

**A COMPARATIVE ANALYSIS OF GROUNDWATER CONDITIONS IN
TWO STUDY AREAS ON TILL AND GLACIOLACUSTRINE SEDIMENTS,
LETHBRIDGE, ALBERTA**

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ABSTRACT

Irrigation rates in excess of plant evapotranspiration requirements have been identified as a major contributor to the development of raised water tables in the City of Lethbridge. These high water tables have created problems such as coulee slope instability, basement flooding and structural instability.

This study characterized water table conditions in Lakeview subdivision, an area that experiences basement flooding. Soil texture data from this subdivision is used to address speculation that geologic controls contribute to high water tables in the city of Lethbridge. Linear regression analysis comparing mean sand and clay fractions to mean water table depth revealed that variations in soil texture have no statistical relationship to variations in water table depth.

Glacio-lacustrine sediments underlie Lakeview subdivision while tills predominate in the Varsity Village area. Lakeview subdivision is also approximately 20 years older than Varsity Village and the two are compared to gain some understanding of how water tables develop over time. Comparison of mean water table depths in irrigated and non-irrigated land cover classes in both Varsity Village and Lakeview revealed a significant difference in Varsity Village while Lakeview showed no statistical difference. Finally, a water scheduling program is developed to decrease or reduce the build-up of water tables and alleviate some of the problems that result.

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Chapter 1

Introduction

1.1 Introduction

Urbanization can have major impacts on the hydrology of a region. A well known factor of urbanization is the covering of significant portions of land with surfaces that are typically impermeable to water (Foster, 1990). The impermeable nature of these land surfaces result in increases of the response rate, peak flow, duration of flow, and total flow of runoff (Lazaro, 1979). Due to these increases in runoff it was often expected that groundwater recharge in an urban environment would be less than the pre-urbanization recharge rates. This is not the case, as groundwater recharge is often found to be higher following urbanization than before (Lerner, 1990). Groundwater recharge occurs when water moves down through the unsaturated zone of the ground and replenishes groundwater.

Leaking water mains, sewers, septic tanks, soakways (an area where water is collected and allowed to infiltrate the ground), and over-irrigation of parks, lawns and gardens are some of the contributors to increased groundwater recharge in urban areas. Increases in

groundwater recharge will often cause changes to the water table. The water table marks the upper boundary of water saturated soil in the subsurface zone. Elevated water tables often result from an increase to the groundwater recharge and are water tables that lie at higher elevations than those prior to urbanization.

Over-irrigation of parks, lawns and gardens has resulted in increases to water table elevations in a number of urban locations (Foster et al., 1994; Lerner, 1990; Rushton and Al-Othman, 1994; Karnieli et al., 1984). In dry climates where irrigation is common, over-irrigation of parks and gardens by both the will result in more water being applied to these areas than the vegetation requires. Residential over-irrigation occurs because city residents have not been provided with the information necessary to know how much water is needed to maintain the plants. Some of the excess water applied to these areas will contribute to groundwater recharge. Once elevated water tables develop, a number of groundwater problems may arise. Structural instability, basement flooding, and slope instability have been reported in a number of locations (Foster et al., 1994; Greenwood, 1994; Karnieli et al., 1984; Rushton and Al-Othman, 1994).

1.2 Problem Statement

For a number of years the City of Lethbridge has been experiencing a variety of groundwater problems. Slope instability, basement flooding, and structural instability are all groundwater-related problems which have been identified in the City of Lethbridge during previous studies (Berg et al., 1996; Berg, 1997; Ruban and Thomson,

1983; Thomson and Morgenstern, 1977). These groundwater problems have been a major expense to the City of Lethbridge and frustrating for the residents who are directly affected by them. Possible sources of water contributing to the development of these groundwater conditions are of major interest to the City of Lethbridge

Curiously, Lethbridge experiences high water table conditions in an area that is considered sub-humid to semi-arid (Agroclimatic Atlas of Alberta, 1990). The city itself is built on the prairie surface and lies approximately 100 m above the floor of a major meltwater channel, today occupied by the Oldman that divides the older south and north portions of the city from the more recently developed west side. Nevertheless, water tables are found within one to two metres of the surface in many areas of the city. In contrast, undeveloped, dryland, outlying areas of the city typically have water tables deeper than seven metres (Geiger, 1962; Ruban and Thomson, 1983).

Urbanization has been identified as the key to the dramatic changes in local groundwater conditions. Specifically, increases to water table elevations within Lethbridge are linked to excessive application of irrigation to urban parks and residential lawns and gardens (Berg et al., 1996; Berg, 1997; Berg and Byrne, 1998). Data reported by Berg and Byrne (1998) revealed that during the irrigation period from 1990 to 1996, total water (irrigation and precipitation) applied to parks in the Varsity Village subdivision of Lethbridge was on average 2.3 times the amount of water that was evapotranspired by the park turfgrass (Table I.1). When compared to estimated evapotranspiration (ET), household water balance data revealed that 2.3 times as much total water (irrigation, roof

runoff, and precipitation) was applied to lawns (Table 1.1). Average annual evapotranspiration for the period (1990-1996) was approximately 330 mm, typically leaving a surplus of over 300 mm of water that contributes directly to groundwater recharge (Berg and Byrne, 1998).

Year	Parks			Households		
	Irrigation (mm)	Precipitation (mm)	ET (mm)	Irrigation (mm)	Precipitation and Roof Runoff (mm)	ET (mm)
1990	526.6	163.5	370.8	503.9	259.0	370.8
1991	482.9	265.6	358.8	275.7	411.5	358.8
1992	488.7	252.4	300.7	350.3	390.1	300.7
1993	427.3	423.0	286.4	164.4	651.5	286.4
1994	525.7	179.3	331.6	438.5	274.6	331.6
1995	487.0	356.2	300.4			
1996	508.8	168.1	380.8			

Table 1.1 Water Balance Data Showing the Amount of Water Added to Lawns and the Amount of Water Used. (Data Modified from Berg and Byrne, 1998).

The majority of previous work has been conducted in West Lethbridge, specifically The University of Lethbridge campus and Varsity Village, but little work has been conducted in other areas of the city. For this study Lakeview subdivision, located in the southeast corner of Lethbridge is used for comparison with previously completed work in Varsity Village.

1.2 Objectives

The Lakeview study area provides an opportunity to address the following issues.

Lakeview has been identified as an area that suffers from basement flooding. It has long been assumed that water flowing from Henderson Lake is the major contributor to locally elevated water tables and therefore is the major reason for the basement flooding that occurs in Lakeview. Analysis of water table surfaces and depth to water table data provide greater insight into the flow of groundwater in Lakeview subdivision.

Comparison of work done in Varsity Village with that in Lakeview sheds light on whether or not raised water tables in Lethbridge are affected by differences in underlying stratigraphy, and how these water tables develop over time. Since Lakeview was developed 15-20 years prior to Varsity Village, the comparison of the two subdivisions may provide insight into how longer periods of exposure to irrigation have changed the water tables over time.

Finally, a water conservation program was developed and introduced to raise public awareness about problems arising from over irrigation of urban lawns and gardens. The program provides the public with information about the amount of water turfgrass uses, how to measure the water they are applying to the soil, and tips on how to reduce the water used by the plants.

The three objectives of the study are therefore:

1. To characterize the groundwater conditions that exist in Lakeview subdivision, including possible water sources and flow directions.
2. To compare the surficial geology and groundwater conditions in Lakeview and Varsity Village subdivisions using spatial modelling techniques.
3. To develop a water management program for decreasing/reversing the build up of water tables in an urban residential environment.

Chapter 2

Literature Review

2.1 Introduction

This section provides some background of how water moves through the hydrologic cycle and into the subsurface. Soil water is of primary importance in this study and is discussed in this chapter. Turfgrass is also of interest since the water scheduling model that will be described in later chapters is designed specifically for this type of vegetation. Urban effects on water entering the subsurface are also discussed in this chapter.

2.2 Hydrologic Cycle

The hydrologic cycle involves the constant circulation of H₂O (water) from the oceans to the air, to the ground and back to the oceans (figure 2.1). The cycle acts to collect, purify, and redistribute the water contained within the hydrosphere (Brady and Weil, 1996; Dingman, 1994; Miller, 1994). Water is stored as part of the hydrologic cycle as liquid water in water bodies (ocean, lake, or river) on the surface and as soil and

groundwater below the surface. The atmosphere stores water in a gaseous state as water vapour or in liquid form in clouds while the solid form of water is stored as snow and ice.

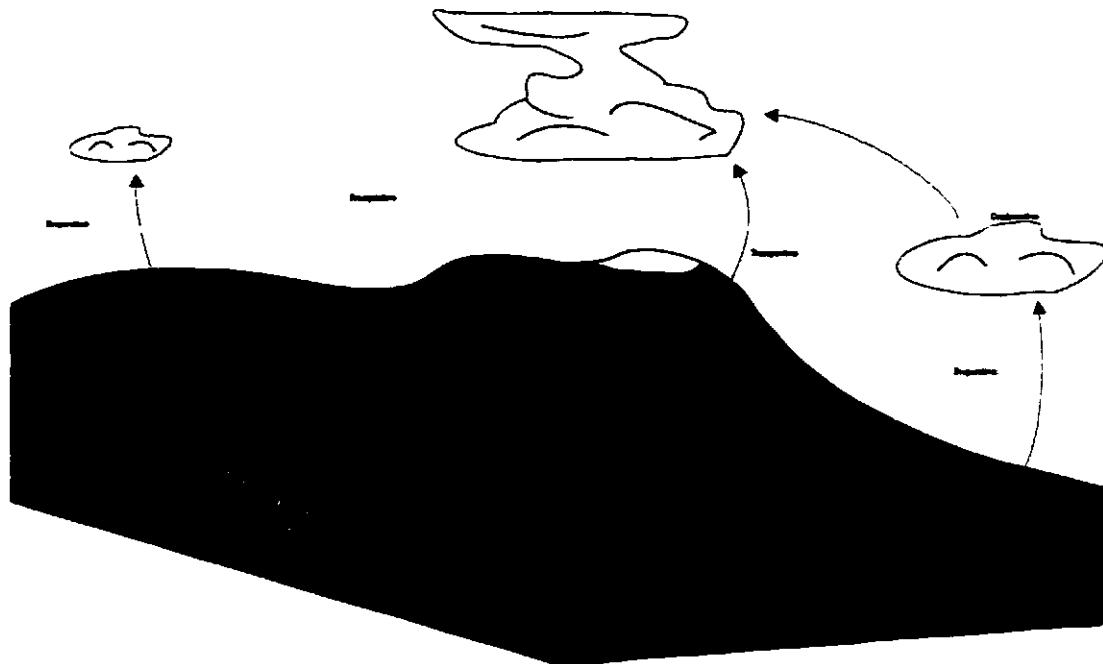


Figure 2.1 The hydrologic cycle.

There are four primary processes that drive the hydrologic cycle and these are:

- .Precipitation
- .Evapotranspiration
- .Runoff
- .Groundwater

Evapotranspiration is the combined processes of evaporation and transpiration (Bothe and Abraham, 1987; Briggs et al., 1993; Moran and Morgan, 1995). Evaporation is the transformation of water from a liquid to a gaseous state while transpiration is water taken from the soil and released into the atmosphere through the tiny pores of plant leaves (stomata) (Bothe and Abraham, 1987; Moran and Morgan, 1995). The driving force behind evapotranspiration is the energy provided by solar radiation. Whether from the soil or from leaf surfaces, 2.26 kJ are needed to transform one gram of water from a

liquid to a gas (Zumdhall, 1993). This energy is readily available here on Earth from the Sun. Such a phase change results in a heat transfer within the atmosphere. This is known as latent heating and represents any transport of heat in the atmosphere that results from a phase change of water (Briggs et al., 1993; Moran and Morgan, 1995).

Evapotranspiration is important to this study since it is a large user of soil water in the Lethbridge area. The largest amount of evapotranspiration will occur under warm dry conditions (Ward, 1975). Southern Alberta has a climate that experiences high evapotranspiration rates. The amount of evapotranspiration that occurs on a given day is the result of a number of factors. Equations used to estimate the amount of evapotranspiration will be discussed in greater detail later in this thesis.

