

Geomorphic and hydrologic effects on nutrient distribution in riparian areas surrounding  
the Sooke Lake Reservoir.

by

Deborah Bryant  
BSc., Trent University, 1997

A Thesis Submitted in Partial Fulfillment  
of the Requirements for the Degree of

MASTER OF SCIENCE

in the Biology Department

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**Abstract**

We examined the physical and chemical soil characteristics in the cleared riparian areas at the Sooke Lake Reservoir, where the growing population has necessitated the expansion of the drinking water reservoir in Victoria, British Columbia. Additionally, hydrologic functioning was studied to establish the pathways riparian nutrients followed to the reservoir. In order to understand the potential release of nitrogen and phosphorous following inundation, both saturated riparian and upland areas were chosen as part of 17 transects encompassing the entire reservoir in four major soil types (Morainal, Colluvial, Fluvial and Organic). Various nutrient concentrations (TDP, TP,  $\text{PO}_4^{3-}$ , DOC, TC, IC,  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ ,  $\text{NH}_4^+$ , TN, TDN) were measured in relation to geomorphic features. Areal analyses confirm the hypotheses that nutrient concentrations differ with soil type, depth (0-10 cm, 10-30 cm, 30-60 cm) and hill slope. Hydrologic data established that seasonality and therefore transect connectivity is an important aspect for nutrient transport in the riparian areas via leaching and preferential flowpaths.

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## Dedication

For my Parents who had the wisdom to recognise and convey the most important things in life; love, laughter and a solid foundation.

And for KBM, the best team mate I could wish for.

“For your kindness, I'm in debt to you  
For your selflessness, my admiration.”

## Abbreviations

C = Colluvial

DOC = Dissolved Organic Carbon

F = Fluvial

IC = Inorganic Carbon

M = Morainal

O = Organic

SE = Standard Error

SLR = Sooke Lake Reservoir

SRP = Soluble Reactive Phosphorous

TC = Total Carbon

TDN = Total Dissolved Nitrogen

TDP = Total Dissolved Phosphorous

TN = Total Nitrogen

TP = Total Phosphorous

# Chapter 1 General Introduction

## 1.1 THESIS OBJECTIVES

The primary objective of this thesis was to identify differences in nutrient distribution ( $\text{NO}_3^-$ ,  $\text{NO}_2^-$ ,  $\text{NH}_4^+$ , TDN, TN,  $\text{PO}_4^{3-}$ , TDP, TP, DOC, IC, TC) among four different soil types (Morainal, Fluvial, Colluvial and Organic), in cleared riparian areas surrounding a drinking water reservoir, Sooke Lake Reservoir (SLR). Both saturated riparian and upland areas were chosen as part of 17 transects surrounding the entire reservoir.

Providing watershed managers with the knowledge of soil nutrient distribution and hydrologic pathways at SLR will allow them to anticipate potential release of nutrients.

Nutrients are predominantly delivered to water bodies via subsurface flow through riparian areas. The hydrology of riparian zones may be strongly influenced by the hydrogeologic setting (Lowrance *et al.* 1997, Vidon and Hill 2004) and topography can have significant effects on the hydrologic functioning of riparian areas through the hydraulic gradient, volume and velocity of water entering the area (Devito *et al.* 2000). Because of the shallow soils of the riparian areas in SLR, we expected topography to be the main factor in establishing the hydrologic flow patterns. The role of geomorphology and subsurface hydrology on the movement and accumulation of nutrients through riparian areas was documented.

## 1.2 STUDY AREA

The Sooke Lake Reservoir is located approximately 30 km NW of Victoria on SE Vancouver Island (48°33' N and 123° 41' W). On average this area receives 1465 mm of annual precipitation (Canada 1994). Most of the precipitation falls in November, December, and January, while July and August receive the least amount. Mean January

and July air temperatures are 2.7°C and 17.3°C respectively (Canada 1994). During this study the sites received 457.5 mm of rain during sampling periods and 577.3 mm of rain over the entire time period. The catchment area is dominated by coastal douglas fir (*Pseudotsuga menziesii* Franco), western red cedar (*Thuja plicata* Donn), and arbutus (*Arbutus menziesii* Pursh). All sites had been harvested prior to sample collection except Fluvial transects 1, 2, 5 and 6. Slash was removed with an excavator to minimise disturbance. Vegetation that grew in after harvesting included salal (*Gaultheria shallon* Pursh), Oregon-grape (*Mahonia nervosa* Pursh Nutt), trailing blackberry (*Rubus ursinus* Cham. & Schldl.) and scotch broom (*Cytisus scoparius* Link).

Seventeen riparian transects surrounding the reservoir were identified as representative of the soil at the Sooke lake reservoir and encompassed differences in geomorphology (Fig. 1). Four predominant soil types were targeted around the reservoir; Morainal (M), Fluvial (F), Organic (O) and Colluvial (C). Six Morainal and Fluvial transects were chosen because of their spatial representation around the Sooke Lake Reservoir and to include different slopes. Three transects were considered at low slope (<25% at M1-M3, F1-F3, O1, O2) and three transects at high slope (>25% at M4-M6, F4-F6, C4-C6). Only two organic areas existed, both at low slope. Three high slope Colluvial transects (C4, C5, C6) were chosen with sampling accessibility in mind. Because of the difficulty to find Colluvial sites that were not simply rock outcrops, two transects were established in close proximity to one another (C5, C6). During the soils study (chapter 2), all transects extended from 182 m elevation to 188 m elevation, where 182 m represents the toe of the slope and 188 m represents the top of the slope. Additionally, 188 m would still remain as a control site following inundation.

For the hydrologic study (chapter 3), one well was installed at three specific elevations, 182 m, 186 m, and 188 m along all transects. In the case of the wetlands, site 1 is closest to the reservoir and site 3 is the furthest. Two piezometers, one shallow and one deep were installed at each elevation along M2, M5, M6, F1, F4, F5 and C6 transects. Both wetland transects (O2 and O3) had both wells and piezometers installed.

### **1.3 RIPARIAN AREAS**

Riparian zones are the biogeochemical boundary between terrestrial and aquatic environments. Much attention has been paid to the importance of riparian areas as controllers of non-point source flux of nutrients (Peterjohn and Correll 1984, Haycock 1997, Rosenblatt *et al.* 2001). It comes as no surprise that, when addressing water quality, a thorough examination of riparian areas is warranted (Peterjohn and Correll 1984, Carpenter *et al.* 1998). The approach taken in this thesis was to examine the functioning of riparian areas at SLR in relation to geomorphology. This method of approach is supported by other studies where riparian areas were mainly influenced by landscape hydrogeological characteristics (Lowrance *et al.* 1997, Devito *et al.* 2000, Vidon and Hill 2004). In addition to identifying geomorphic areas of high nutrient content, the hydrology was studied at SLR to identify the linkages between hydrology and biogeochemistry known to affect the water quality function of riparian areas (Lowrance *et al.* 1997).

### **1.4 SOILS**

Many studies involving nutrient function in riparian areas have focused on various aspects of landscape controls or features of geomorphology (Pinay *et al.* 1995, Hill and Cardaci 2004, Vidon and Hill 2004). Soil variability, slope, and particle size distribution

are all factors that need to be considered in evaluating non-point source pollution (Calhoun *et al.* 2002). Landscape controls, such as slope, soil depth, topography, particle size, bulk density and also soil moisture status have been shown to be critical in the control of chemical transformations and pathways in nutrient release (Gold *et al.* 2001, Vidon and Hill 2004). This study focuses on geomorphic features as factors to test the distribution of nutrient concentrations.

Forested riparian areas have been well established as being effective controllers in the transport of pollutants (Perry *et al.* 1999, Rosenblatt *et al.* 2001). Further, they have long been viewed as nitrate sinks and removers (Peterjohn and Correll 1984, Pinay *et al.* 1995). However, cleared riparian zones have not been a focus in the literature.

Quantifying the effect of geomorphic features on nutrient concentration in a cleared riparian area at SLR will provide much needed information on the location of soil nutrients and their potential release into drinking water reservoirs. Understanding what physical processes influence these concentrations will better equip managers to anticipate adverse effects on drinking water as a result of nutrient loading. In addition to identifying the relationship between geomorphology and nutrient concentration, we strive to identify management implications for the SLR. In doing so, this study sets the groundwork for future research on nutrient transport in cleared riparian areas and to better management practices.

## **1.5 HYDROLOGY**

Researchers have noted that knowledge of hydrology is essential to understanding nitrate removal rates and N movement in riparian buffers (Hill 1990, Gilliam 1994, Mitchell 2001), but few have made detailed studies of local hydrology (Gilliam J.W.

1996). The flowpath of water from upslope areas influences chemical inputs as well as the degree and location of interaction within the riparian zone. By installing wells and piezometers at the top of a slope (188 m), midslope (186 m), and at the bottom of a slope (182 m), examination of the relationships between riparian zone hydrology and chemical transformation processes similar to studies by Hill (1990), Cirimo and McDonnell (1997), and Devito and Hill (1996) was permitted.

## **1.6 WATER QUALITY**

The detrimental effects of nitrogen and phosphorous nutrient loading into receiving waters, for example eutrophication, are widely known, but has been rarely examined in a single study since Dillon and Rigler (1974). Moreover, soil plays an important role in water quality in terms of non-point source pollution (Gburek and Sharpley 1998) and soil variability, slope, and particle size distribution are all factors that need to be considered in evaluating nutrient loading (Calhoun *et al.* 2002). This thesis addresses both nitrogen, phosphorous and carbon loadings at SLR along with examining the effects of soil characteristics, slope and particle size on their concentration.

## **1.7 NITROGEN**

The release of  $\text{NO}_3^-$  may be controlled by watershed hydrology (McHale 2002). Riparian areas connected to large upland aquifers with more vertical flow through sediments, or areas that have internal hydrologic flow paths dominated by surface transport, have less effective  $\text{NO}_3^-$  retention (Hill 1990). Dilution from other groundwater connections may be a cause for decreased nitrate. However, aside from denitrification and plant uptake, a decrease in nitrate concentration in riparian areas can result from water passing below a riparian buffer at depths where the riparian areas

provide no buffer. During storm events a rising water table may flush any  $\text{NO}_3^-$  that has accumulated in upper soil layers to adjacent waters.

### **1.8 PHOSPHOROUS**

As with  $\text{NO}_3^-$ , subsurface water can provide an important non point source of phosphorous to SLR. Some riparian zones have been shown to act as P sinks during baseflow (Peterjohn and Correll 1984, Devito and Dillon 1993) and others observed riparian zones acting as P sinks on a seasonal basis (Mulholland *et al.* 2000). An area can become saturated with P allowing soil to act as a source rather than a sink.

Removal mechanisms of P in riparian zones include sorption of soluble P by surface soils, microbial and plant uptake. There has been debate over how much P can be retained by riparian areas. Generally, removal of dissolved P in surface runoff in riparian areas is considered to be effective (Lyons 1998).

A riparian zone may remove P to varying degrees based on seasonality and landscape position. This is because of seasonal changes in depth to water table, and temperature.

### **1.9 DISSOLVED ORGANIC CARBON**

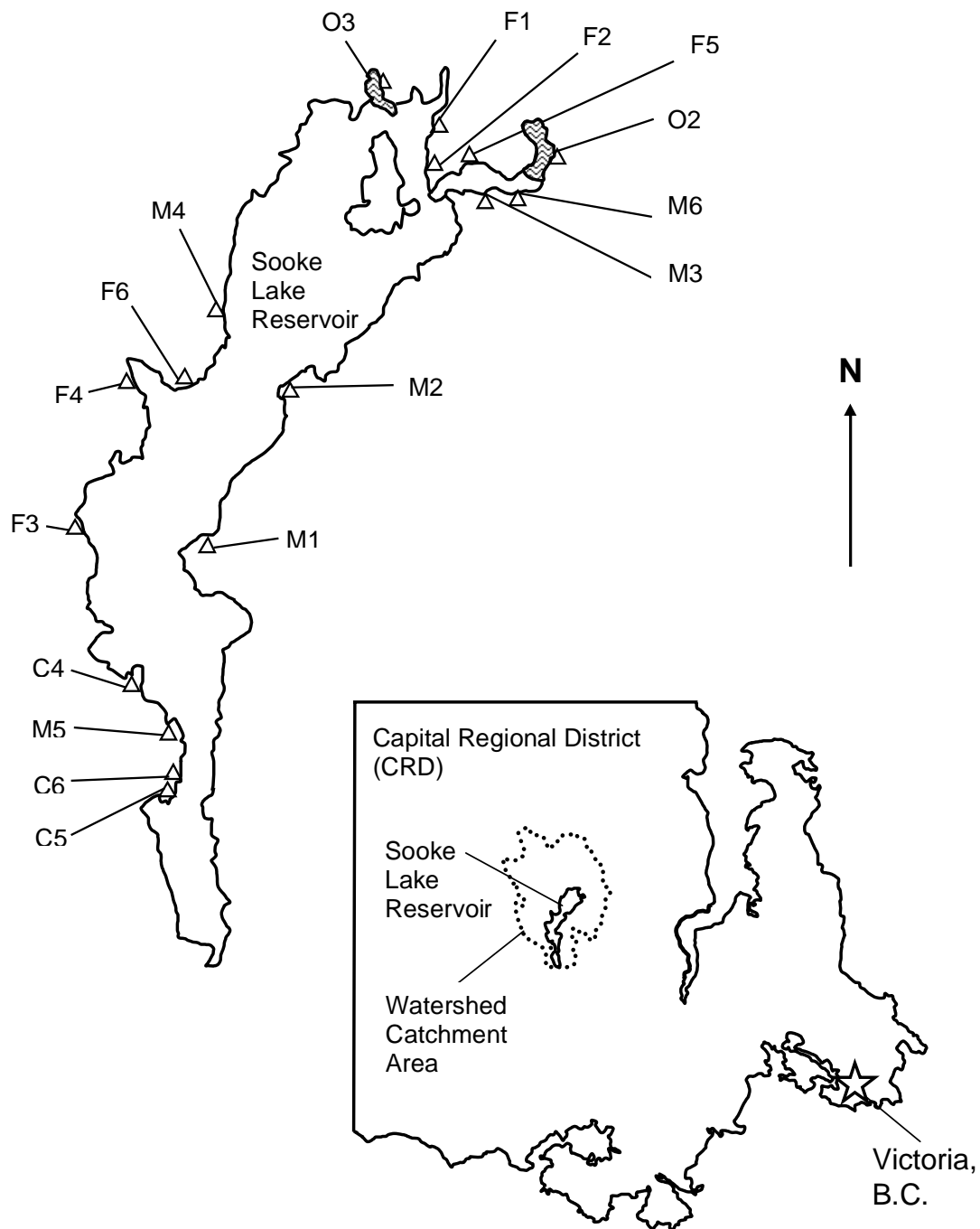
Dissolved organic carbon (DOC) is released from vegetation and soil organic matter. Concentrations of DOC seem to be high during warm periods where soil water content is low and after the input of fresh plant material. DOC contributes to the acidity of water, mobility and toxicity of metals and organic pollutants, and the availability of nutrients in soils and aquatic systems.

Variation in DOC concentrations and export from terrestrial catchments may be explained by differences in soil properties within catchments. Mechanisms whereby DOC is produced by vegetation and soil, ability of soils to retain DOC, and hydrologic

pathways that DOC takes from precipitation to the adjacent water body are critical in understanding DOC dynamic and the role of DOC in the C cycle (Moore 1997).

### **1.10 STRUCTURE OF CHAPTERS**

This thesis is comprised of four chapters: the general introductory chapter (chapter 1), two chapters reporting on two distinct aspects of the riparian areas surrounding Sooke Lake Reservoir (chapter 2 and 3), and a concluding chapter (chapter 4). The major findings of this thesis indicate that soil type has a large effect on nutrient concentration and that seasonality has a strong influence on the connectivity of subsurface flowpaths.



**Figure 1.** Sooke Lake Reservoir location and transect site map. Letters represent: M = Morainal, F = Fluvial, C = Colluvial, and O = Organic

## Chapter 2 Geomorphic Effects on Nutrient Distribution in Riparian Areas surrounding the Sooke Lake Reservoir

### 2.1 INTRODUCTION

Riparian zones are the biogeochemical boundary between terrestrial and aquatic environments, and when addressing water quality issues riparian areas must be examined (Peterjohn and Correll 1984, Carpenter *et al.* 1998). Nitrogen and phosphorous nutrient loading into receiving waters can cause detrimental effects, such as eutrophication (Dillon and Rigler 1974). Given these facts, this study has addressed both issues.

In Victoria, British Columbia, population growth increased water demand beyond the capacity of the drinking water reservoir at Sooke Lake, necessitating a higher dam be built to increase the reservoir's volume. Upon completion of a new dam in 2002, 131 ha of riparian land was flooded. The Capital Regional District (CRD) cleared 133 ha of riparian land in preparation for this inundation. Thus, detailed knowledge of the physical and chemical dynamics in the riparian soils was required to understand the impact of flooding on the reservoir.

Many studies involving nutrient function in riparian areas have focused on various aspects of landscape controls or features of geomorphology (Pinay *et al.* 1995, Hill and Cardaci 2004, Vidon and Hill 2004). Soil variability, slope, and particle size distribution are all factors that need to be considered in evaluating non-point source pollution (Calhoun *et al.* 2002). Landscape controls, such as slope, soil depth, topography, particle size, bulk density and also soil moisture status have been shown to be critical in the control of chemical transformations and pathways in nutrient release (Gold *et al.* 2001, Vidon and Hill 2004). This study focuses on geomorphic features as factors to test the distribution of nutrient concentrations.

Forested riparian areas have been well established as being effective controllers in the transport of nutrients as pollutants (Perry *et al.* 1999, Rosenblatt *et al.* 2001). Further, they have long been viewed as nitrate sinks and removers (Peterjohn and Correll 1984, Pinay *et al.* 1995). However, cleared riparian zones have not been a focus in the literature.

Quantifying the effect of geomorphic features on nutrient concentration in a cleared riparian area will provide much needed information on the location of soil nutrients and their potential release into drinking water reservoirs. Understanding what physical processes influence these concentrations will better equip managers. This study's objectives are to identify the relationship between geomorphology and nutrient concentration; and identify any management implications for the Sooke Lake Reservoir. This study sets the groundwork for studies on nutrient transport in cleared riparian areas and to better management practices.

## **2.2 MATERIALS AND METHODS**

### **2.2.1 Study area**

The Sooke Lake Reservoir is located approximately 30 km NW of Victoria on SE Vancouver Island (48° 33' N and 123° 41' W). The study area is part of the Nanaimo lowland, and part of the Coastal Western Hemlock Very Dry Maritime Subzone (Meidinger and Pojar 1991), this includes all land on the east coast of Vancouver Island that falls below 600 m elevation (Stewart 2001). The summers are warm and dry and winters are wet and mild with relatively little snowfall. On average this area receives 1465 mm of annual precipitation (Atmospheric Environment Service 1993). Most of the precipitation falls in November, December, and January, while July and August receive the least amount. Mean January and July air temperatures are 2.7°C and 17.3°C

respectively (Atmospheric Environment Service 1993). During January 2002 and May 2003, the study site received 577.3 mm of rain, of which 457.5 mm was received during the sampling period. The catchment area is dominated by coastal douglas fir (*Pseudotsuga menziesii* Franco), western red cedar (*Thuja plicata* Donn), and arbutus (*Arbutus menziesii* Pursh). All sites had been harvested prior to sample collection except Fluvial transects 1, 2, 5 and 6. Slash was removed with an excavator to minimise disturbance. Vegetation that grew in after harvesting includes salal (*Gaultheria shallon* Pursh), Oregon-grape (*Mahonia nervosa* Pursh Nutt), trailing blackberry (*Rubus ursinus* Cham. & Schldl.) and scotch broom (*Cytisus scoparius* Link).

Seventeen riparian transects surrounding the reservoir were identified as suitable to meet the needs of the project. Four predominant soil types were targeted around the reservoir; Morainal (M), Fluvial (F), Organic (O) and Colluvial (C). Six Morainal and Fluvial transects were chosen because of their spatial representation around the Sooke Lake Reservoir and to include different slopes. Three transects were considered at low slope (<25% at M1-M3, F1-F3, O1, O2, O3) and three transects at high slope (>25% at M4-M6, F4-F6, C4-C6). Only two organic areas existed, both at low slope. Three high slope Colluvial transects (C4, C5, C6) were chosen with sampling accessibility in mind. Because of the difficulty to find Colluvial sites that were not simply rock outcrops, two transects were established in close proximity to one another (C5, C6). All transects extended from 182 m elevation to 188 m elevation (Fig. 1).

The two major types of bedrock underlying the study area are Lower Paleozoic Colquitz and Wark Gneiss (Muller 1980). The most abundant soil type is a Humo-Ferric

Podzol. The most common soils are the Orthic Humo-Ferric Podzol (OHFP), Orthic-Dystric Brunisol (ODB), and Duric Dystric Brunisol (DDB; Table1).

Clay was the least abundant soil texture found at the Sooke sites ranging from 8.6% at Fluvial sites to 7.0 % at Colluvial sites (9.8% at Fluvial sites to 15.2 % at Colluvial sites using sieving). The percentage of silt was lower, ranging from 6.7% at Fluvial sites to 8.3% at Colluvial sites. Sand was the most abundant soil texture, ranging from 82.2% at Fluvial sites to 75.3% at Colluvial sites. The greatest variability of texture within soil type was found within Morainal sites Clay ( $SE \pm 1.2$ ), Silt ( $SE \pm 0.7$ ), Sand ( $SE \pm 1.6$  N=6) and the least within Colluvial sites Clay ( $SE \pm 0.36$ ), Silt ( $SE \pm 0.72$ ) , Sand ( $SE \pm 0.9\%$  N=2). Generally sandy loams or loamy sands dominate at the site.

### **2.1.2 Soil sampling**

Sampling took place between November 23, 2001 and January 30, 2002. Transects were surveyed in by crews employed by the CRD. The surveyors established points every meter from 182 m through to 186 m and again at 188 m. 105 soil pits were dug at every surveyed meter and soil samples were taken at three depths (0-10 cm, 10-30 cm and 30-60 cm). Samples were collected from each cardinal direction of the pit within the depths of concern, using a trowel. These samples were used for soil extractions, archival samples and for calculating soil moisture content. Bulb cores were taken at each elevation to determine bulk densities. At the 182 m pit a cumulative sample (0-60 cm) was taken for particle size examination. Particle size was determined by both sieving and hydrometer methods (Gee and Bauder 1986). Due to time constraints sampling took place during the wettest months for the region (Atmospheric Environment Service 1993)

and as a result some samples could not be collected because of high water tables. At the Organic sites, samples were collected using a bucket soil auger.

Soil samples arrived at the lab within 12 hours of sampling. All nutrient analyses were carried out immediately. Samples were mixed thoroughly and large woody debris removed. Once in the lab, the soil cores were then weighed using an analytical balance ( $\pm 0.01$  g). The soil was dried at  $105^{\circ}$  C for 24 hours. Soils used for thermogravimetric determination of soil moistures were treated the same as the bulk densities. Soil extractions were prepared using dried soil (5 g) added to a plastic centrifuge vial (50 mL Corning <sup>TM</sup>, One Riverfront Plaza, Corning, NY) to which 2M KCl (50 mL) or deionized water (50 mL) was added. Once the fluids were added to the soil in a centrifuge tube, they were agitated for one hour on a shaking table. The samples were then centrifuged for 10 minutes and immediately filtered through a nitrocellulose filter (47mm 0.45  $\mu$ m pore general filtration membrane filter, Fisherbrand 09-719-1B, Fisher Scientific, Ottawa, Ont.). The filtered extract was then divided into scintillation vials specific for each nutrient analysis, and then frozen to  $-20^{\circ}$  C.

Samples that were analyzed for dissolved organic carbon were filtered through polyvinyl durapore filters (47 mm 0.45  $\mu$ m Durapore, Fisherbrand HVLPO4700, Fisher Scientific, Ottawa, Ont.). Soil KCl extract from soil samples were analysed for  $\text{NO}_3^-$  and  $\text{NO}_2^-$ , while soil deionized water extract were analyzed for all other variables (Sparks 1996).

Soil extraction analyses were carried out on a Lachat autoanalyzer using colorometric/automated cadmium-reduction methods (Zellweger Analytics, Milwaukee WI 1999). Total dissolved phosphorous (TDP) was analysed using the Murphy-Riley

Method (Murphy 1962) on a visible spectrophotometer (Pharmacia Biotech Ultrospec, Uppsala, Sweden).

Soil concentrations were converted from a per gram basis to an areal basis using mean bulk density measurements for each soil type at each depth, with the exception of O soils which were calculated based on numbers provided by Mitsch and Gosslink (2000).

### **2.2.3 Statistical analyses**

Descriptive statistics were calculated for particle size, bulk density and soil moisture. To determine if nutrient concentrations varied according to soil type, a one factor multivariate analysis of variance (MANOVA) was performed (Zar 1996). Soil type was considered the independent variable and nutrients were considered the dependent variables. Wilks Lambda P value was used to test the significance of the variables' relationship (Zar 1996). To determine which nutrients differed among which soil types, univariate analysis of variance (ANOVA) was performed. A three factor ANOVA was carried out to determine the effects of slope, elevation and depth on the concentration of each nutrient in M and F soils only. All non-significant interactions were removed. P values reported are from analyses that do not include non-significant interactions. Significant results were further analysed by multiple comparisons (Bonferroni-Dunn) to establish which soil types differed for each nutrient tested. A two factor ANOVA was carried out to determine the effect of elevation and slope in C soils on nutrient concentration. The effect of depth on nutrient concentration in O soils was tested by a one factor ANOVA. A significance level of  $P=0.05$  was used for all analyses. Data was analysed using Statview (v5.0, SAS institute, Cary, NC).

## 2.3 RESULTS

### 2.3.1 Particle size

Clay soils are characterised as mineral particles of less than 20 $\mu\text{m}$ , while silt soils are defined as mineral particles with dimensions of 500-20  $\mu\text{m}$ . Sand was characterised as mineral particles between 125  $\mu\text{m}$  - 2 mm, and was abundant through all soil types. Colluvial soils have the greatest percentage of clay (15.22%) and silt (8.33%), compared with F (9.8%, 6.3%) and M (12.5%, 6.8%) soils (Gee and Bauder 1986).

### 2.3.2 Bulk density

Mean bulk density ( $\text{g}/\text{cm}^3$ ) was greatest in 30-60 cm depths at Morainal and Fluvial sites and 10-30 cm at Colluvial sites as this was the deepest possible sample. The lowest values were found in the 0-10 cm sites. All sites were very rocky (Neimann and Edgell 1993; Table 2).

### 2.3.3 Soil type

Nutrient concentrations were very highly significantly different among soil types (MANOVA  $P < 0.0001$ ), indicating uneven distribution of nutrients throughout the riparian areas of SLR, likely caused by differences in geomorphology, as exemplified by soil type.

All nutrients with the exception of TDN differed very highly significantly with soil type (Fig. 2, Table 3). TDP, TDN and  $\text{NO}_3^-$  concentrations were greatest in Colluvial soils, with  $\text{NO}_2^-$  concentrations only slightly lower in C soils than the greatest concentration found in F soils. Significant ANOVA analysis was followed by multiple comparisons that indicated all differences between soil types were very highly significant. Specifically,  $\text{NO}_3^-$  concentrations differed significantly between C and F and

C and O soil types.  $\text{NO}_2^-$  concentrations differed significantly between F and O and C and O soil types. TDP concentrations differed significantly between C and M, C and O and F and O soil types. DOC concentrations differed significantly between F and M and F and O soil types.

#### **2.3.4 Slope, elevation, and depth in F and M soils**

Elevation had no effect on any nutrient concentration in either M or F soil type, consequently elevation was omitted from Fig. 3A & B, and the three-way interaction was removed. Morainal and Fluvial soil types are the only soil types which included all three geomorphic features, and are thereby the soil types included in these analyses.

#### **2.3.5 Slope and depth: M soils**

The only significant interaction that occurred in M soils was between slope and depth. This suggests that the differences in  $\text{NO}_3^-$  and TDN concentrations between high and low slope transects depends on the sampling depth of the soil. Despite this interaction there are still clear main effects of slope and depth on  $\text{NO}_3^-$  ( $P=0.009$ ,  $P=0.0001$ ) and TDN ( $P=0.0001$ ,  $P=0.0005$ ) concentrations.

Concentrations of  $\text{NO}_2^-$  were significantly higher in high slope than low slope sites ( $P=0.0013$ ) and there was a significant effect of depth on  $\text{NO}_2^-$  ( $P=0.0016$ ) and DOC ( $P=<0.0001$ ) concentrations. Multiple comparisons revealed a significantly lower concentration of DOC and  $\text{NO}_2^-$  in 0-10 cm depth soils than at 10-30 cm or 30-60 cm depth.

### **2.3.6 Slope and depth: F soils**

In F soils, concentration of TDN and DOC was significantly higher in high slope than low slope sites ( $P=0.022$  and  $P=0.0001$  respectively) and there was a very highly significant effect of depth on all nutrient concentrations ( $\text{NO}_3^-$   $P=0.0021$ ,  $\text{NO}_2^-$   $P=0.0001$ , TDN  $P=0.0153$ , DOC  $P=0.0003$ ) with the exception of TDP. Multiple comparisons revealed a significantly lower concentration of  $\text{NO}_3^-$ ,  $\text{NO}_2^-$  in surface (0-10 cm) soil depth than at subsurface (10-30 cm or 30-60 cm) soil depth, and a significantly lower concentration of TDN and DOC in 0-10 cm and 30-60 cm soil depth. These results clarify the importance of nutrient distribution with depth.

### **2.3.7 Elevation and depth in Colluvial soils**

Elevation had a very highly significant effect on TDP concentrations (ANOVA,  $P<0.0001$ ); more specifically every depth differed significantly with 188 m (Fig. 4). Two factor ANOVA's were used to test if elevation and depth had an effect on nutrient concentrations in Colluvial soils. There was no two way effect on any nutrient. Depth however, had a very highly significant effect on  $\text{NO}_2^-$  and DOC (ANOVA,  $P=0.0001$ ). Multiple comparisons revealed that there were very highly significant differences between 0-10 cm and 10-30 cm, and between 0-10 cm and 30-60cm depth.

### **2.3.8 Depth in Organic soils**

One factor ANOVA's were used to test if depth had an effect on nutrient concentration in organic soils (Fig. 5). Depth had an effect on  $\text{NO}_2^-$  ( $P<0.0001$ ),  $\text{NO}_3^-$  ( $P<0.0001$ ) and DOC ( $P<0.0001$ ). TDP and TDN were not affected by depth ( $P=0.025$  and  $P=0.156$  respectively).

## 2.4 DISCUSSION

At SLR, nutrient concentrations differ among the four predominant soil types, which indicates that geomorphology influences the cycling of nutrients. At SLR there was a significant difference among all soil types and all nutrients, except TDN, and at all depths. This was anticipated and is supported by other research (Kutiel and Shaviv 1992, Venuto *et al.* 2003). Soil type is based on the lithology and parent material of the area. Once geomorphic conditions have been established, biological and chemical changes occur.

### 2.4.1 Geomorphic features: slope, elevation, particle size

We expected steeper slopes would encourage soil erosion potential and therefore nutrient translocation. We found that slope did have an influence at M and F sites. Fluvial soils had greater concentrations of  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ , and TDP in low slope transects while greater concentrations of TDN and DOC were located in high slope transects. In M soils, TDN,  $\text{NO}_3^-$ ,  $\text{NO}_2^-$  and DOC concentrations were greater in high slope transects while TDP concentrations were greater in low slope transects. The M patterns dispute the idea that steep slopes lose nutrients through soil erosion (Wang *et al.* 2001). It could be that the higher concentration of nutrients on steep slopes are found in preferential pathways as indicated in Kleinman *et al.* (2003).

We found that elevation did not have any relationship with nutrient concentration, with one exception, TDP in Colluvial soils. This relationship indicates that all three sites along each transect had similar nutrient concentrations. Our study does not support the findings of Wang *et al.* (2001) that revealed a tendency for greater values of nutrients at the bottom of a slope.

Soil texture at C, M, and F sites is dominated by sand and gravel. This information alone allows insight into hydrological, chemical, and therefore microbial possibilities. Sandy podzols dominate at SLR, with F soils having the largest percentage of sand and C soils having the largest percentage of clay among all soil types. Sandy podzols have a low water holding capacity, not beneficial for bacteria in general and specifically not denitrifying bacteria (Groffman *et al.* 1992). Sudden, divisive seasons of very dry and very wet dominate the climate at SLR. When a cleared riparian zone with high hydraulic conductivity “wets up”, leaching generally occurs taking with it nutrients that have little time to interact with the soil matrix, and therefore little time for chemical transformation. The importance of understanding this geomorphic characteristic can be exemplified further. Studies have shown that nitrogen cycling increases with decreasing particle size (McClaugherty *et al.* 1985, Groffman *et al.* 1993). In coarser soils the vegetation tends to be of lower litter quality, and therefore low N mineralization and low soil  $\text{NO}_3^-$  results. At SLR the litter (f and h layer) is very thin or non existent. Lamb (1975) found a pattern of net mineralization associated with soil type. The lowest mineralization rates were found in sandy Podzol soils having large f and h layer accumulations.

Soils with smaller particle size means greater moisture holding capacity and higher base cation content. In other words, over time more C and N accumulates in the soil. This is not a common trend with gravely and sandy soils, where accumulation is slower. Prescott *et al.* (2000) found that even within stands of the same species, differences in soil texture may lead to measurable differences in N cycling by influencing the build up of soil N. Reich *et al.* (1997) concluded from his study of 50 hardwood and conifer stands that soil properties exert a large influence on N mineralization rates. They found

that soil texture had significant impacts on N mineralization and net primary productivity, and that soil water content can decrease N mineralization by decreasing aerobic activity.

