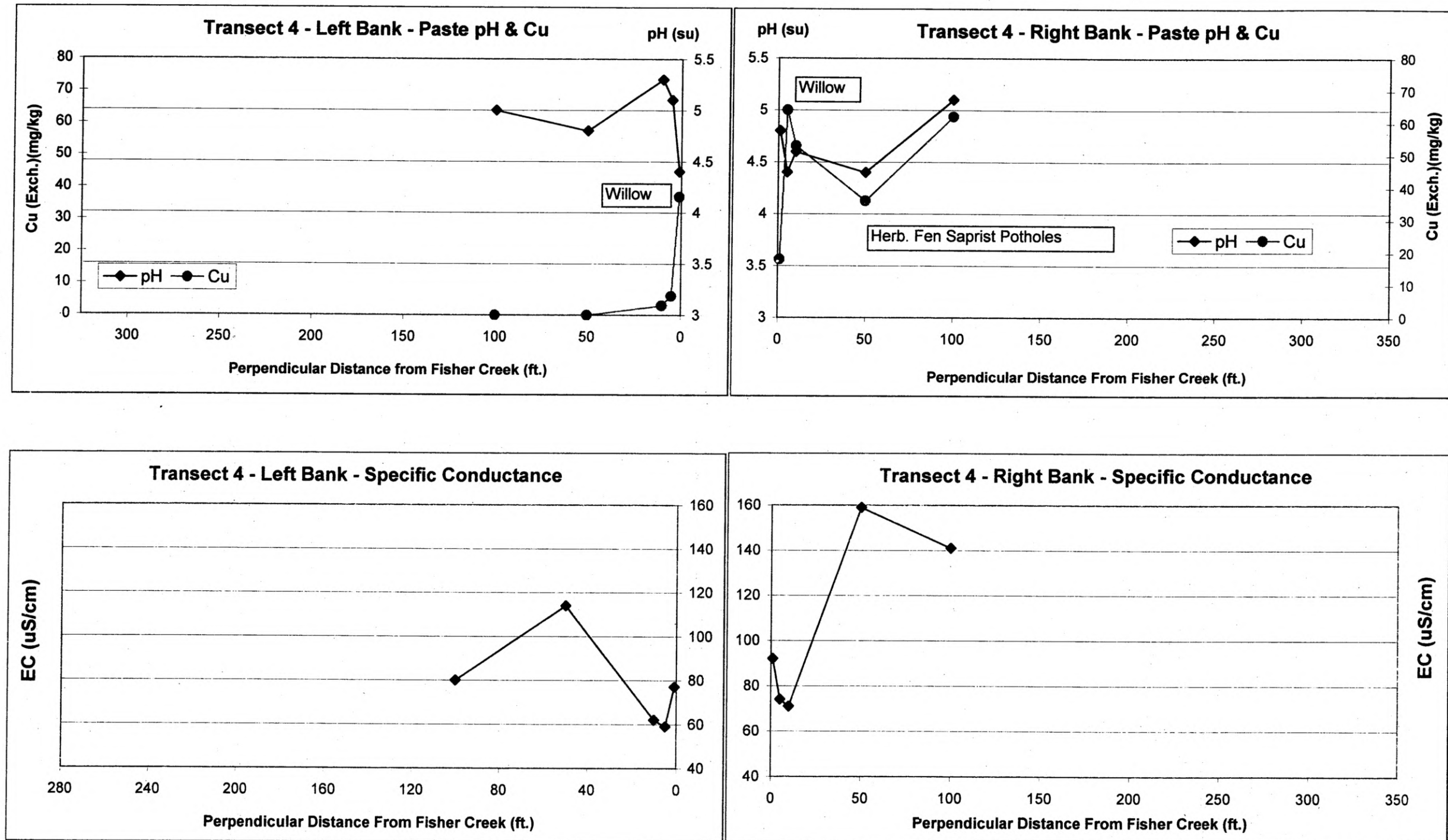


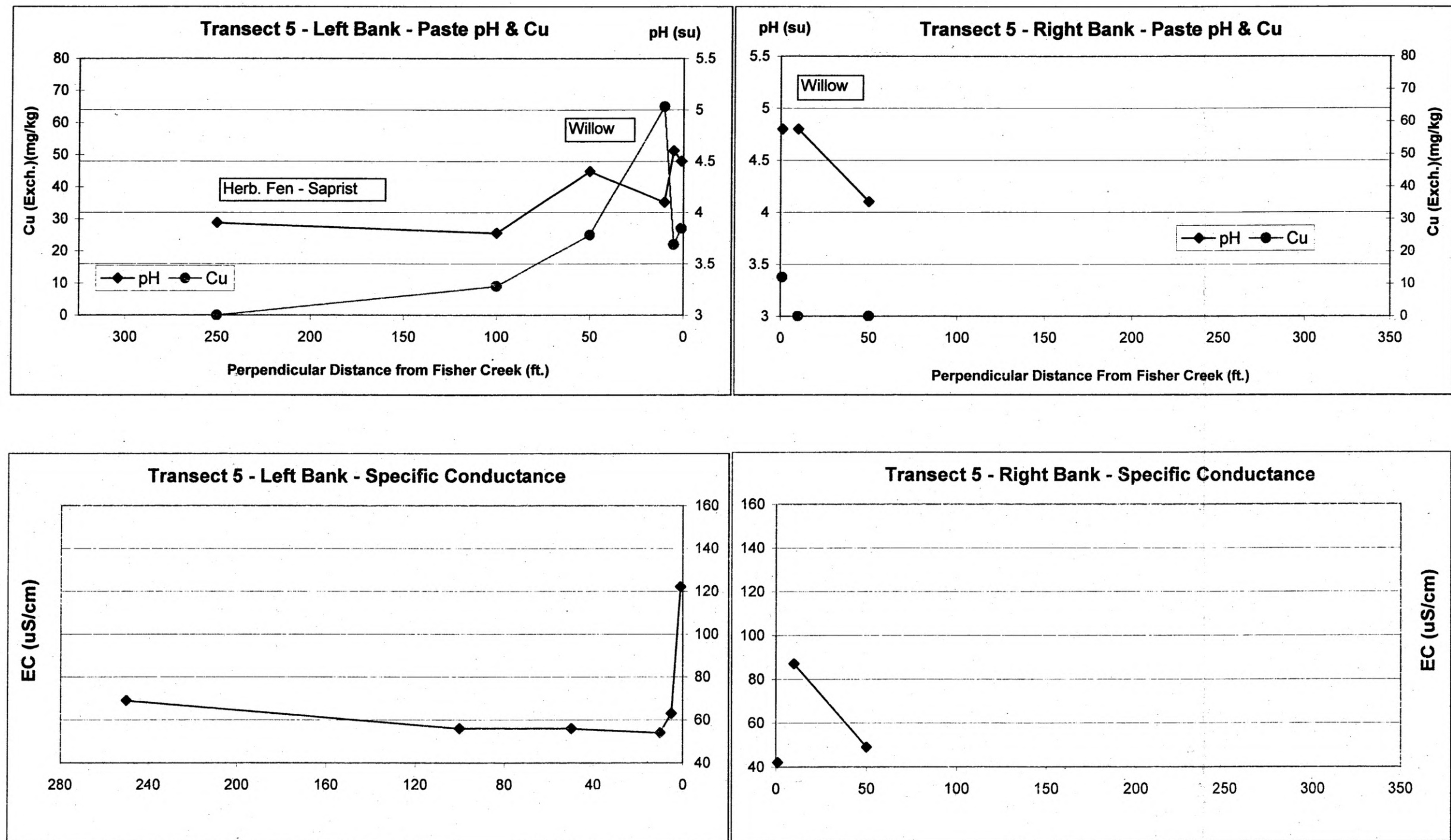
Figure B3. Transect 3: Paste pH, exchangeable copper and EC of wetland floodplain soils.