Condensation is the transformation of water from a gaseous to a liquid state (Briggs et al., 1993; Moran and Morgan, 1995). Water vapour moves upward into the atmosphere due to convection of warm air heated by the Earth's surface. As this air rises and cools, the water vapour condenses around cloud condensation nuclei (dust and small particles), forming clouds (Moran and Morgan, 1995). Formation of ice or snow occurs if the air is cold enough or further cooling is promoted by strong updrafts carrying the condensed water higher into the atmosphere. As the condensate gathers in a cloud, the droplets will become larger through collision-coalescence in a warm cloud ($> 0^{\circ}\text{C}$) and the Bergeron Process in a cold cloud ($< 0^{\circ}\text{C}$) (Moran and Morgan, 1995). Collision-coalescence in a warm cloud involves the collision and merging of different sized water droplets, as larger droplets descend faster than smaller ones. The Bergeron Process involves the growth of

ice crystals at the expense of supercooled water droplets. In this process, as water vapour is deposited onto the ice crystals, supercooled water droplets vapourize since the saturation vapour pressure is greater over water than over ice. Once the mass of the water droplets grows large enough that it is no longer supported by the rising air it will fall back to the Earth's surface. Water falling from clouds to the Earth's surface in either liquid or solid form is called precipitation.

Precipitation that is not evapotranspired or infiltrated into the soil will flow over the land surface as runoff. As runoff flows over the land surface it is concentrated into channels of increasing size (i.e. rivulets → streams → rivers). Water in a river or stream channel will flow until it becomes stored in a pond or lake. Storage in a pond or lake will occur for varying periods of time. The length of time water is stored is partly dependent on the size of the water body. An average sized lake will store water for approximately one decade, while turnover time for water in the ocean is about 37 000 years (Miller, 1994). Irregardless of the length of time runoff is stored, if it is not evapotranspired and does not infiltrate into the subsurface system, in most cases it will continue to flow towards the ocean.

When precipitation falls on a land surface and infiltrates into the soil, it has entered the subsurface water portion of the hydrologic cycle. Subsurface water is of primary importance to this study and will be examined closely in the following section.

2.3 Subsurface Water

There are a number of hydrologic zones in the subsurface system that help to describe the movement of water in soil as groundwater. These zones are displayed in figure 2.2.

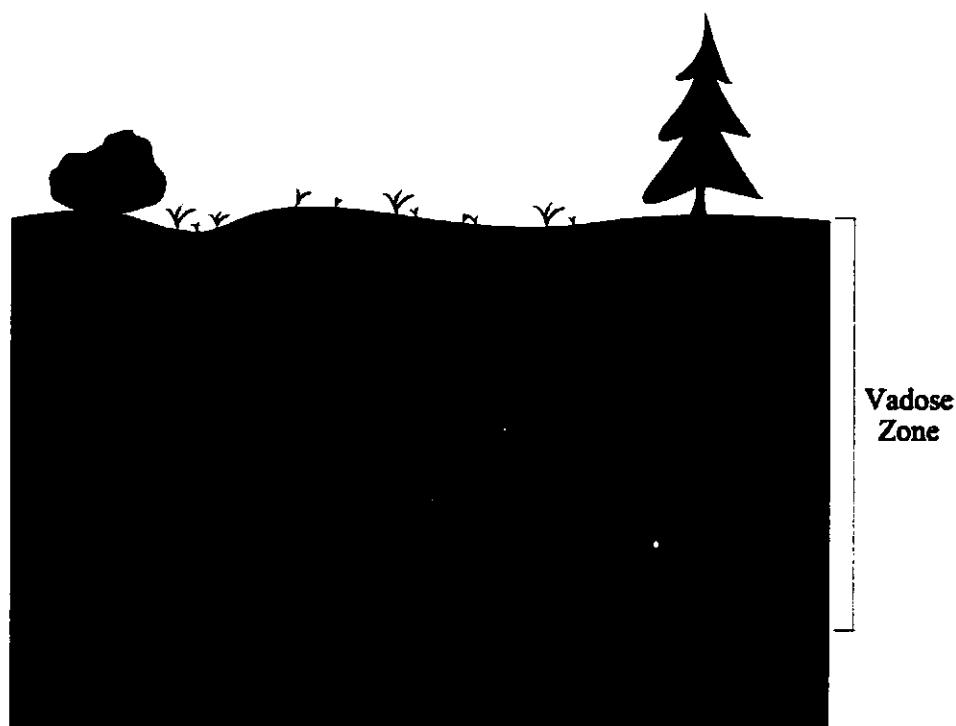


Figure 2.2 Hydrologic soil zones (after Dingman, 1994)

The zone of meteoric water content furthest from the Earth's surface is known as the groundwater or phreatic zone (Dingman, 1994). Within this zone all pore spaces, large and small, are saturated with water. The water table marks the upper boundary of the groundwater zone. Seasonal variations, individual storms and water losses due to evapotranspiration cause the water table to rise and fall over time.

Overlying the groundwater zone is the tension-saturated zone or capillary fringe. Pore spaces within the capillary fringe are near saturation due to the upward movement of water from the water table. Upward movements of water result from the phenomenon known as capillarity.

Capillarity can be demonstrated using a capillary tube (A fine glass tube). When a capillary tube is lowered into water, liquid will begin to move up the tube as shown in figure 2.3.

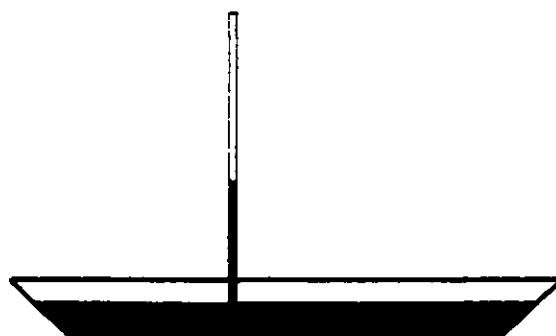


Figure 2.3 An example of capillarity.

This upward movement of water can be attributed to the adhesive or adsorptive forces attracting water molecules to the capillary tube walls as well as the cohesive forces of water molecules to one another (Brady and Weil, 1996; Dingman, 1994). The cohesive forces are responsible for the surface tension displayed by water. Water will continue to rise within the tube until the gravitational force pulling down on the column of water is equal to the combined attraction of the adhesive and cohesive forces (Brady and Weil, 1996; Dingman, 1994).

As the radius of the capillary tube is reduced, the height of water rise within the tube increases. This relationship is characterized by the equation (Brady and Weil, 1996):

$$h = 2T / rdg \quad (2.1)$$

Where: h = the height of capillary rise in the tube

T = surface tension

r = radius of the tube

d = density of the liquid

g = force of gravity

Capillarity occurs within the soil, but due to the irregularity of pore sizes and spaces, the total height of capillary rise is highly varied with soil type.

Above the capillary zone lies the intermediate zone. Within the intermediate zone, water movement largely occurs through the downward percolation of infiltrated water due to gravity. Upward movement can also occur in this zone and is once again attributed to capillarity. The depth of the intermediate zone varies according to the climate and seasons, growing deeper when drier conditions are prevalent.

The final zone, lying immediately below the soil surface, is the root or soil-moisture zone. This zone is characterized as the area from which water can be used and transpired by plants or evaporated from the soil surface (Dingman, 1994). Water enters this zone through infiltration and is extracted due to evapotranspiration and percolation of water down to the water table. Interflow also occurs in the upper soil horizons. This is the lateral movement of water through the soil and will often occur following significant precipitation events.

The vadose zone is the unsaturated zone between the ground surface and the water table. This zone includes the root zone, the intermediate zone, and the tension saturated zone. Vadose zone commonly refers to the zone of negative water pressures above the water table (Dingman, 1994)

2.3.1 Soil Water Retention

Capillarity, adsorption and osmosis are all important forces in soil moisture retention (Ward, 1975). The surface tension force that develops in the small amounts of water that may be found between any two soil particles makes it difficult to be removed by gravity or the water potential gradient (discussed below). The smaller the pore spaces and the greater the curvature of the water surface, the more strongly this water will be held (Ward, 1975). This is why water in clay soils is removed much more slowly under evaporative stress than water from sandy soils.

Adsorption is the force that causes very thin films of water to become attached to soil particles. The attraction of water to these soil particles is electrostatic in nature, with the polar water molecules attaching themselves to the charged surfaces of the soil solids (Ward, 1975). Once again adsorption also contributes to the enhanced ability of clay soils to retain water for longer periods than sandy soils. Since the total surface area of the soil compared to the total volume of soil is larger in a clay soil than that of a sandy soil (Brady and Weil, 1996), clay soils have a larger capacity to hold water by adsorption (Ward, 1975). It is reported that the specific surface (area per unit weight) for clay is

between 10 to 1000 square metre per gram (m^2/g), while the smallest particles of silt and sand would range between 1 and $0.1 \text{ m}^2/\text{g}$ (Brady and Weil, 1996).

Osmosis also retains water in a soil. Dissolved salts in a soil increase the force with which water is held (Brady and Weil, 1996; Ward, 1975). Plants have a difficult time removing water from saline soils since water is so strongly held by the dissolved salts in the soil.

2.3.2 Movement of Liquids in the Subsurface

2.3.2.1 Soil Water

Movement of soil water involves the tendency of all substances to move from a state of higher energy to that of lower energy (Brady and Weil, 1996). Within the soil, there are three major forces affecting the amount of energy soil water possesses. These forces are:

- Matric
- Osmotic
- Gravity

A matric force involves the adhesion or attraction of water to soil solids (matrix). Matric forces are responsible for capillarity and soil moisture retention within the soil. Differences in matric forces create water movement from areas of high soil moisture content to those of low soil moisture, a phenomena which is prevalent within the capillary zone and responsible for supplying plant roots with soil moisture.

Osmotic forces arise through the presence of salts in the soil solution (Brady and Weil, 1996). Salts or organic compounds act to decrease the energy of water because they attract the water molecules. The major implication of osmotic force is soil moisture uptake by plant roots. If the concentration of salts in the soil solution exceeds that in the plant, water uptake by plant roots is not possible.

The force of gravity acts on water as it does on all objects on Earth. Gravity is the major force responsible for the downward movement of water following heavy precipitation or irrigation events.

2.3.2.2 Groundwater

Hydraulic head is the total mechanical energy per unit weight and is calculated from three factors: kinetic energy, gravitational potential energy, and energy of fluid pressures. The equation to calculate hydraulic energy (E) is (Fetter, 1994):

$$E = v^2/2g + z + P/\rho g \quad (2.2)$$

Where: v = velocity

g = acceleration of gravity

z = elevation of the center of gravity of the fluid above the reference elevation.

P = pressure

ρ = density

Since the kinetic energy developed from flowing groundwater is very small compared to the energy contributed by the other two terms (Fetter, 1994), this equation can be simplified to:

$$E = z + P/\rho g \quad (2.3)$$

Further simplification of the equation comes from the knowledge that $P = \rho gh_p$, where h_p is the height of the water column providing a pressure head (Fetter, 1994). The equation now becomes (Fetter, 1994):

$$E = z + h_p \quad (2.4)$$

with the units metres.

Groundwater will move in the direction that minimizes its mechanical energy. In order to minimize hydraulic head, water will flow from higher elevations to progressively lower ones. As water flows from high to low elevations, it will flow normal to the water contour lines. An illustration of this is shown in figure 2.4 where water originating at A and B, will generally flow towards C and D respectively.

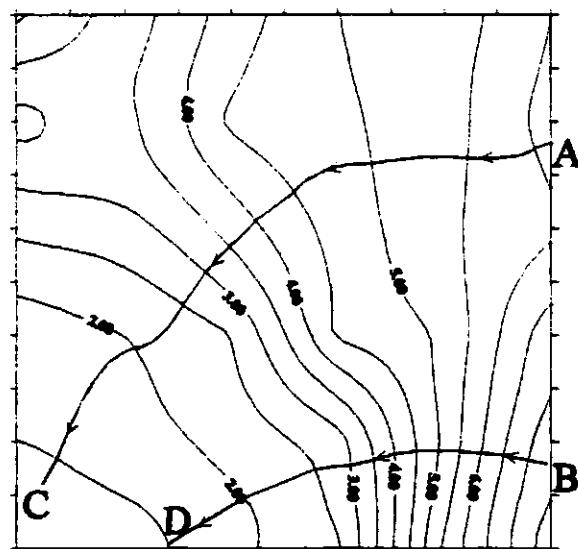


Figure 2.4 Illustration of two possible routes of water flow.

Groundwater flow through a porous medium broadly follows Darcy's Law. Darcy's Law is expressed using the following equation (Fetter, 1994):

$$Q = -KA \left(\frac{dh}{dl} \right) \quad (2.5)$$

Where: Q = discharge

K = hydraulic conductivity

A = cross-sectional area

dh = change in head between two points

dl = small distance between the two points

2.4 Plant-Soil Relations

Movement of water from the soil to plants plays an important role in this study. In order for plants to remain healthy, they must obtain sufficient quantities of water from the soil. This water is used by plants to produce food, maintain turgidity and temperature, and transport nutrients. If water is not readily available from the soil, the health of the plant will quickly deteriorate.