Kirby *et al.* (1997) have helped establish the well accepted fact that phosphorous leaches readily through sandy soils because of the coarse structure and lack of sorption sites. van Es (2004) found that P losses were more related to seasonal precipitation patterns than to the soil particles. This three year study also indicated that P loss to subsurface water was affected by soil type, where P was lost through a clay loam by preferential flow and through a sandy loam due to bypass flow. Djodjic *et al.* (2004) confirmed the idea that sandy soils with low sorption capacity have a high ability to release P unlike clay soils where there is prolonged contact between soil and soil water and P is thereby immobilised. P movement has also been associated with macropore flow in other studies (Kleinman *et al.* 2003) and is promoted by low saturated conductivity, common at SLR.

#### **2.4.2 Nitrogen distribution**

TDN is the main variable responsible for the difference in nutrient concentration with slope at SLR. In surface soils (0-10 cm)  $\text{NO}_2^-$  and TDN are almost twice the concentration in high slope versus low slope transects (Fig. 4). In particular high slope transects in M soils consistently had greater concentrations of all N components at all depths. It was expected that low slope transects would contain a greater concentration of nutrients due to a decrease in loss by erosion. It is surprising that high slope transects contain the greatest concentration of nutrients despite possible erosion.

### 2.4.3 Nitrogen: soil depth

M and F sites follow similar trends where N component concentrations increase with depth. Surface soils (0-10 cm) at C sites have the greatest mean concentration of  $\text{NO}_3^-$ . On the contrary  $\text{NO}_2^-$ , and TDN increase with depth. A study by Coats (1976) showed a decrease in  $\text{NO}_3^-$  concentrations with depth, while soil solution  $\text{NO}_3^-$  concentrations increased with depth in a study by Sollins *et al.* (1981). They expected the highest  $\text{NO}_3^-$  concentration differences to be in the most highly rooted zone, but instead the greatest concentration was below 1m. A similar trend was found in C soils at SLR where  $\text{NO}_3^-$  concentration was higher at the surface (0-10 cm). A similar result was also found with TDN that increased with soil depth.

Leaching is a logical mode of transport because sampling did take place during the months of heaviest precipitation (Atmospheric Environmental Service 1993) and following months of low precipitation. Any nutrients that may have been mineralized could have been flushed out during or slightly prior to our sampling dates. Autumn is commonly found to be the time of highest nutrient transport based on water yield. It is well accepted that following deforestation there is an increase in soil temperature and moisture (Lundborg 1997, Vance and Chapin 2001). These changes favour N mineralization and then nitrification, which without vegetation can lead to leaching (Stevens and Hornung 1988).

Trends in soil moisture may explain some of the differences seen in nutrient concentration with depth (Fig. 6). Soil moisture decreases with increasing depth in M, F, and C soils, a trend also found with decreasing TDP concentrations with soil depth in the

same soil types. This trend is opposite to all other nutrients, where concentration increases with soil depth.

#### **2.4.4 Nitrogen in wetlands**

$\text{NO}_3^-$ ,  $\text{NO}_2^-$ , and TDN all follow the same pattern, increasing concentration with depth. It would seem likely that denitrification would be occurring throughout the soil depth in these saturated areas. Instead, lowest N concentrations occur in the top 10 cm of soil. There are a number of processes that may explain the vertical trend in nitrogen components. For instance, high flow conditions may cause nutrient desorption at the sediment surface. Raisin and Mitchell (1995) found that increased discharge in wetlands resulted in an increase in release of nutrients. Groundwater discharge may also deliver  $\text{NO}_3^-$  and  $\text{NO}_2^-$  at depth (McHale 2002). Lower nitrogen concentrations at 0-10 cm depth may also be a result of plant uptake.

Clay content increased with depth at both organic sites, and it can therefore be hypothesized that the cation exchange capacity also increased with depth. This would reflect the TDN results but not the  $\text{NO}_3^-$  and  $\text{NO}_2^-$  trends.

#### **2.4.5 Phosphorous distribution**

It is understood that P movement in soils follows the direction of surface and subsurface flow. Therefore, accumulation is expected at the lower end of a hydrologic landscape (Smeck 1973). In Macrae *et al.* (2005), P content is shown to increase downslope due to redistribution (Smeck 1973, Honeycutt *et al.* 1990). It is logical that soils at the top of a toposequence (or upper end of the hydrologic gradient) would have lower nutrient concentrations than at the bottom. The only significant relationship along the toposequence from 188 m (top) to 182 m (low), indicates the opposite trend. In C

soils, the 188 m site has the largest TDP concentration and the concentration decreases with decreasing elevation. Subsurface flow cannot explain that trend, perhaps the 188 m site has the rock formation most resistant to erosion which guards against translocation or was a chemical binding site.

#### **2.4.6 Phosphorous: soil depth**

In a cleared riparian zone, harvesting has caused a decrease in P uptake by plants, and may subsequently increase weathering of soil and decomposition of litter. Nutrient movement will be dominated by chemical and physical translocation. When preferential flow occurs, P does not have the opportunity to interact with the soil matrix thereby passing active sorption sites. Because only the dissolved part of phosphorous was analysed in this study it is understood that any erosion or runoff that may have carried particulate P to the reservoir was not measured.

TDP does not follow a specific pattern among all soil types with depth. TDP at M and F transects decreases, and C increases with depth. The greatest mean TDP occurs in C soils and particularly at transect C5. In C soils the highest concentration of TDP was found between 10-30 cm. However, of all terrestrial soils, the highest mean TDP concentration was found between 0-10 cm. The high values at 0-10 cm depth may indicate overall low nutrient abundance. All the P is coming from plant material and is incorporated at the 0-10 cm depth according to Jobbagy and Jackson (2001). All C soils are on steep slopes which may account for the lower TDP concentration at 0-10 cm depth, due to surface runoff or flow through top 10 cm of soil, or simply erosion. At 10-30 cm depth TDP may be explained by leaching, where P concentrates around preferential pathways (Haygarth and Sharpley 2000). C soils also have the highest clay

content that could explain a slowing in diffusion, if low flow conditions allowed soil interaction.

Given the trend with elevation and Colluvial TDP concentrations, it would seem that TDP accumulated in the higher elevations and flowed faster further downslope to the bottom of the transect. F sites are the only soils where TDP concentrations decrease with depth, although M sites followed a very similar trend, with concentrations decreasing to 30 cm depth. TDP and soil moisture have a positive relationship in M and F soils ( $P=0.0005$  and  $0.0004$  respectively). TDP content was high at 10-60 cm depth at these sites, TDP moved through the profile and was possibly chemically bound.

#### **2.4.7 Phosphorous in wetlands**

The wetland areas at SLR may act as a source or sink for nutrient loading, depending on the balance between adsorption and release, and water residence time in the soils. It is difficult to ascertain what processes are occurring in these wetlands based on a single sampling event. No Fe, Al or Ca data preclude any definitive information on phosphorous binding, but based on the fact that these soils are humo-ferric podzols it is expected that Fe may play an important role. Wetland sampling was carried out in January, a time of very high stream flow and also of plant turnover. If the inflowing water from the watershed had a higher concentration of TDP than that in the soil water, P retention by Al, Fe, and organic matter may have increased (Froelich 1988). With plant turnover, decomposition would provide microbial populations with a carbon supply and phosphorous may have also been immobilized. With the sudden inflow of precipitation, higher concentrated TDP may have diffused up the water column and been transported to the reservoir.

However, the most likely scenario to explain the very low nutrient concentrations in the wetland soils is subsurface water flow or preferential flow. These flow regimes would provide a very quick path for nutrient movement where there is little interaction with the soil matrix (Jensen *et al.* 1998, Rutherford and Nguyen 2004). High precipitation has also been shown to cause preferential flow and movement through a very shallow part of the soil column (Scott *et al.* 1998). This may also explain why concentrations were so low at the 0-10 cm depth. Soils at 30 cm and deeper in the wetlands were sandy clayey silts (data not shown). The smaller particle size lends itself to holding greater amounts of P (Smeck 1985), which is exemplified at SLR.

## 2.5 CONCLUSIONS

The geomorphology of the SLR implies differences in the distribution of nutrients. Soil type plays the largest role in identifying which parts of these riparian areas contain the largest concentration of nutrients and may therefore be most problematic to managers. Particle size plays a major role in nutrient delivery throughout the riparian areas, the coarse sandy soils allowing for leaching. Leaching also plays a role in the redistribution of nutrients with depth. Unexpectedly, the distribution of nutrients did not follow a pattern previously reported in other studies (Kirkby *et al.* 1997) where nutrients accumulated at the bottom of the slope. The steepness of the slope was a factor in M and F soils, where TDN,  $\text{NO}_2^-$ , and  $\text{NO}_3^-$  were greater at high slope transects in F soils and high slope transects in M soils only TDP concentrations were lower in high slope transects. Overriding all these processes is the hydrology in the riparian areas. Preferential flow and leaching are the most prevalent processes when considering the distribution of nutrients in these cleared riparian zones. This paper shows that watershed

managers need to understand the types of soil surrounding drinking water reservoirs, and give specific attention to Colluvial soils. It is also evident that the hydrology of these areas is paramount to managers.

**Table 1.** Physical characteristics of each transect in the study.

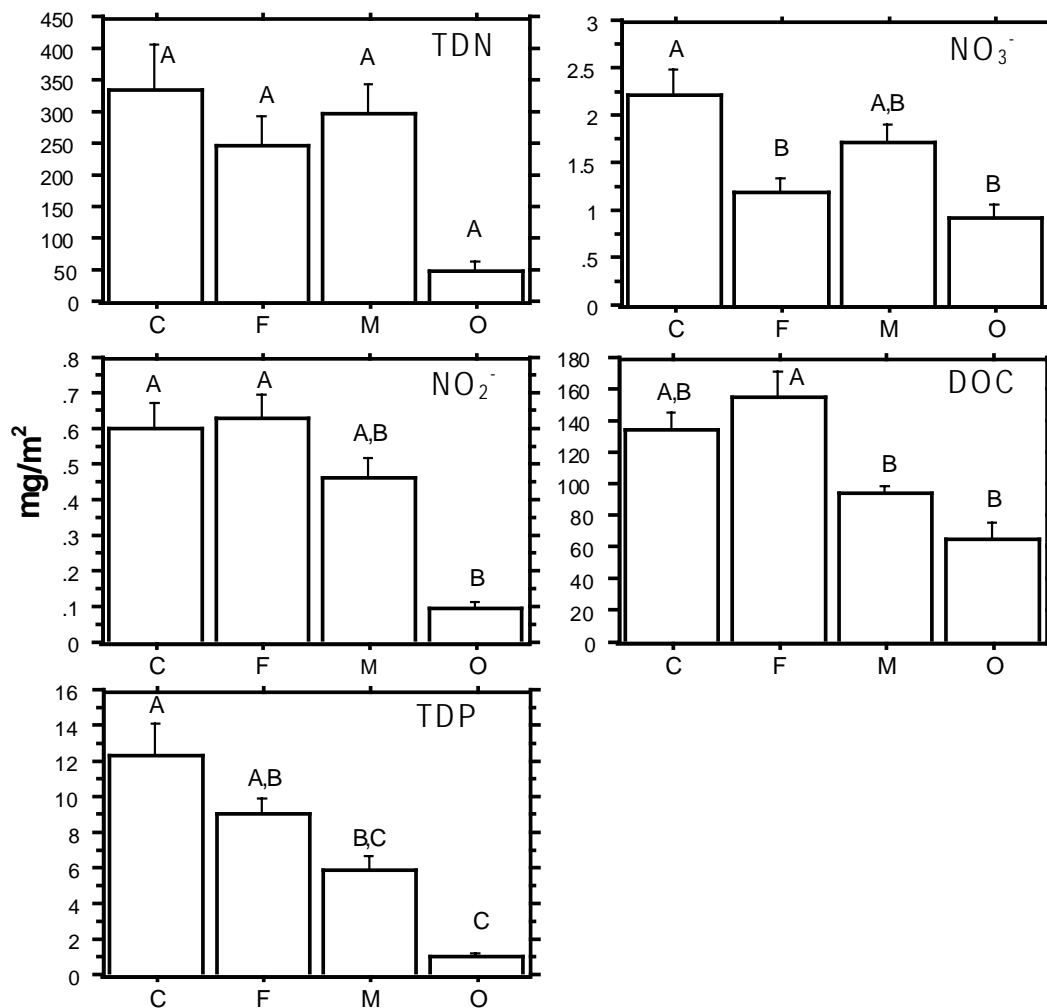
SITE	Classification	Phase	Parent Material	SLOPE %	Vegetation	Humus form	Rooting Depth (cm)
M1-182-188	Sombrio and Orthic Humo-Ferric Podzol	v. gravelly Ah horizon 10 cm or >	sandy, dimictic till blanket	8-10%	grasses	hemimor	30+ - 65+
M2-182-188	Duric-Humo-Ferric Podzol	v. gravelly Ah horizon 10 cm or >	sandy, dimictic till blanket	5-10%	salal, oregon grape	hemimor, none	50+ - 75+
M3-182-188	Gleyed, Duric and Orthic Dystric Brunisol	v. gravelly	sandy, gravely fluvial blanket dimictic till blanket	15%	grasses, sword fern, red cedar, douglas fir	Lignomor, hemimor	25+ - 51
M4-182-188	Orthic Sombrio Brunisol and Orthic Humo-Ferric Podzol	v. gravelly	sandy, dimictic till blanket	30%	minor salal	none	75+ - 130+
M5-182-188	Sombrio Humo-Ferric Podzol	Ah horizon 10cm or >	sandy, dimictic till blanket	30%- 45%	none	none	63+ - 130
M6-182-188	Duric Dystric Brunisol	None to v. gravelly	sandy, dimictic till blanket	5%-30%	grasses, sword fern, red cedar, douglas fir	hemimor	48-75+
F1-182-188	Duric Sombrio Brunisol	v. gravelly Ah horizon 10 cm or >	sandy, dimictic till blanket	15%-20%	salal, sword fern, blackberry, douglas fir	hemimor	40 - 56+
F2-182-188	Duric Dystric Brunisol	v. gravelly Ah horizon 10 cm or >	sandy, dimictic till blanket	5%-20%	salal, sword fern, blackberry, douglas fir, grass	Hemimor, none	41-80
F3-182-188	Orthic Humo-Ferric Podzol	v. gravelly	sandy, dimictic till blanket	7%	grasses	none	65
F4-182-188	Orthic Humic Gleysol, Duric Humo-Ferric Podzol	imperfectly drained Ah horizon 10 cm or >	gravely, sandy fluvial deposit	5%-15%	grasses	Lignomoder	54+
F5-182-188	Orthic Dystric Brunisol	v. gravelly	sandy, dimictic till blanket	45%	salal, douglas fir, oregon grape	hemimor	61-86
F6-182-188	Orthic Dystric Brunisol, Orthic Humo-Ferric Podzol	Shallow lithic v. gravelly	sandy diamictic till blanket to veneer	30%-45%	douglas fir, arbutus, w. red cedar, salal	hemimor	40-66
C4-182-186	Orthic Humo-Ferric Podzol	v. gravelly	sandy, dimictic till blanket	30%-40%	salal, oregon grape	hemimor	65-93+
C5-182-188	Orthic Humo Ferric Podzol	Shallow Lithic	Sandy, diamictic till blanket to Silty, sandy, rubbly colluvial blanket	70%	salal, blueberry, oregon grape, scotch broom	hemimor	63+ - 90
C6-182-188	Orthic Humo-Ferric Podzol	Ah horizon 10 cm or > shallow	Silty, sandy, rubbly colluvial blanket	70%	salal, blueberry, oregon grape, scotch broom	hemimor	35+ - 72+

**Table 2.** Mean bulk density ( $\text{g}/\text{cm}^3$ ) within each soil type, at each depth but including all elevations. Organic Bulk Densities were values taken from Mitsch and Gosselink, (2000).

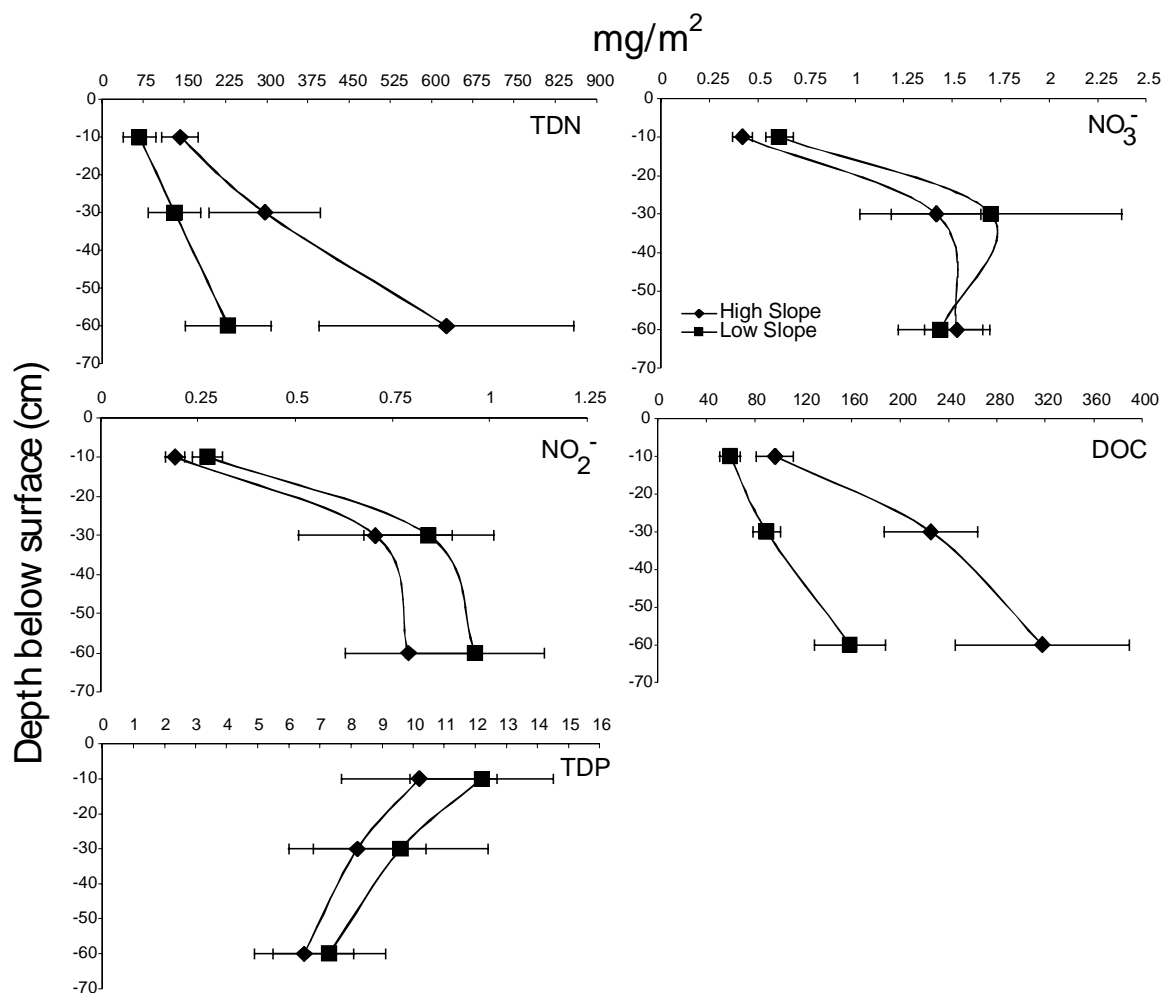
	<b>Mean</b>	<b>SE</b>
<b>Morainal</b>		
0-10 cm	0.466	0.045
10-30 cm	0.563	0.051
30-60 cm	0.555	0.054
<b>Fluvial</b>		
0-10 cm	0.447	0.046
10-30 cm	0.614	0.07
30-60 cm	0.713	0.074
<b>Colluvial</b>		
0-10 cm	0.460	0.084
10-30 cm	0.665	0.381
<b>Organic</b>		
0-10 cm	0.200	
10-30 cm	0.300	
30-60 cm	0.400	

**Table 3.** Effect of soil type on the concentration of each individual nutrient.

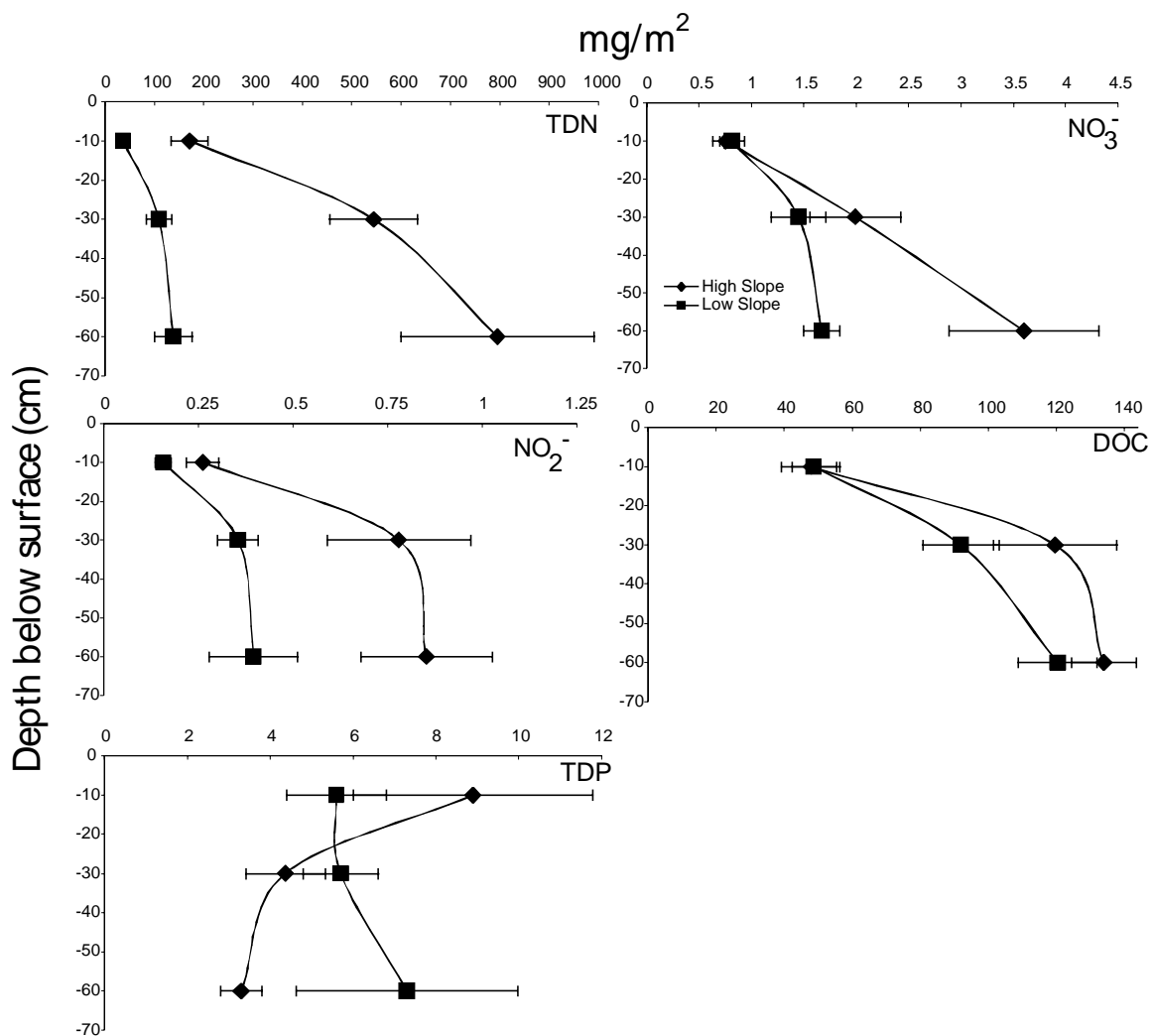
Nutrient	Factor	df	MS	P
TDP	soil type	3	843.763	<0.0001
	residual	278	89	
NO <sub>3</sub> -	soil type	3	14.808	0.0012
	residual	267	2.715	
NO <sub>2</sub> -	soil type	3	1.711	0.0015
	residual	275	0.325	
TDN	soil type	3	416436.1	0.1313
	residual	278	220193	
DOC	soil type	3	89712.01	0.0002
	residual	273	12835.14	



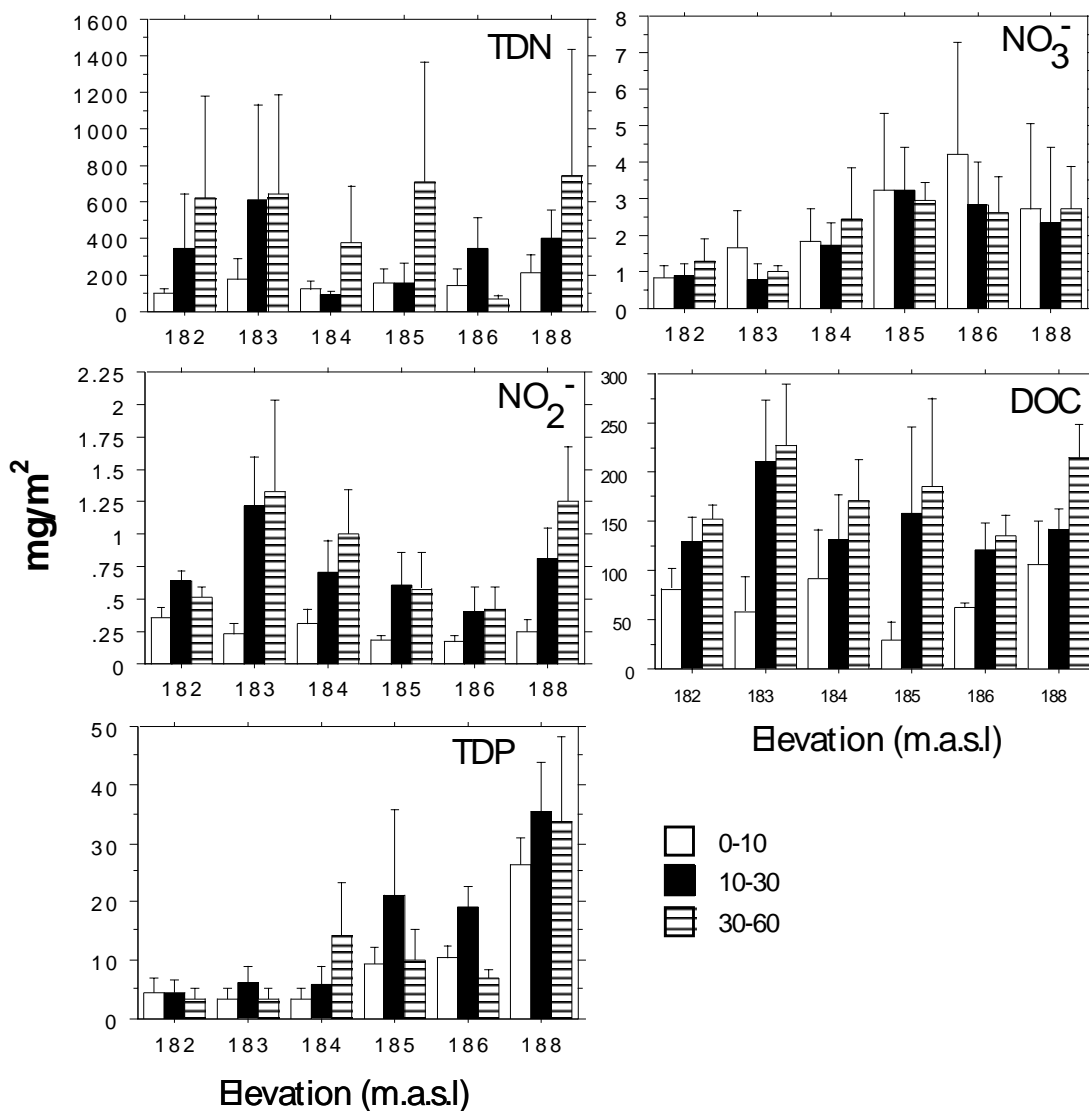
**Figure 2.** Nutrient concentrations in the four soil types studied at SLR: Colluvial (C), Fluvial (F), Morainal (M) and Organic (O). Letters A,B,C, D indicate differences among soil types following multiple comparisons test. Columns that share letters are not significantly different.  $\alpha = 0.0083$  set by Bonferroni-Dunn test. Note: Differences in scale on the Y axis. Error bars are  $\pm 1$  standard error bar.



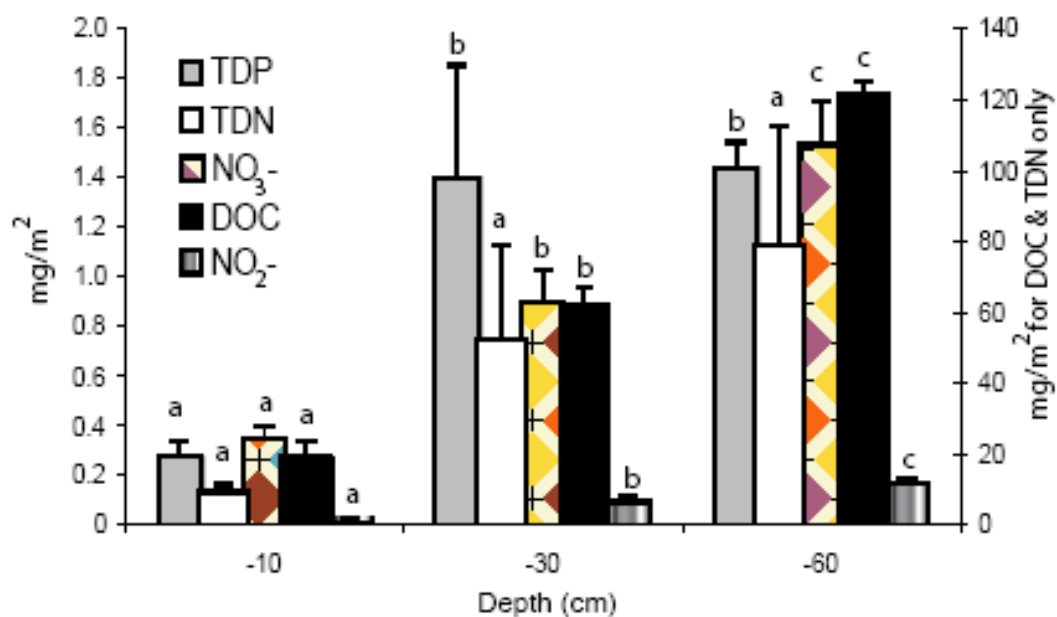
**Figure 3.** Nutrient concentrations in fluvial soils at SLR in high (>25%) and low (<25%) slope transects. Low slope transects in fluvial soils have greater concentrations of NO<sub>3</sub><sup>-</sup>, NO<sub>2</sub><sup>-</sup>, and TDP than high slope transects, whereas TDN and DOC show the opposite trend. Both fluvial and morainal soils tend to exhibit greater nutrient concentration with depth. Colluvial and organic soils were not included as they were characterised by only one slope type, steep or flat respectively. Symbols represent mean and error bars 1 S.E. Lines connecting points are for clarity and do not represent data.



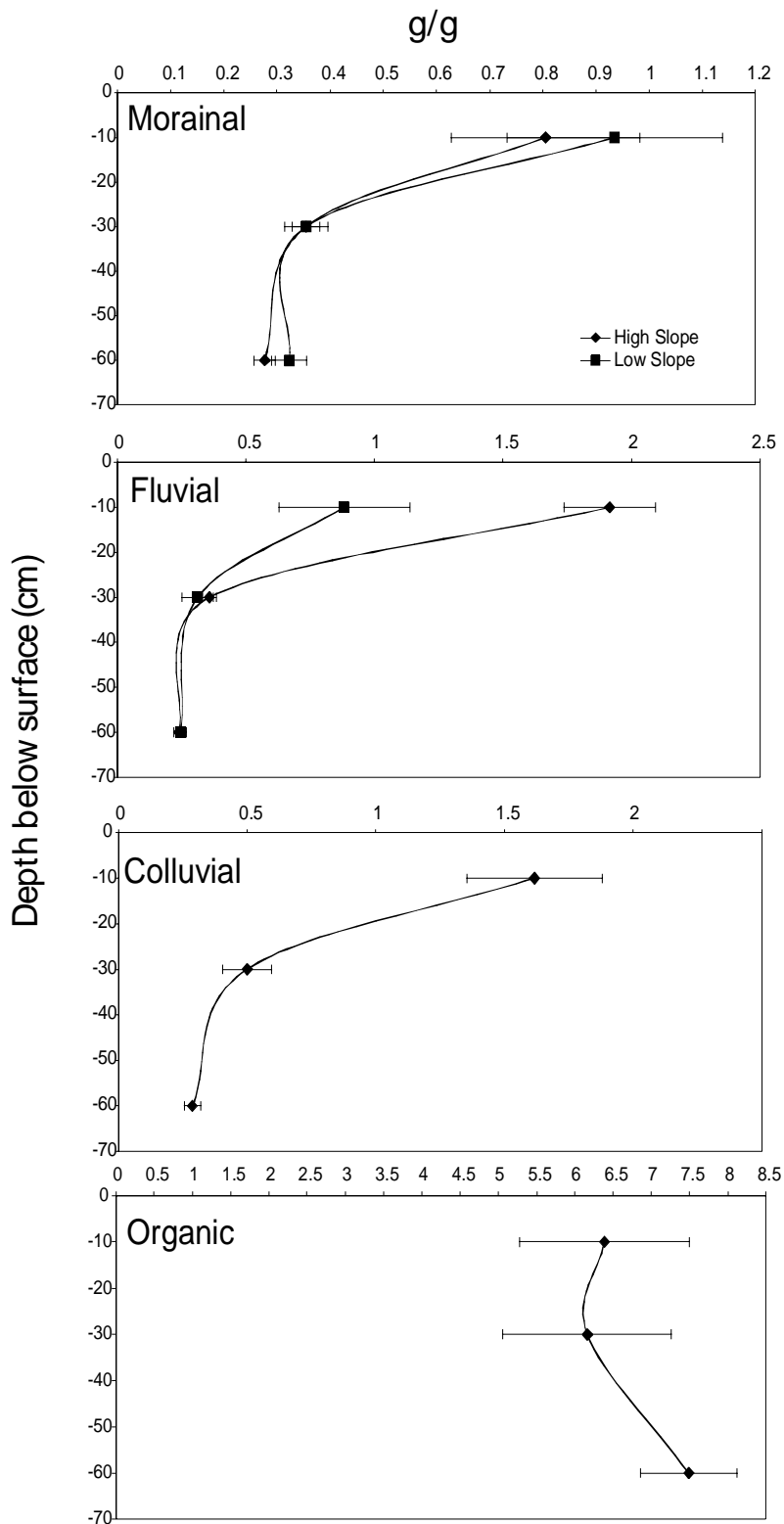
**Figure 4.** Nutrient concentrations in morainal soils at SLR in high (>25%) and low (<25%) slope transects. Only TDP in morainal soils differs from the trend of high slope transects having greater concentrations of nutrients. Both fluvial and morainal soils tend to exhibit greater nutrient concentration with depth. Colluvial and organic soils were not included as they were characterised by only one slope type, steep or flat respectively. Symbols represent mean and error bars 1 S.E. Lines connecting points are for clarity and do not represent data.