File: D:\research\11x17pH-ECgraphs\1.xls



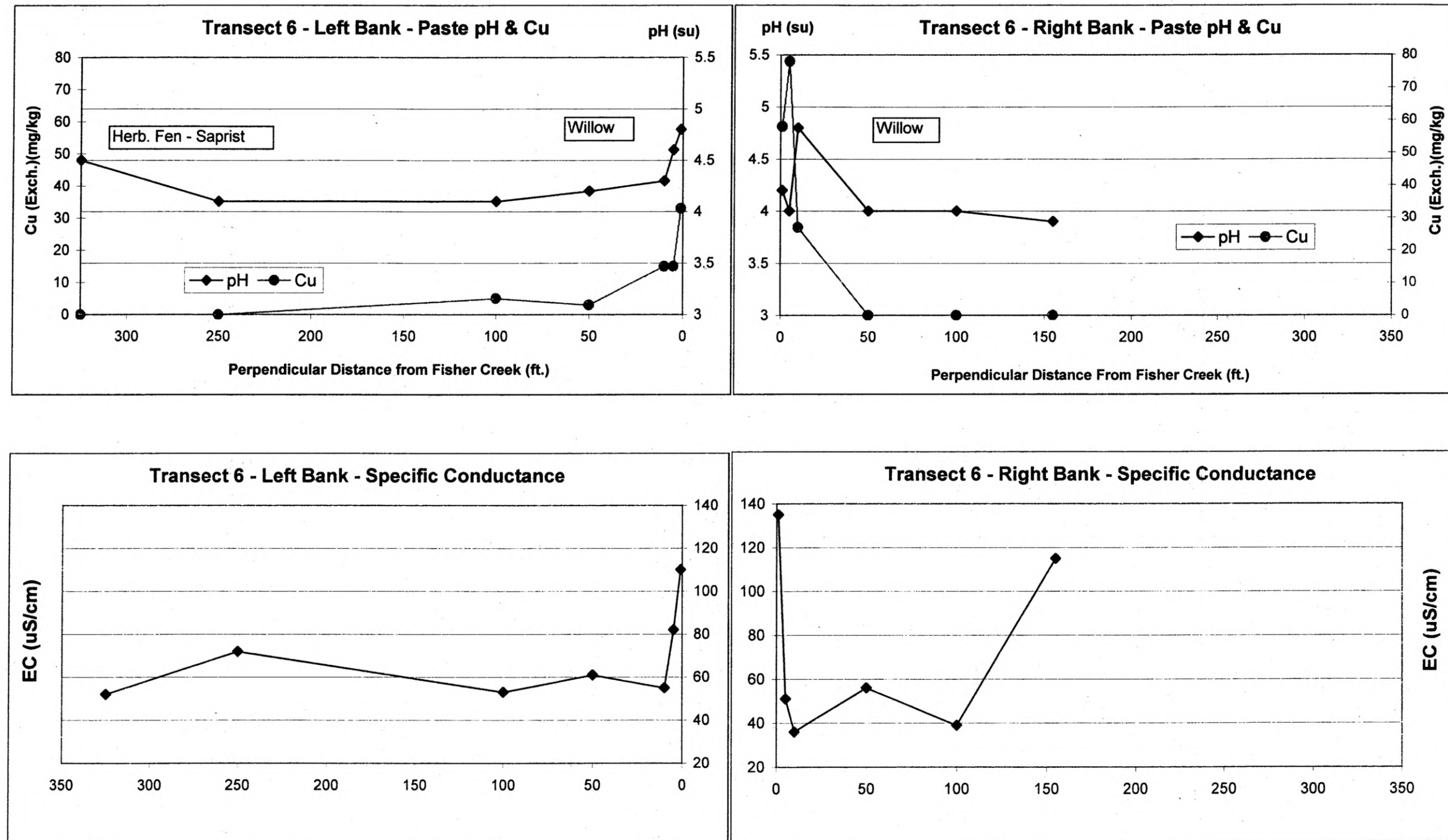
File: D:\research\11x17pH-ECgraphs.xls

Figure B4. Transect 4: Paste pH, exchangeable copper and EC of wetland floodplain soils.



File: D:\research\11x17pH-ECgraphs.xls

Figure B5. Transect 5: Paste pH, exchangeable copper and EC of wetland floodplain soils.



File: D:\research\11x17pH-ECgraphs.xls

Figure B6. Transect 6: Paste pH, exchangeable copper and EC of wetland floodplain soils.

APPENDIX C

TRANSECT AVERAGES OF pH, EC and EXCHANGEABLE CU

Appendix C. Transect average paste pH, EC and exchangeable copper concentrations.

Transect	Avg. pH (both samples)		Avg. EC (both samples)		Avg. Exch. Cu (mg/kg)	No. of Samples (n =)
	(su)	(by depth)	(uS/cm)	(by depth)		
Overall	4.4		80			102
		0 to 15 cm = 4.3		0 to 15 cm = 77	19	51
		0 to 30 cm = 4.4		0 to 30 cm = 82		51
Transect 1 (upstream)	3.8		80			18
		0 to 15 cm = 3.9		0 to 15 cm = 70	17	9
		0 to 30 cm = 3.7		0 to 30 cm = 91		9
Transect 2	4.6		83			8
		0 to 15 cm = 4.5		0 to 15 cm = 97	10	4
		0 to 30 cm = 4.7		0 to 30 cm = 69		4
Transect 3	4.3		93			12
		0 to 15 cm = 4.3		0 to 15 cm = 84	14	6
		0 to 30 cm = 4.2		0 to 30 cm = 103		6
Transect 4	4.9		93			20
		0 to 15 cm = 4.8		0 to 15 cm = 93	28	10
		0 to 30 cm = 4.9		0 to 30 cm = 93		10
Transect 5	4.4		74			18
		0 to 15 cm = 4.3		0 to 15 cm = 65	18	9
		0 to 30 cm = 4.4		0 to 30 cm = 93		9
Transect 6 (downstream)	4.3		65			26
		0 to 15 cm = 4.3		0 to 15 cm = 70	18	13
		0 to 30 cm = 4.4		0 to 30 cm = 60		13