The ability of soil to absorb and store water is essential for the survival of plants. Rain or irrigation must infiltrate the ground and be stored in the soil. The storage of water in the soil will permit enough time for plant roots to absorb and use the moisture. Without the water storing capabilities of the soil, water would quickly run off to stream channels and back to the ocean.

Pore space makes up a large portion of the total volume of soil and helps to make soils the most appropriate medium for plant growth. A loam soil with good conditions for plant growth has about 50 % pore space, 45 % mineral content, and 5 % organic content (Brady and Weil, 1995; Toop and Williams, 1991). Either water or organic or

atmospheric gas occupies the pore space of this soil, with the proportion of these for optimum plant growth ranging between 20 to 30 % (Brady and Weil, 1995; Toop and Williams, 1991).

When all pore spaces in a soil are occupied with water, the soil is said to be at saturation. Saturation of a soil will usually occur following a heavy rainfall or irrigation. Following such an event, some of the water will drain downward through the vadose zone in response to the hydraulic gradient (Brady and Weil, 1996), largely as a result of gravity. Following a period of one to three days the amount of downward drainage of water becomes negligible and the soil is said to be at field capacity (Brady and Weil, 1996; Hansen et al., 1980; Hillel, 1998). Water drainage during the initial one to three days is water that had occupied soil macropore spaces. Once field capacity is reached, only the capillary pores or micropores remain filled with water. These micropores provide plant roots with a readily accessible supply of water.

Plant roots continue to extract water from the soil until the permanent wilting point is reached. For a given plant species, the permanent wilting point is the point that water remaining in the soil is so tightly bound to the soil matrix, that it cannot be extracted by plant roots (Hansen et al., 1980; Salisbury and Ross, 1992). A plant will begin to wilt during the daytime in an attempt to conserve water and at night these plants will usually recover from this wilted state. If water extraction continues however, a state of permanent wilt will occur and there will be no recovery of the plant at night. If a plant remains in a state of permanent wilt, it will die. Different plants species will reach a

state of permanent wilt after different periods of time. This is due to the varying adaptations that plants have to deal with dry periods including deeper root systems and mechanisms to store or retain water.

Field capacity and permanent wilting point are constants that can be estimated by direct measurement of soil moisture. These 'constants' are artificial boundaries that are subjectively determined and are dependent on the climate, species of vegetation, and soil-hydrological characteristics of an area (Ward, 1975). Due to the variability of these characteristics from one area to another and the different plant species, field capacity and permanent wilting point are also extremely variable. Estimation of field capacity can be determined by collecting soil samples from an area following drainage of excess water. Wilting point could be estimated by gathering soil samples once visible plant wilt has begun and then determining the soil water content of these samples. Using soil texture data collected from southern Alberta, Oosterveld and Chang (1980) derived equations to estimate the soil moisture content of soils at both field capacity and wilting point. The following equation was derived by Oosterveld and Chang (1980) to calculate soil moisture content at field capacity:

$$\theta_{fc} = (25.713 + 0.469C - 0.1845 - 0.0329D)C^{-0.080} \quad (2.6)$$

Where: θ_{fc} = soil moisture content at field capacity
C = clay content in percent weight
D = mean depth of sample in centimetres

Since this equation was found to not perform well at high clay contents with high moisture tensions, the same paper derived an equation to estimate the soil moisture

content when the moisture tension was -1500 kPa. This value was used as the moisture tension at wilting point. The equation derived was (Oosterveld and Chang, 1980):

$$\theta_{1500\text{kPa}} = 4.035 + 0.299C - 0.0345 - 0.016D \quad (2.7)$$

Matric potential of soil moisture conditions can also be given in kilopascals (kPa). When a soil is at field capacity, the matric potential of that soil should be between -10 to -33 kPa. Capillary water that is available for plant root uptake will have a matric potential that lies between an upper limit of -10 to -33 kPa and a lower limit of -3100 kPa. A matric potential lower than -3100 kPa represents hygroscopic water and is too tightly bound to soil solids to be utilized by plant roots (Brady and Weil, 1996; Hillel, 1998). The above potentials have negative pressures because of the suction created by capillary and adsorptive forces. If the soil is saturated the pressure is greater than atmospheric pressure and will be a positive value. When the soil is not saturated it will have a negative pressure. Buckingham (1907) was the first to suggest the use of the term capillary potential to represent the negative pressure potential of soil water but the term became inadequate once it was determined that absorptive forces also worked within the soil.

Driven by a potential gradient, water diffuses into the root from the soil by the process of osmosis. Osmosis is a passive process of transporting water across a membrane. With osmosis, no energy is utilized by the plant for water to be absorbed by the roots. In

plants, osmosis is driven by two factors:

1. The movement of water from an area where the water solution is hypoosmotic (lower solute concentration) to an area where the solution is hyperosmotic (higher solute concentration).
2. Pressure created by the presence of a cell wall around plant cells.

These two factors have been combined into a single measurement called water potential, which is abbreviated by the Greek letter psi (ψ) and calculated using the following equation (Campbell, 1993):

$$\psi = P - \pi \quad (2.8)$$

Where: P = physical pressure created by cell wall
 π = osmotic pressure

Water will move across a membrane from the side where the water potential is highest to the side that has a lower water potential.

Water movement and retention is governed by the same basic principles through the entire soil-plant-atmosphere continuum (Brady and Weil, 1995). Water follows the water potential gradient from the soil to the plant roots, up the stem of the plant to the leaves and is transpired through the stomata into the atmosphere. Approximate water potentials for each of these areas are shown in table 2.1 (Brady and Weil, 1995).

Zone	Water Potential (kPa)
Soil	-50
Root	-70
Lower Stem	-75
Upper Stem	-85
Leaf Surface	-500
Atmosphere	-20 000

Table 2.1. Water potentials of zones as water is transported through plants from the soil to the atmosphere.

If enough water is drawn from the soil, the water potential of the soil will drop below that of the roots. If this occurs, the roots will be unable to draw water from the soil, and will begin to wilt. Once soil moisture has reached this level, the soil is now at the wilting point.

2.5 Turfgrasses

Turfgrasses are widely used in front lawns and these have become a typical North American landscape feature (Jenkins, 1994). Billions of dollars are spent every year by homeowners in the United States to maintain lawns (Jenkins, 1994). In Canada, 1997 sod sales were more than 62 million dollars with sales in the prairie provinces (Alberta, Saskatchewan, and Manitoba) of over 9 million dollars (Statistics Canada, 1997). How the front lawn has become such a widespread phenomenon is difficult to explain,

however when used in an urban environment, turfgrasses do have many benefits, such as (Beard and Green, 1994):

- dust stabilization and prevention of soil erosion
- promotes groundwater recharge and maintains surface water quality
- decomposes organic chemicals
- improves and restores the quality of soil
- heat dissipation
- reduces noise and glare
- reduces human exposure to pests, allergy-related pollens, and diseases
- promotes road safety (higher visibility, stable zone for vehicle stoppage).
- wildlife habitat
- provides a safe surface for recreational activities
- promotes aesthetic beauty in sites dominated by concrete
- provides a fire break around homes

Of key interest for this study is the role turfgrasses play in the promotion of groundwater recharge. Turfgrass covers have a high root and shoot density that slows the velocity of runoff. By trapping and holding this runoff, turfgrass results in more water infiltrating the soil (Beard and Green, 1994). Earthworms also thrive in the ecosystem provided by turfgrasses and populations of 200 to 300 m⁻² can be supported (Potter et al., 1985). These earthworms work to increase the amount of soil macropore spaces (Beard and Green, 1994). The above factors promote infiltration in areas covered by turfgrass and act to reduce the amount of water runoff loss. Studies on one site in Maryland have shown that runoff from turfgrass averages only 0.6 mm/ha/month (Gross et al., 1990). This means that water that falls or is applied to turfgrass covered areas is more likely to infiltrate the ground and contribute to the water table.

The two main turfgrasses used in the Lethbridge area are Kentucky Bluegrass and Red Fescue. A major sod company in the Lethbridge area distributes sod composed of a mixture of 75 % Kentucky Bluegrass and 25 % Red Fescue. Both species of turfgrasses

are classed as cool season turfgrasses, having a temperature optimum of 16 to 24°C (Beard, 1973).

Kentucky Bluegrass is a widely used cool season turfgrass. This type of turfgrass is well adapted to cool humid regions of the world, but can be utilized in cool semiarid regions if irrigation is provided. Kentucky Bluegrass grows best under moist soil conditions in full sunlight or slight shading (Beard, 1973). The recuperative potential of Kentucky Bluegrass is good, making it ideal for use on golf courses, airports, and athletic fields. Dormancy of this turfgrass can occur during long periods of water and temperature stress. Once moisture conditions return to a more favourable range, Kentucky Bluegrass is able to recover from this dormant state. The root system grows to depths of 40 to 60 cm, with much of the root system concentrated in the top 15 to 25 cm (Beard, 1973).

Red Fescue, often referred to as Creeping Red Fescue, is the best cool season turfgrass for use in dry shaded conditions (Beard, 1973). While it is well adapted to shade, Red Fescue will still grow better in full sunlight. Red Fescue uses water at a much slower rate than Kentucky Bluegrass and does not tolerate wet, poorly drained soils. This turfgrass is not widely used on sports fields or golf courses since it does not have a very good recovery rate compared to that of Kentucky Bluegrass. Kentucky Bluegrass and Red Fescue are often used together in seed mixtures. While not excessively competitive, Red Fescue is able to establish itself much faster than Kentucky Bluegrass. The two grasses are compatible with one another and in a well established plot of a Red Fescue

and Kentucky Bluegrass mixture, the Red Fescue will predominate in areas that are shaded or droughty, and the Kentucky Bluegrass will become dominant in moist areas with full sunlight.

2.5.1 Maintaining Healthy Turfgrass

Indicators of turfgrass quality include uniformity, density, texture, growth habit, smoothness, and colour. Colour is one of the best indicators of the general condition of turfgrass (Beard, 1973) and for the layperson, one of the easiest to recognize. To produce a good quality turfgrass the plant must be kept in good health. The root system must be extensive and actively growing to maintain a vibrant root hair zone. Plant leaves and stems should be turgid and produce good yield. A dark green turfgrass is the preferred colour of most individuals and indicates high chlorophyll content and active photosynthesis.

Excessive application of water is detrimental to turfgrass health. The root system of turfgrass draws water from progressively deeper depths as depletion of soil moisture occurs. Excessive irrigation allows roots to continuously draw water from shallow depths, negating the need for deep root systems. As irrigation frequency increases, changes to turfgrass include (Beard, 1973):

- reduced shoot growth
- increased shoot density
- reduced chlorophyll content
- reduced succulence
- reduced rooting depth

These turfgrass responses can be traced to increases in soil moisture which cause a lack of soil aeration. Poor soil aeration results in a soil oxygen deficiency and concentration of carbon dioxide in the soil. Oxygen deficient soils restrict root growth and contribute to a general decline in turfgrass quality, vigour, and root depth (Beard, 1973).

Turfgrasses with restricted root systems are more susceptible to drought and wilting. Since the root systems of well watered turfgrasses do not have to grow deep to obtain their water requirements, the roots remain close to the surface. This leaves the turfgrass semi-dependent on irrigation and when sudden reductions in irrigation occur, the turfgrass root system is unable to respond quick enough and grow deeper into the soil to withdraw sufficient quantities of water. Sudden reductions in irrigation quantities and frequency to a heavily watered turfgrass will cause the turfgrass to turn brown and dry up. Instead, reductions in irrigation should be gradual to allow the turfgrass roots to gradually grow deeper into the soil. Irrigation should be applied until the soil is wet to a considerable depth with the first onset of visible wilting, maintaining the available soil moisture level in the upper 50% range (Beard, 1973). This irrigation regime increases the depth of the root system along with the wilt tolerance of the turf.

In order to maintain the soil moisture level within a particular range, it is necessary to have some knowledge about the soil texture of the area. By determining the soil texture and using this information in conjunction with plant characteristics, an estimate of field capacity and wilting point can be determined. Methods used to determine soil texture are discussed in the following section.

2.6 Methods of Soil Textural Analysis

There are several methods that can be used to obtain the distribution of soil particle sizes in a sediment sample. Three main methods used to determine soil particle size include sieving, the pipette method, and the hydrometer method. Each of these methods attempts to measure soil particle sizes using certain criteria. Sieving determines the size of soil particles using meshes with square or circular openings. The smallest opening that a particle can pass will determine the size of that particle. Both the pipette and hydrometer methods determine soil particle sizes using sedimentation. In this method, separation of varying soil particle sizes is done using the differences in settling times for different sized particles through a fluid, usually water. For example, a sand sized particle will fall out of suspension in water much faster than a clay sized particle.