**Figure 5.** Distribution of nutrients in Colluvial soils at various elevations and depth. Data representing averages of two transects and elevation was measured as meters above sea level (m.a.s.l). Except in the case of TDP, nutrients were not significantly different at the various elevations following a two-factor ANOVA ( $P < 0.0001$ ).  $\text{NO}_3^-$ ,  $\text{NO}_2^-$ , and TDN at 30-60 cm depth generally had the greatest concentrations.



**Figure 6.** Nutrient concentration at various depths in an Organic soil. Columns represent the mean, error bars 1 S.E.M. Depth had a significant effect on the concentration of NO<sub>2</sub><sup>-</sup>, NO<sub>3</sub><sup>-</sup>, and DOC (one factor ANOVA). Different letters indicate significant differences between depths for a single nutrient only. Differences among nutrients at a single depth were not tested.



**Figure 7.** Mean soil moisture in each soil type. Moisture was greatest at the surface (0-10 cm) in all soil types except organic soils. In all soil types except organic, soil moisture is greatest in 0-10 cm depth. Lines between points do not represent data.

## Chapter 3 Hydrologic Function in the Riparian Areas surrounding the Sooke Lake Reservoir

### 3.1 INTRODUCTION

Nutrients are primarily delivered to water bodies via subsurface flow through surrounding riparian areas. The hydrology of riparian zones can be strongly influenced by hydrogeologic setting (Lowrance *et al.* 1997), topography and stratigraphy (Vidon and Hill 2004). For example, Devito *et al.* (2000) found that topography affected the hydrologic functioning of riparian areas through the hydraulic gradient, volume and velocity of water entering the area. In order to track the movement of nutrients (i.e. biogeochemical movement) through riparian areas, it is crucial to determine the hydrologic flow and pathway (Gold *et al.* 2001). In this chapter we study how landscape controls hydrologic flow patterns at the Sooke Lake Reservoir by examining the influence of topography and soil type, and describe the hydrologic function of the riparian areas.

Few studies couple water level fluctuations and physical parameters in varying soil types in the same lithology (Vidon and Hill 2004). This chapter does both by examining hydrologic functioning in the riparian areas surrounding SLR in four different soil types: Morainal (M), Colluvial (C), Fluvial (F) and Organic (O). The main objective here is to provide a thorough understanding of the local hydrologic system. Because of the shallow soils of the riparian areas, we expect topography to be the main factor in establishing the hydrologic flow patterns. We also hypothesize that in the wetland sites water will flow from site 3 (furthest from the reservoir) to site 1 (closest to the reservoir) due to topography. This flow pattern would be a function of both local and regional flow

patterns because of riparian hillslopes and nearby Begby Lake which sits higher in the landscape.

In addition, SLR has the geology that lends itself to good hydrological connection because it has a shallow confining layer, but a very high hydraulic conductivity. This characteristic has been highlighted as an important role in the development of connectivity (Ocampo *et al.* 2006). Connectivity is the connection of subsurface water flow in the soil of riparian zones and is important because it dictates the hydrologic pathway by which nutrients are delivered to nearby water bodies. Taking this into consideration, we generated hydrographs to document the connectivity between upland sites (188 m) and lowland areas (182 m). The importance of seasonality is illustrated through hydrographs, and is a common technique used to determine the effect of water in both the level of flow occurring throughout the year and to isolate episodic events. In the Pacific Northwest peak flows occur in the winter or early spring (Hall 1988). To examine the effect of seasonality on flow pattern, we focused on seven characteristic transects surrounding the SLR during two dates, each representing dry or storm event conditions, that highlight changes in connectivity between the upland and riparian sites.

Overall, the purpose of this chapter is 1) to examine the influence of topography and soil type on flow pattern in SLR, and 2) to describe the hydrologic function in SLR riparian areas by examining seasonal hydrologic connectivity between hillslopes and low lying areas.

## **3.2 MATERIALS and METHODS**

### **3.2.1 Study area**

The study area has been described in Chapter 1.

Transects were surveyed in by crews employed by the CRD. The surveyors established points at 182 m, 186 m and at 188 m elevation above sea level (a.s.l). Transects were situated perpendicular to the reservoir, and parallel to the anticipated direction of subsurface flow. Transects were used to represent flow conditions for each soil type. One well was installed at each elevation along all transects. In the case of the wetlands, site 1 is closest to the reservoir and site 3 is the furthest. Two piezometers, one shallow and one deep were installed at each elevation along M2, M5, M6, F1, F4, F5 and C6 transects, and is referred to as a piezometric nest. Both wetland transects (O2 and O3) had both wells and piezometers installed. They were installed using Dutch and Oakfield model C hand soil augers. Wells and piezometers were constructed from schedule 40 PVC, the wells were 0.0508 m outside diameter and piezometers were 0.01905 m outside diameter. Wells were slotted the entire depth of the pipe and were installed to a depth of 1 m to 1.5 m (referred to with the transect name, and elevation of the instrument, e.g. M5-182-W or O3-3-W). Piezometers were slotted at the bottom 0.15 to 0.30 m of the instrument, the shallow piezometer reached 0.5 m – 0.75 m and the deep piezometer was installed to a depth of 0.8 m to 1.8 m depth (referred to with the transect name, elevation and the depth of the instrument, e.g. C6-182-50 or M5-186-150). At the O3 site, piezometers were not installed until mid-September 2002 and so no head (water level) data exists before then. With the exception of M1, all focal sites had piezometer nests but may not be reflected in the graphs if they were dry.

Deeper wells hereafter referred to as DEEP, were installed to a depth of 3-4 m with the slotted pipe extending from 0.6 m to the depth of the hole. These instruments (this term includes wells and piezometers) were installed at the highest elevation, 188 m (M1, M4,

M6, F1, and F3), and at 186 m for one transect (M6), and are referred to as M1-188-DEEP etc. Holes for the DEEP wells were installed by an air-hose drilling 0.1016m carbide drill rig. These holes were sealed with bentonite, to stop surface or preferential flow.

We focus on seven sites that represent characteristic soil type, slope (topography) and depth. O3, C6, M1, M2, M5, F1, and F4. M1 was chosen because of the DEEP well, drilled at the 188 m site. These DEEP wells offer more data during dry periods. M2 is a flat site with piezometers and M5 is a steep site also with piezometers. F1 is a flat site with piezometers as well as a DEEP well and F4 is a steep transect with piezometers. The O3 site sits below Begby Lake, and will likely indicate any regional connectivity at the site, and the affect of the upland aquifer on this wetland is intriguing.

The sampling period took place from January 31, 2002 to May 1, 2003 to ensure a complete year was included. Two dates, September 16, 2002 and November 18, 2002, were chosen to represent average dry conditions and storm conditions respectively, for the following three reasons. First, they agree with average levels of precipitation over the last 30 years. From Fig. 8 we see that precipitation levels in September lie within that of an average dry period, while precipitation levels in November lie within the average amount of precipitation falling during the wettest times of the year. In 2002, September 16 was representative of the dry period of summer, with very little precipitation falling in the preceding five months (Fig. 9). In contrast, November 18, 2002 was the middle of a 6 day storm event, that lasted from November 14, 2002 to November 20, 2002. During the storm, 54.6 mm of precipitation fell between November 14, 2002 and November 18, 2002 with a total precipitation of 122.4 mm recorded by November 20, 2002. The

greatest amount of precipitation (61.9 mm) fell on November 19, 2002 (Fig. 9). Note, for the O3 transect we had to use September 30, 2002 as a representative dry date because piezometers were installed later at this transect and required time to be developed.

Secondly, using these two dates distil our results down to the period in which the most data is available for examining the contrast between wet and dry conditions. Thirdly, all sites had the greatest reaction to this storm event, when compared with all other storm events.

Head measurements were taken between January, 2002 to May, 2003, with the maximum number of measurements equalling 79 (O2) and a minimum equalling 38 (F5). Measurement frequency changed seasonally based on precipitation levels, from weekly during winter to monthly in the summer months. Head measurements were taken using a water level indicator (Geotechnical Instruments™, Leamington Spa, UK). Precipitation measurements were taken by CRD (Capital Regional District) using a tipping bucket (Forest Technology Systems™, Victoria, Canada).

### **3.2.2 Hydraulic conductivity**

The Hvorslev Slug test method (Hvorslev 1951) was used to determine the hydraulic conductivity at: all wetland sites, M1-188-DEEP, M3-182-W, M4-186-W, M4-188-DEEP, F3-188-DEEP, and F3-182-W. Shallow groundwater exchange within each transect (between 188 m and 182 m) for C, F and M sites, and within each transect (between site 1 and the reservoir) in Organic transects was calculated using Darcy's Equation (Freeze and Cherry 1979):

$$Q = -K \cdot A \cdot dh/dl, \quad (\text{eqn. 1})$$

where  $K$  is the saturated hydraulic conductivity (KSAT; m/s),  $A$  is the cross sectional area of flow ( $m^2$ ), and  $dh/dl$  is the hydraulic gradient (dimensionless). Cross sectional area ( $A$ ) was calculated based on distance between each site within the transect and the depth of the instrument. Mean KSAT values are listed in Table 4. If measurements could not be taken at a particular site, we used the nearest site of the same soil type. For the M1 and M2 sites we used the KSAT measured at the M1-DEEP well. For C6, F1, and F4 we used the KSAT values from F3. For M5 we used KSAT data from M4. M4 was spatially closest to Colluvial soils and this may be why the discharge rates are so close to C6.

### **3.2.3 Discharge**

Discharge was calculated using equation 1, specifically from the deepest piezometer at the 188 m site to the deepest piezometer at the 182 m site, along each transect. This measurement is site specific because the length of each transect varies. One factor analysis of variance (ANOVA) was used to establish if there was a significant effect of soil type on storm discharge rates, using all discharge rates calculated at all 17 sites. Statistical analyses were performed using Statview™ (v5.0, SAS Institute, Cary, NC).

### **3.2.4 Hydraulic gradient**

Vertical hydraulic gradients were based on the hydraulic head in both piezometers, and the distance between the piezometers in a single nest. The hydraulic gradients calculated were used to determine the direction of the subsurface flow.

### 3.3 RESULTS

Flow conditions at SLR vary significantly at different times of the year. This is a direct result of precipitation patterns. Shallow groundwater does not play a significant part in subsurface flow until the soil “wets up” and storm events occur. Precipitation data illustrates that the greatest amount of precipitation falls from November to March (Fig. 8). It also shows that in 2002 and 2003 monthly precipitation was greater than the average monthly precipitation from 1970-2001 at SLR with the exception of October. Precipitation that fell during the study period is illustrated in Fig. 8, which also illustrates the reservoir water level. There is an obvious downward trend in the water level until January 2003. The downward draw is a seasonal trend that was caused by little input to the reservoir but also by consistent drawdown by drinking water consumers. This trend was altered once the higher dam was built and completed in December 20, 2002, and reservoir levels were forever changed. Site profiles describe the location of the wells and piezometers at each transect, and the soil environment they are installed in (Appendix 1).

#### 3.3.1 Saturated hydraulic conductivity (Ksat)

Saturated Hydraulic Conductivity was greatest at the M4 transect, followed by the F3 transect (Table 4). The hydraulic conductivity of the remaining transects were more than an order of magnitude smaller than either M4 or F3. The average for the entire riparian area at SLR was  $2.16 \times 10^{-06}$  m/s .

#### 3.3.2 Discharge rates

All discharge rates increased during the storm event with the exception of M1 and M5, which peaked on November 25, 2002, at  $9.06 \times 10^{-05}$  m<sup>3</sup>/s (Table 5). M1 increased until December 9, 2002 at  $4.83 \times 10^{-06}$  m<sup>3</sup>/s. ANOVA results revealed that soil type had a

significant effect on discharge rate ( $P= 0.04$ ; Fig. 10). This difference appears to be driven by a much lower discharge rate in Organic soils when compared to Morainal and Fluvial soils. The fastest mean discharge rates occurred in Colluvial soils ( $7.07 \times 10^{-05} \text{ m}^3/\text{s}$ ), but the fastest transect specific discharge rate occurred at the M5 transect during the storm event ( $8.99 \times 10^{-05} \text{ m}^3/\text{s}$ ). The mean Organic and Fluvial site data indicate the greatest difference in discharge rates between dry (September 16, 2002;  $7.93 \times 10^{-09} \text{ m}^3/\text{s}$ ,  $3.17 \times 10^{-05} \text{ m}^3/\text{s}$  respectively) and storm conditions (November 18, 2002;  $1.75 \times 10^{-08} \text{ m}^3/\text{s}$ ,  $7.07 \times 10^{-05} \text{ m}^3/\text{s}$ ).

### **3.3.3 Subsurface water flow**

The seasonal soil saturation is clearly visible in hydrographs illustrating the water levels for the entire sampling period (Fig. 11). In general, water levels began dropping in February, reached a low in August-September and began to rise again in November. This seasonality is important to establish a more complete understanding of the hydrologic patterns at SLR. This data can then be applied to chemistry data to determine when nutrient loading will be greatest at SLR.

### **3.3.4 Subsurface event response**

At the O3 site the vertical hydraulic gradient clearly switched from a downward recharge trend to an upward discharge trend during the storm event (Table 6). However, the rest of the focal sites remained recharging even during the storm event.

The storm event snapshot was captured at each focal site (Fig. 11a-g). These figures use head levels to show the end of the dry period leading up to the storm event until the end of December. At many sites, there was a time lag before the subsurface head became apparent. Storm peaks occurred at different sites and within the same sites at different

times (Fig. 12a-f). At the O3-1 site, the well and piezometer head peaked on November 15, 2002. All sites along this transect were discharging subsurface water on November 15, 2002, this did not occur again during the event. It is apparent that the wetland head was responsive to precipitation with an approximate one day lag. The greatest head response was always found at O3-W. All sites (188, 186 and 182) at the Colluvial transect peaked on November 18, 2002, except for C6-186-85 and C6-182-W, which peaked on November 21, 2002. The 182 m site was consistent through the event and the 186 site the least consistent with the shallow piezometer never receiving water. There was slight subsurface discharge at the C-182 and C-186 site on November 21, 2002. All Morainal sites peaked on November 18, 2002, except M5-182-50, which peaked on November 21, 2002. The greatest response was always in the shallow piezometer, and the greatest variation in head between dates at the deep piezometer occurred at the 188 m site. At M2 only the wells and the 186-50 piezometer wet up on November 18, 2002. The two Fluvial transects showed differences. At F1 all instruments responded after 54mm of rain whereas at F4 all instruments peaked two days later, with the exception of F4-186-110, where it peaked on November 18, 2002. The shallow piezometer only responded at the 182 m site. The F1-188 DEEP instrument was recharging deep subsurface water on November 15, 2002, but discharge became apparent on November 18, 2002.

### **3.3.5 Seasonal response**

Hydrologic flow patterns are illustrated for the dry period (September 16, 2002) and wet period (November 18, 2002) described above, and can be found in Appendix 2. The November 18, 2002 figures show that after 54 mm of rain, all soil types and all sites were

still recharging on both flat and steep slopes except for the wetland site where subsurface water discharged at the 1 site during the dry conditions and was discharging from mid-transect during the storm event. The F4-186 and M1-188 sites were all discharging on November 18, 2002. On November 21, 2002, after an additional 62 mm of rain, there was an upward hydraulic gradient at M1-188. This gradient was consistent from December 5, 2002 to January 30, 2003. There was another storm event on March 14, 2002 (834 mm of rain following the November event) and some sites (F1-186, F4-186, O3-3, M1-188, and M5-182) showed signs of discharging. There was still no discharging at the Colluvial sites and no clear difference between the three different sites. The O3-3 site continued to discharge until the end of the study period.

### **3.4 DISCUSSION**

#### **3.4.1 Hydrologic connections**

The similarity between SLR geology and the geology of the Canadian Shield suggests that a minimum of 2 m of overlying till above a confining layer is necessary before permanent upland/lowland linkages can exist (Vidon and Hill 2004). At SLR, a confining layer of bedrock or large boulders was found three meters below the surface and the instruments generally sat in sandy soils.

As such, hydrological connection was expected along each transect during the winter months and during storm events when precipitation was greatest.

There was a complete hydrologic connection along all transects at all depths in only three of 17 transects during the storm event (Morainal 1 and 5, and Fluvial 1). No connectivity was caught by manual measurements in any Morainal, Fluvial or Colluvial sites throughout the entire time series. Despite no measurable connectivity along transects, the entire riparian area continued to recharge indicating that inflow to the SLR

must be discharging at a depth below what was monitored (Vidon and Hill 2004).

Perhaps because of the high hydraulic conductivity, the subsurface flow moves along the confining layer. Indeed, overland flow was observed at a 186 m site on a few occasions (November 2002, March 2003). This occurred on a very short, steep sloped (30% grade) transect (M4), and was also a factor of preferential flow as a result of large dead roots from forest harvesting.

### **3.4.2 DEEP wells – continuous flow**

Continuous flow did occur at the M1-DEEP, and F1-DEEP sites. In the M1-188-DEEP well the water table did not dip below the 3.32m depth of this well. The F1-188-DEEP well was also deep enough (2.86m) to have a consistent water level. Both of these DEEP wells were installed in either boulders or bedrock. This indicates that there was water storage or a perched water table in the bedrock at 188 m level. This may also be a sign of regional discharge. Determining the source of subsurface water can provide information on how that water body is sustained and on the biogeochemistry of subsurface water. This is also valuable when considering the impact of disturbance (Ferone and Devito 2004). No other instrument in the Colluvial, Fluvial or Morainal soils indicated a constant head measurement for the entire 15-month sampling period. This strongly indicated that there was no continuous flow in the riparian areas.

### **3.4.3 Wetland connectivity**

The hydrologic connectivity of a wetland can affect the ecology and water chemistry of a wetland (Devito and Hill 1997), and therefore the hydrogeologic landscape must be considered when discussing groundwater flow in wetlands (Winter and Woo 1990, Devito *et al.* 1996). The study area O3, sits below a shallow water lake (Begby),

connected seasonally by a stream. This wetland can be classified as a swamp (WS53; MacKenzie and Moran 2004), characterized by western redcedar (*Thuja plicata* Lumber), sword fern (*Polystichum munitum* Kaulf), skunk cabbage (*Lysichiton americanus* Haulten) and occurs in topographic depressions receiving discharge. Therefore, there is continuous subsurface flow sustaining the swamp. Although O3 was continuously receiving subsurface input, water levels were still visibly affected by precipitation events. These patterns suggest that the connection is to a local flow system.

#### **3.4.4 Subsurface event response**

All soil types, both slopes and all points along the hillslope were recharging through the entire year. It is apparent from Fig. 10 that the entire SLR site is very much influenced by precipitation events. This was anticipated given the very sandy and shallow soils. Preferential flow was also anticipated in the riparian areas because of recent logging, which causes large subsurface holes due to dead tree stumps and woody debris.

At Colluvial transects, the top and bottom of the slope responded on November 18, 2002, while the mid slope responded at the end of the storm event. There was however, never any response in the top 0.5 m at the midslope site. It is likely that due to the very stony and sandy composition of the soil and preferential pathways, the soil was never saturated above 0.5 m depth. The flowpaths must have passed below this instrument with saturation levels reaching only 0.8 m below the surface after significant precipitation.

At Morainal sites, there was a difference in subsurface flow patterns between the steep and shallow transects. M5 responded quickly to the storm event (after 44 mm of precipitation), which was anticipated given the steepness of the slope (30-45%) and

sandy soils. M5 also had the fastest discharge rates ( $8.99 \times 10^{-05} \text{ m}^3/\text{s}$ ). M5 responded differently than C6, another steep slope. Specifically, all instruments responded to the event on November 18, 2002 at the M5 midslope but did not respond at C6. However, at the bottom of the slope the 0.5 m piezometer took 2 days longer to respond. The topography of the bedrock may have affected this flow pattern (Buttle *et al.* 2004), where the soil was shallower at 186 m at M5 than at C6. This illustrates that the water travels below 0.5 m from the midslope to the reservoir. Middle or upper sections of hillslopes generate runoff due to preferential flow. Under very wet conditions these pathways can cause linkages of surface depressions (Fitzgerald *et al.* 2003). At the flat transect, M2, only the shallow midslope piezometer responded on November 18, 2002, but on November 21, 2002, the entire 182 m site was responding. These two Morainal (M) sites were located on opposite sides of the reservoir. M5 had a forested upland directly behind it that may provide more subsurface water storage than at the M2 site. It was hypothesized that willow trees in proximity to the M2 transect may have had an influence on subsurface flow patterns.

There were also differences between the steep and flat Fluvial transects. The steep transect (F4) took longer to respond to the storm event than the flat transect (F1). F4 seemed to follow the pattern of the other steep transects where subsurface flow was below 0.5 m. The DEEP well at F1-188 indicated that there was more surface input at the 188 m site than subsurface water. This may indicate a switch from a regional flow system to a localized system. Although many studies found that flatter areas receive deeper subsurface input than steep slopes (Dietrich and Montgomery 1995), this was not

observed at F1 and F4. This may be due to short transect lengths and closeness to the reservoir.

At the O3 site, baseflow conditions continued through the year, as a result of connectivity to Begby Lake. The finer sediment found in the wetlands at 0.5 m and deeper acted as a hydrologic boundary. During storm events the wetland reacted quickly because it was already saturated from baseflow. Overland flow occurred because of the combination of precipitation and subsurface discharge. Subsurface water discharge continued until November 20, 2002.

#### **3.4.5 Influence of reservoir on low elevation sites**

Precipitation, urban water demand, and dam construction all contribute to water level fluctuations at SLR. These fluctuations impacted the low elevation, 182 m sites. Burt *et al.* (2002) reported that it is unusual for water bodies adjacent to riparian zones to influence the riparian zone, as hydraulic gradients leading away from the water body towards the land should be rare. However, there were flow reversals (hydraulic gradient flowed toward the riparian zone) between February 2003 and April 2003, and once the new dam was built, the hydraulic gradient was toward the riparian zone from February 28, 2003 until April 2003. The flow reversals into the riparian areas observed here are unique because they arise from an anthropogenic cause. Often flow reversals occur in peatlands due to droughts or evapotranspiration demands (Winter 1995). Wetlands that are closely located to a lake will certainly share a groundwater system (Winter 1999). From March 2003 until May 8, 2003, the hydraulic gradient was towards O3, again indicating flow reversal. These hydrologic patterns will have ramifications on the water chemistry patterns. For example, there may be an increase in denitrification due to

increased residence time with the soil (Correll *et al.* 1997), or subsurface water patterns at the 182 m site will indicate higher concentrations of nutrients.

### 3.5 CONCLUSIONS

These data indicate there is no subsurface water storage at 1.5 m below the ground surface with the exception of the wetlands. Even during rainfall events there was little discharge in the riparian areas surrounding SLR. Surprisingly, we did not see discharge at the 182 m site. It was expected that because the riparian areas of SLR generally consist of a thin layer of soil underlain by bedrock that there would always be discharge at 182 m (Buttle and Turcotte 1999), especially during a storm event.

It appears that landscape controls the hydrologic flow patterns at SLR. As anticipated topography, soil and geology are the main factors controlling hydrologic flow. However, differences in soil type seemed to have little to do with flow pattern in the Colluvial, Fluvial, and Morainal riparian areas surrounding SLR. The overall flow system seems to be predominately ephemeral. As part of these flow patterns, complete transect connectivity only occurred at three sites (M5, M1, and F1) and was driven by storm events. Subsurface flow may have occurred more continuously or with more connectivity at a greater depth than what was monitored. Given that the riparian areas were cleared and there was shallow bedrock, especially at the Colluvial soils, it is likely that preferential pathways played a large role in subsurface flow.

Continuous flow at the DEEP wells suggests that subsurface water was delivered via regional flowpaths. It also suggests that there is storage capacity in the bedrock. Wetland sites also received continuous flow, although only ever discharged during storm events. Subsurface inputs are likely from Begby Lake and other regional sources.

There has been criticism that shallow subsurface systems have not been monitored in sufficient detail, specific omissions such as transect length and sampling frequency are cited (Ocampo *et al.* 2006). With transects less than 50 m (except M2 and O3) and daily head measurements at best, our study may have been improved by more frequent measurements and therefore a better comprehension of subsurface water pathways.

Regardless of these shortcomings, we found that subsurface event flow moves quickly through the riparian areas. There is some evidence of regional subsurface flow, but it is minimal. With less time spent interacting with the soil, there will be less transport of nutrients to the SLR (Vidon and Hill 2004b).

**Table 4.** Saturated hydraulic conductivity (K) was established using the Hvorslev method. The mean was taken on three trials for each instrument (n=3), unless otherwise noted. The K value for Colluvial sites was taken from the geographically closest site F3 ( $1.01 \times 10^{-5}$ ).

Instrument	K (m/s)	Standard Error	Soil Type (Fetter, 2001)
O3-1-s	$1.13 \times 10^{-6}$	n=1	Fine Sands
O3-1-d	$2.21 \times 10^{-7}$	n=1	Silty Sand
O3-2-s	$1.23 \times 10^{-8}$	n=1	Clayey sands
O3-2-d	$2.4 \times 10^{-7}$	n=1	Silty Sand
O3-3-s	$2.20 \times 10^{-8}$	n=1	Clayey sands
O3-3-d	$1.67 \times 10^{-8}$	n=1	Clayey sands
F3-188-DEEP	$6.52 \times 10^{-7}$	$5.69 \times 10^{-9}$	Fine Sands
F3-182-W	$1.01 \times 10^{-5}$	$6.26 \times 10^{-7}$	Well Sorted Sands
O2-3-W	$3.46 \times 10^{-8}$	n=1	Clay
O2-3-d	$1.67 \times 10^{-8}$	n=1	Clayey sands
O2-3-s	$1.02 \times 10^{-8}$	n=1	Clayey sands
O2-2-s	$1.68 \times 10^{-7}$	n=1	Fine Sands
O2-2-d	$8.49 \times 10^{-7}$	$5.48 \times 10^{-8}$	Silty Sand
O2-1-s	$2.1 \times 10^{-6}$	$4.29 \times 10^{-7}$	Fine Sands
O2-1-d	$1.33 \times 10^{-6}$	$3.27 \times 10^{-8}$	Fine Sands
M1-188-DEEP	$8.35 \times 10^{-7}$	$2.66 \times 10^{-7}$	Silty Sand
M4-186-W	$1.42 \times 10^{-5}$	$2.28 \times 10^{-6}$	Well Sorted Sands
M3-182-W	$3.00 \times 10^{-6}$	n=1	Fine Sands
M4-188-DEEP	$6.10 \times 10^{-6}$	$2.79 \times 10^{-6}$	Fine Sands

**Table 5.** Discharge, Q, at all focal sites in both Dry and Storm conditions. Discharge rates are calculated from the 188 m site to the 182 m site, and in the case of the wetlands from site 3 to 1.

SITE	Discharge - Q (m <sup>3</sup> /s)	
	DRY	STORM
O3	7.93 x 10 <sup>-9</sup>	1.75 X 10 <sup>-8</sup>
C6	5.99 x 10 <sup>-5</sup>	6.13 x 10 <sup>-5</sup>
M1	4.78 x 10 <sup>-6</sup>	4.54 x 10 <sup>-6</sup>
M1-DEEP	1.03 x 10 <sup>-7</sup>	4.99 x 10 <sup>-6</sup>
M2	ND	4.95 x 10 <sup>-6</sup>
M5	9.00 x 10 <sup>-5</sup>	8.99 x 10 <sup>-5</sup>
F1	ND	6.26 x 10 <sup>-5</sup>
F1-DEEP	ND	2.33 x 10 <sup>-8</sup>
F4	ND	5.92 x 10 <sup>-5</sup>

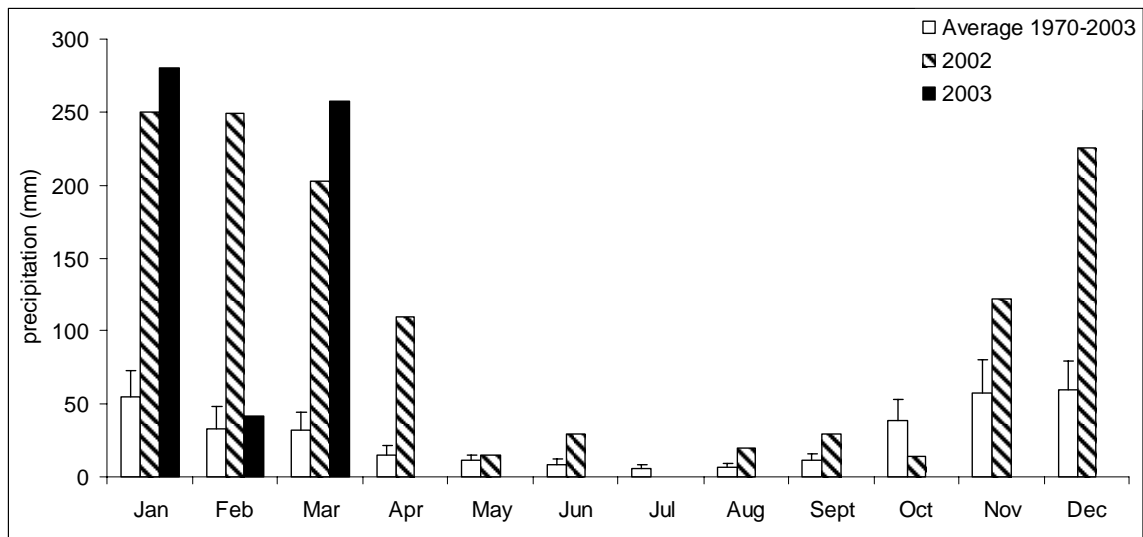
ND: No Data due to dry wells

Dates: STORM 11/18/02, DRY 09/16/02

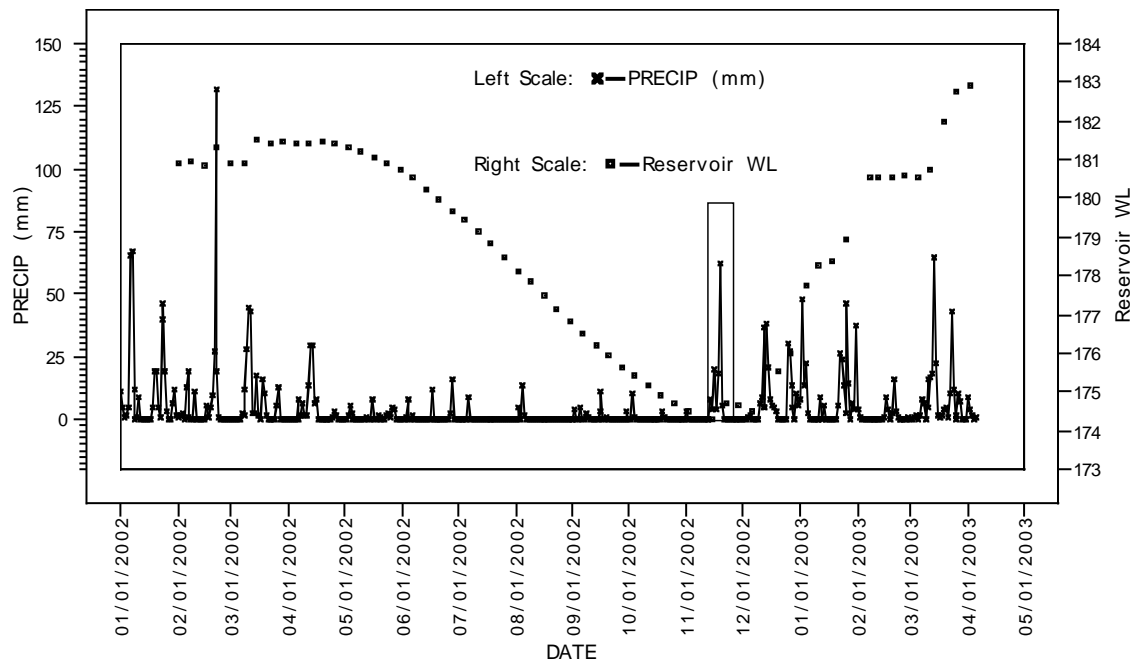
**Table 6.** Vertical hydraulic gradient (HG) at piezometers of the focal sites in four soil types: Organic (O3), Morainal (M2, M5, M6), Fluvial (F1, F4, F5), and Colluvial (C6). Negative HG values indicate flow from high head to low head.

SITE	DRY 09/16/02			WET 11/18/02		
	Vertical HG	Gradient Direction	Q (m3/s)	Vertical HG	Gradient Direction	Q (m3/s)
O3-1-75:180	0.823	downward	$1.27 \times 10^{-6}$	-0.115	upward	$2.41 \times 10^{-7}$
O3-2-75:180	0.194	downward	$4.41 \times 10^{-7}$	-0.332	upward	$7.54 \times 10^{-7}$
O3-3-75:180	0.29	downward	$4.57 \times 10^{-8}$	0.262	downward	$4.13 \times 10^{-8}$
M2-182-50:80	ND			85.52	upward	$1.41 \times 10^{-5}$
M2-186-50:140	ND			No Data Dry		
M2-188-50:140	ND			No Data Dry		
M5-182-50:180	ND			0.65	downward	$1.66 \times 10^{-6}$
M5-186-50:180	ND			0.817	downward	$1.01 \times 10^{-4}$
M5-188-50:180	24.14	downward	$1.15 \times 10^{-4}$	9.52	downward	$4.06 \times 10^{-5}$
M6-182-50:180	ND			3.96	downward	$6.59 \times 10^{-6}$
M6-186-50:170	ND			2.69	downward	$4.22 \times 10^{-5}$
M6-188-50:180	ND					
F1-182-50:110	ND			-1.02	downward	$2.26 \times 10^{-5}$
F1-186-50:110	ND			1.01	downward	$2.23 \times 10^{-5}$
F1-188-50:110	ND					
F4-182-50:110	ND			-0.27	downward	$-5.93 \times 10^{-6}$
F4-186-50:110	ND			-1.01	downward	$-2.25 \times 10^{-5}$
F4-188-50:110	ND			-0.99	downward	$-3.11 \times 10^{-5}$
F5-182-50:120	ND			-0.99	downward	$-2.79 \times 10^{-5}$
F5-186-60:110	ND			2.68	downward	$6.49 \times 10^{-5}$
F5-188-50:120	ND					
C6-182-50:110	-0.82	downward	$1.82 \times 10^{-5}$	-0.82	downward	$1.81 \times 10^{-5}$
C6-186-50:110	ND			-3.76		DRY
C6-188-50:110	-0.94	downward	$1.59 \times 10^{-5}$	-0.91	downward	$1.53 \times 10^{-5}$

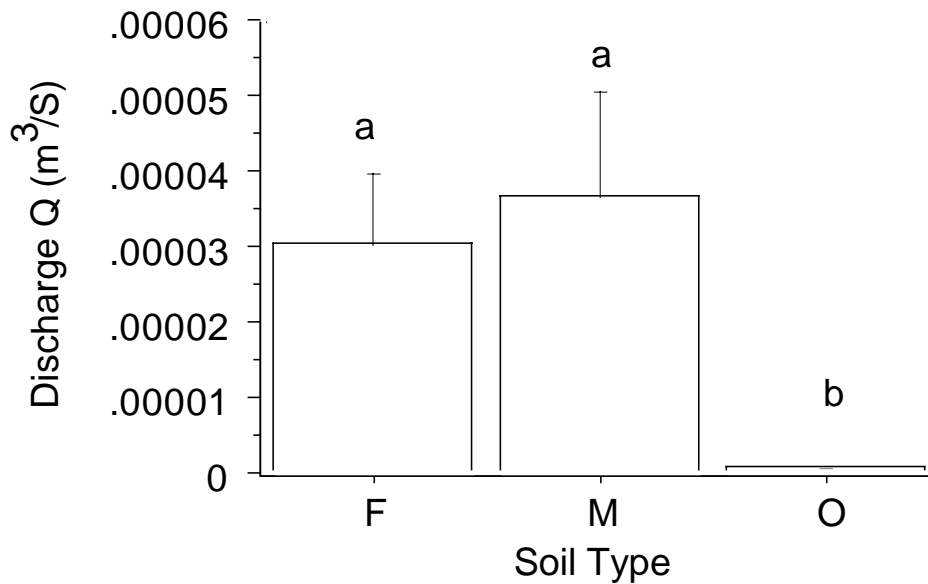
ND refers to No Data.



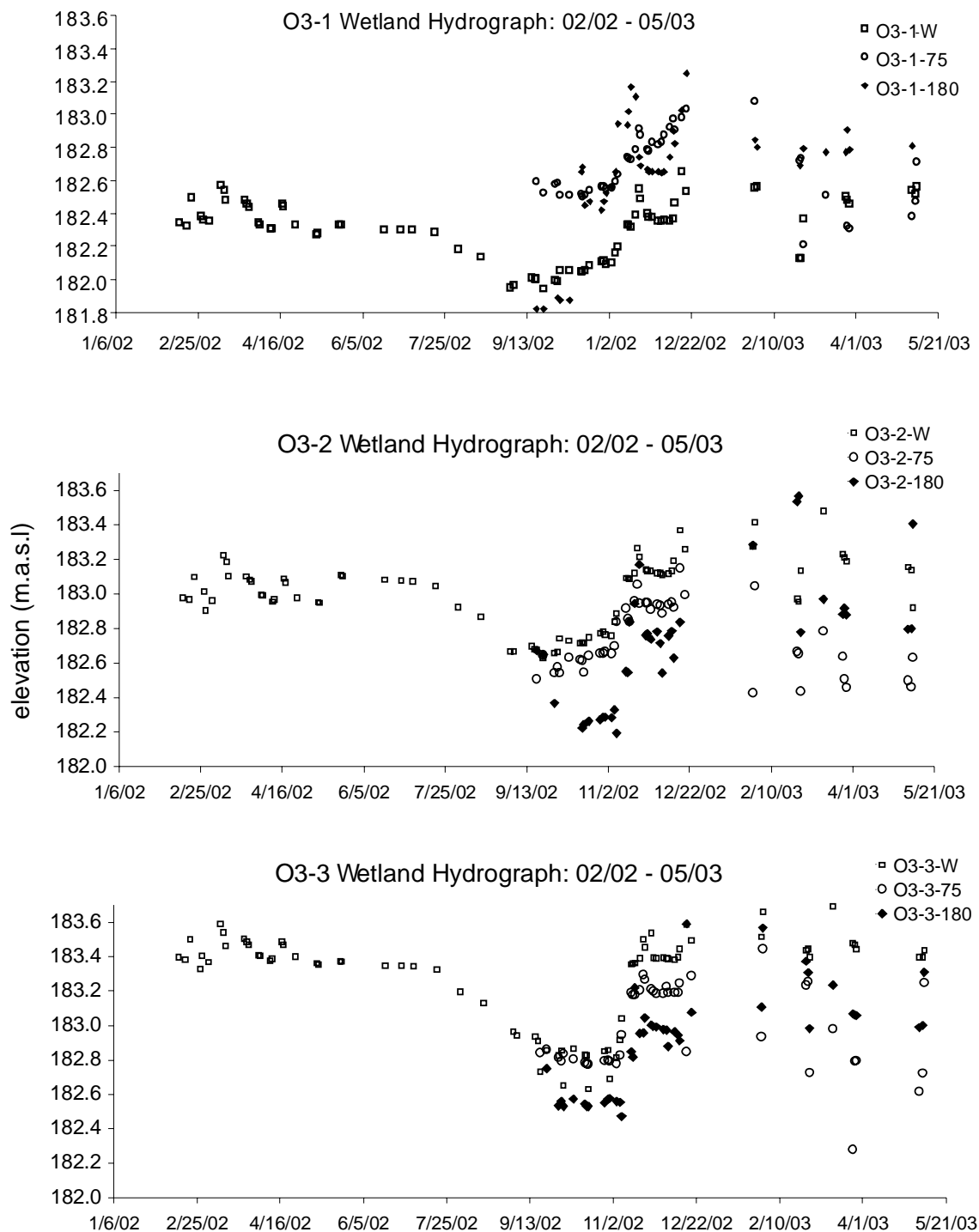
**Figure 8.** Precipitation at SLR on a monthly average from 1970-2001 and the total precipitation at SLR between January 2002 and April 2003. Error bars indicate standard error. There was no precipitation data available for April 2003.



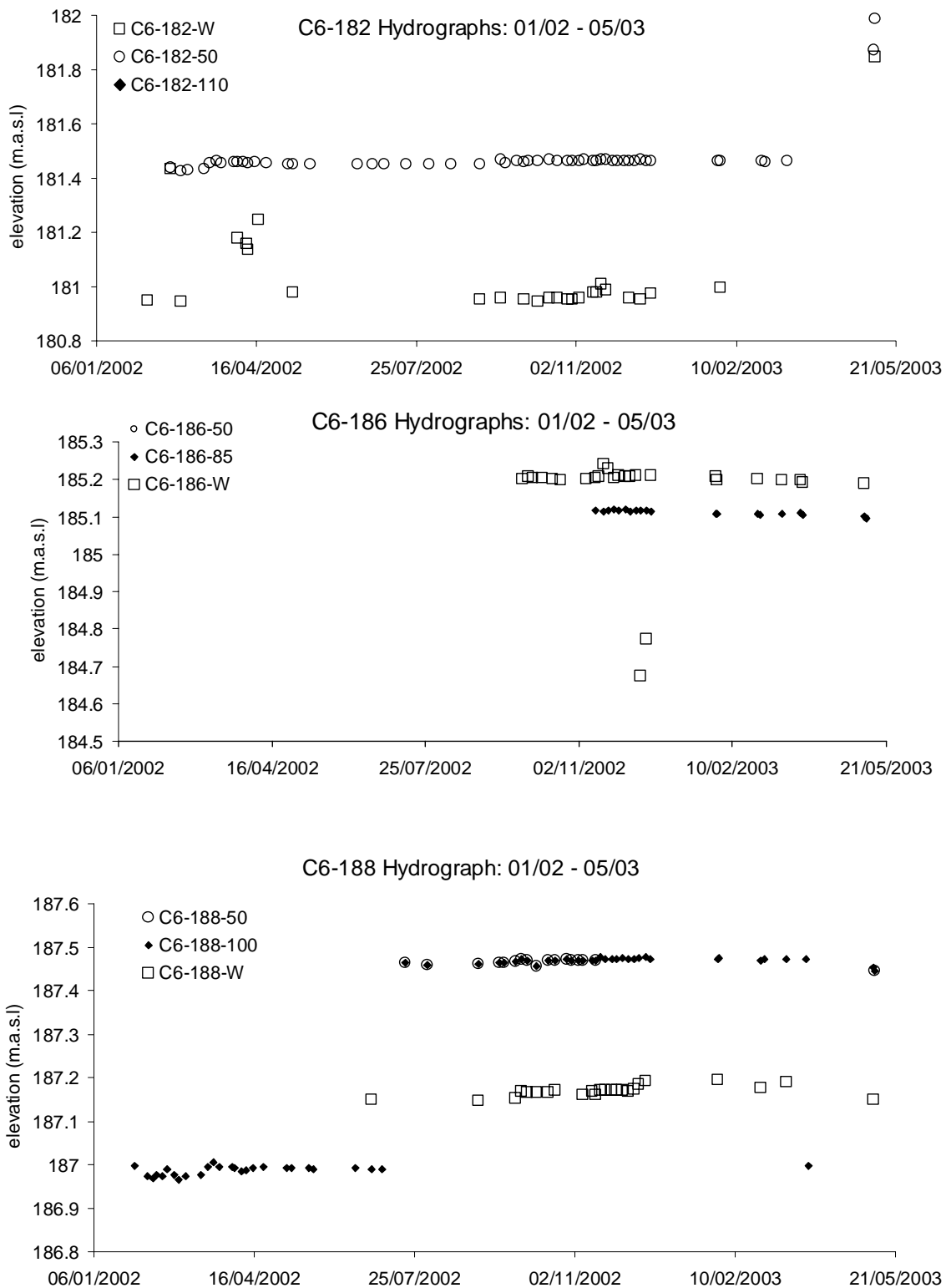
**Figure 9.** Precipitation at SLR during the sampling period (January 2002 to May 2003). Reservoir water level fluctuations are also indicated. Dates are shown in month/day/year.



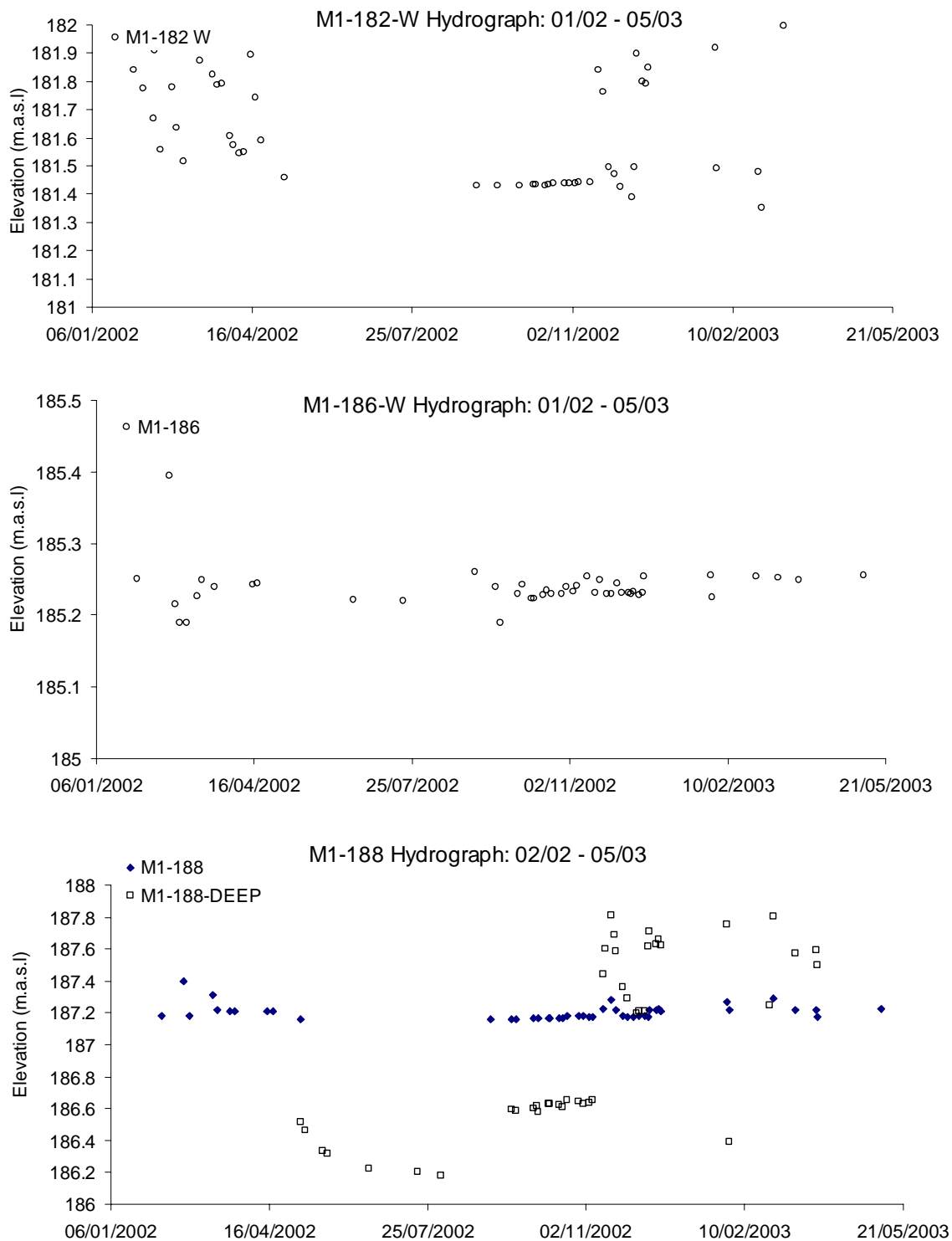
**Figure 10.** Hydraulic discharge rates (Q) in three different soil types: fluvial (F, n=5), Morainal (M, n=6) and Organic (O, n=6). Each bar represents average discharge with error bars equivalent to 1 SE. Different letters above the bars indicate significant differences (P=0.04) based on ANOVA results.



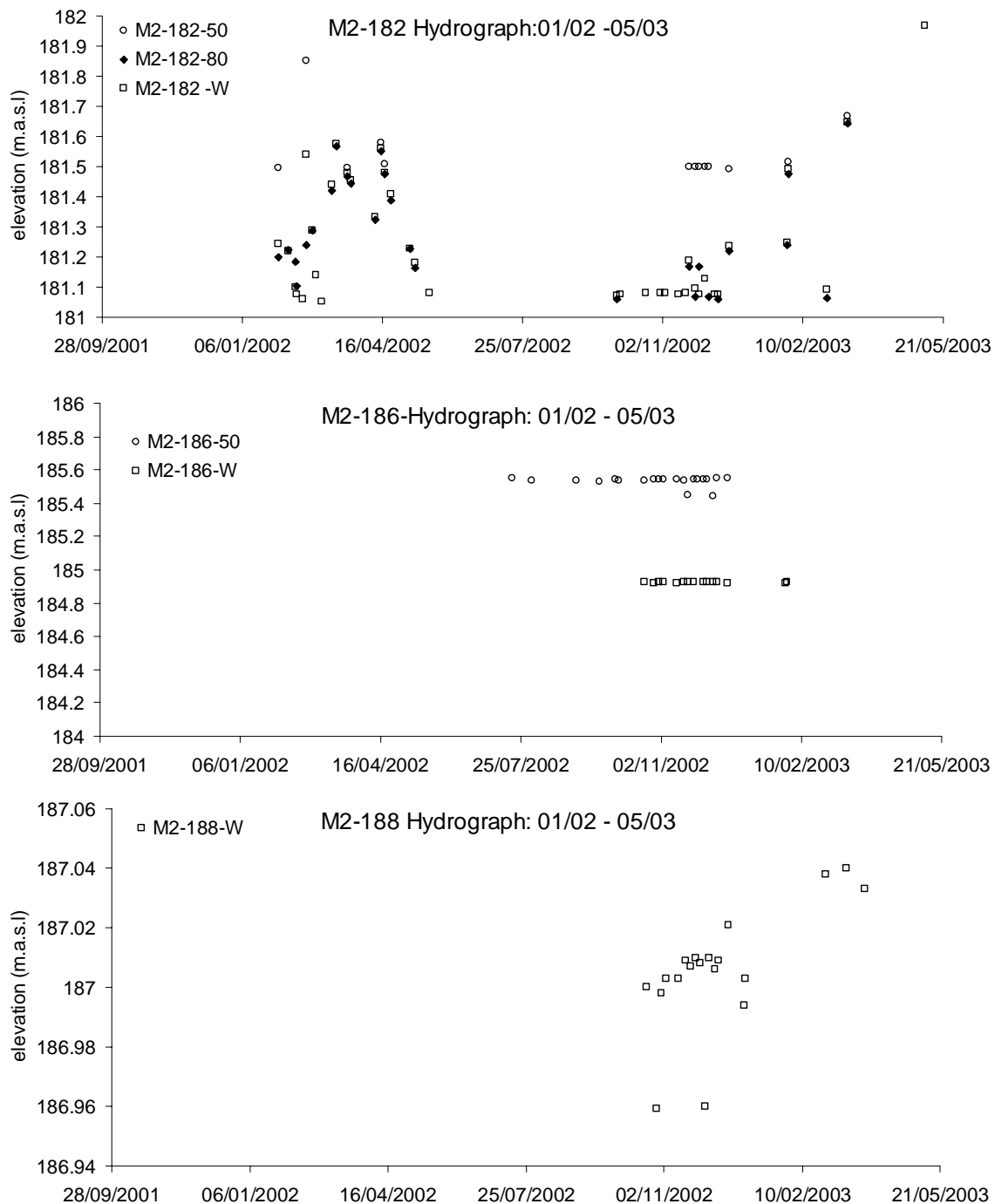
**Figure 11A.** Wetland (O3) hydrographs for the period January 2002 to May 2003. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 75 refers to the shallow piezometer at 0.75 m depth, and 180 refers to the deep piezometer at 1.8 m depth. Site 1 is closest to the reservoir and site 3 is farthest from the reservoir.



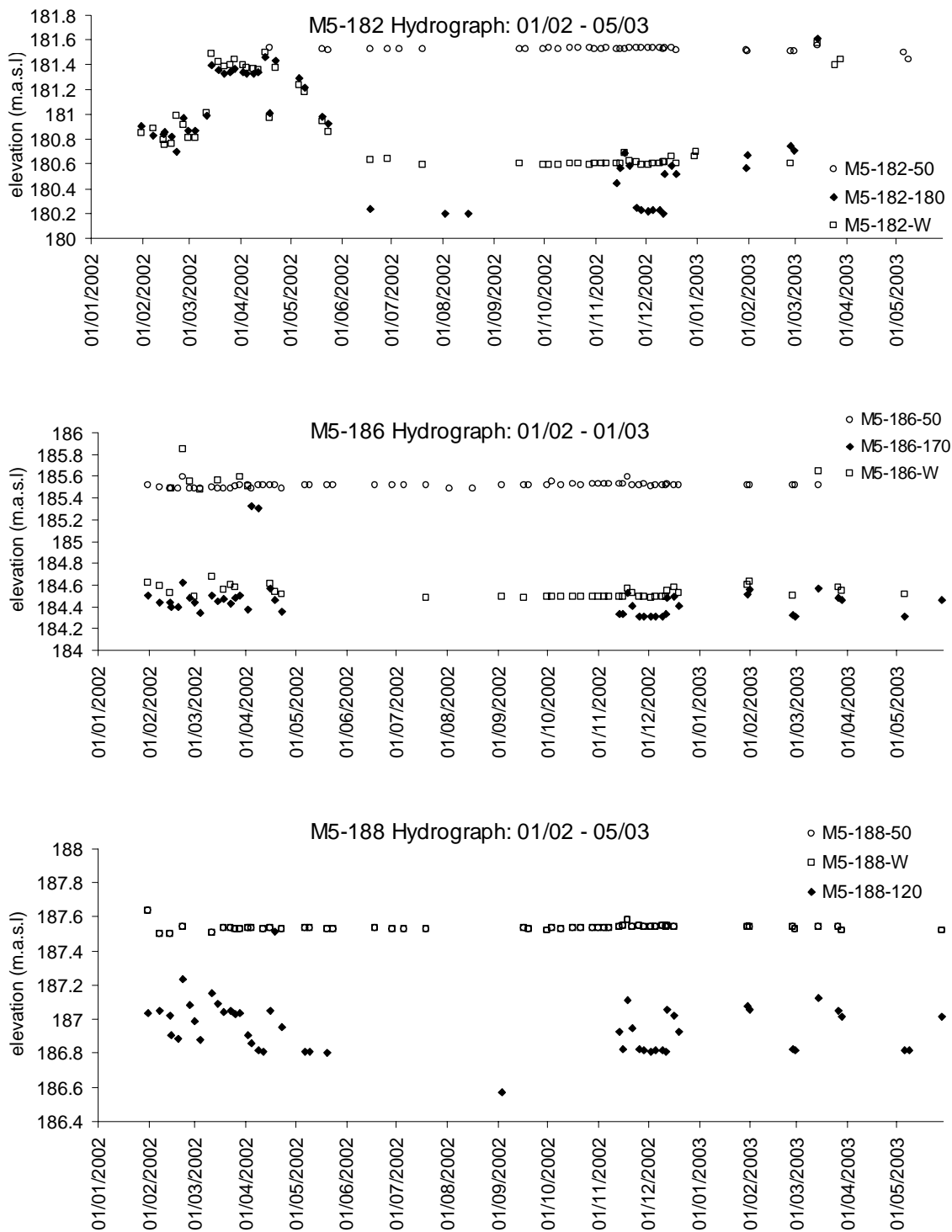
**Figure 11B.** Colluvial (C6) hydrographs for the period January 2002 to May 2003. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 50 refers to the shallow piezometer at 0.50 m depth, and 100 refers to the deep piezometer at 1.0 m depth. Each graph illustrates the nest at 182 m, 186 m, and 188 m.



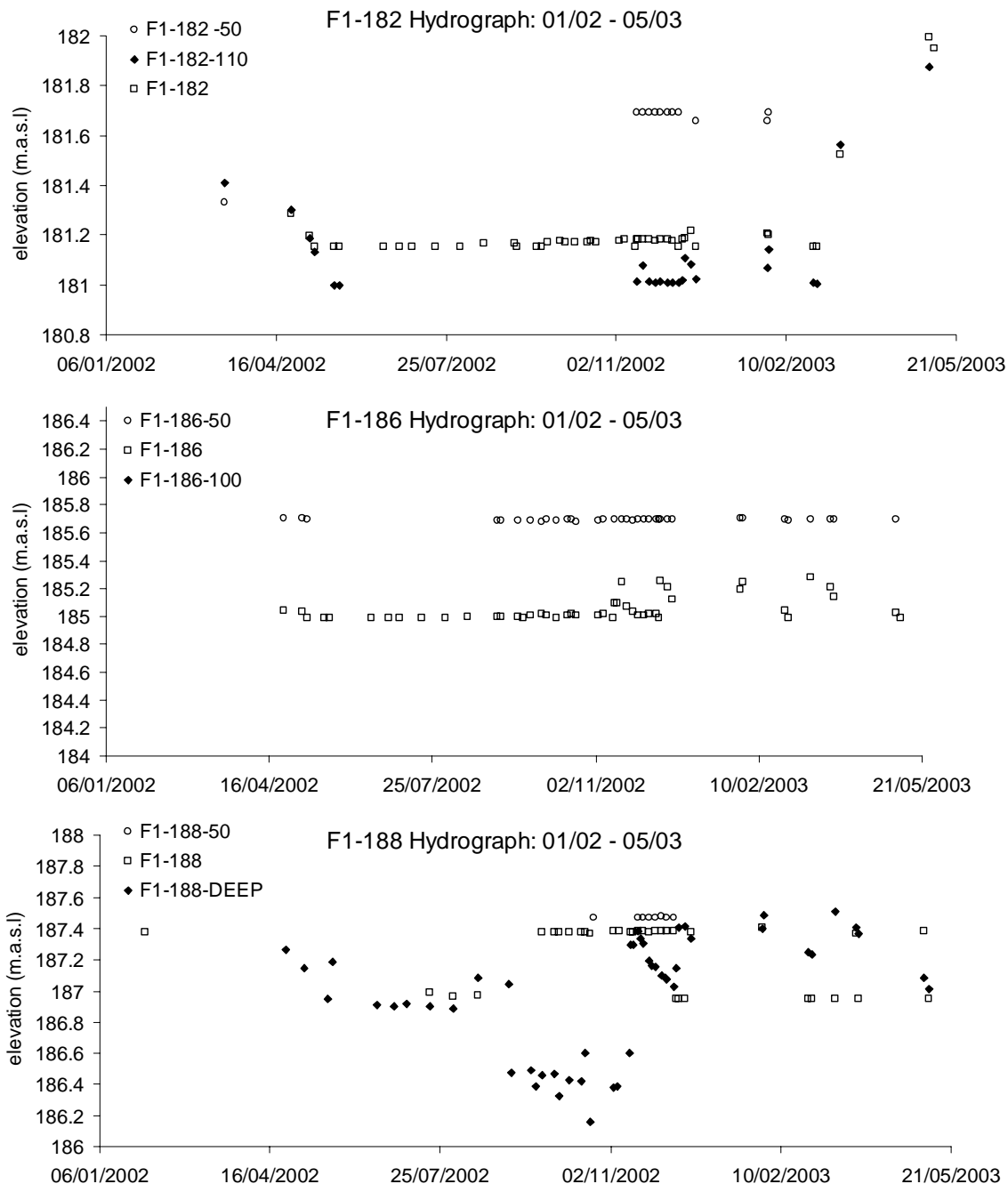
**Figure 11C.** Morainal (M1) hydrographs for the period January 2002 to May 2003. Head measurements are in meters above sea level (m.a.s.l.). M1-188, M1-186, and M1-182 are the wells along this transect and M1-188-DEEP is the deep well at 188 m.



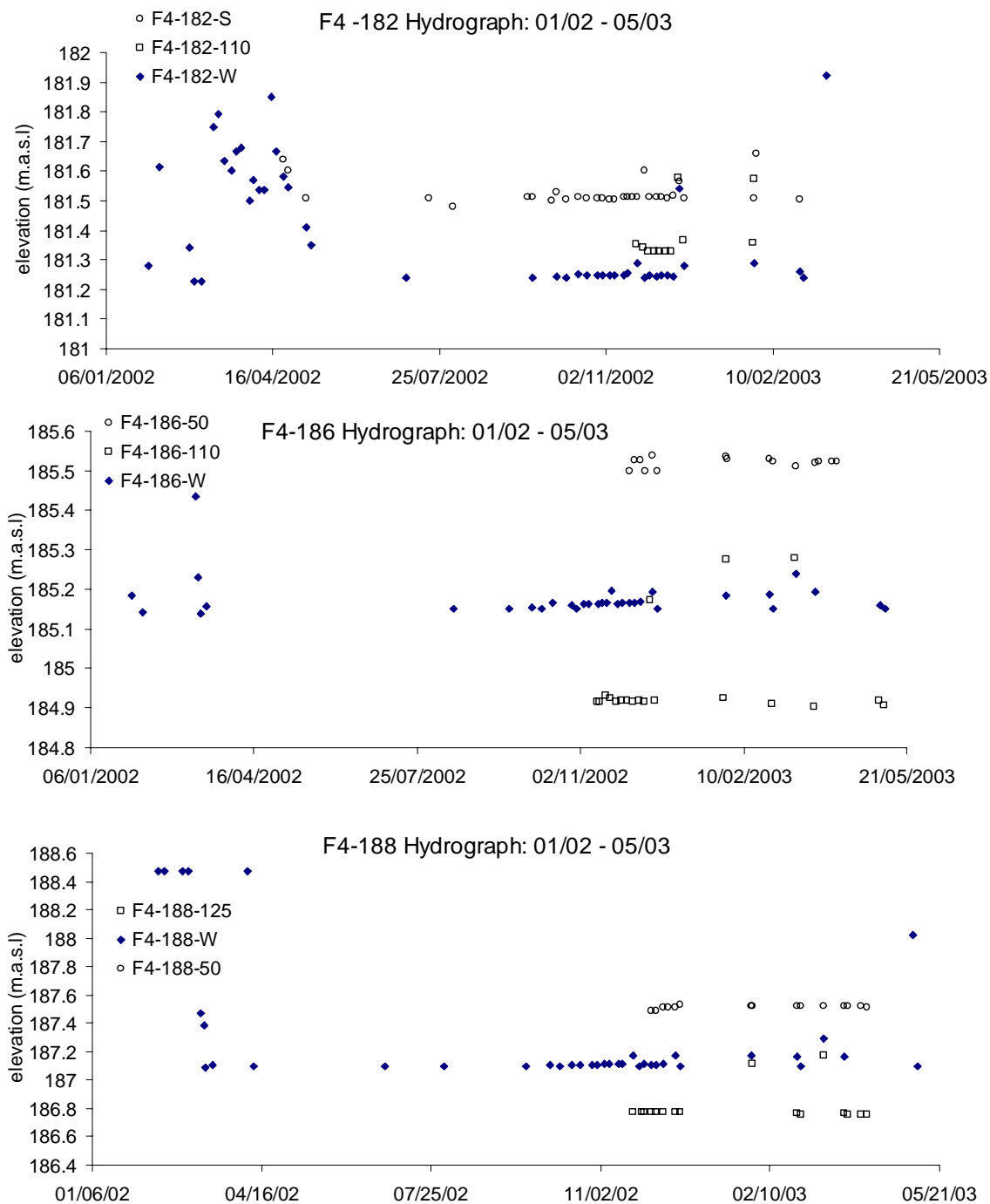
**Figure 11D.** Morainal (M2) hydrographs for the period January 2002 to May 2003. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 50 refers to the shallow piezometer at 0.50 m depth, and 80 refers to the deep piezometer at 0.8 m depth. Each graph illustrates the nest at 182 m, 186 m, and 188 m.