The sieving method separates soil particle sizes according to a particles ability to pass or not pass through particular sieve-size openings. The finest sieve opening that will produce an accurate separation and is commonly used in soil studies is the 63μ sieve. This size of sieve requires water to flush particles through the sieve opening. For sieves coarser than 63μ , separation of the soil particles occurs by placing the sediment sample into a sieve with a mesh of known size, and shaking the sample long enough to allow all particles smaller than the mesh size to pass through. Ranges of soil particle sizes can be determined by using a series of meshes, arranged from coarser to finer. For this study, sieves of 2 mm, 0.5 mm, and 63 microns (0.063 mm) were used. Particles that did not pass through the 2 mm sieve were classed as gravel, those that did not pass through the

0.5 mm sieve were considered coarse and medium grained sand, and those not passing through the 63 micron sieve were classed as fine sand.

Sieving, while simple in principle, does have some problems. Since particles are unevenly shaped, and sieve openings may not be completely equal in size throughout, it is essential that sufficient amounts of time be given to allow for particles to come in contact with the mesh in various positions as well as in contact with the largest openings on the sieve.

The pipette method depends on the fact that sedimentation will eliminate all particles (P1) with a particular settling velocity from a given depth, while the other particles (P2) having settling velocities slower than those of P1 will be retained at this depth (Day, 1965). Using Stokes' law:

$$V = kr^2 \quad (2.9)$$

Where: V = settling velocity

k = constant related to the density and viscosity of water
and the acceleration due to gravity

r = radius

it is possible to determine the time (t) that particles of a particular settling velocity will be removed by gravity from a depth (d), of a solution. To determine the proportion of that particular particle size in the sediment sample, a pipette can be used to collect a sample (aliquot) from the depth (d) that particles of that size would have been removed by gravity once time (t) has been reached. By determining the weight of particles in the aliquot and comparing that to the original concentration of particles in solution, the proportion of the aliquot to the original concentration can be determined.

Another method that uses sedimentation and Stokes' law is the hydrometer method. This method was the one used in this study and has been used in other particle size analyses in southern Alberta (Berg, 1997; Hendry, 1982; Oosterveld and Chang, 1980). The hydrometer method is similar to the pipette method, but uses a hydrometer to measure the concentration of solids remaining in suspension. Concentration of solids remaining in suspension is determined by the buoyancy of the hydrometer in the solution. As more particles settle out of suspension, the hydrometer will be less buoyant in the solution. Once again using Stokes' law, particular particle sizes will have specific settling velocities. By taking readings after specific periods of time, this will allow for the determination of the concentration of particles remaining in suspension and for the calculation of the amount of particles of a particular size range that have settled out. The hydrometer method is described in greater detail in Chapter 4.3.1.

2.7 Urban water management

Urban areas create a number of changes to the hydrology of an area. Land under development during urbanization undergoes a progression from a rural area, where the vegetation is either indigenous or agricultural, to a zone with little or no vegetation. This area is then transformed to include houses, commercial buildings, parking lots, and roads. The vegetation that remains following urban development is often composed of exotic species of plants and species that are perceived to be more desirable, both of which are unnatural and sometimes poorly suited to that area, often resulting in the need for additional water inputs to support this vegetation.

Along with a loss of vegetation, the rural to urban transition also brings a major loss in the water storage capacity of an urban area. Rain falling over a vegetated area will be intercepted and stored by leaves and branches of vegetation canopies (Dingman, 1994). As the storage capacity of the vegetative cover is exceeded, water will begin to drip through the canopy and either infiltrate into the soil or become stored on the surface (ponding) (Dingman, 1994). Once the water has infiltrated the soil, the soil will retain the water until it is saturated, when the water will begin to percolate down to the water table. Because vegetation, the soil, and ponding retain water, any water contributed to a river channel following a rainfall event will reach the channel after a time lag (Dingman, 1994; Hall, 1984). This time lag may be as little as a couple of hours or as long as a couple days, depending on a number of factors including the precipitation or input event itself (ie. intensity and amount of rainfall) and characteristics of the area (geology, soils, terrain, land use, vegetation) (Briggs et al., 1993; Dingman, 1994; Hall 1984).

Rain falling over an urban area falls over large areas that have been cleared of much of their vegetation and replaced with surfaces that are often impervious to water. Any rain that falls over such an area will fall directly on the surface and immediately pond in surface depressions. These depressions will quickly reach their storage capacity since infiltration is near zero and surface runoff will begin. Storm sewers quickly remove the surface runoff to avoid flooding within an urban area. The result is a much faster response rate of the water outflows into a river channel following a precipitation event.

Given the low infiltration capacity of roads, parking lots, and buildings, along with the rapid removal of water by storm sewers, one would expect that urban contributions to the groundwater to be very small. Evidence suggests the opposite is true in arid, semi-arid and sub-humid climates. Prior to urban development, most water inputs to the soil come from precipitation or agricultural irrigation. In order to keep cities more natural, humans like to include parks and residential yards or gardens within the subdivision. These areas are typically vegetated with species of plants that are not indigenous to the area and are not well suited to the climate of the area. To ensure the survival of these often exotic plants in a drier climate, supplemental water must be provided. Additional water is usually provided by pumping water from nearby water bodies and applying this water to plants using irrigation. While irrigating plants is necessary to their survival under dry conditions, more water can be applied to the plant than it is able to use. This is the case in Lethbridge, Alberta where irrigation of turfgrass has been shown to exceed the evapotranspiration requirements by as much as 206 percent (Berg and Byrne, 1998). Water applied in excess of evapotranspiration requirements will contribute directly to water table development. As mentioned earlier, little of the excess water applied to turfgrass will contribute to runoff. The enhanced infiltration capacity of turfgrass covered soils allows for very small amounts of runoff (Beard and Green, 1994).

Roof runoff also contributes large volumes of water to residential lawns. The roof of a building effectively provides a larger catchment area for precipitation. Water collected on the roofs of buildings is often discharged onto turfgrass covered areas. Berg (1997) found that in Varsity Village subdivision of Lethbridge, Alberta, approximately 38 % of

an average lot was occupied by houses, garages, or other structures. 85 % of these homeowners discharged roof runoff onto turf, with the remaining 15 % discharging water onto impermeable surfaces (Berg, 1997). The average depth of roof runoff in Varsity Village reported by Berg (1997) over five summers (May-September) was 140 mm.

2.8 Previous Research

The problem of high water tables in the City of Lethbridge was originally examined in a Masters thesis written by Aaron Berg (1997). This study was conducted in Varsity Village subdivision and the University of Lethbridge campus. The study by Berg was initiated by the observation of water table related problems within the City of Lethbridge including slope failures, flooding, asphalt instability, and increased discharge to the waste water collection system. Several sources of input to groundwater were identified including: precipitation, leakage of water from sewers, storage tanks, mains, artificial lakes and reservoirs, and over-irrigation of lawns and gardens. Berg (1997) focussed on water contributions to the local groundwater due to turfgrass irrigation practice and water storage.

Irrigation inputs between May and September 1990-1996 were found to be far above the evapotranspiration requirements of the turfgrass by Berg (1997). The water that was applied in excess of the turfgrass evapotranspiration requirements was believed to contribute directly to the development of high water tables in Varsity Village and the University of Lethbridge campus. Berg (1997) found the relationship between irrigation

and water table depth to be so strong that in order to predict water table elevation, the following equation was derived:

$$WTD = P (-253.3558) + 781.8962 \quad (2.10)$$

Where: WTD = water table depth (cm)
P = logarithm of expected amount of percolation
through the root zone (mm)

2.9 Summary

This chapter dealt with how water moves through the hydrologic cycle and into the subsurface portion of this cycle. Soil water was discussed in detail because of the importance it has in this study. Important information about turfgrass was also discussed above, since the water scheduling model to be described later is concerned with the amount of water that should be applied to turfgrass. Urban effects on water movement to the subsurface portion of the hydrologic cycle were also discussed.

Chapter 3

Study Areas

3.1 Introduction

In this chapter, information about the two areas used in this study is provided. The goal is to help the reader develop an understanding of the features that affect the Lethbridge area. Geology, hydrogeology, regional physiography, climate, soils, vegetation and groundwater problems of the study areas are addressed.

3.2 Regional Physiography

The present-day surface of the Lethbridge area was largely shaped by continental ice during the Late Wisconsinan (10,000-25,000 BP) and by contemporary dryland processes that have also operated with varying amplitude and frequency throughout the Holocene (0-10,000 BP). In West Lethbridge the gently rolling prairie surface was formed as a till dominated moraine, while to the east the generally flat terrain is the result of sediments deposited in a glacial lake. Deposition of sediments during glaciation had the effect of

levelling the terrain, since lower elevations tended to be the areas that received the most deposition. This is especially so in the case of the 10 to 15 km wide preglacial valley of the Oldman River.

Moving against the regional slope, Laurentide ice moved into the study area from the north parallel to flows of Cordilleran ice. Both the Cordilleran and Laurentide ice sheets deflected one another towards the southeast. Laurentide ice advanced into the area on several occasions, with the Lethbridge Moraine (Figure 3.1) marking the furthest extent of Laurentide ice during Late Wisconsin time (Stalker, 1977) or a distinctive still-stand or readvance of ice during recession from a Late Wisconsin maximum position further to the west (R. J. Rogerson, pers. comm., 1999). The Lethbridge Moraine was named by

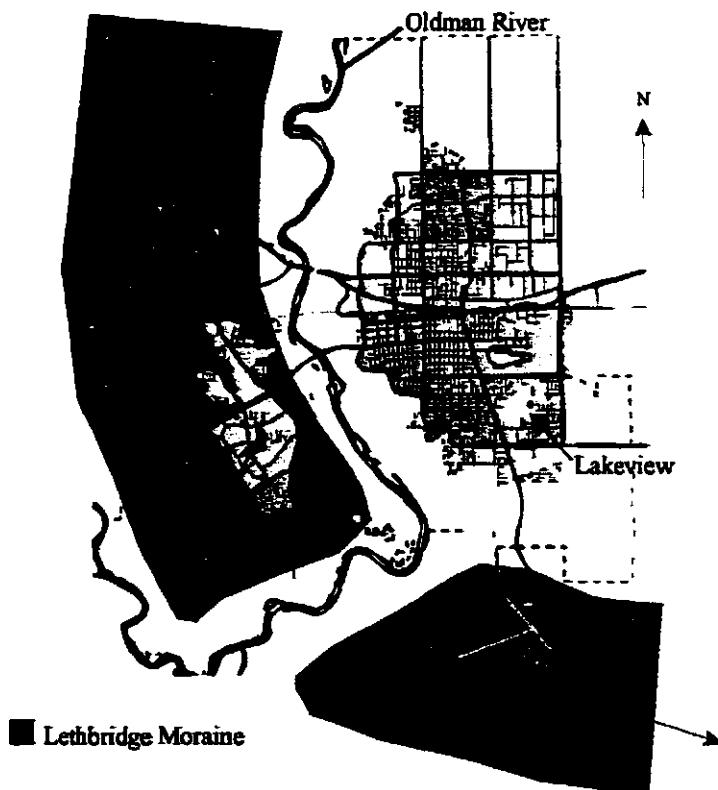


Figure 3.1 Position of Lethbridge Moraine.

Horberg (1952) with the eastern portion being named the Etzikom Moraine by Westgate (1968). West Lethbridge is built on a portion of the Lethbridge Moraine.

As continental ice moved into the area, preglacial river channels became blocked and long, narrow lakes formed within their valleys. This blockage deflected river drainage to the southeast along the ice margin rather than in their original easterly direction, parallel to the regional slope. As Laurentide ice reached its maximum extent, blockage of the ancestral Oldman River created Glacial Lake Macleod to the west of the Lethbridge Moraine. Water drained from this lake along the ice margin and the large volumes of water discharging from this lake formed present day Etzikom Coulee. Similar events during recession of the ice margin formed other coulees including: Whiskey Gap, Lonely Valley, Middle Coulee, Kipp Coulee, Verdigris Coulee, Chin Coulee, Forty Mile Coulee, Pakowki Coulee, and Seven Persons Coulee.

As temperatures increased, the ice sheet receded to the east and meltwater from the glacier became dammed between the Lethbridge Moraine and the ice margin, now located east of Lethbridge, forming glacial Lake Lethbridge (Horberg, 1952). Over time a channel was cut through the Lethbridge Moraine and drainage from glacial Lake Lethbridge joined with water from glacial Lake Macleod which then flowed southeast through Etzikom Coulee and out the Milk River.

Continued ice recession brought a reversal in flow direction to the section of meltwater channel running through the Lethbridge region. The river then flowed in the northerly

direction that we see today completing a large loop around West Lethbridge in the general eastward flow of the Oldman River. Laurentide ice continued to recede in a direction matching that of the regional flow direction, reducing the base level of the Oldman River. The decrease in the base level encouraged further deepening of the Oldman River valley running through the Lethbridge area (Stalker and Barendregt, 1993). Deepening of the Oldman River valley was further aided by the continuing divergence of meltwater from northern regions. Downcutting slowed as the ice retreated further north, allowing northern waters to flow through other valleys, and returning flow down the Oldman River to volumes closer to present (Stalker and Barendregt, 1993). Today the river valley (Figure 3.2) dissecting Lethbridge is approximately 100 metres deep and varies in width from 1.5 to 3.0 kilometres. Deglaciation of the Lethbridge area was complete by 11 200 BP (Vreeken, 1989).



Figure 3.2 View of the river valley looking west towards the University of Lethbridge.

There are a series of short, narrow, parallel or subparallel tributary valleys that extend from the main river valley (Figure 3.3). These tributary valleys are known as coulees and have a distinctive pattern of alignment in the area extending from Lethbridge to Pincher Creek in the Rocky Mountain Foothills. The preferred alignment of coulees in this region is N 70° E and occurs in marked contrast to orientations seen in other areas (Beaty, 1975). Coulees to the east of Lethbridge generally form with an orientation approximately normal to the valley axes (Beaty, 1975). Several attempts have been made to explain the formation of these aligned coulees including: wind, control by subsurface structures, differing erosion rates of strata, and regional slope effects (Beaty, 1975).

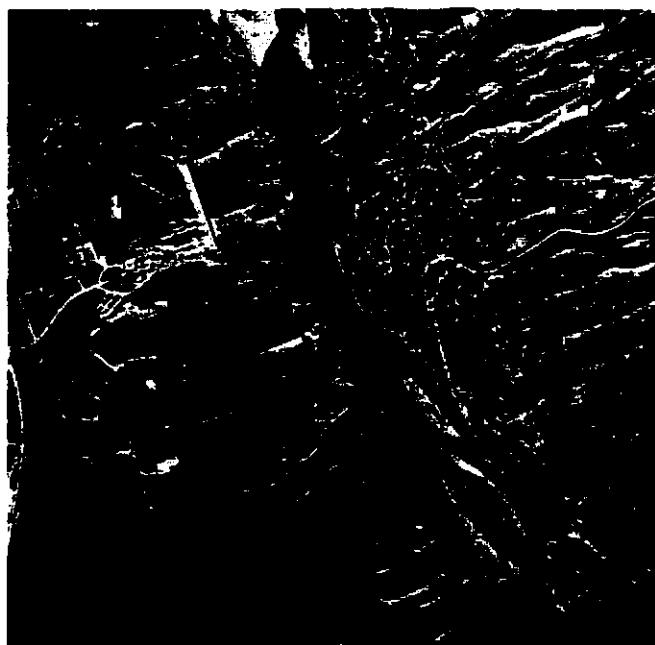


Figure 3.3 Aerial photo (1983) showing the parallel or sub-parallel coulees extending from the Oldman River Valley. The University of Lethbridge campus lies in the upper left hand corner of the photo.

Beaty (1975) identified three distinct features of these coulees:

- A. The preferred coulee orientation of N 70° E corresponds to the mean wind direction of chinook winds in southern Alberta.

- B. Coulee alignment occurs only in the southwestern corner of Alberta and corresponds with the area experiencing the strongest chinook winds.
- C. The dominant location of aligned coulees is on windward physiographic surfaces.

Wind effects are best able to account for these observations of coulee alignment. Beaty proposed that coulees formed through the following process:

1. Major rivers had nearly assumed their present vertical position and their valleys had gained sufficient relief for coulee development by 6 000 - 8 000 years ago.
2. Windward topographic surfaces within the chinook region retained less snow and were drier than other slopes. As a result, less vegetation grew on these slopes making them more susceptible to erosion.
3. Wind driven snow and rain carved narrow, shallow, elongated surficial furrows on southwesterly facing slopes. These surficial furrows were enlarged later by surface runoff.
4. Continued enlargement of coulees occurred through the erosional work of surface runoff from summer thunderstorms and spring melt.

Control by subsurface structures on coulee formation does not seem adequate. If subsurface structures were the main control, it would be expected that coulee alignment would occur throughout Alberta rather than just in the southwest portion. Elsewhere, the widespread occurrence of coulee alignment does not occur, making this theory less likely in accounting for the phenomena.

Another feature common in the river valleys of Lethbridge are small step-like features known as terracettes or "cattle steps". These structures form on the sides of valley walls as a result of surface creep associated with melting and drying and are then a naturally occurring slope process rather than the result of cattle grazing on these slopes, although grazing by cattle may serve to accentuate some of these terracettes. Terracettes typically

vary in height from a few centimetres to two metres, with widths between one half to one metre (Ruban and Thomson, 1983).

3.3 Geology and Hydrogeology of the Lethbridge area

3.3.1 Bedrock Geology

Incision of the deep river valleys into the prairie surfaces has provided numerous exposures of bedrock and glacial deposits. Sedimentary bedrock comprises the oldest of the exposed substrate and was deposited in nearly horizontal beds during the Upper Cretaceous and Tertiary periods. The beds laid down during the Tertiary have been largely eroded from the Lethbridge area. Horberg (1952) lists the bedrock deposited during this period to include, from oldest to youngest, the Foremost, Oldman, Bearpaw, Blood Reserve, and St. Mary River Formations, however only the Oldman and Bearpaw Formations are exposed within the Lethbridge area.

The Oldman Formation is the older of the two deposits found within the river valleys near Lethbridge and is sometimes grouped with the Foremost Formation to form the Belly River group (Nielsen, 1971; Sracek, 1993; Thomson and Morgenstern, 1977). This formation has been described as a pale grey to light greenish grey mixture of sandstones and shales (Nielsen, 1970). In some localities, ironstone concretions and limestone beds can be found (Ruban and Thomson, 1983). Near the upper portion of the formation the Lethbridge Member or Galt coal seam can be found (Nielsen, 1971; Ruban and

Thomson, 1983). This formation was deposited in a freshwater environment (Nielsen, 1971). The Oldman Formation has reported thicknesses of up to 210 metres (Sracek, 1993).

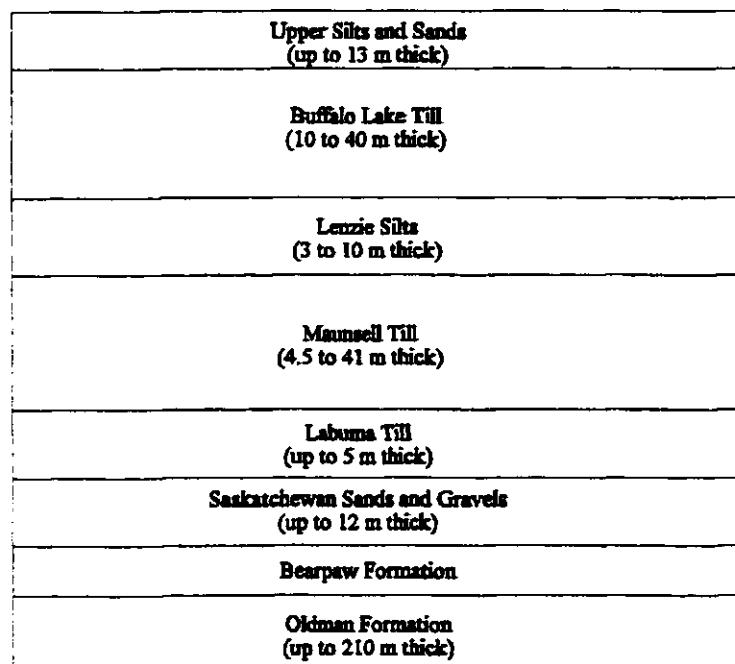


Figure 3.4 Diagram showing the stratigraphic position of major deposits seen in the Oldman River valley near Lethbridge, Alberta.

Directly overlying the Oldman Formation is the Bearpaw Formation. The Bearpaw Formation is of marine origin (Sracek, 1993). Sediments of the Bearpaw Formation were deposited in the Bearpaw Sea, a shallow epeiric sea that covered the study area during the Late Cretaceous. Dark grey in colour, this deposit is composed mainly of marine shales but also contains bentonitic silt horizons, a consequence of volcanic eruptions that occurred to the west and south of the Lethbridge area approximately 66 million to 90 million years ago (Thomson and Morgenstern, 1977). The ash was devitrified in the warm shallow marine water and altered into the mineral bentonite.

Directly overlying bedrock in the Lethbridge area are the unconsolidated Saskatchewan Sands and Gravels. Deposition of this unit began in the Oligocene and continued until the onset of the Quaternary glaciation (Stalker, 1968). The Saskatchewan Sands and Gravels were deposited as braid plains in preglacial alluvial river valleys, trending eastward or northward from the Rocky Mountains (Sracek, 1993). This deposit has been described as a clean, well-sorted, round to subrounded river gravel with a sand matrix (Ruban and Thomson, 1983). Horberg (1952) identified the gravels to contain greater than 50 percent quartzite and chert with smaller amounts of argillite, limestone, volcanics, and Cretaceous sandstone and shale. Since the Saskatchewan Sands and Gravels were deposited before the Laurentide ice sheet entered the area, there is a complete absence of Precambrian Shield clasts (Stalker, 1968).

The City of Lethbridge lies on a major preglacial river valley and fill known as the Lethbridge Valley that has a width of 10 to 16 kilometres (Geiger, 1965). Saskatchewan Sands and Gravels were deposited within the Lethbridge Valley with the thickness varying up to 12 metres (Nielsen, 1970). This deposit, located between less permeable till and Bearpaw shale forms the Lethbridge Aquifer (Sracek, 1993). At one time this aquifer may have contained large amounts of water but incision of the Oldman River exposed the deposit and significant de-watering took place (Sracek, 1993).

3.3.2 Glacial Geology

The basal till directly overlying the Saskatchewan Sands and Gravels in the study area was identified by Horberg (1952) and is referred to by Stalker (1963) as the Labuma Till. Horberg (1952) was the first to distinguish the basal till from the overlying till using its columnar structure, clayey composition (owing to the large percentage of dark coloured marine shales (Bearpaw formation) incorporated in the matrix), low pebble content, and the presence of a pebble zone at the top of the deposit. The basal till has a greyish-brown colour and is up to five metres thick (Sracek, 1993). Cementation by calcareous material and compaction by pressures of overriding ice have made the basal till into a very indurated, dense unit. The basal till is frequently more indurated than the Oldman or Bearpaw Formations below (Nielsen, 1971) and is the darkest coloured till in western Canada.

Within the study area, a second till directly overlies the basal till. Stalker (1963) refers to this as the Maunsell till and notes that there is a sharp contact between the Maunsell and the Labuma tills. When compared to the latter, the Maunsell till contains more pebbles, but fewer from the Shield region, and the structure, while columnar, is not as pronounced as that of the basal till (Horberg, 1952; Nielsen, 1971). The Maunsell represents the most extensive unit deposited in the study area and varies greatly in thickness. Its variable thickness is due to the fact that since it was so thick, it was the major unit responsible for concealing the irregularities in the bedrock surface (Horberg, 1952). Nielsen (1971) reported measured thicknesses ranging from 4.5 to 41 metres. Oxidation

has occurred in the upper portion of the Maunsell till to a depth of three metres (Horberg, 1952; Nielsen, 1971). Oxidation of the till is attributed to groundwater movement through joints and fractures within the till and has given the upper portion of the till a brown-grey colour compared to the dark grey of the unoxidized till (Nielsen, 1971).

The Maunsell till is often identified by the presence of megablocks. Megablocks are large, thin masses of material that have been moved to their present location by glaciers. The method that megablocks are transported is not fully understood, but under the proper conditions, transportation of these large masses of material is possible with little deformation of the sediments occurring. Stalker (1975) described the Laundry Hill megablock (Figure 3.5) that lies within the city of Lethbridge limits. An outcrop of this megablock occurs along the eastern edge of the Oldman River valley directly to the east of Fort Whoop-Up. Small portions of it are also found on the western edge of the valley but north of Whoop-Up Drive, meaning the megablock was over 1 km wide. It is estimated that prior to river erosion the Laundry Hill megablock had a mass of over 2 700 000 tonnes (Stalker, 1975).



Figure 3.5 Laundry Hill megablock.

Existence of megablocks in the Maunsell till has encouraged some researchers to divide this unit into an upper and lower unit, using the megablocks as the dividing layer (Nielsen, 1971; Ruban and Thomson, 1983). This division is difficult in some areas however, since megablocks are occasionally deformed into intensely folded structures.