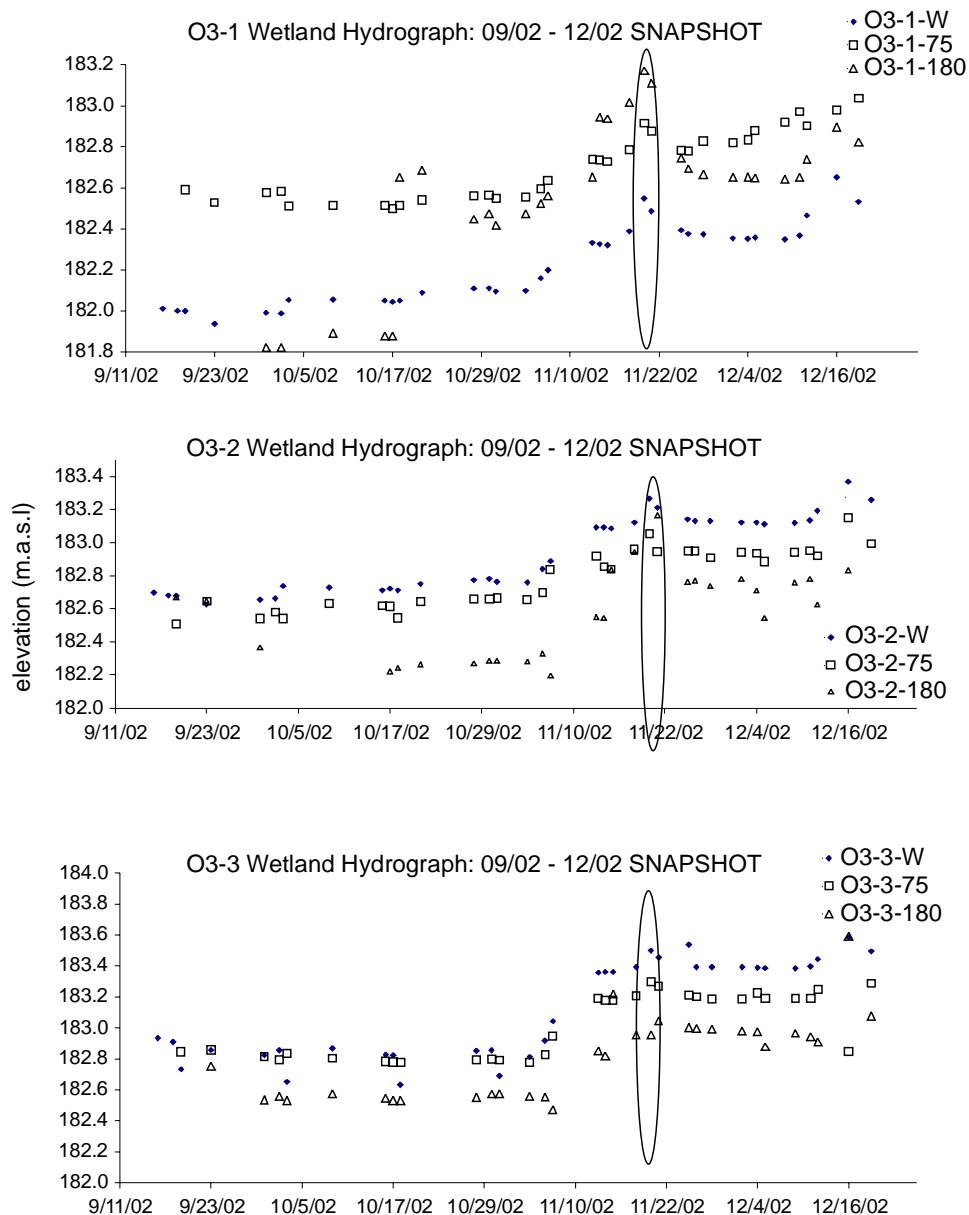
**Figure 11E.** Morainal (M5) hydrographs for the period January 2002 to May 2003. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 50 refers to the shallow piezometer at 0.50 m depth, and 120, 170 and 180 refers to the deep piezometer at 1.2 m, 1.7 m, and 1.8 m depth. Each graph illustrates the nest at 182 m, 186 m, and 188 m.



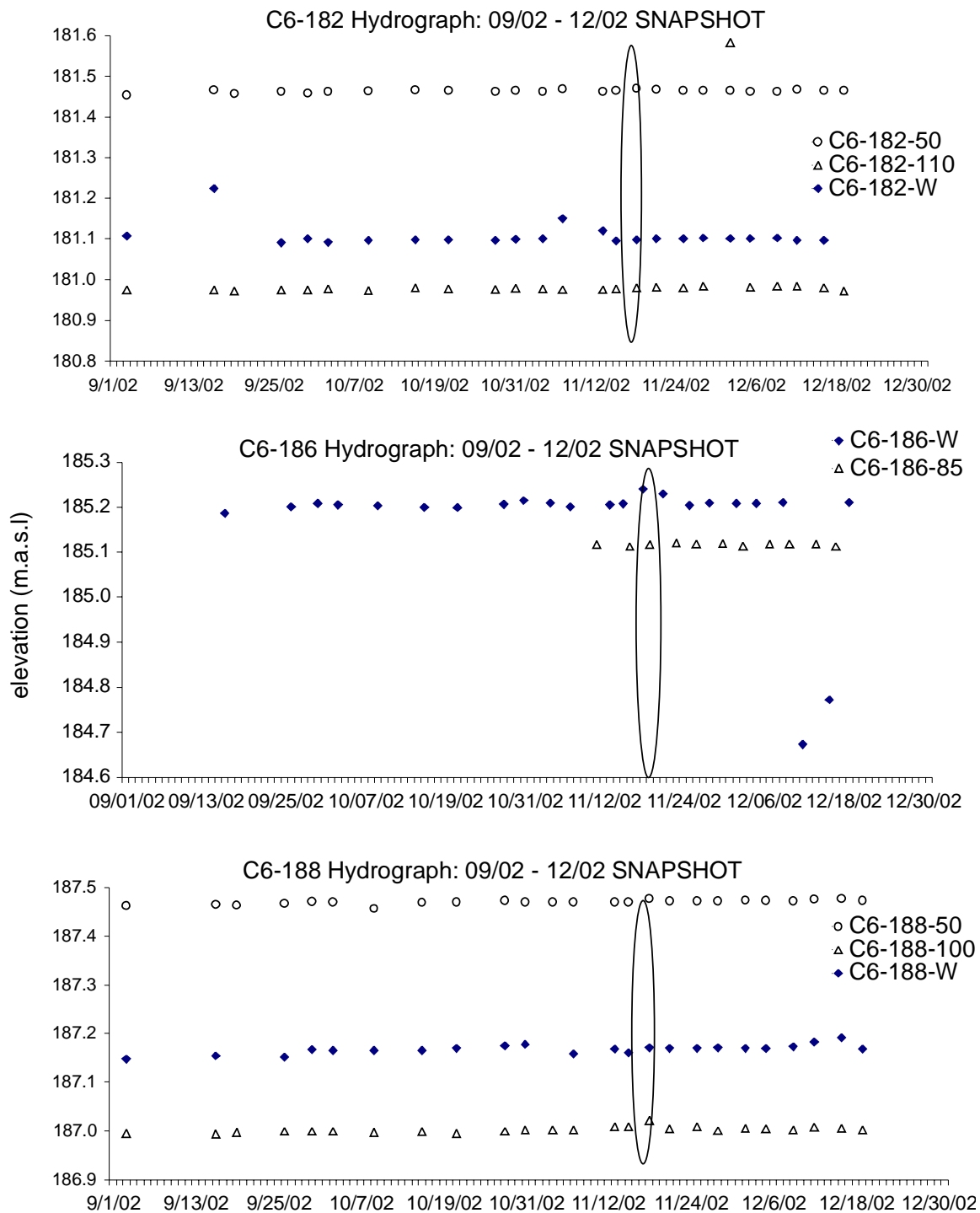
**Figure 11F.** Fluvial (F1) hydrographs for the period January 2002 to May 2003. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 50 refers to the shallow piezometer at 0.50 m depth, and 100 and 110 refers to the deep piezo meter at 1.0 m and 1.1 m depth. F1-188-DEEP refers to the deep well installed at 188 m. Each graph illustrates the nest at 182 m, 186 m, and 188 m.



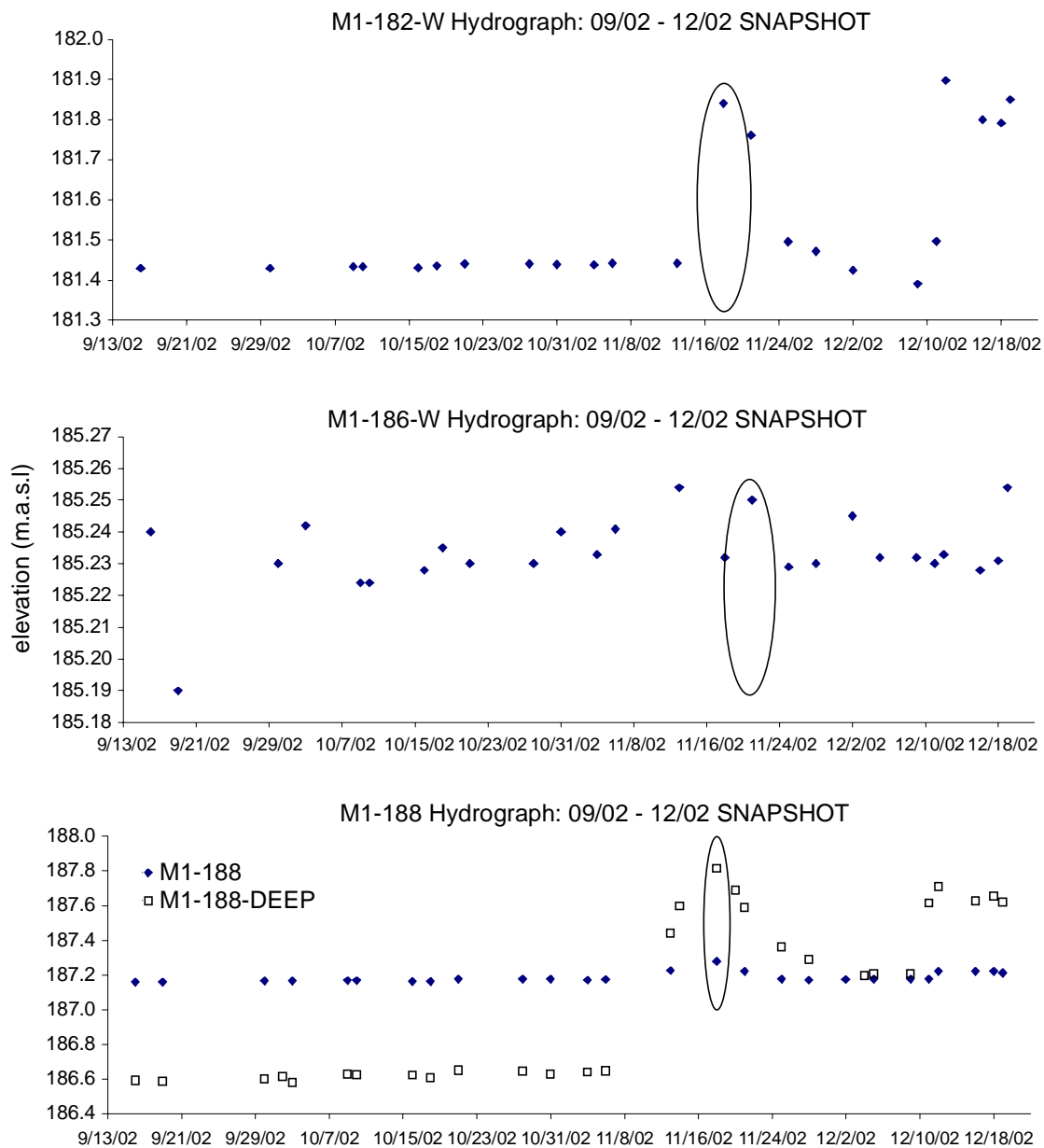
**Figure 11G.** Fluvial (F4) hydrographs for the period January 2002 to May 2003. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 50 refers to the shallow piezometer at 0.50 m depth, and 110 and 125 refers to the deep piezometers at 1.1 m and 1.25 m depth. Each graph illustrates the nest at 182 m, 186 m, and 188 m.



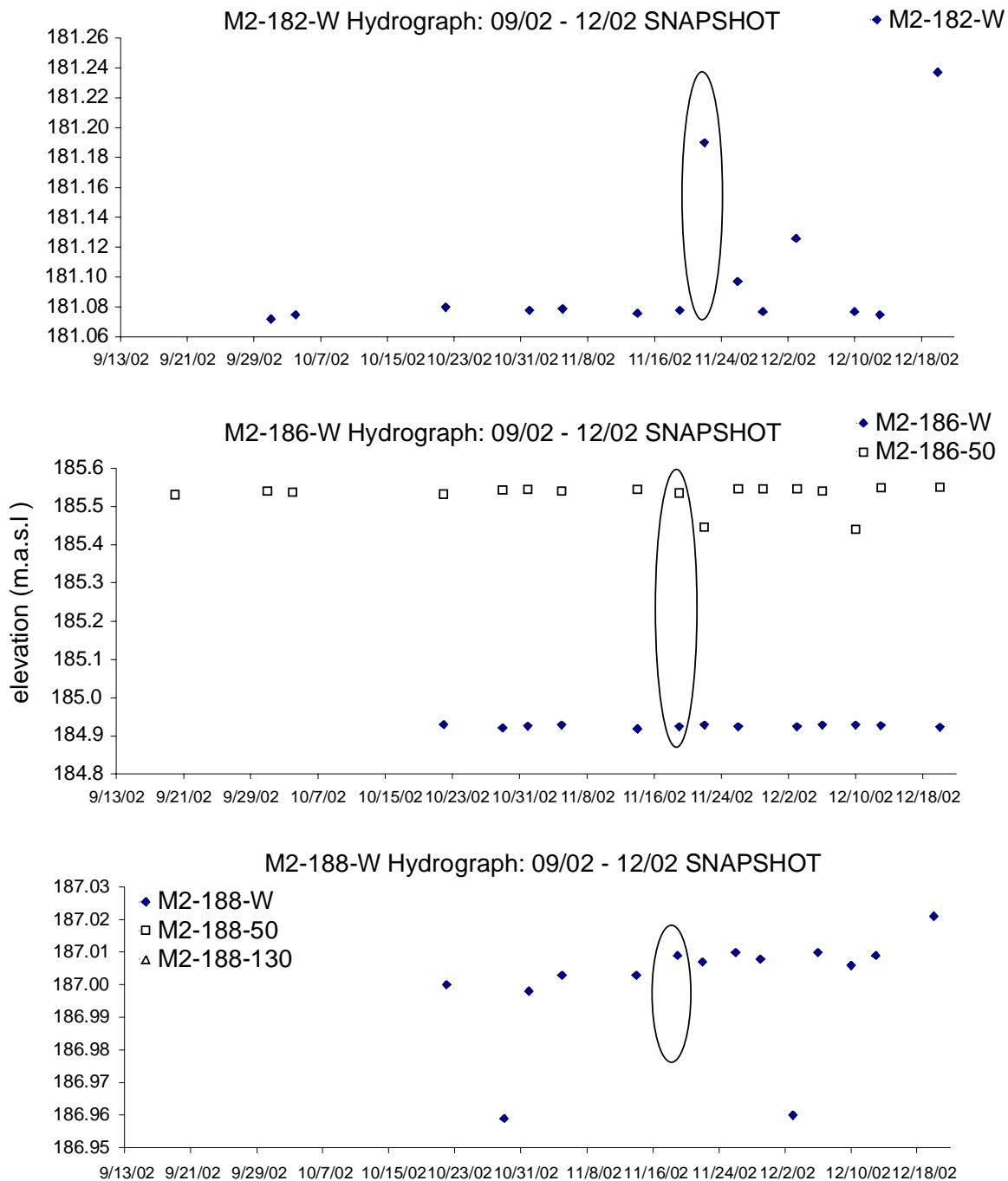
**Figure 12A.** Hydrographs of the organic soil transect (O3) during a storm event on November 18, 2002. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 50 refers to the shallow piezometer at 0.50 m depth, and 180 refers to the deep piezometer at 1.8 m depth. Each graph illustrates the nest at 182 m, 186 m, and 188 m. The oval indicates the storm event.



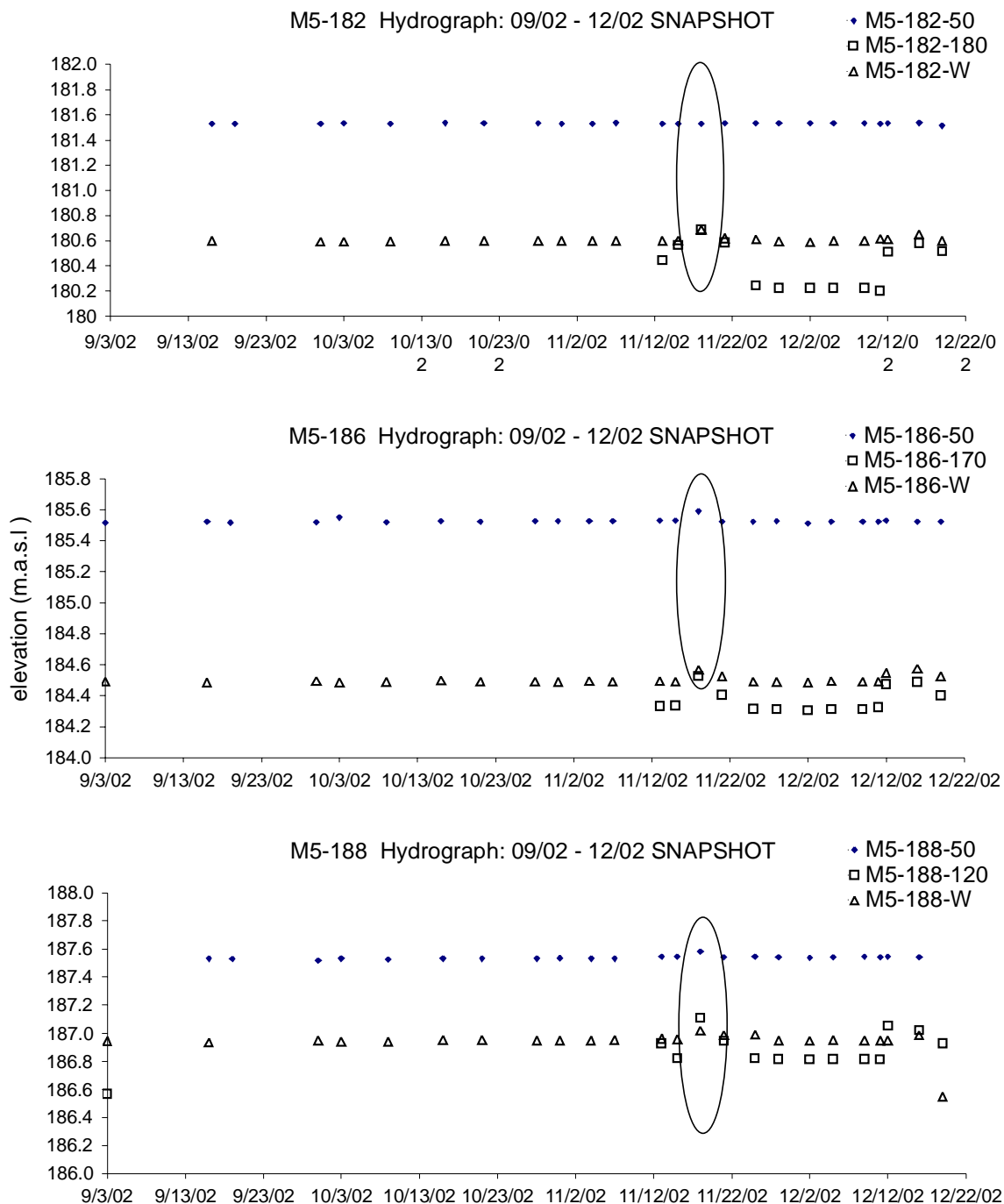
**Figure 12B.** Hydrographs of the Colluvial soil transect (C6) during a storm event on November 18, 2002. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 50 refers to the shallow piezometer at 0.50 m depth, and 100, 85 and 110 refers to the deep piezometer at 1.0 m, 0.85 m, and 1.1 m depth. Each graph illustrates the nest at 182 m, 186 m, and 188 m. The oval indicates the storm event.



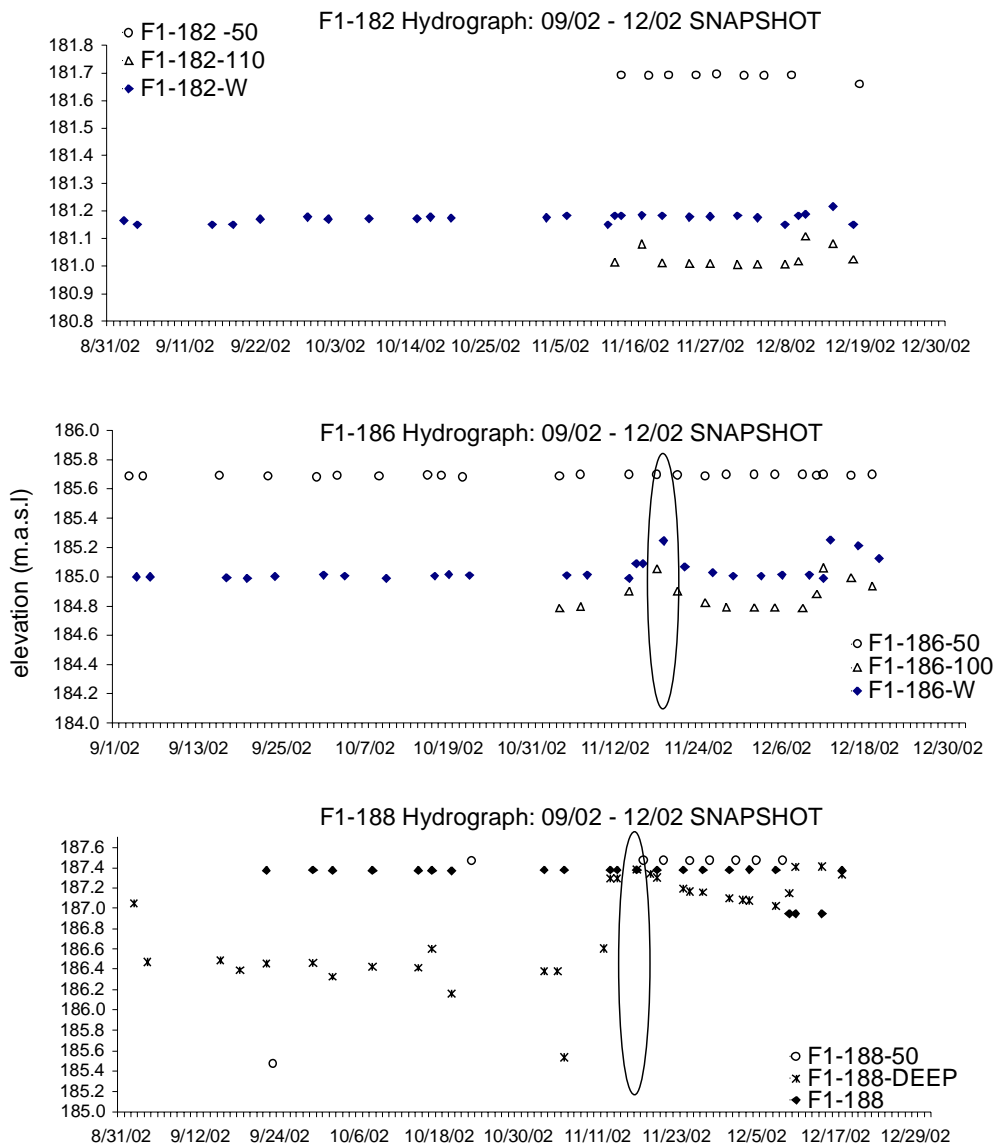
**Figure 12C.** Hydrographs of a morainal soil transect (M1) during a storm event on November 18, 2002. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, DEEP refers to the deep well at 188 m. Each graph illustrates the nest at 182 m, 186 m, and 188 m. The oval indicates the storm event.



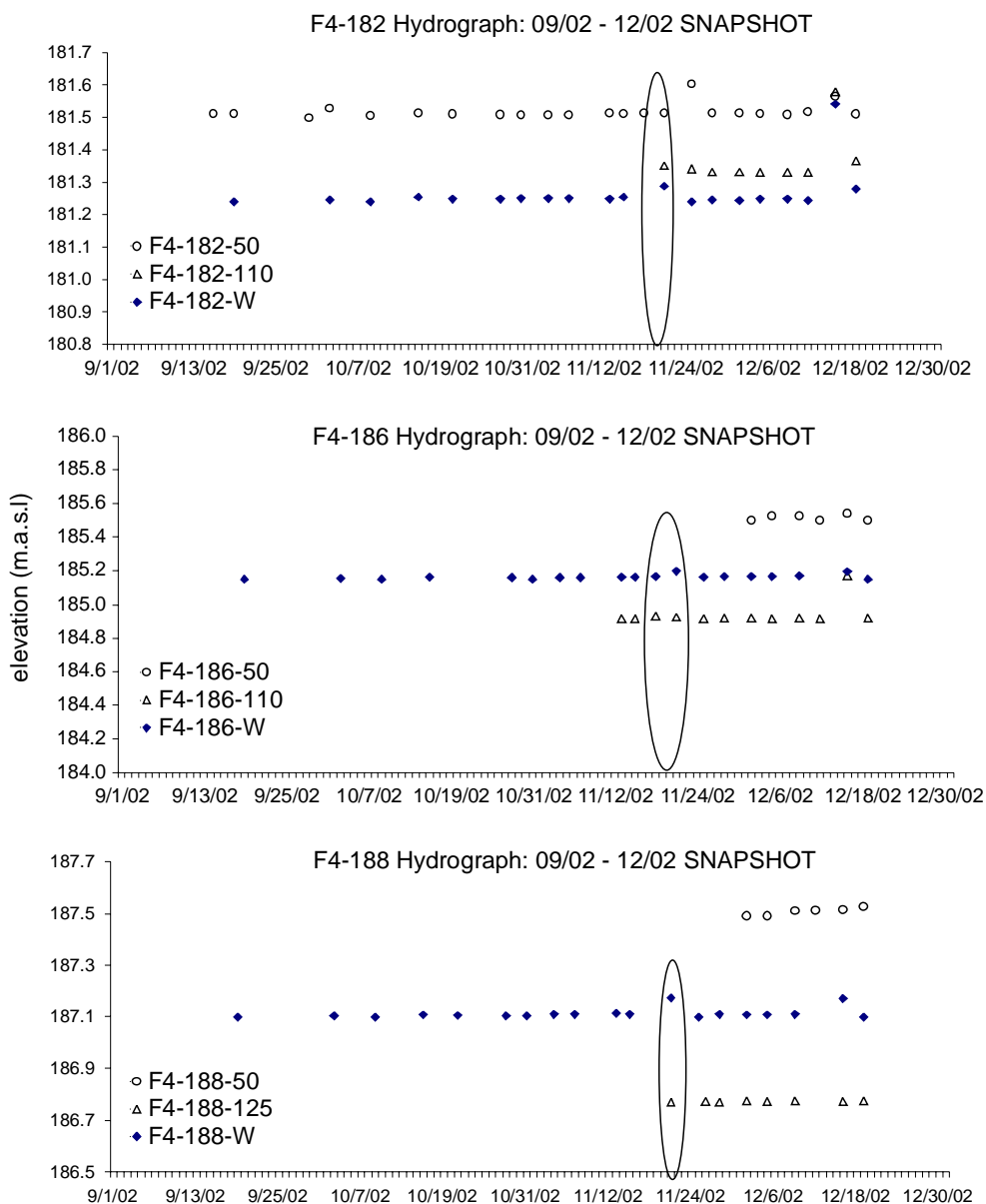
**Figure 12D.** Hydrographs of the morainal soil transect (M2) during a storm event on November 18, 2002. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 50 refers to the shallow piezometer at 0.50 m depth, and 130 refers to the deep piezometer at 1.3 m depth. Each graph illustrates the nest at 182 m, 186 m, and 188 m. The oval indicates the storm event.



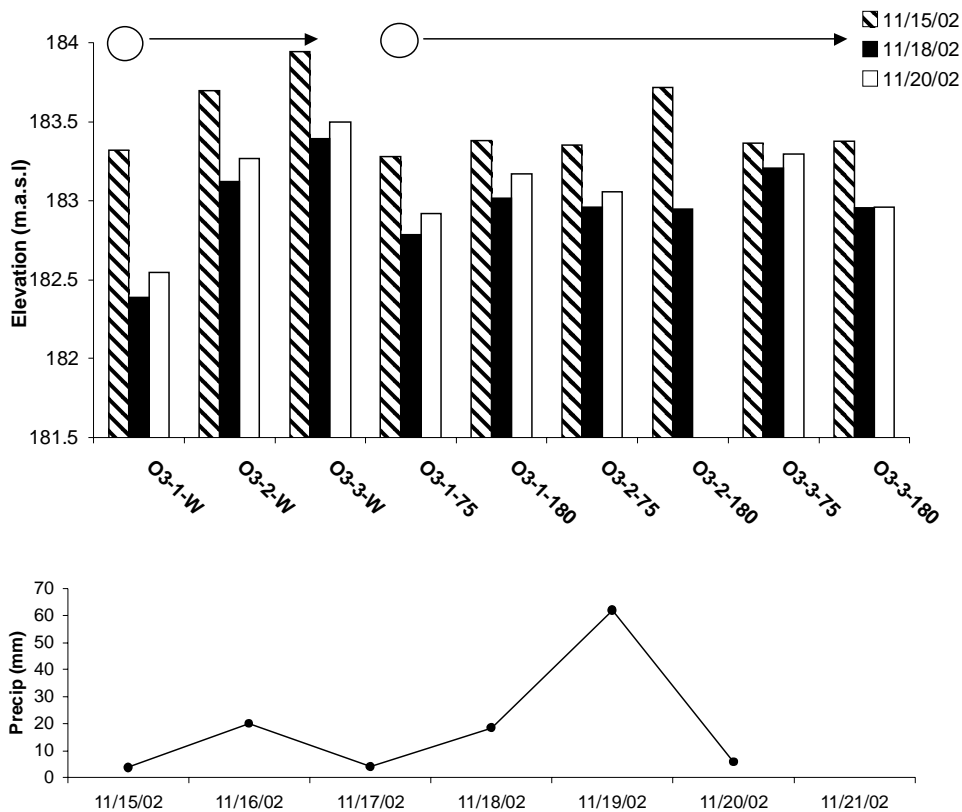
**Figure 12E.** Hydrographs of a morainal soil transect (M5) during a storm event on November 18, 2002. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 50 refers to the shallow piezometer at 0.50 m depth, and 120, 170, 180 refers to the deep piezometer at 1.2 m, 1.7 m, and 1.8 m depth. Each graph illustrates the nest at 182 m, 186 m, and 188 m. The oval indicates the storm event.



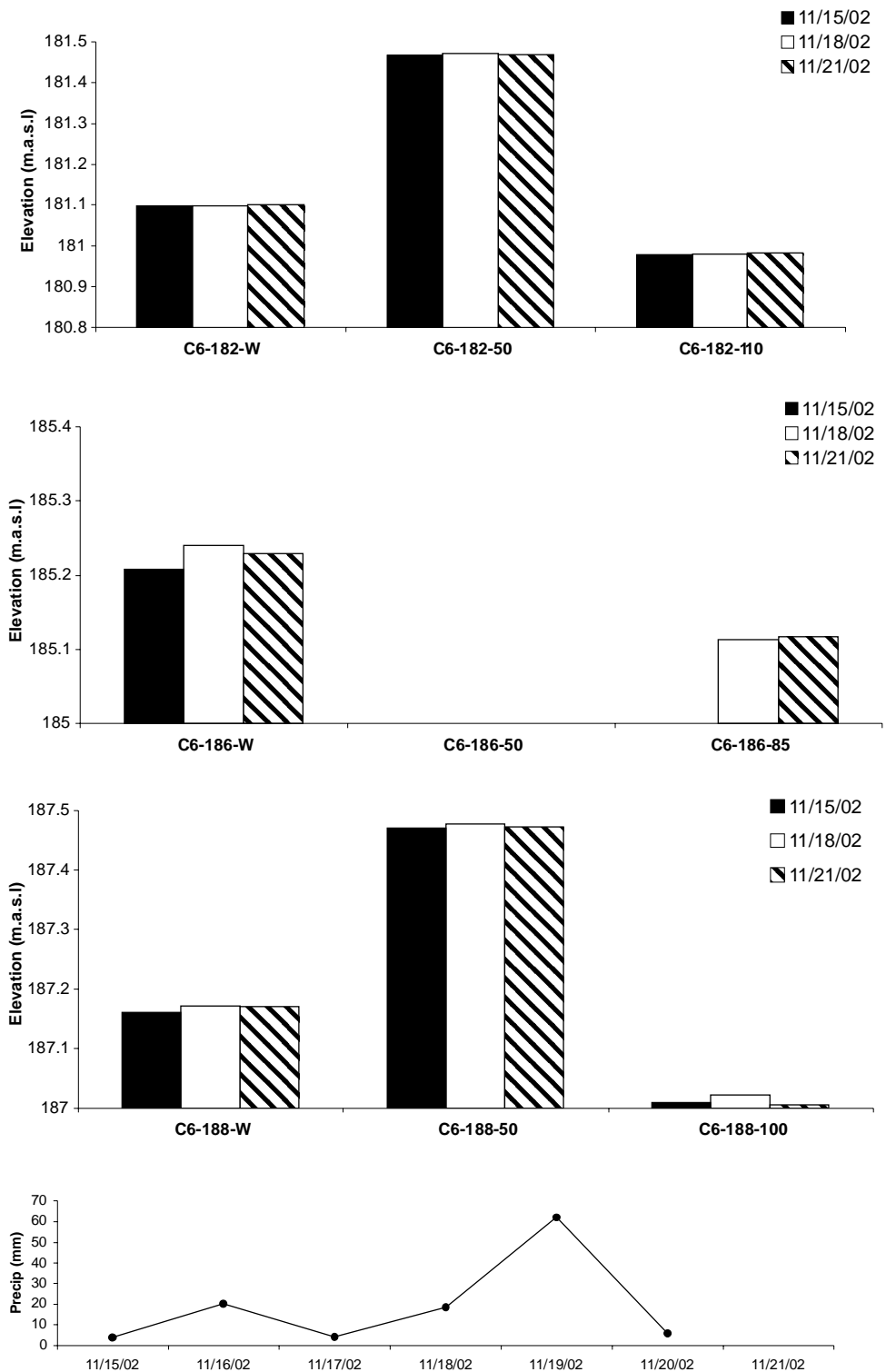
**Figure 12F.** Hydrographs of a fluvial soil transect (F1) during a storm event on November 18, 2002. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 50 refers to the shallow piezometer at 0.50 m depth, and 100 and 110 refers to the deep piezometer at 1.0 m and 1.1 m depth. DEEP refers to the deep well at 188 m. Each graph illustrates the nest at 182 m, 186 m, and 188 m. The oval indicates the storm event.