Lying between the Maunsell and Upper Till is a distinct, stratified layer named the Lenzie Silts. This layer of laminated sands, silts, and clays has a thickness of 3 to 10 metres in the Lethbridge area (Nielsen, 1971). The Lenzie Silts are easily recognized in outcrops since the light brown colour stands out against the darker tills above and below. Deposition of the Lenzie Silts occurred in ice marginal lakes that came into being as the ice sheet that deposited the Maunsell Till retreated from the area (Horberg, 1952; Nielsen, 1971), or perhaps just before the arrival of the glacier that deposited the next till (the lower Buffalo Lake Till discussed below). Advancing ice may have likewise blocked drainage and created an ice marginal lacustrine environment where the Lenzie Silts could have been deposited.

The Upper Till represents the material deposited during the final advance or readvance of Laurentide Ice into the Lethbridge area. Buffalo Lake Till, divided into an upper and lower member, is the name given to the upper till by Stalker (1968) and it forms the till unit that gives rise to the Lethbridge Moraine, a major end moraine that can be traced for hundreds of kilometers to the east and northwest of Lethbridge. Stalker (1968) argues that the Lethbridge Moraine represents the furthest extent of Laurentide Ice during this readvance, because deposits of this unit are not found to the west or south of the

Lethbridge Moraine. Others, notably Lionel Jackson (1997), have argued on the basis of cosmogenic ^{36}Cl dates of surface erratics, that this late Wisconsinan ice sheet that laid down the Buffalo Lake till, extended west of Lethbridge to the limit of Laurentide Glaciation (~ 1050 m). Clayey to silty in texture, the till is dark grey in colour where unoxidized and buff where oxidized. Sand lenses are common in the Upper Till and there are more boulders present than in the Lower Till. Upper Till deposits vary from 10 to 40 metres deep in the Lethbridge area (Nielsen, 1971).

In several studies, all the till units above have been divided into two members based on the oxidation or weathering that has occurred to the till (Hendry et al., 1982; Hendry et al. 1986; Hendry, 1988; Hendry et al. 1989; Sracek, 1993). These members are referred to as the oxidized (weathered) and unoxidized (nonweathered) till and are characterized by their colour, presence of fractures and the differences in chemistry of pore water (Sracek, 1993). The oxidized till has a brown to greyish-brown colour and fractures are quite common. Unoxidized till can be recognized by the lack of visible fractures in the till and its grey or bluish-grey colour. Colour differences between the two tills is the easiest way of differentiating between the two members. Hendry (1988) found that there was a large difference in the rate of vertical groundwater flow between the two members. He reported that ground-water velocity through the unoxidized till zone would only be from two to six metres every 1000 years. The oxidized till has a much faster vertical groundwater velocity of about 0.1 metres per year. Hendry attributed the faster vertical velocities of the oxidized till to the presence of fractures within this unit. It is important to remember that the oxidized and unoxidized till units described here do not represent

separate units from those described above, but are the same units that have been grouped differently due to different classification criteria. The slow groundwater movement through the oxidized and unoxidized tills is in marked contrast to the relatively fast infiltration of water that can be seen in turfgrass covered areas. Berg (1997) conducted 17 flooding ring infiltration experiments on household turfgrasses in Varsity Village and found a mean infiltration rate of 4.38×10^{-5} m/s.

As Laurentide ice retreated from the Lethbridge area, meltwater from the glacier collected between the glacial ice and the Lethbridge Moraine forming Glacial Lake Lethbridge. Sedimentation within Glacial Lake Lethbridge to the east of the Lethbridge moraine resulted in the deposition of lacustrine sediments. Ice rafted debris, drop stones, and sand stringers can also be found as deposits within the lacustrine silts and clays. Horberg (1952) grouped these lacustrine silts and clays along with glaciofluvial sands and gravels, loess, alluvial wash, colluvium, volcanic ash, buried soils, dune sands, floodplain alluvium and surficial soils to form the ‘Upper Silts and Clays’. This deposit is found above the Buffalo Lake Till to the east of the Lethbridge Moraine. In the Lethbridge area, Nielsen (1971) estimated the maximum thickness of this deposit to be 13 metres. Reworking of lacustrine silts and sands by the strong southern Alberta winds would have begun immediately after Glacial Lake Lethbridge and other glacial lakes to the west drained and began to dry up. These sediments formed dunes and loess deposits that can be found in the Lethbridge region, but no such deposits were found in either of the study areas.

Water tables in the Lethbridge area are described as perched since they are found high above the regional groundwater system that lies approximately 50 - 75 m below the surface (Tokarsky, 1974). These perched water tables form due to the till and glaciolacustrine deposits of low hydraulic conductivity (the volume flow rate of water through a cross-sectional area of porous medium) that lie between the perched water tables and the regional groundwater system. Water reaching these deposits will build up and what water is able to percolate down to the regional groundwater system would do so only after a long period of time.

Tills found in the Varsity Village study area are generally unsorted and unstratified and contain a range of clast sizes (0.5 to 60 cm). Particle sizes in this till range from clay to large boulders, but clay and clay loam textures predominate. Tills are generally massive and free of bedding (Selby, 1985) but where tills were laid down under stagnant or nearly stagnant conditions, pockets of bedded sediments (ie. sand lenses) laid down by small subglacial streams are present. Sand lenses are common in the surface tills of the Lethbridge area and can be quite large, however a sand lens is generally contained as an isolated pocket surrounded by finer sediments. Sediments within the till are highly compacted due to the weight of overlying ice that would have been present at various times during deposition and associated with the compaction are loading, dewatering, and other deformation structures.

Fractures (Figure 3.6) are common in till and can have the effect of enhancing the hydraulic conductivity of the till. In a study by Hendry (1982), the hydraulic conductivity

of the compacted till matrix was found to be about 10^{-10} m/s, while the apparent mean hydraulic conductivities due to small-scale (10 mm) and large scale (20 mm) fractures was 5×10^{-9} m/s and 2×10^{-7} m/s respectively.



Figure 3.6 Photograph of till fractures.

Glacio-lacustrine deposits found in the Lakeview study area contain strong evidence of sorting and stratification. In places, varves may be present as a result of alternating deposition of fine and coarse sediments (winter/summer deposition respectively). In other areas sediments are rhythmically bedded suggesting less regular temporal regimes. Sand beds can be found in these glacio-lacustrine deposits as well. These sand beds occur as sand stringers and were deposited as a result of glacial streams discharging into a glacial lake or braid plain. These sand stringers can be quite extensive. Drop stones are also found in glacio-lacustrine deposits and are the result of ice calving from a glacier and floating into a glacial lake. There ice bergs slowly drop their debris as they melt. Ice rafted debris is also carried in this way and may be found in glacio-lacustrine

deposits as a well-defined layered deposit, or as an irregular pile of poorly sorted and stratified debris (Selby, 1985).

3.4 Climate, Soils and Vegetation of the Lethbridge Area

3.4.1 Climate

Lethbridge lies in the prairie grassland climate region of Alberta (Agroclimatic Atlas of Alberta, 1990). The grasslands are described as a subhumid to semiarid climate with low precipitation and relatively hot summers. Lethbridge receives 386.5 mm of precipitation annually and has a mean temperature of 5.4°C as shown in Figure 3.7 (Canadian Climate Normals, 1961-1990). Mean annual potential evapotranspiration 100 km to the northeast of Lethbridge has been estimated to be 600 mm (Hendry et al., 1986). Total evaporation from a class A evaporation pan at Lethbridge totalled over 1300 mm between April and October (Grace and Hobbs, 1986).

Chinook winds are an interesting feature of the southern Alberta climate. The name chinook comes from the Native word meaning "Snow Eater", a good description for the warm, dry winds that blow over the Rocky Mountains. Chinooks have been known to raise the temperature during the winter as much as 21°C in only four minutes (Moran and Morgan, 1995) and can remove the entire snow cover within only a few hours. These winds blow predominantly from a west-southwest direction and are driven

by the circulation of cyclones or anticyclones situated well to the lee side east of the Rocky Mountains. As air ascends the windward slopes of the Rockies, most of the water

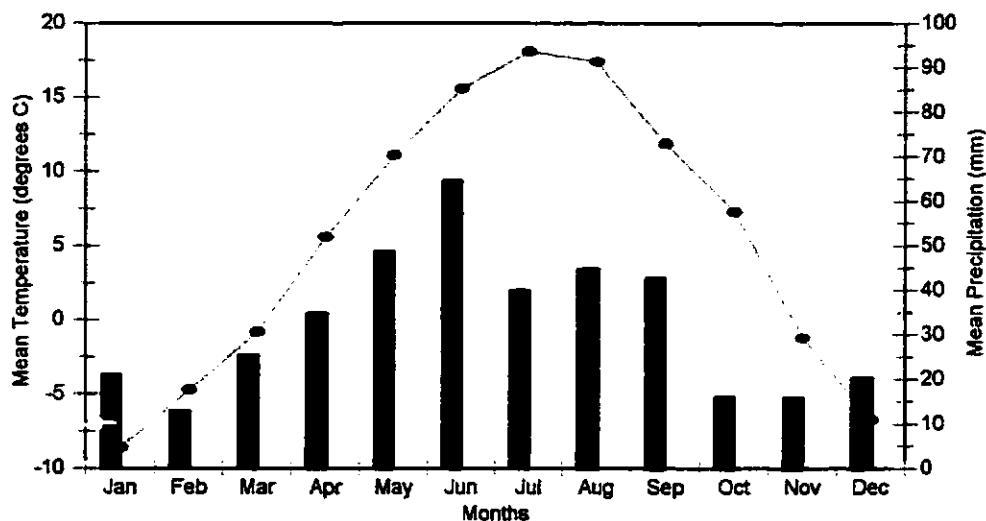


Figure 3.7 Climograph for the Canadian Agricultural Research Station located in Lethbridge, Alberta. (Canadian Climate Normals, 1961-1990).

vapour is lost due to condensation and precipitation. As this air rises, it will cool at the moist adiabatic lapse rate (ca. 6°C/km). Once these winds reach the lee side of the mountain range, the air has been depleted of moisture and as a result will warm at its dry adiabatic lapse rate (ca. 10°C/km) as it descends.

The strongest chinook winds can be found directly downwind of and in line with the Crowsnest Pass, a major break in the southern Front Ranges of the Canadian Rockies (Beaty, 1975). East of Lethbridge, the velocity of chinook winds tends to drop off

rapidly. Chinook winds are active throughout the year, but the effects are most obvious during the winter.

3.4.2 Soils

Soils underlying Varsity Village subdivision are typically Dark Brown Chernozemic soils (Kocaoglu and Pettapiece, 1980; Sracek, 1993). Kocaoglu and Pettapiece (1980) gave the soil unit in this area the name Readymade-Lethbridge and described it's composition as containing fine-loamy morainal material along with a fine-loamy to fine-silty lacustrine veneer. These soils largely developed on tills in hummocky, undulating moraines (also referred to as donut moraines) with a thin, variable lacustrine veneer sometimes present (Kocaoglu and Pettapiece, 1980). Such a lacustrine veneer was not found in Varsity Village subdivision.

Lakeview subdivision is also classed as a Dark Brown Chernozemic soil (Kocaoglu and Pettapiece, 1980). Composition of these soils is described as a fine-loamy to fine-silty lacustine veneer over fine-loamy tills (Kocaoglu and Pettapiece, 1980). The lacustrine veneer is approximately 2 to 4 m thick. Soils around Lakeview subdivision have developed on a thin blanket of lacustrine material. The A horizons of the majority of soils in both study areas show medium hydraulic conductivity and relatively high infiltration rates (Sracek, 1993). Figure 3.8 shows the Dark Brown Chernozemic soils found in the Lethbridge area.

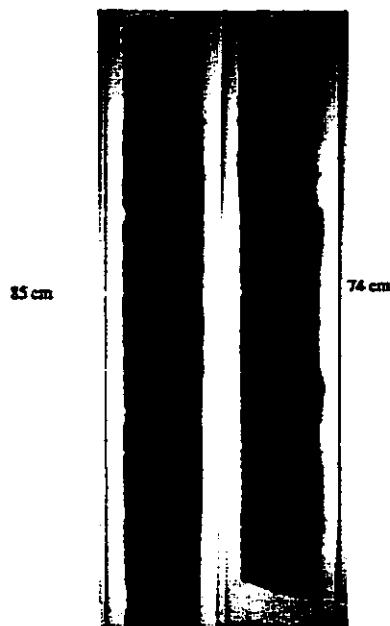


Figure 3.8 Soil monoliths of the dark brown chernozemic soils found in the Lethbridge area.

3.4.3 Vegetation

At one time vegetation in the Lethbridge area was predominantly grasses. Lethbridge lies in the mixed grass prairie ecozone (Kerr et al., 1993). Grasses are the dominant vegetation along the coulee slopes and prairie surface above the river valley cutting through the city of Lethbridge. There are two major factors determining the distribution of plants in the coulee areas; aspect and wind speed and direction. The predominantly west to southwesterly winds, in particular the strong chinook winds (Kuijt, 1972), cause plants on west facing slopes to desiccate faster than those on east facing slopes. Similarly, a south facing slope in the northern hemisphere will receive more solar

radiation resulting in faster snow melt (increasing the runoff and decreasing infiltration), more evapotranspiration, and faster desiccation. In the Lethbridge area this results in drier soils, hence native species that grow well on these slopes are adapted to drier conditions. Major species of native grasses found in the Lethbridge area are Bluegrass's (*Poa* species), Needle and Thread Grass (*Stipa comata*), June grass (*Koeleria macrantha*), Northern Wheatgrass (*Agropyron dasystachyum*), Blue grama grass (*Bouteloua gracilis*), sun-loving sedges (*Carex* species), and Plains Reed Grass (*Calamagrostis montanensis*) (Gerling et al., 1996).

Low growing forbs have been identified in this region and are a vital part of the system. These include the Leafy musineon (*Musineon divaricatum*), Little Club-Moss (*Selaginella densa*), Field Chickweed (*Cerastium arvense*), Butte Marigold (*Hymenoxys acuialis*), Crocus Anemone (*Anemone patens*), Smooth Penstemon (*Penstemon nitidus*), Pasture Sage (*Artemisia frigida*), Moss Phlox (*Phlox hoodii*) and the Three-flowered avens (*Geum triflorum*). The Prickly Pear (*Opuntia polycantha*) is a wide spread cactus on south-facing slopes, while the Purple Cactus (*Mammalaria vesparia*) can also be found, but it is not as widespread as the Prickly Pear (Kuijt, 1972).

Woody plants do not grow well in a mixed grass prairie ecozone since they require additional moisture to thrive. One woody shrub that has been able to grow in these conditions is Skunkbush (*Rhus trilobata*), suggesting this shrub is very drought tolerant. In the troughs of coulees or on coulee slopes sheltered from the prevailing winds, conditions of higher soil moisture develop. Here woody plants are able to obtain the

water that they need to survive. These woody plants consist of Western Snowberry (*Symphoricarpos occidentalis*), Golden Currant (*Ribes aureum*), Western Chokecherry (*Prunus virginiana*), Saskatoon (*Amelanchier alnifolia*), Silver Buffaloberry (*Shepherdia argentea*), Winter Fat (*Eurotia lanata*), Buckbrush (*Symphoricarpos occidentalis*) and Bristly Gooseberry (*Ribes setosum*) (Kuijt, 1972).

As one approaches the river bottom the vegetation becomes more dense to very dense, and shrubs such as the Western Virgins Bower (*Clematis ligusticifolia*) and the Wolf Willow (*Eleagnus commutata*) are common. Larger trees are also able to grow in the river bottom, these being the Plains Cottonwood (*Populus sargentii*) and the Narrow Leaved Cottonwood (*Populus angustifolia*) (Kuijt, 1972). These trees are able to root deeply and utilize the higher water tables found in the river bottom. Survival of cottonwood seedlings is largely dependent on river flooding. Seedlings must be positioned where it is moist enough to ensure rapid germination, low enough on the flood plain to allow root growth to match the dropping water table, and high enough to avoid removal by subsequent river flows (Gom and Rood, 1999). Construction of the Oldman River Dam produced fears that fewer Cottonwood seedlings would survive as a result of controlled and less frequent flooding. While flooding may not occur as frequently as prior to construction of the Oldman River Dam, it still can occur as evidenced by the flood in June 1995 (Figure 3.9).



Figure 3.9 Flooding in the Oldman river valley (1995).

Much of the land in southern Alberta is used for cultivation or pasture land. Wheat, barley, forages, row crops and canola crops take up the majority of farmland around the Lethbridge area.

Within the city of Lethbridge, urban residents introduce a number of exotic plants to their yards and gardens. A common feature of urban parks and gardens are turfgrasses such as Kentucky Bluegrass (*Poa* species) and Red Fescue(*Festuca* species). In addition to turfgrass, a wide range of plants are used in residential gardens from water thirsty roses to native plants such as Common Yarrow (*Achillea millefolium*). Many different types of ornamental shrubs, deciduous and coniferous trees have also been introduced to the urban environment.

3.5 Description of Varsity Village and Lakeview Study Areas

3.5.1 Varsity Village Study Area

For this study, two areas were examined within the city of Lethbridge, Alberta. Relative locations of the two subdivisions are shown in Figure 3.10. The first area included Varsity Village and the University of Lethbridge Campus, both of which are located on the west side of the city. Varsity Village is bounded along the northern and southern edges by two subdivisions and to the west by open prairie under dry-land grain crops or grazing. The University of Lethbridge campus defines the eastern boundary of the subdivision. The University campus is along the coulee edge and lies just west of the Oldman River. Together, Varsity Village and The University of Lethbridge campus cover an area of approximately 368 hectares. Throughout the thesis, the study area comprising the Varsity Village subdivision and The University of Lethbridge will be referred to as the Varsity Village study area.

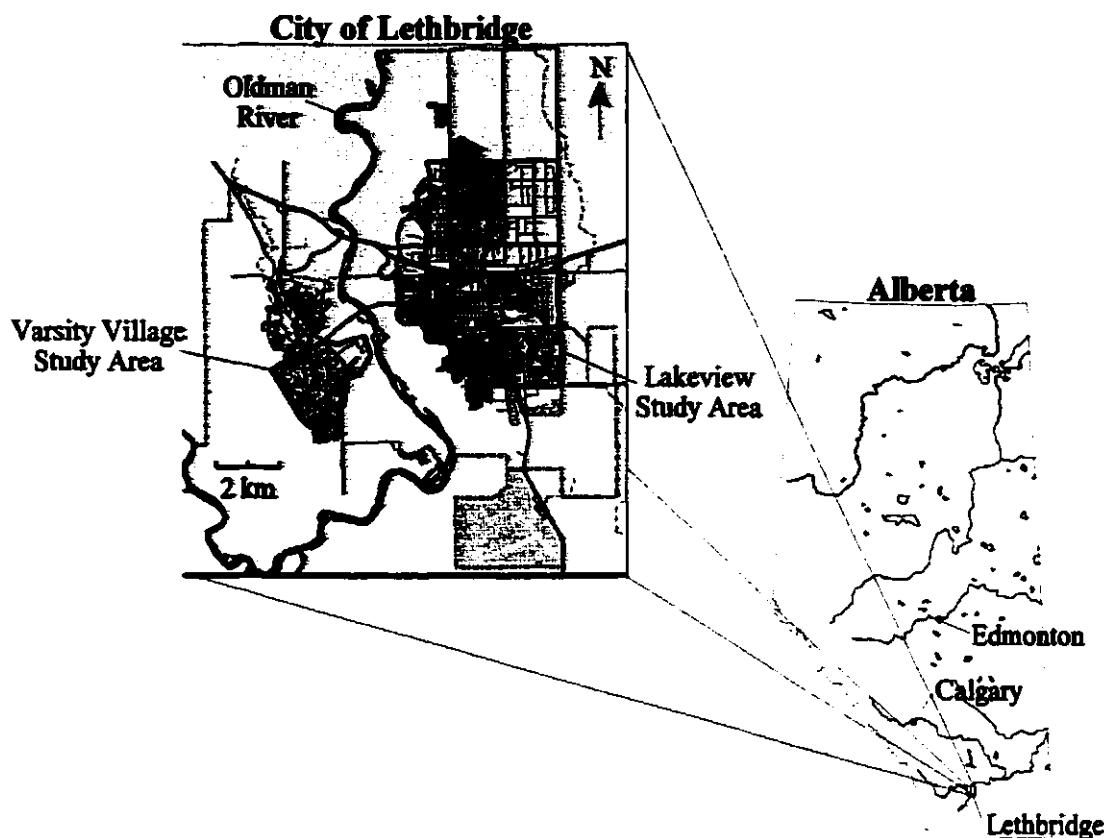


Figure 3.10 Relative positions of the two study areas in the City of Lethbridge.

There are five water bodies within the Varsity Village study area (Figure 3.11): Nicholas Sheran Lake, the University of Lethbridge irrigation reservoir (Aperture Lake), the campus wetland, Rotary Brook, and the Oldman River. Periodic inputs of water are necessary to maintain water levels in all water bodies with the exception of the Oldman River, the only naturally occurring water body in the study area. The flow of the Oldman River has been partly regulated by the Oldman River Dam since 1992.

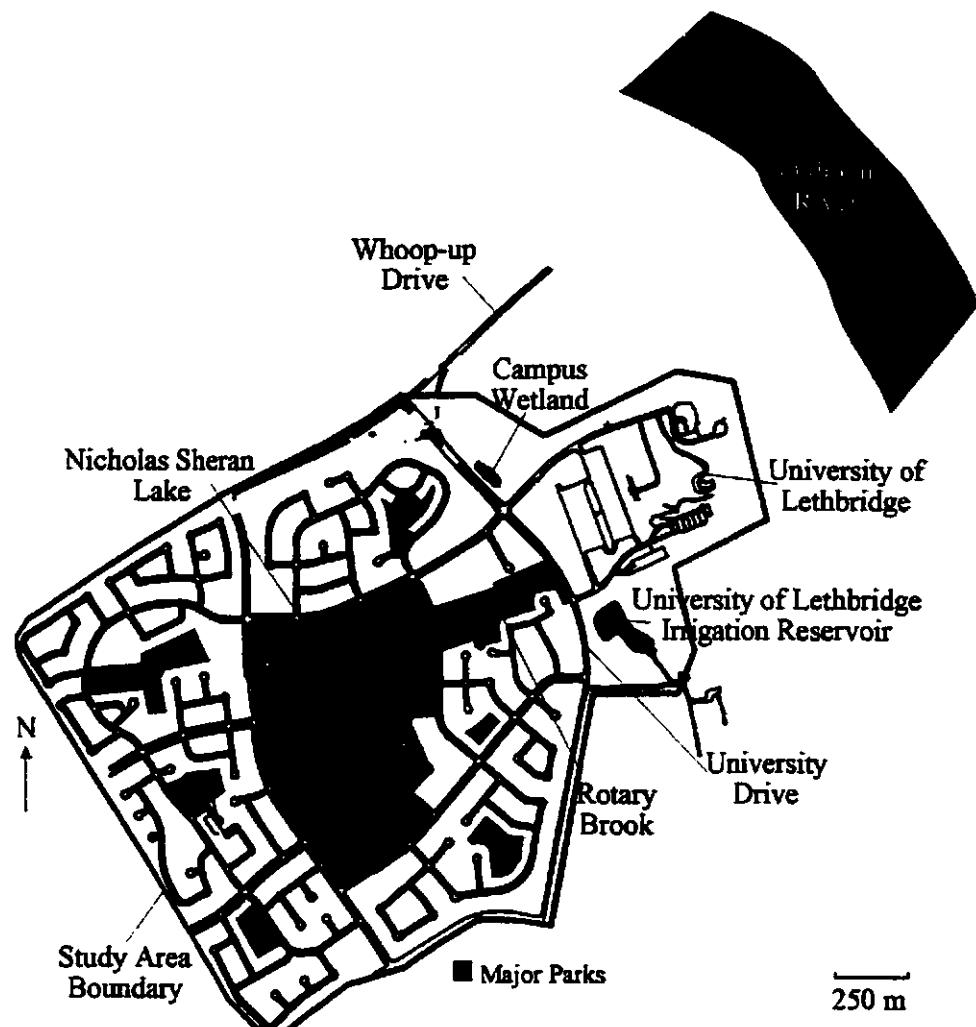


Figure 3.11 Water bodies and major roads found in Varsity Village study area.

Nicholas Sheran Lake, lying in the center of Varsity Village subdivision was created in the mid 1970's to serve as a recreational area and as a source of irrigation water for surrounding parks. The lake has not been lined and requires water inflows from the Lethbridge Northern Irrigation District to maintain its water level.

At the south end of the University of Lethbridge campus lies the University of Lethbridge irrigation reservoir (Aperture Lake). This reservoir is lined with 0.15 mm black plastic and was constructed in approximately 1971 during construction of the campus. Water from this reservoir is used to water turfgrass on the University of Lethbridge campus.

The campus wetland is located to the north of the University of Lethbridge campus along University Drive. The wetland has not been lined and requires inputs from the University of Lethbridge irrigation reservoir to maintain its water level.

Rotary Brook is a small irrigation canal that runs west to east from Nicholas Sheran Lake to the University of Lethbridge irrigation reservoir. Running throughout much of the irrigation season (May to September), the Rotary Brook provides water to the University of Lethbridge irrigation reservoir (Aperture Lake).