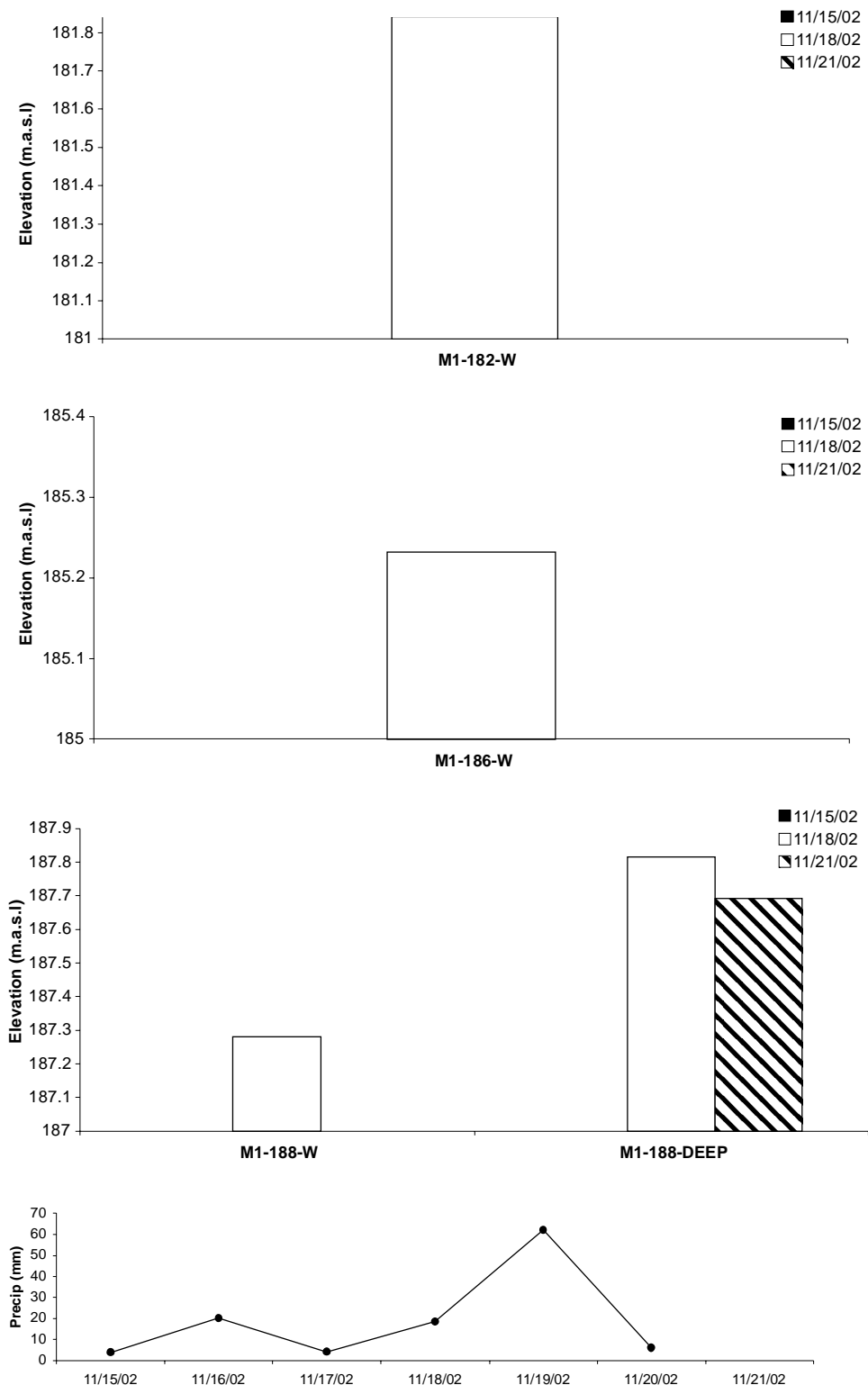
**Figure 12G.** Hydrographs of a fluvial soil transect (F4) during a storm event on November 18, 2002. Head measurements are in meters above sea level (m.a.s.l.). W refers to the well, 50 refers to the shallow piezometer at 0.50 m depth, and 110 and 125 refers to the deep piezometer at 1.1 m and 1.25 m depth. Each graph illustrates the nest at 182 m, 186 m, and 188 m. The oval indicates the storm event.



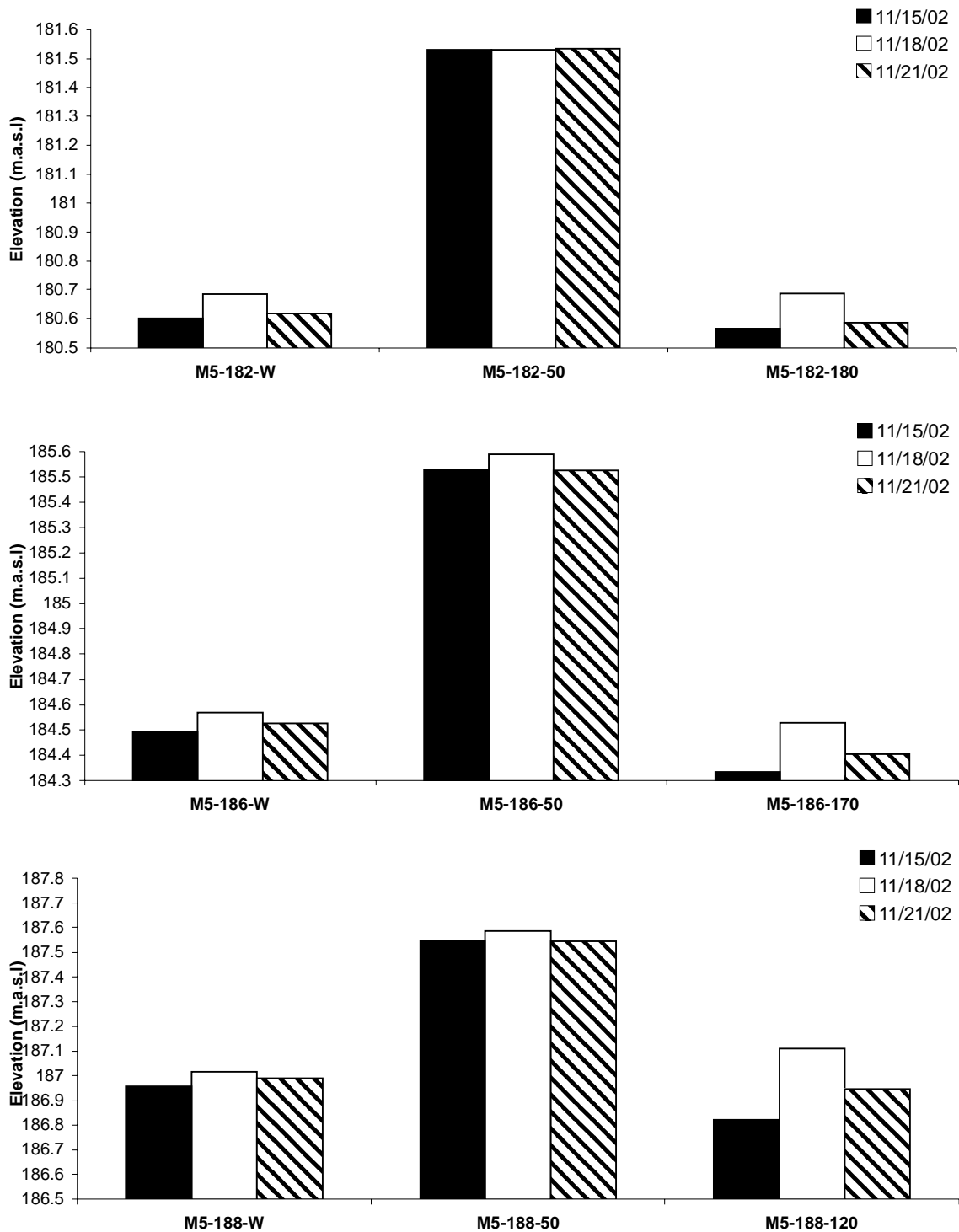
**Figure 13A.** Effect of precipitation on the (O3) wetland during a storm event. The greatest response occurred on November 15, 2002. The circle indicates the site closest to the reservoir and the arrow indicates the site closest to the reservoir and the direction of the transect away from the reservoir. The lower graph indicates the precipitation record from the Rithet Creek meteorological station at SLR.



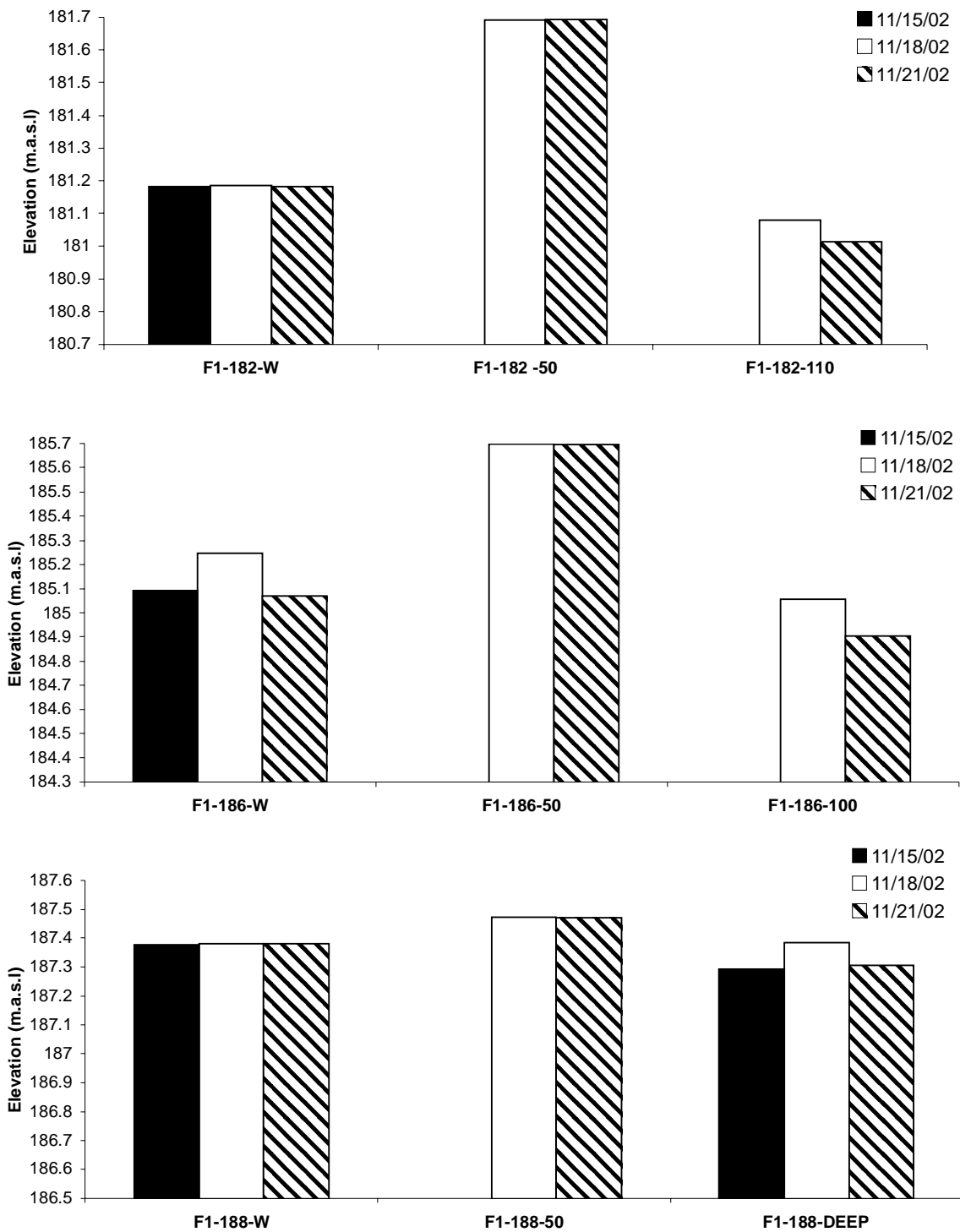
**Figure 13B.** Effect of precipitation on a (C6) Colluvial during a storm event. The greatest response occurred on November 19, 2002. There was never any water measured at C6-186-50. The lower graph indicates the precipitation record from the Rithet Creek meteorological station at SLR.



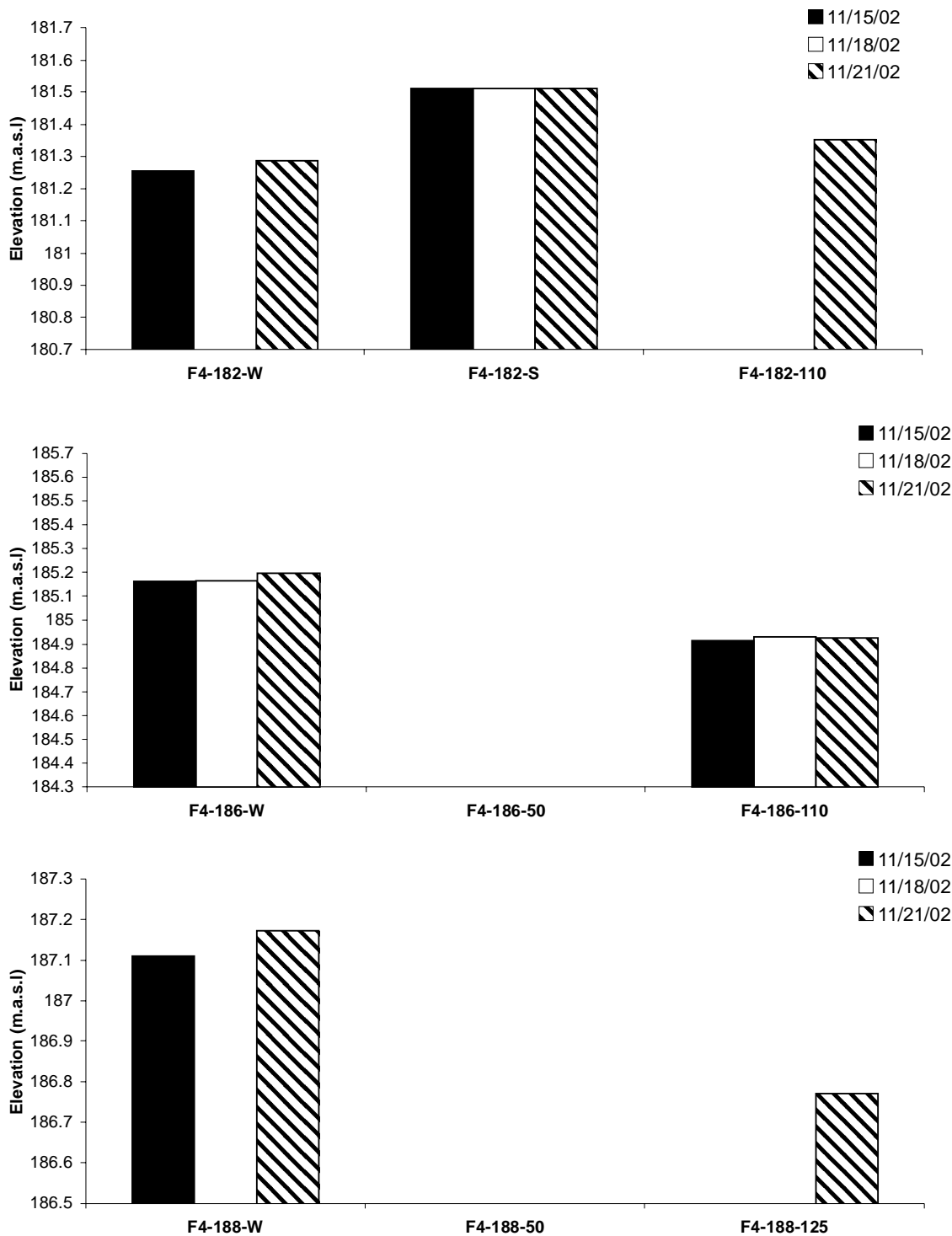
**Figure 13C.** Effect of precipitation on a moraine (M1) site during a storm event. The greatest response occurred on November 19, 2002. The lower graph indicates the precipitation record from the Rithet Creek meteorological station at SLR.



**Figure 13D.** Effect of precipitation on a morainal (M5) site during a storm event. The greatest response occurred on November 18, 2002. The lower graph indicates the precipitation record from the Rithet Creek meteorological station at SLR.



**Figure 13E.** Effect of precipitation on a fluvial (F1) site during a storm event. The greatest response occurred on November 15, 2002. The lower graph indicates the precipitation record from the Rithet Creek meteorological station at SLR.



**Figure 13F.** Effect of precipitation on a fluvial (F4) site during a storm event. The greatest response occurred on November 21, 2002. The lower graph indicates the precipitation record from the Rithet Creek meteorological station at SLR.

## Chapter 4 General Conclusions

### 4.1 THE EFFECT OF GEOMORPHOLOGY ON NUTRIENT CONCENTRATION IN THE RIPARIAN AREAS SURROUNDING SOOKE LAKE RESERVOIR

Geomorphology had a large effect on the distribution of nutrients at SLR. Soil type played the largest role in identifying Colluvial soils as having the largest concentration of nutrients and may therefore be most problematic to managers. Particle size played a major role in nutrient delivery throughout the riparian areas, the sandy soils allowed for leaching. Leaching also played a role in the redistribution of nutrients with depth.

As anticipated, topography and geology were the main factors affecting hydrologic flow paths. However, differences in soil type seemed to have little to do with flow pattern in the Colluvial, Fluvial, and Morainal riparian areas surrounding SLR. The overall flow system seems to be predominately ephemeral. As part of these flow patterns, connectivity along an entire transect was also event driven and only occurred at four sites (M5, M1, O3 and F1). As expected we found that preferential pathways played a large role in subsurface flow, given that these areas were harvested and because of the rocky soil, especially at Colluvial sites.

Preferential flow and leaching are the most prevalent processes when considering the distribution of nutrients in these cleared riparian zones. In general we saw an increase in nutrient concentration with depth, and this pattern can be explained by coupling the soil chemistry, particle size data and the flow patterns quantified in chapters 2 and 3. The sandy soils of SLR were shown to have a high hydrologic conductivity (Table 4) in the order of  $10^{-5}$  m/s that also promotes expeditious flow. Specifically, depth had an effect on  $\text{NO}_2^-$  and DOC in shallow soils at M sites, and especially at F sites where depth had an effect on all nutrient concentrations. Soil chemistry was sampled during the wettest

time of year, and in fact during an unusually wet year (Fig. 8), when hydrologic connectivity would be greatest at SLR, perfect conditions for leaching and preferential flow to the reservoir.

The lowest nutrient concentrations were found at the wetland (O3) site, but a trend of increasing concentration with depth was apparent. This wetland site exists in a topographic depression that becomes a stream channel during the wettest time of year, permitting short nutrient residence time. The soil data does not indicate that the wetland would provide a source of nutrients to the reservoir, however given the time of sampling, the samples may be representative of soil that has recently been flushed. The hydrologic data however, indicates that the middle of the O3 transect is a discharge site. This site likely receives subsurface nutrient loading from Begby Lake and the forested riparian buffer located North of site 3.

Colluvial soils contrast the wetland site in a geomorphic manner, in hydrologic function and in nutrient concentrations. The C sites were very steep, were often rock outcrops and still water always seemed to be recharging. Without the connectivity that is apparent at O3, it matters little that Colluvial soils have the greatest soil concentrations if it is not being transmitted downslope. Interestingly, although soil chemistry data has indicated that C soils contain the greatest concentration of nutrients and O soils contain the least, hydrologic pathways are such that wetlands are more likely to be a source for nutrient loading to the reservoir.

In general, flux calculations from the riparian areas to the reservoir indicate that a very small percentage of nutrients found in the riparian areas are contributed to the reservoir (0.042  $\text{NO}_3^-$  kg/ha/yr from riparian area to the reservoir). As a result it is expected that

any blooms that occur following flooding of the riparian areas may be attributed to remineralisation of organic material or desorption of solid phase nutrients.

#### **4.2 IMPLICATIONS FOR MANAGEMENT AT SLR AND OTHER BEST MANAGEMENT PRACTICES**

Riparian areas are well studied because of their importance to a number of resource sectors requiring management. Most often they are studied in relation to agriculture and forestry, and are managed with water quality in mind. Researchers agree that soil nutrients, hydrology, and water chemistry are all necessary aspects for study because of their influence on water quality (Broadmeadow and Nisbet 2004). Best Management Practices (BMP) are used to direct resource managers, and are generally based on research similar to that carried out in this thesis. This thesis provides a unique perspective to resource managers in that it examined cleared riparian zones, whereas BMPs are generally based on forested riparian areas (Blinn and Kilgore 2001). The results presented here provide evidence that nutrient concentrations differ with soil type and that Colluvial soils contained the greatest nutrient concentrations at all sites. This alone is valuable information for resource managers and drinking water managers alike. Our findings also confirm that the hydrologic flow system must be addressed at both local and regional levels (Devito *et al.* 2000). Hydrologic connectivity and seasonality can inform managers as to when the best time to harvest is, or when the greatest quality impact to drinking water may occur. At SLR, it is evident from hydrograph data that the best time of year to harvest would be from July to September, when hydrologic connectivity and water levels are at their lowest. In contrast, harvesting between November and January would have negative implications for water quality due to nutrient and sediment transport via through flow and overland flow.

Using geomorphology as an indicator for managers is a cost effective method to determine BMPs. Our work echoes that of Vidon and Hill (2006) by showing that soil type and particle size can be used as important geomorphological indicators of nutrient distribution in riparian areas. However, the different units within geomorphology must be used in context when employed as a technique for creating BMPs. For example, using slope as a BMP is common practice, but may not always be applicable. At SLR the distribution of nutrients did not follow a pattern previously reported in other studies (Kirkby *et al.* 1997) where the nutrients accumulated at the bottom of the slope. However, the steepness of the slope had an effect on M and F soils. TDN,  $\text{NO}_2^-$ , and  $\text{NO}_3^-$  were greater at high slope transects in F soils, and in M soils only TDP concentrations were lower in high slope transects. This indicates that variability between soil types must be acknowledged and careful attention must be paid to the differences between nutrient cycles.

#### **4.3 FUTURE WORK**

As implied by Devito *et al.* (2000), harvesting directly up to a water source may not have as great an impact as the hydrologic connectivity or watershed boundaries. SLR is managed with cleared riparian areas but maintains forested uplands. From our hydrologic analysis, we know that connectivity through the bedrock occurs year round. This indicates that a more regional system exists, and if this is the main contribution of nutrients, then keeping the upland forested allows for good management practice where natural nutrient processes can take place.

The next step in this research is to identify differences in geomorphology (soil type, slope, depth, and elevation) that affect riparian subsurface water chemistry, and to

identify their chemical transformations and pathways. Linking biogeochemistry to geomorphic features has been carried out by few researchers (McDonnell 2001; Vidon and Hill 2004), but is suggested by many as a way to determine the effectiveness of chemical reduction within a riparian area (Lowrance *et al.* 1997; Baker and Vervier 2004).

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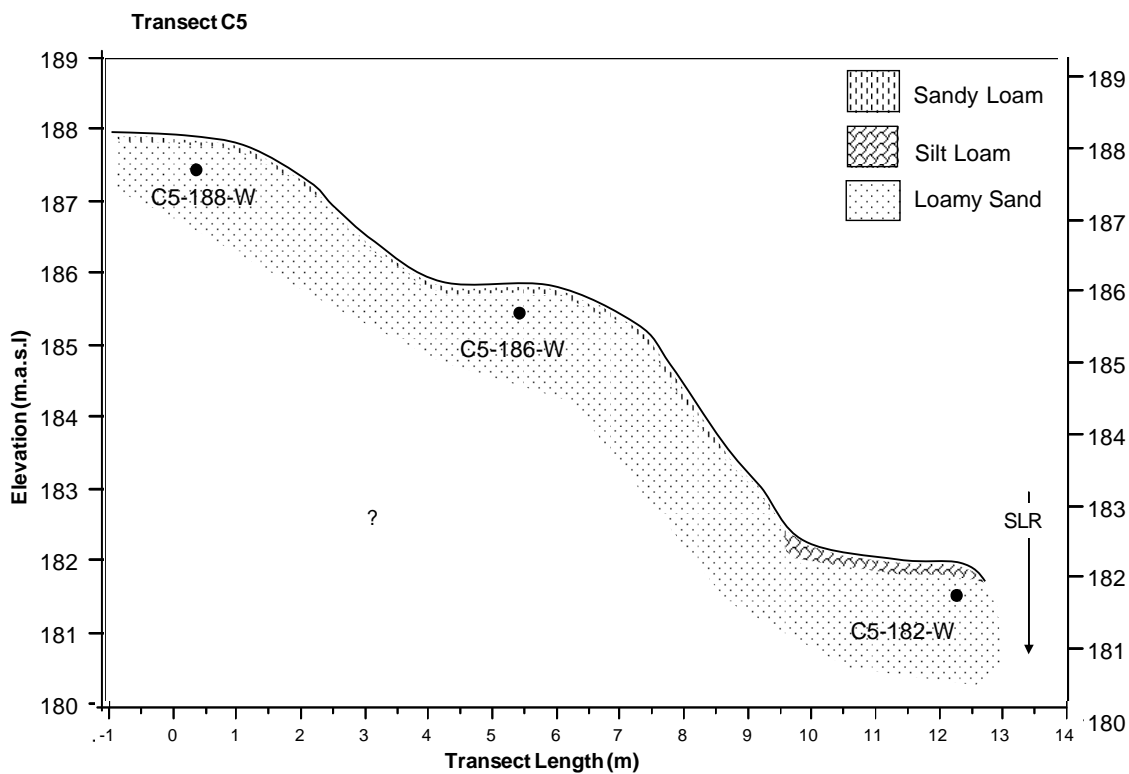
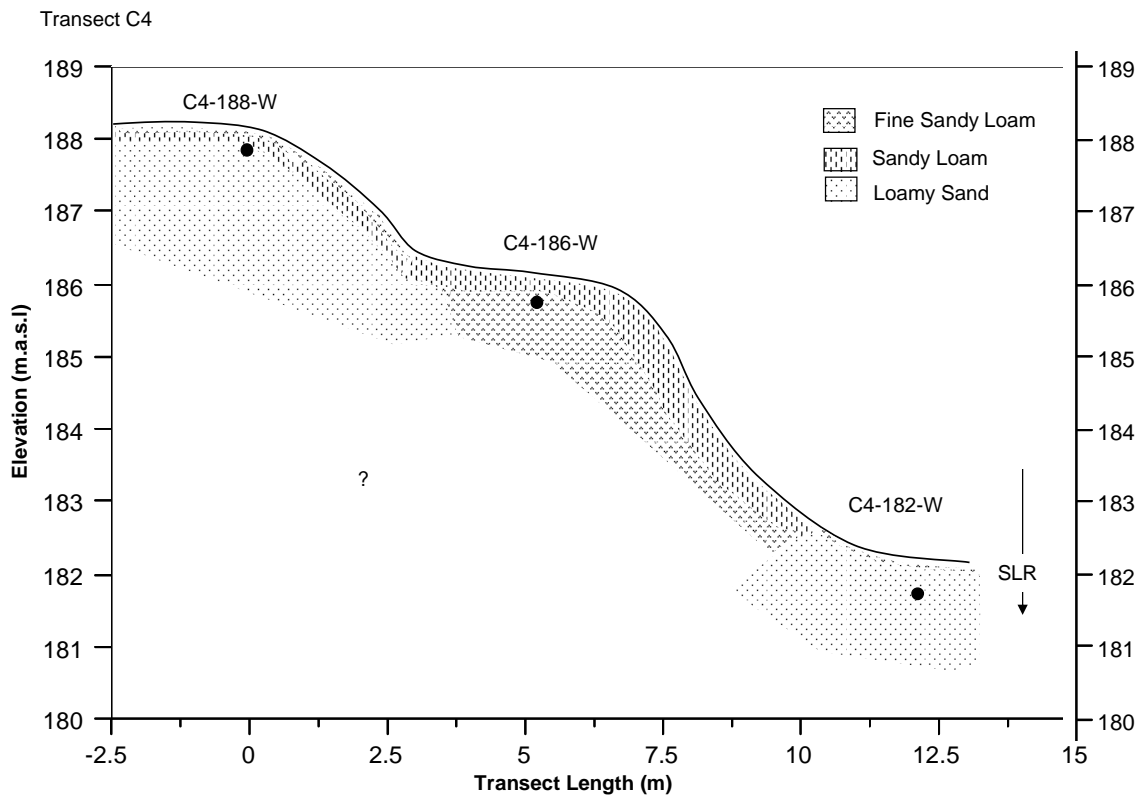
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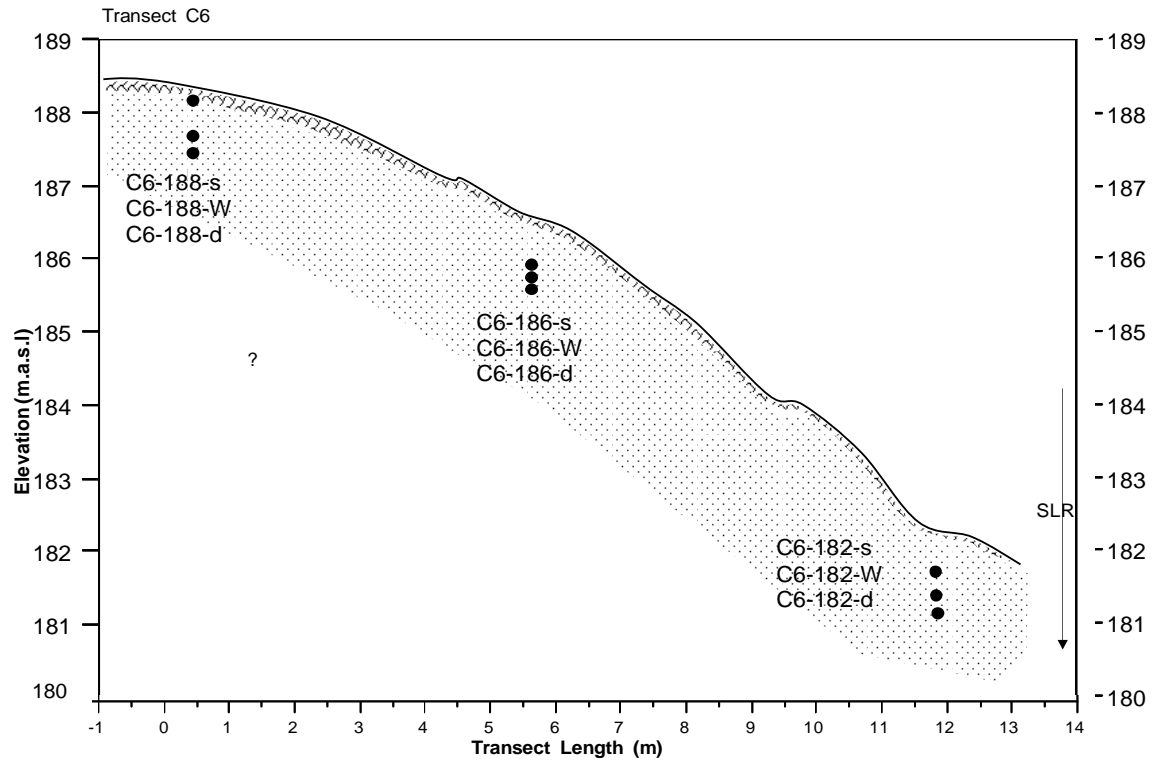
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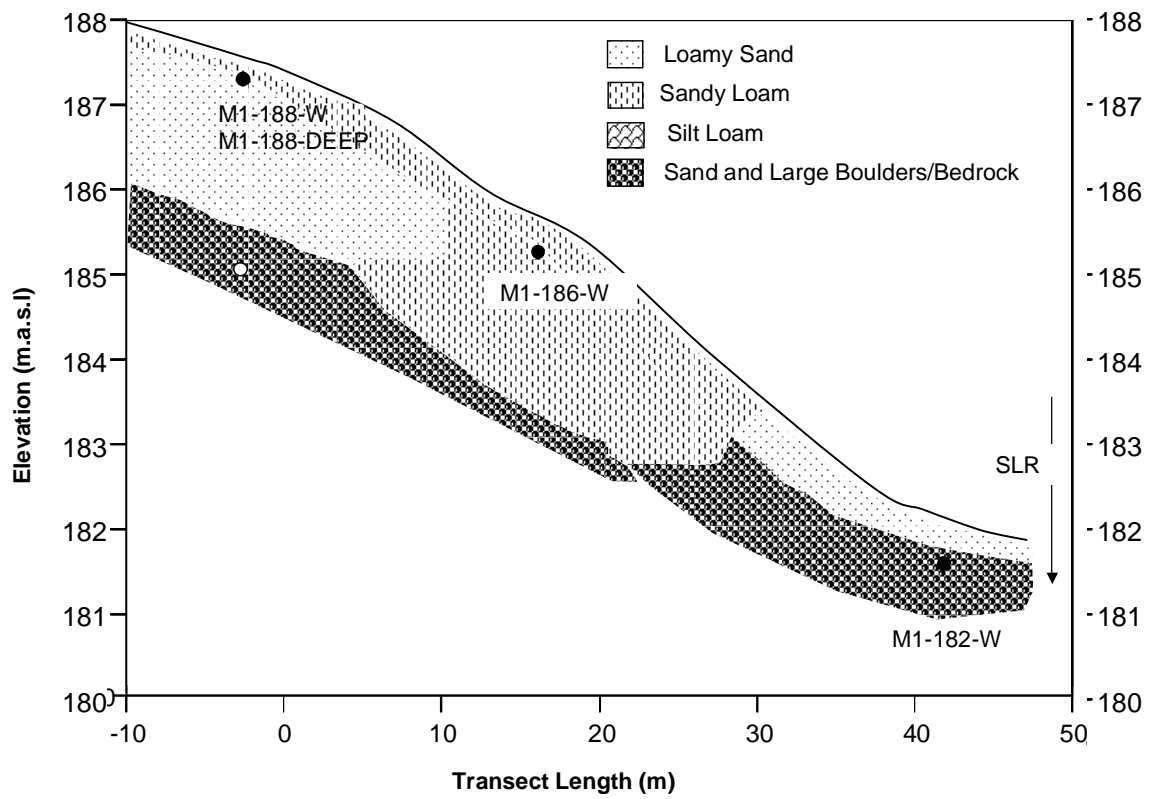
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## Appendix 1

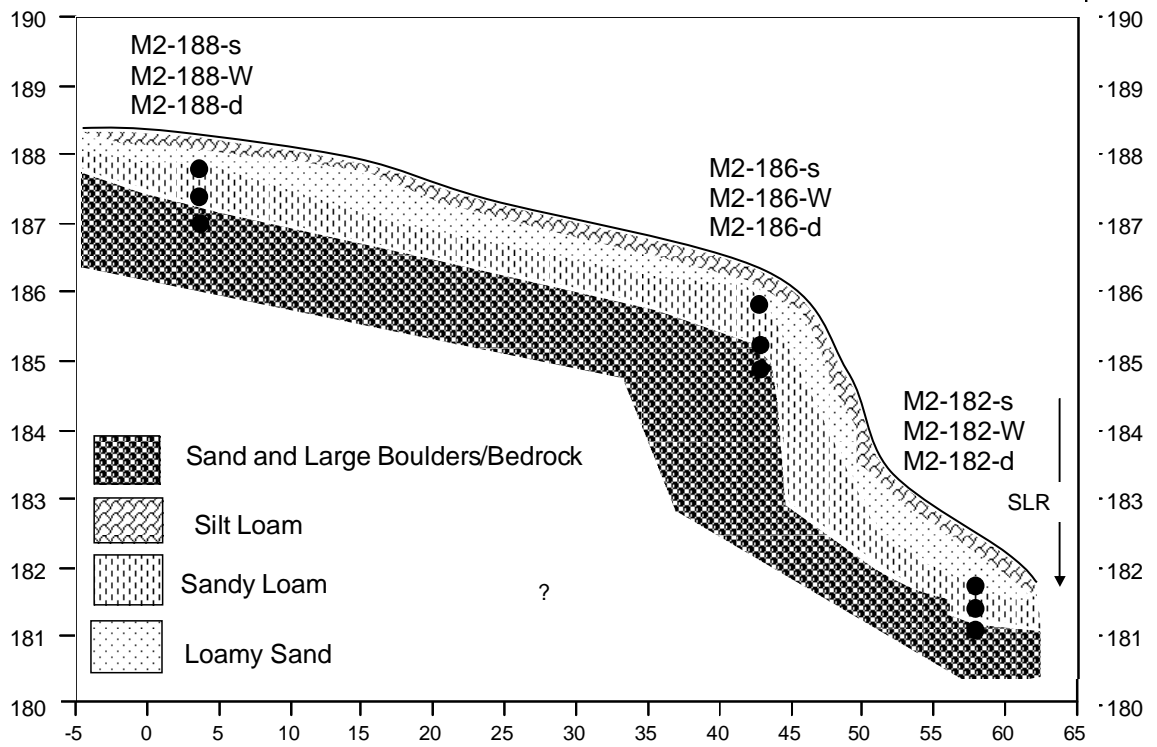
Appendix 1 describes the location of all the instruments installed at the SLR. The y axis is in meters above sea level (m.a.s.l) and the x axis describes the transect length (m).

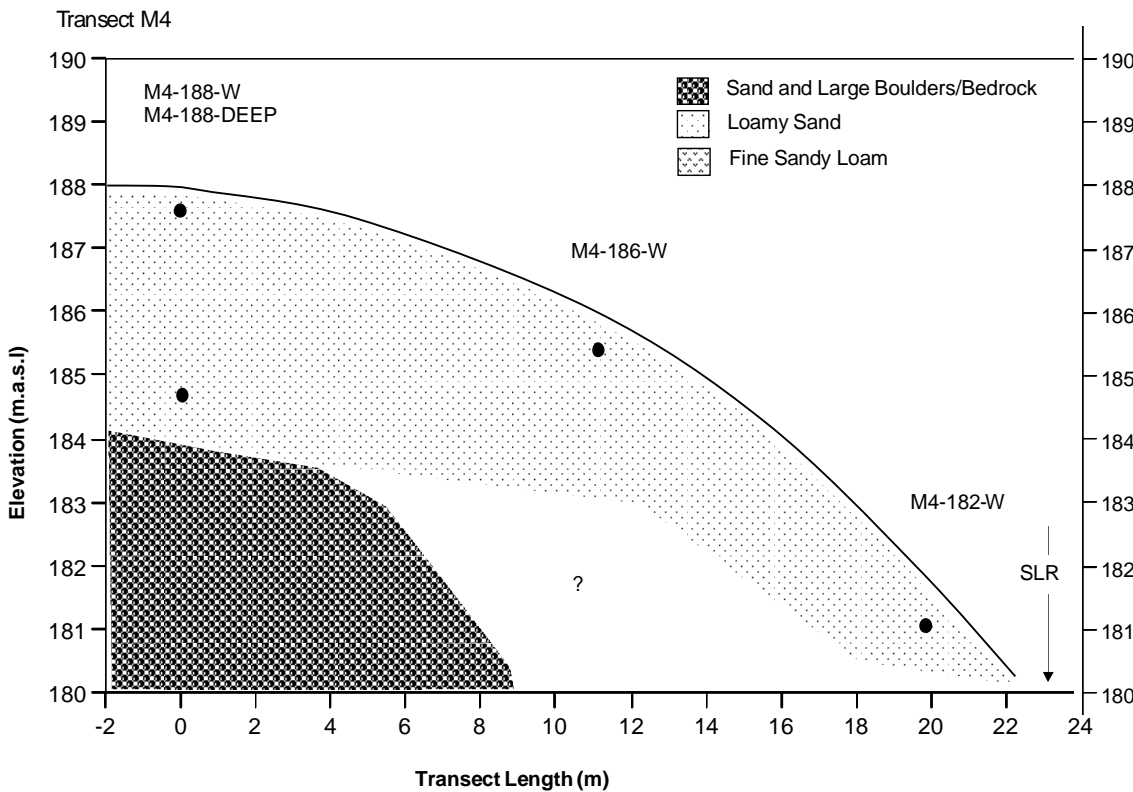
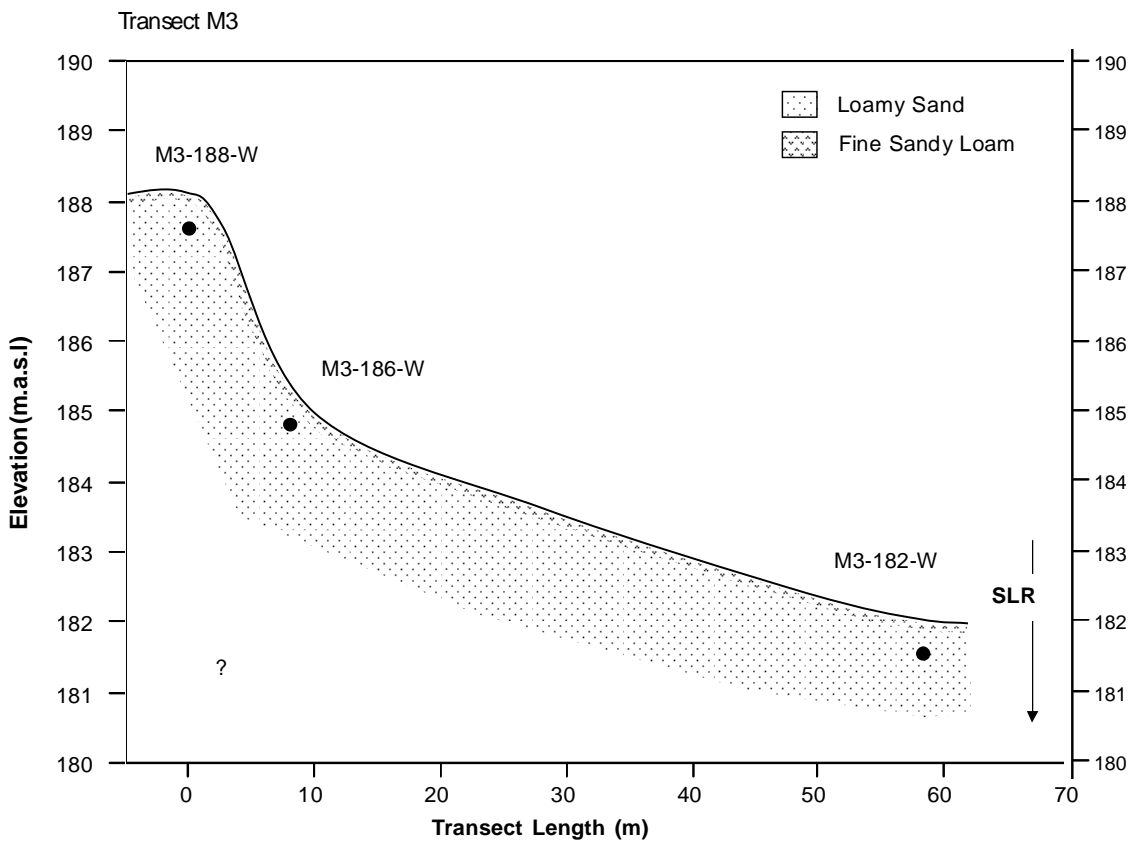


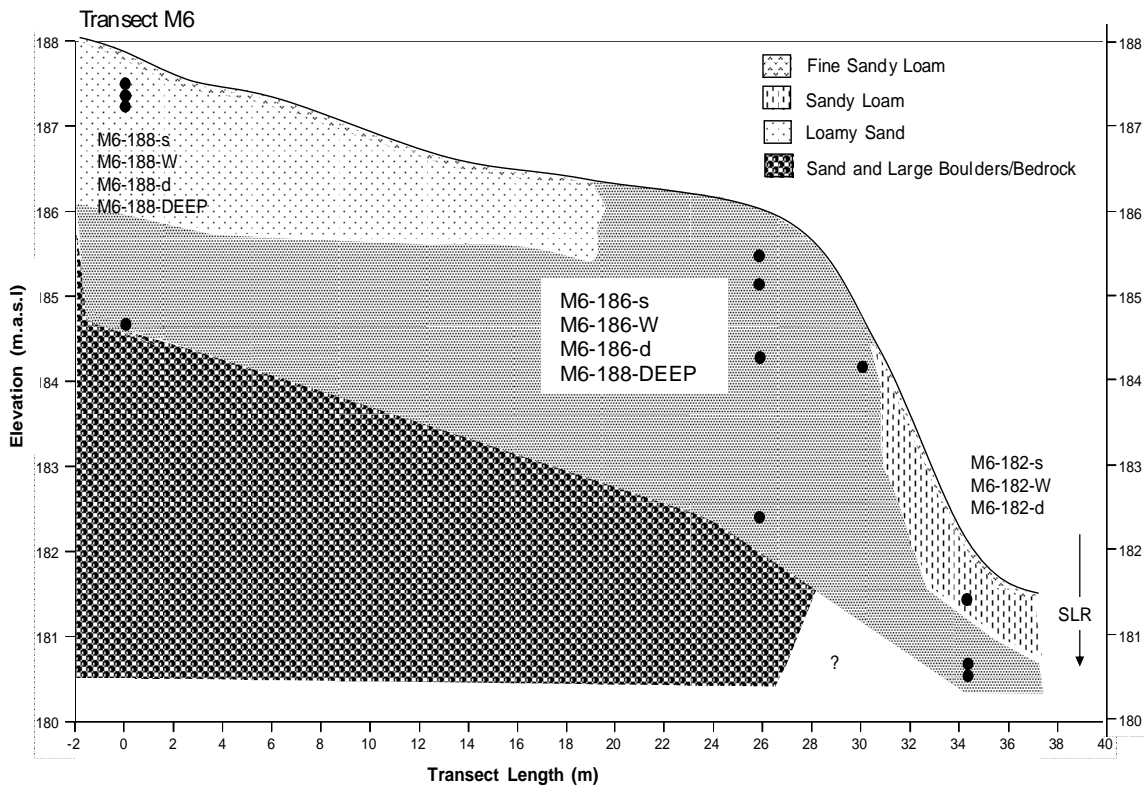
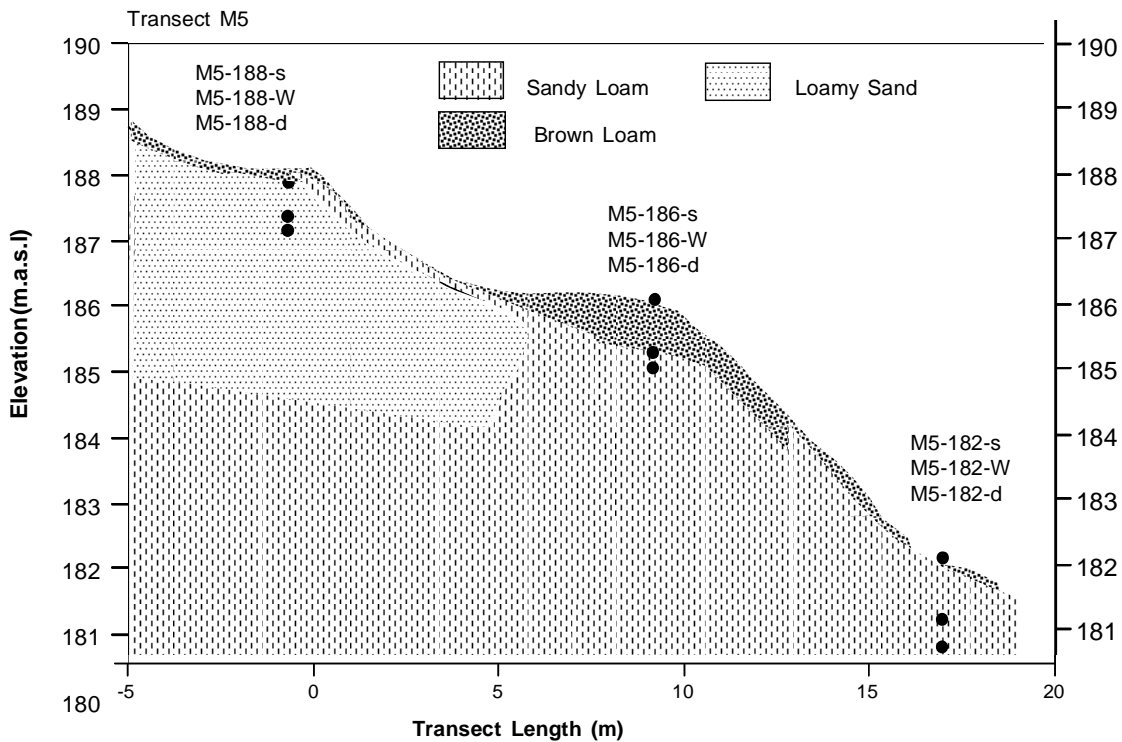


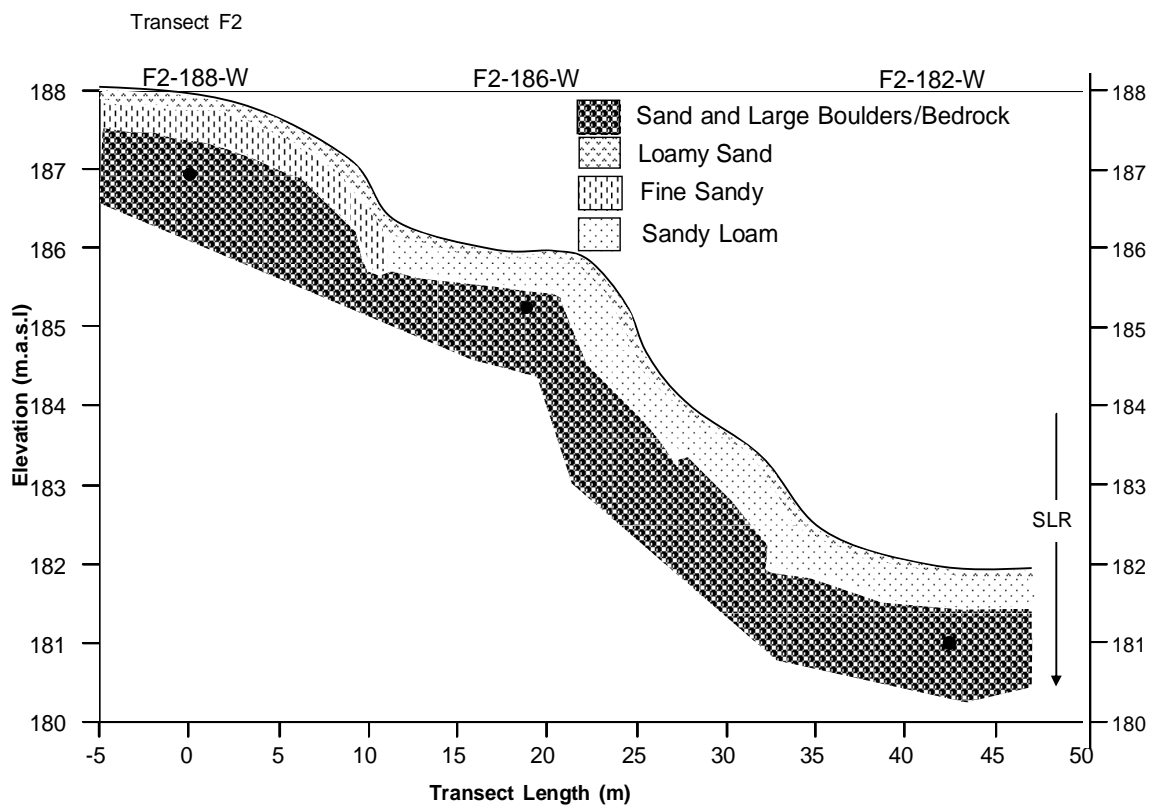
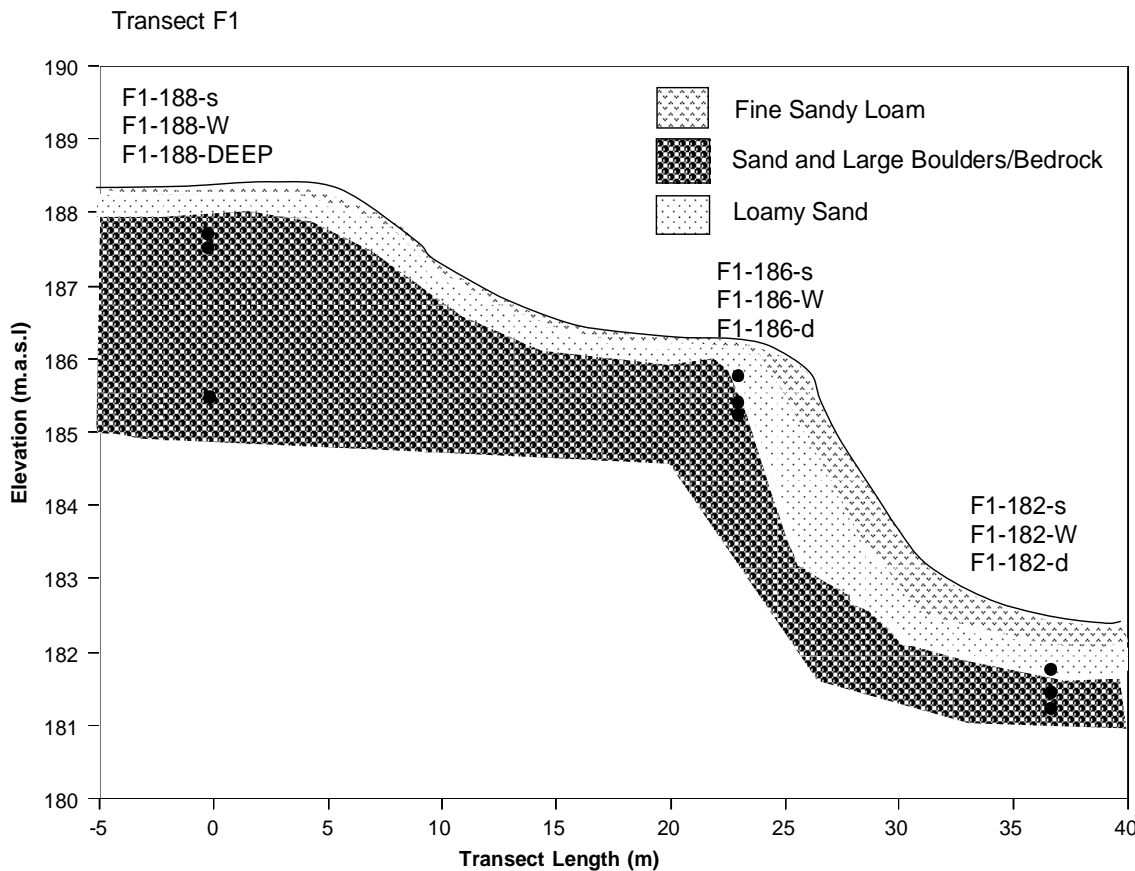


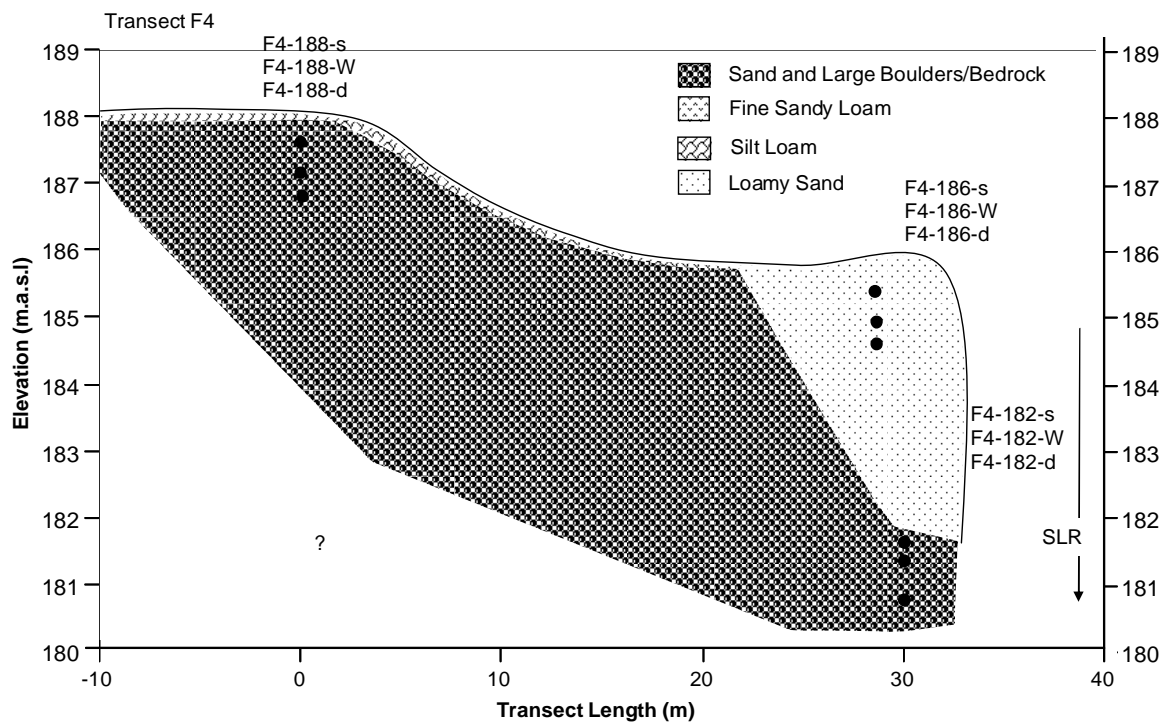
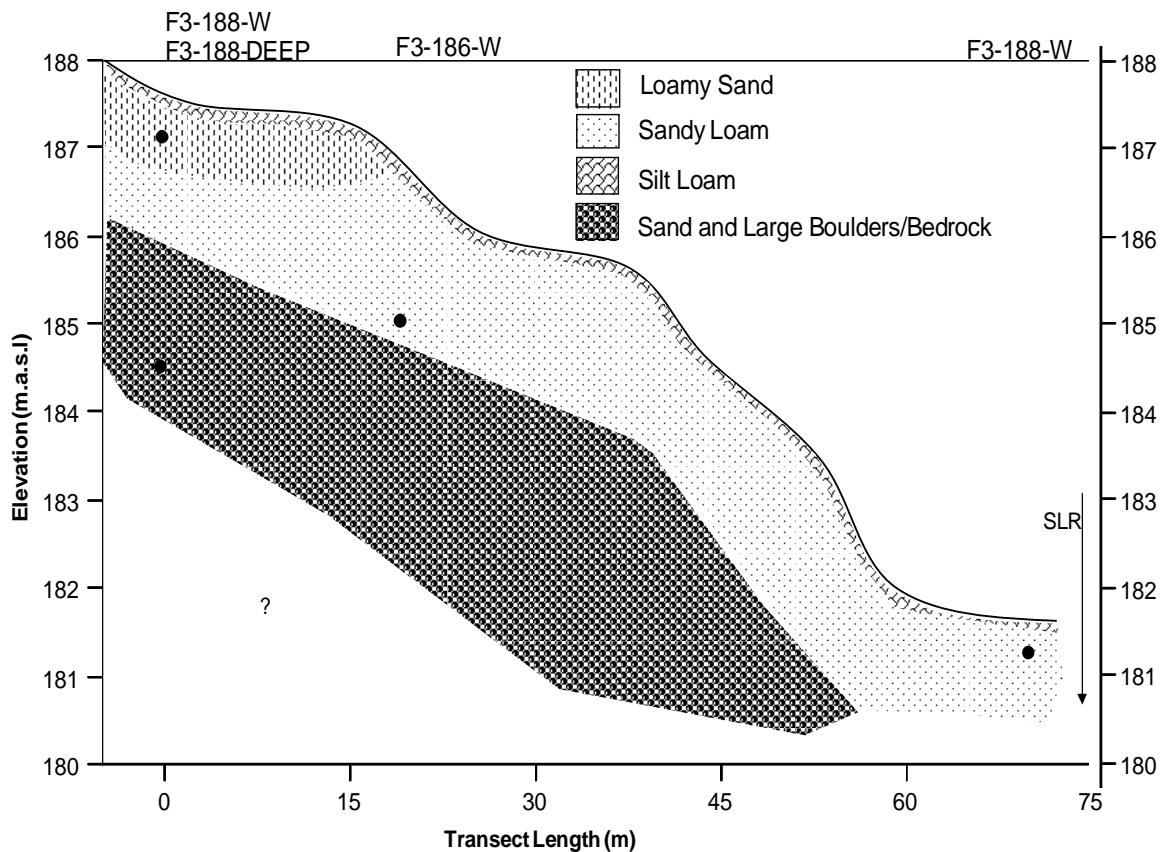
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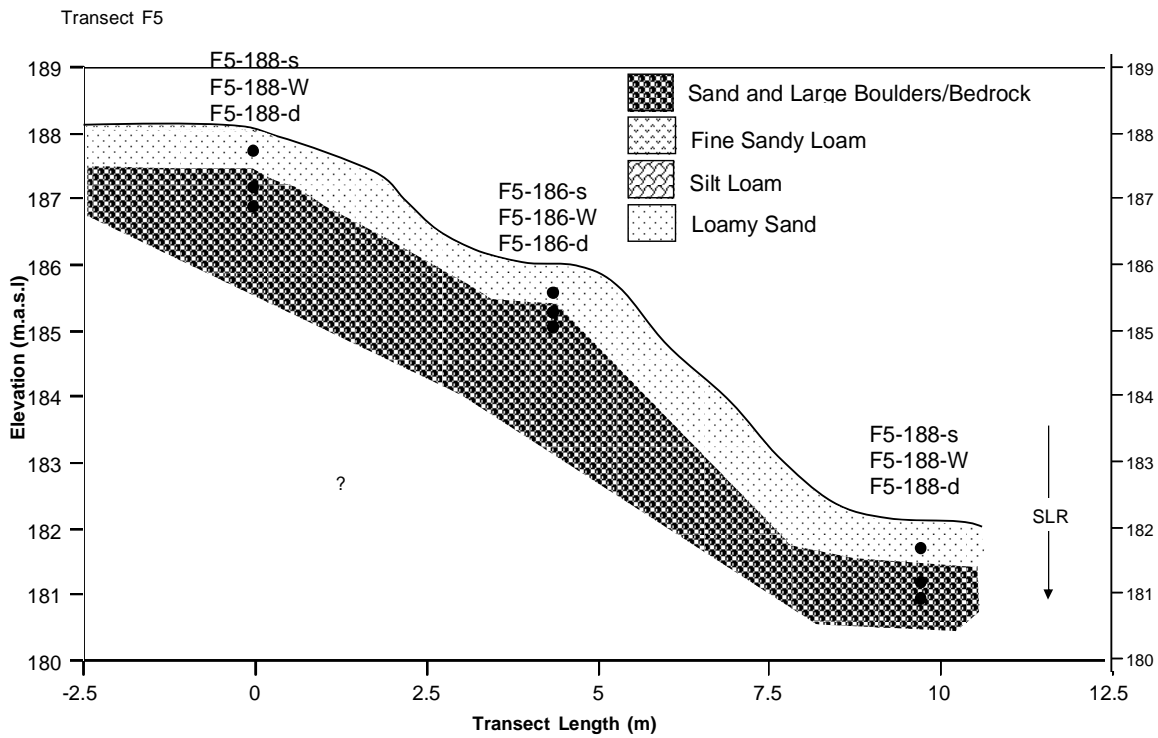


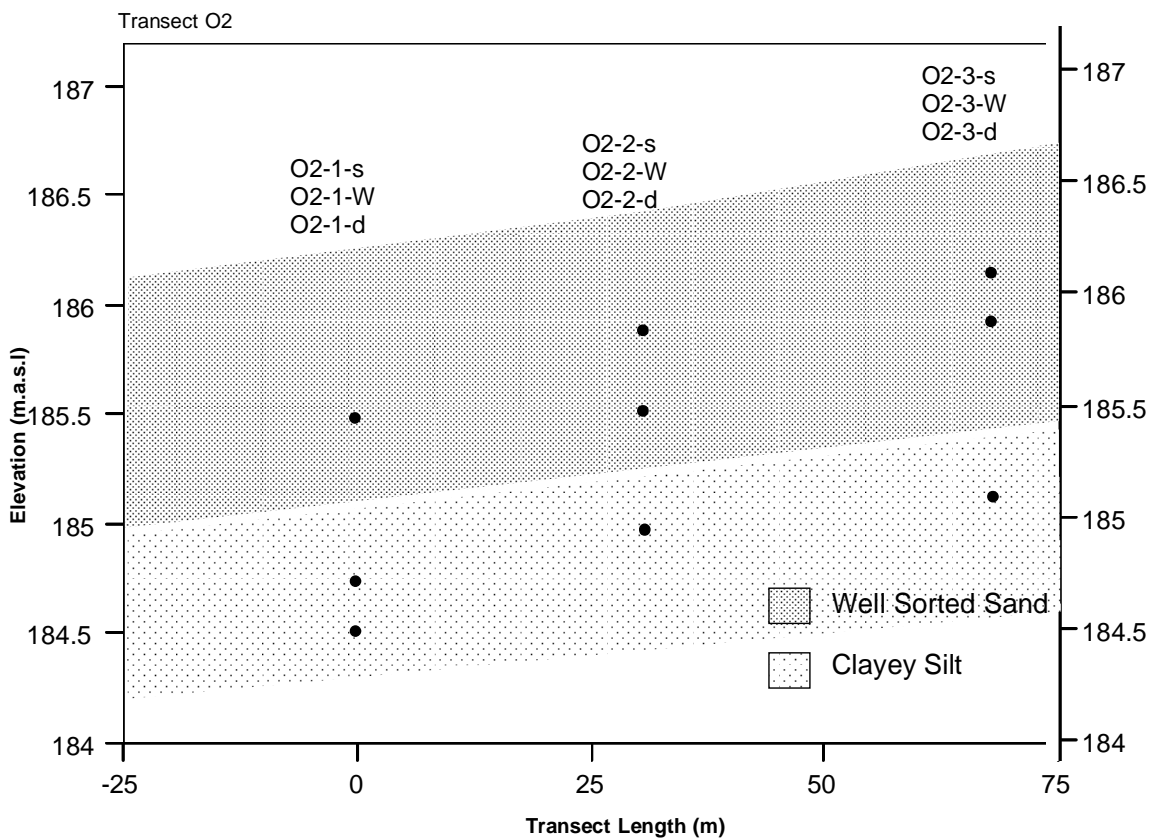
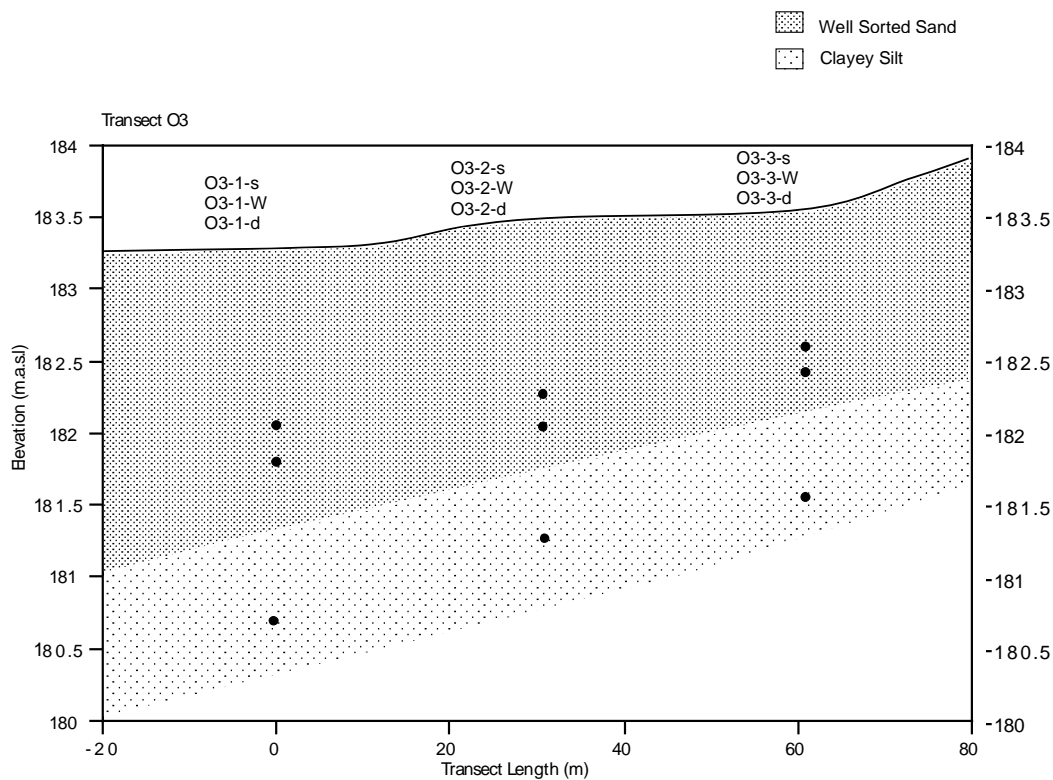






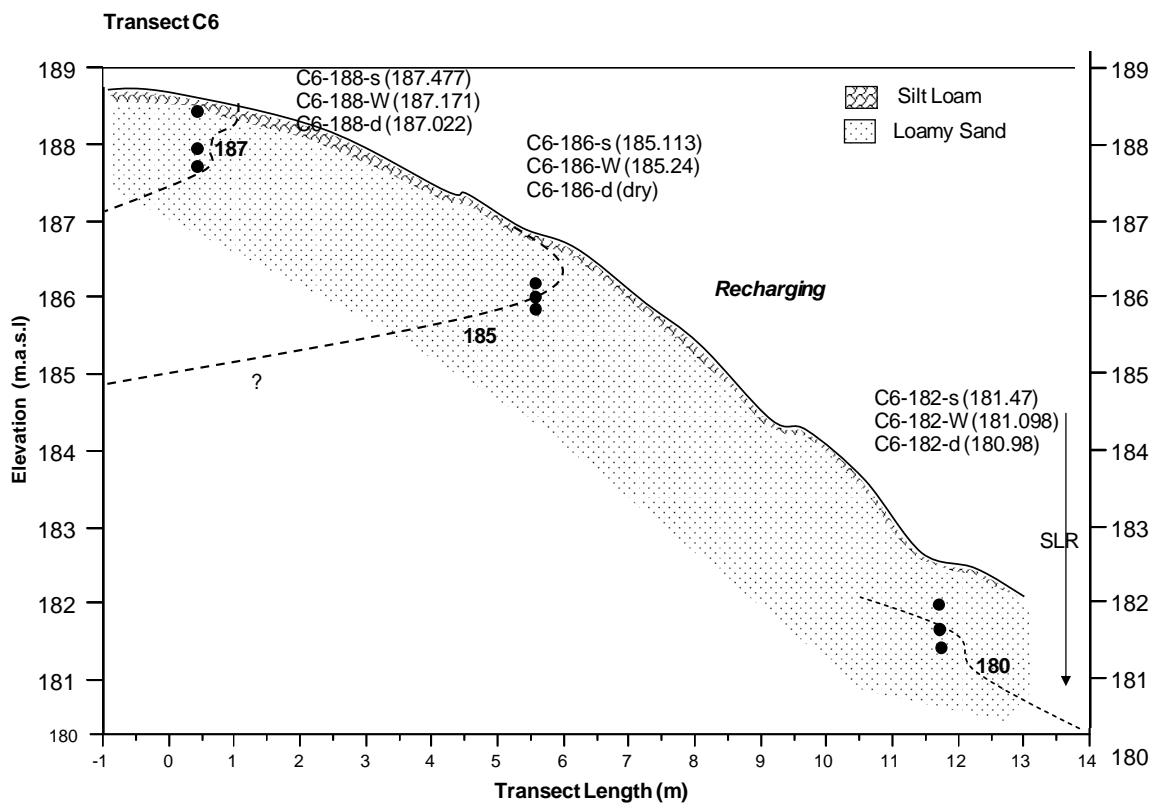


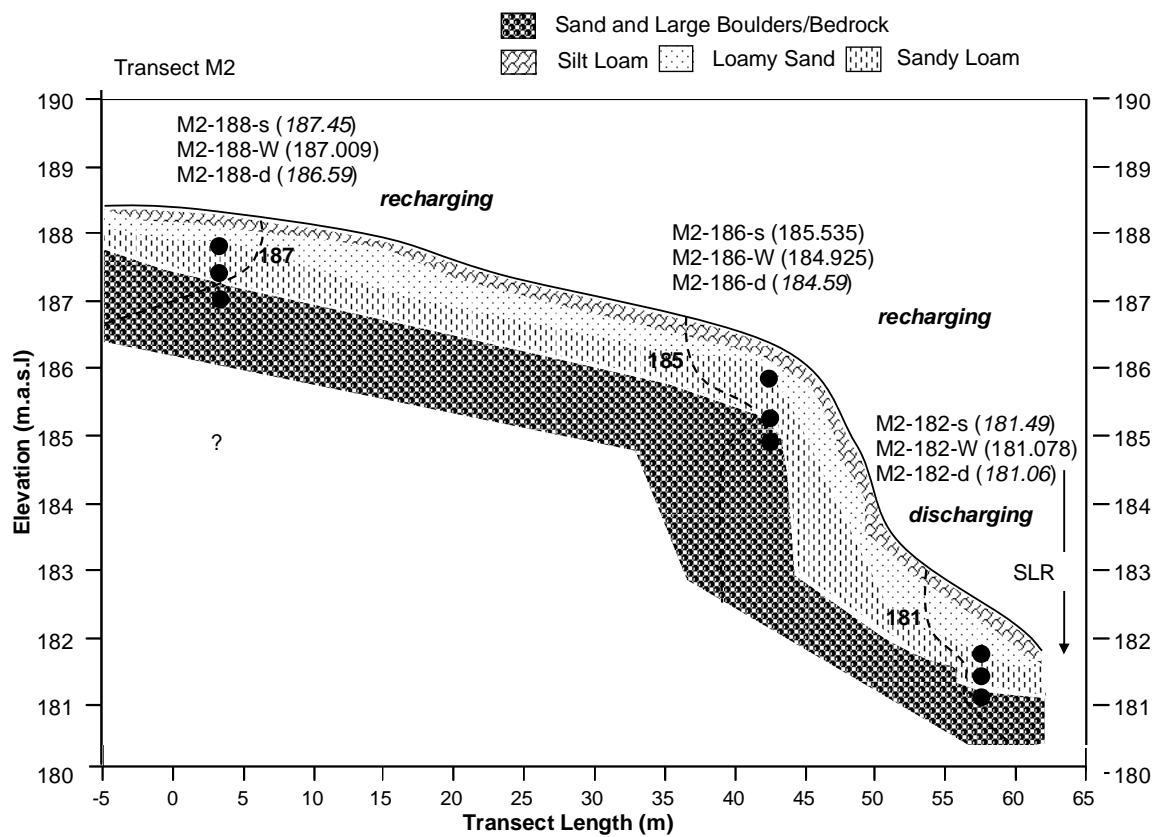
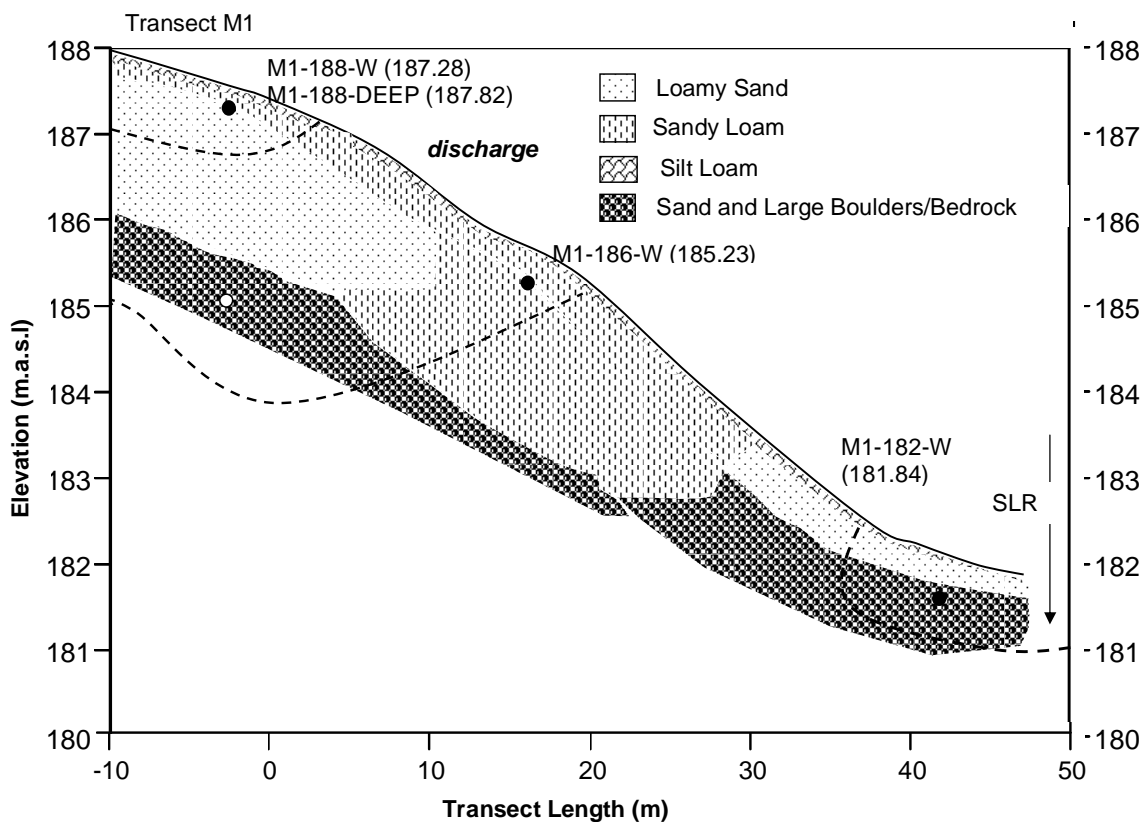


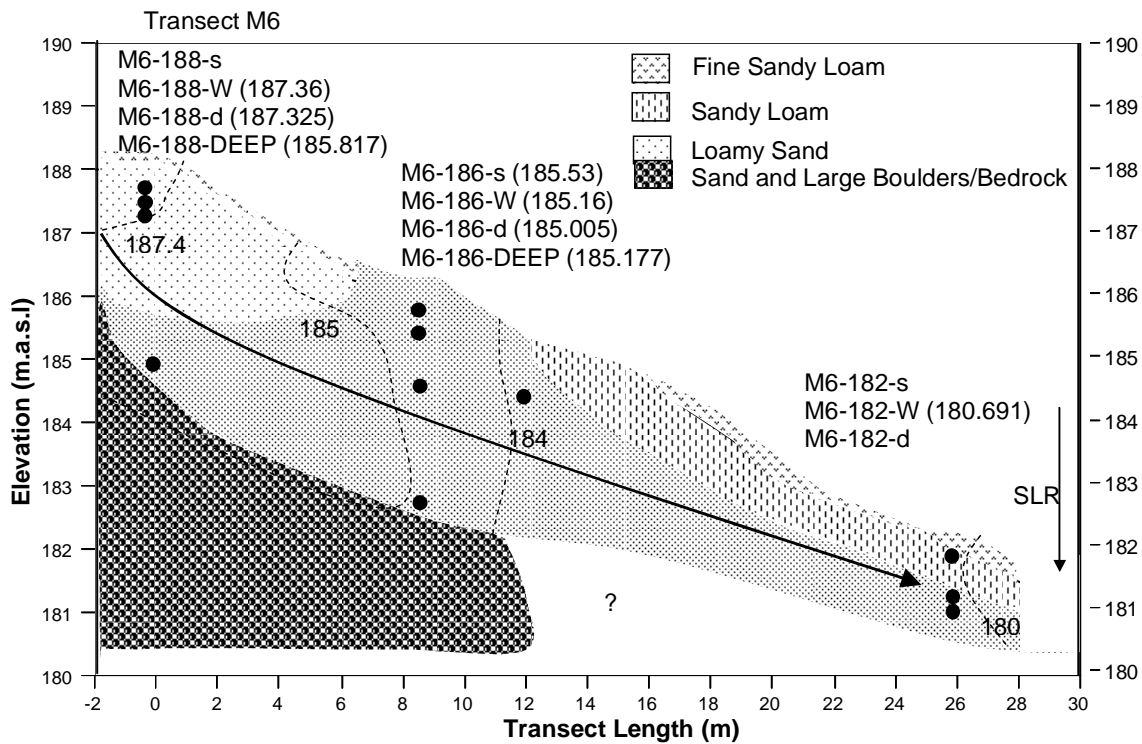
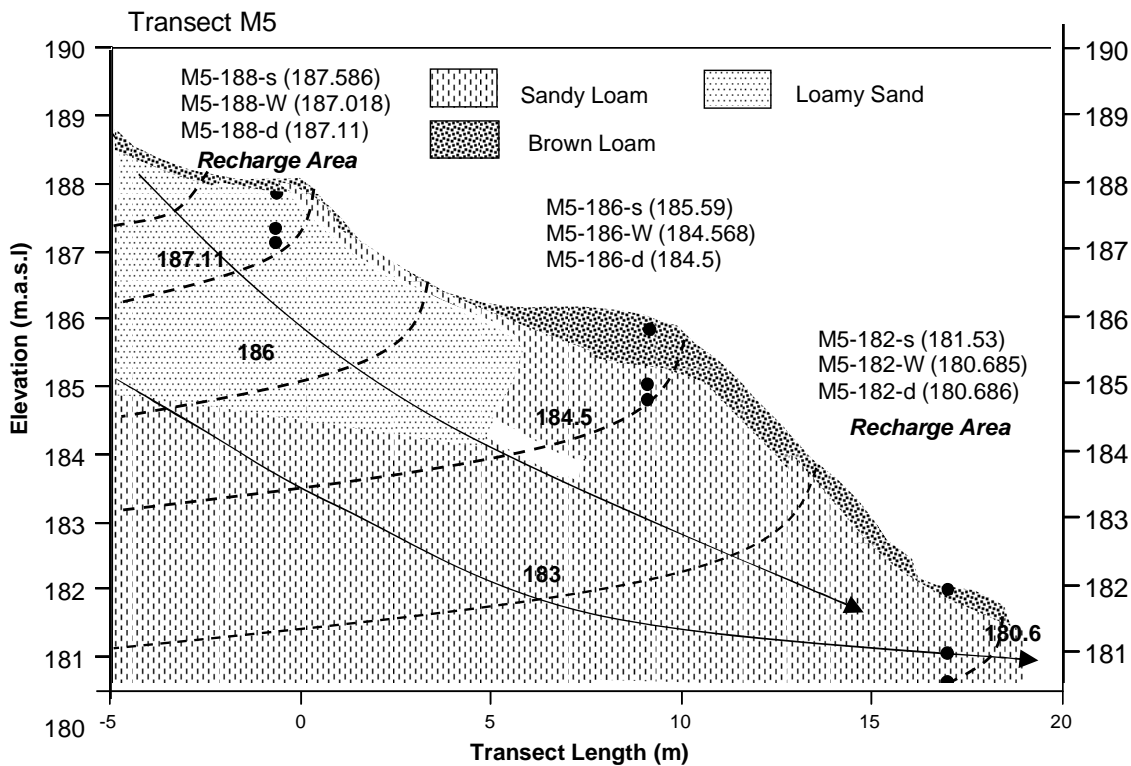


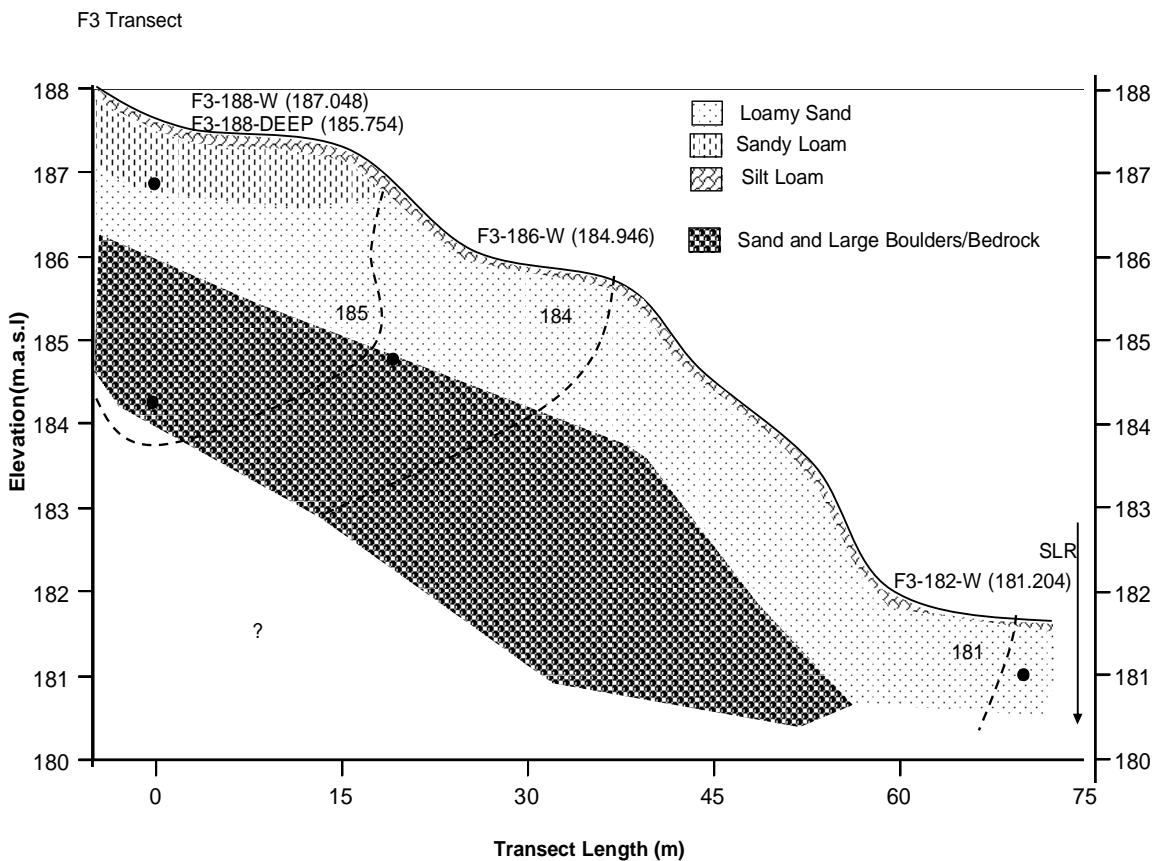
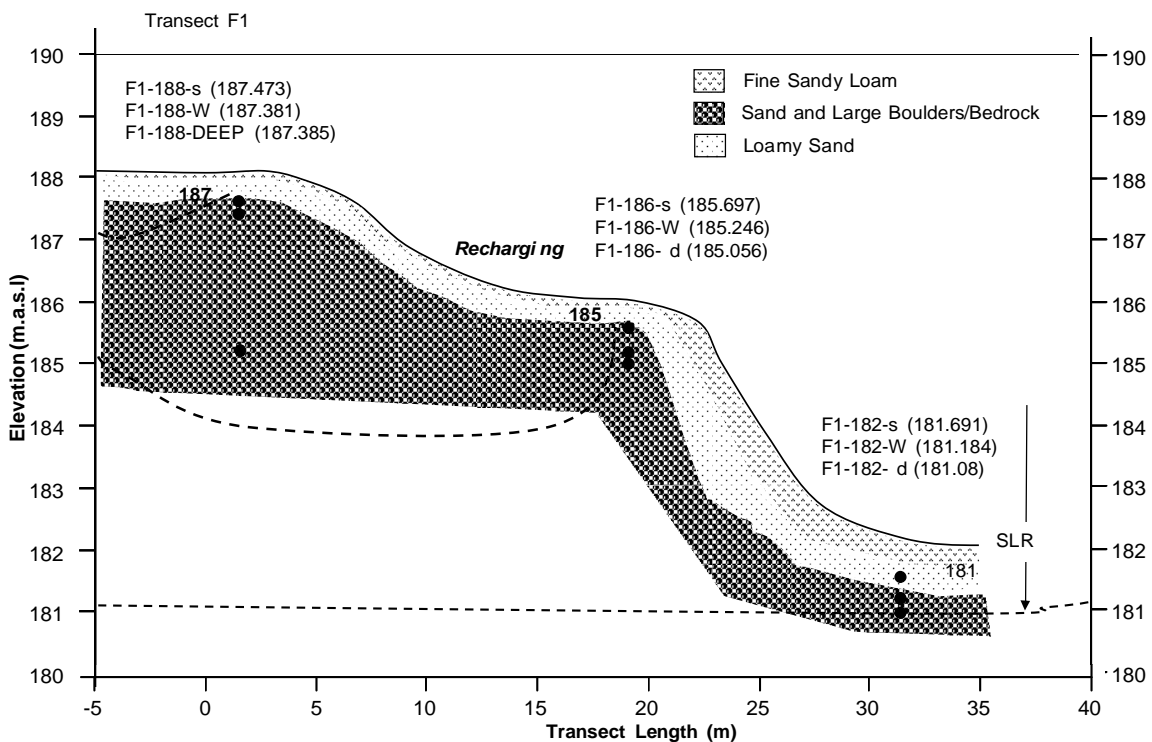
## Appendix 2

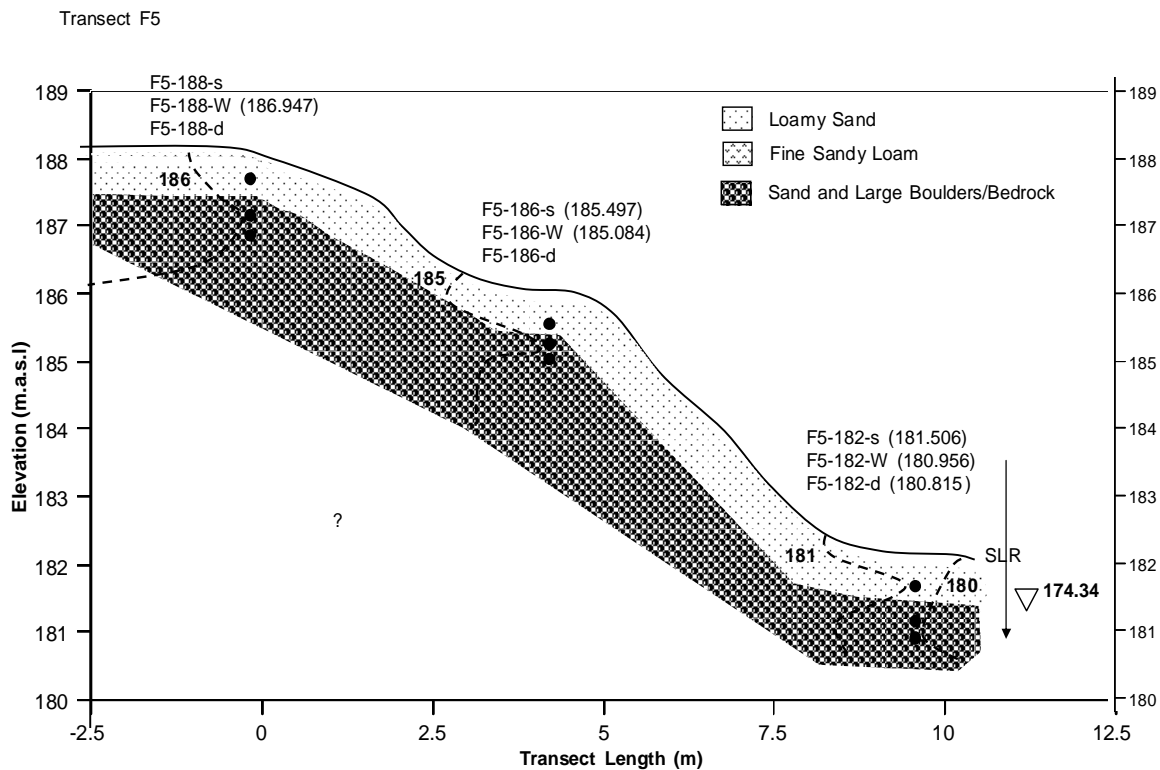
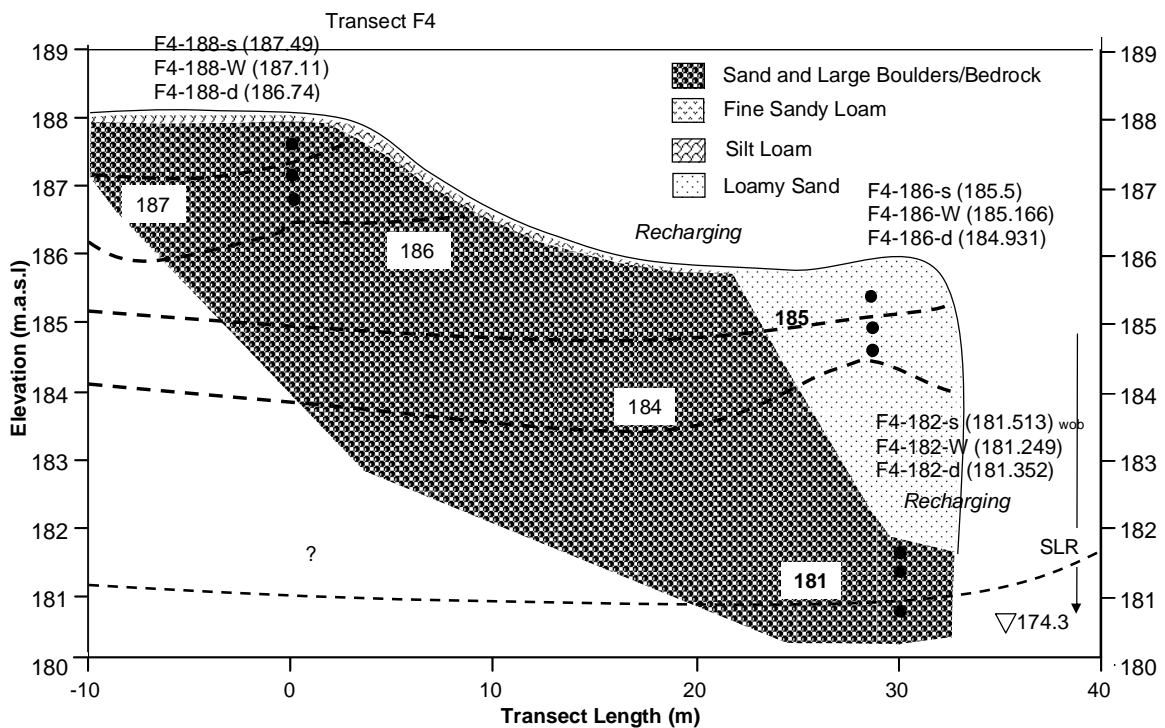
Appendix 2 illustrates the water levels at transects during the wet and dry season. The y axis is in meters above sea level (m.a.s.l) and the x axis describes the transect length (m).

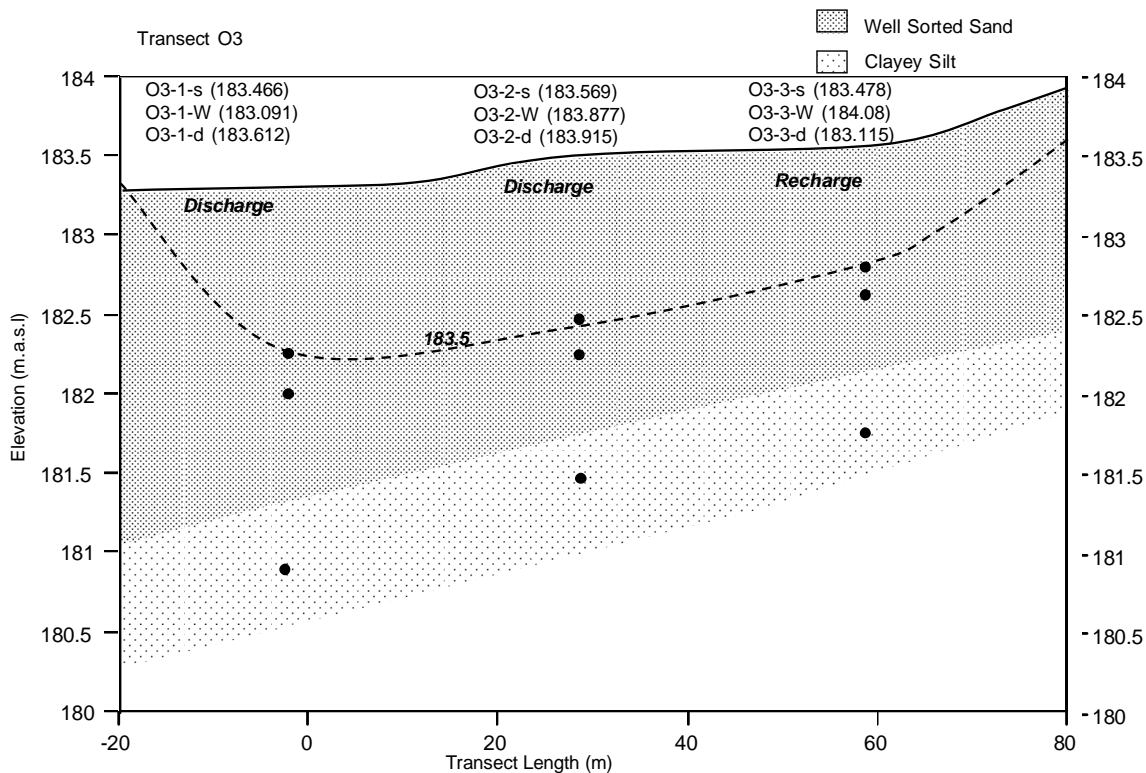
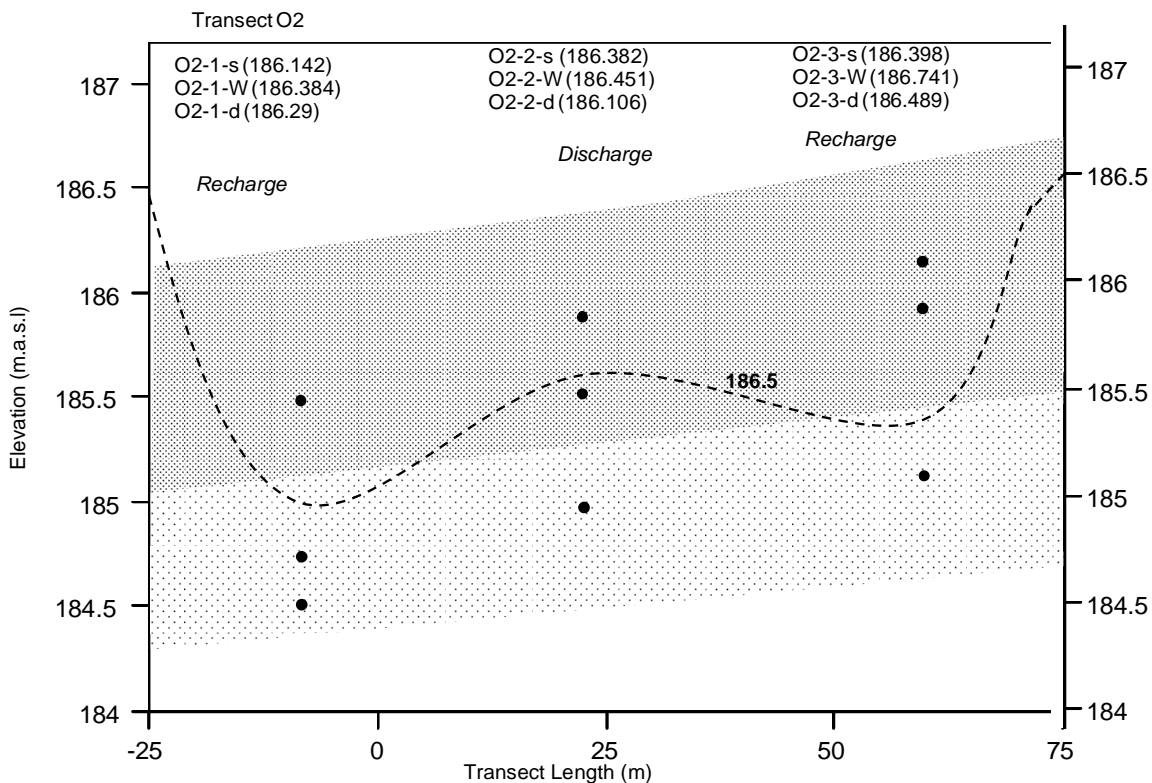












DRY