The Oldman River borders the eastern edge of the University of Lethbridge campus. Lying at the bottom of the Oldman River valley, the river is approximately 100 m below the elevation of Varsity Village. Most of the water used for drinking and watering within the City of Lethbridge is diverted from the Oldman River.

Development in Varsity Village subdivision began during the construction of The University of Lethbridge campus. Sod was turned for the construction of the campus in 1969 and the official opening of the campus occurred in 1972. Development of Varsity Village subdivision occurred during the period 1970 - 1977.

3.5.2 Lakeview Study Area

Lakeview subdivision is in the southeast corner of Lethbridge. The Lakeview study area includes Lakeview subdivision and is bounded on the northern edge by Henderson Lake. Mayor Magrath Drive marks the western edge of Lakeview study area, while Highway 4 and 43rd street provide the southern and eastern boundaries respectively. Lakeview is surrounded by other housing developments, except the eastern edge where irrigated farmland is found. The Lakeview study area covers an approximate area of 330 hectares.

Henderson Lake is the only major water body found near the Lakeview subdivision. Henderson Lake is located in the eastern portion of the City of Lethbridge and along the northern boundary of the study area (Figure 3.12). Henderson Lake was originally known as Slaughterhouse Slough because of a large slaughterhouse that was located nearby. The transformation of Slaughterhouse Slough to Henderson Lake occurred in 1911-1912 (Johnston, 1986). A 91 m long, 2 m embankment was used to seal off the lower end of the 57 hectare depression containing the slough. The 37 hectare Henderson Lake was created by filling the resulting basin using irrigation water (Johnston, 1986). Water levels are still maintained by irrigation water today.

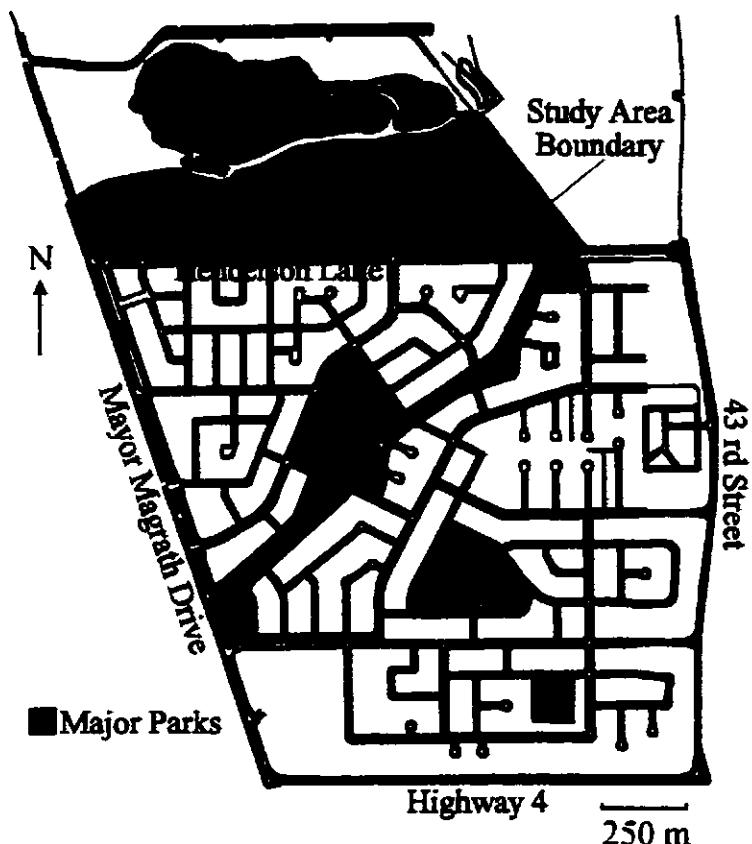


Figure 3.12 Location of Henderson Lake and major roads in Lakeview study area.

There are two other sources of water that lie outside but nearby Lakeview study area. To the east of Lakeview lies an irrigation canal from the St. Mary's irrigation district (Figure 3.13). To the south of the study area is Fairmont Park subdivision containing a lake (Figure 3.13) that at the time of writing has not yet been named.

Construction in Lakeview subdivision began as early as 1949 and continued until the early 1970's. Since development in Lakeview began 20 years prior to that in Varsity

Village, water applied as irrigation in this subdivision has had a longer period of time to accumulate. These two different periods of water accumulation and how they have affected the water table conditions in each subdivision are of interest in this study.

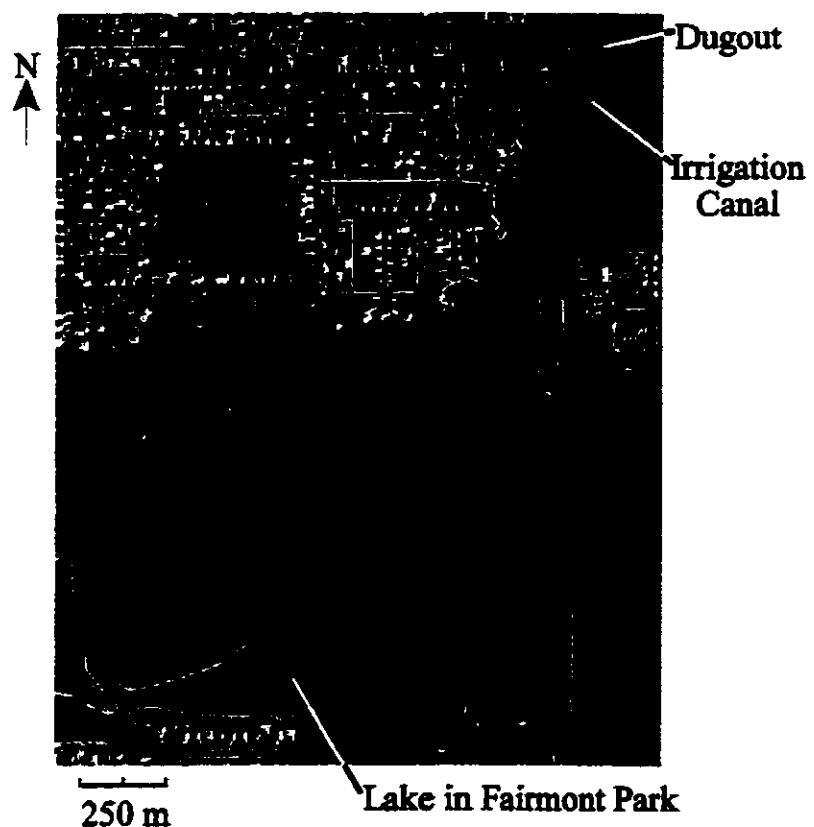


Figure 3.13 Position of irrigation canal and lake in Fairmont Park near Lakeview study area. (Air Photo was taken on May 6, 1999)

3.6 Groundwater Problems

3.6.1 Slope Instability

Slope instability is a well documented problem in the City of Lethbridge (Ruban and Thomson, 1983; Thomson and Morgenstern, 1977). The river valley and coulees dividing the city of Lethbridge represent a large region where slope instability continues to occur. Erosion of toe areas by the Oldman River is a major contributor to slope instability in this river valley. Removal of the toe area (lateral migration of the river) leads to instability through the unloading or steepening of the slope. Beaty (1972), found that microclimatic factors favouring the accumulation and retention of snow had a large affect on the distribution of slumping. He found that 87 % of the slopes investigated occurred on slopes of northerly, northeasterly, easterly, and southeasterly aspect. The aspect of these slopes allow them to be partially sheltered from either the sun, the wind or both, maximizing the amount of water that will infiltrate the soil. Coulee slopes are normally stable, but anthropogenic activities in urban areas work to destabilize coulee slopes. Ruban and Thomsen (1983) identified areas of slope instability along the Oldman River Valley near Lethbridge and outlined some anthropogenic activities that contribute to landslides in this area:

- excessive watering of lawns and gardens in residential areas
- leakage of water from sewer and water mains
- irrigation of farmland in rural districts
- placement of fill along the crest of slopes
- uncontrolled discharge of surface water runoff and irrigation water onto slopes
- ponding of water near the crest of slopes
- increased runoff discharge due to overgrazing of coulee slopes.

Water applied to residential lawns, gardens, and parks is often in excess of turfgrass evapotranspiration requirements. This excess in water application has resulted in the formation of enhanced water tables within the City of Lethbridge (Berg, 1997). An increase in groundwater level creates an increase in the soil pore water pressure. This increase in pore water pressure results in a decrease in the effective stress between soil particles and a subsequent decline in slope stability (Ruban and Thomsen, 1983). There have been recent occurrences of slope failure in the City of Lethbridge. Figure 3.14 shows one such failure that developed in the southern end of the city in Tudor Estates subdivision during 1997.

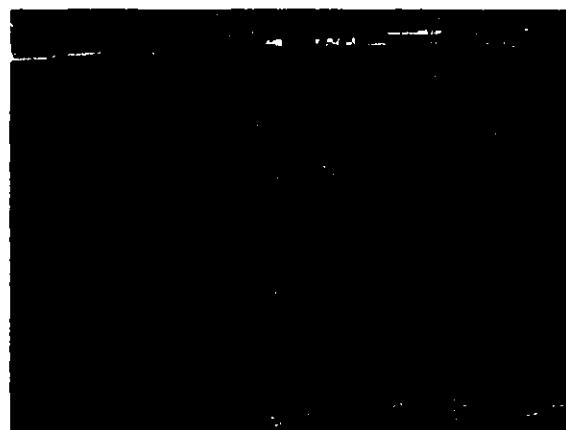


Figure 3.14 Slope failure south of Tudor Estates, Lethbridge, Alberta.
Photo taken in October, 1998.

Thomson and Morgenstern (1977) discussed the stability of valley slopes as they are affected by the geology of the area. They identified the marine Bearpaw Formation as being composed mainly of bentonite-rich, poorly indurated, unstable clay shales. Relatively stable bedrock includes the Oldman and Foremost Formations (Thomson and Morgenstern, 1977). These Formations are nonmarine and composed of sandstones, siltstones and nonbentonitic mudstones. Another deposit that provides increased stability

to valley slopes is the Saskatchewan Sands and Gravels (Thomson and Morgenstern, 1977). The Saskatchewan Sands and Gravels serve to lower water tables, increasing the stability of the slope. Saskatchewan sands and gravels underlie parts of the city of Lethbridge but occurrences of slope instability persist.

3.6.2 Basement Flooding

Basement flooding has been reported to the author as a problem in many different subdivisions of the City of Lethbridge. Many homes within the city have been equipped with sump pumps that regularly discharge water from basements into the sewage or storm water systems during periods of high rainfall. Sump pumps are now required in all newly constructed homes. Water seepage into household basements is possible since water tables have been observed within 2 metres of the soil surface, depths that will lie above the lowest level of many basement floors. Weeping tile around these household foundations can become clogged or partially clogged making them unable to remove water rapidly enough to prevent water accumulation, creating the opportunity for basement flooding.

3.6.3 Structural Instability

During winter months, structural instability of concrete foundations by freezing groundwater has been reported in Heritage Heights subdivision of the City of Lethbridge. Personal communication with one resident revealed that a concrete pad supporting a

patio rose as much as 10 cm during the winter. He believed that freezing soil water was the cause of this instability.

High water tables beneath asphalt covered surfaces have also been observed in the Lethbridge area. Cracks on an asphalt or concrete surface will allow water to infiltrate and can cause problems when the soils of the area have limited permeability. Water that infiltrates beneath these asphalt or concrete surfaces is difficult to remove since an evaporative cap is formed by the impermeable surface (Lerner, 1990). This build up of water can result in the loss of the surfaces load capacity. During paving of the west and far west parking lots at the University of Lethbridge in 1991, saturation of the ground beneath these lots prevented the use of heavy construction equipment.

3.7 Summary

This chapter provided an overview of the regional setting and a description of both Varsity Village and Lakeview study areas. Data regarding the climate, soils, vegetation, regional surficial and bedrock geology, hydrogeology and groundwater problems were discussed. Examination of the data for both study areas will provide a better understanding of the Lethbridge region and will help to understand the problems of water management.

The City of Lethbridge lies in a sub-humid to semi-arid climate. While Lethbridge has a mean precipitation of only 386.5 mm annually (Canadian Climate Normals, 1961-1990),

total evaporation from a class A evaporation pan at Lethbridge totalled over 1300 mm between April and October (Grace and Hobbs, 1986). High rates of evapotranspiration in the Lethbridge area are due to the hot summers and the dry Chinook winds that are common in this area.

Varsity Village study area lies on the west side of the Oldman River valley. Within this study area is Varsity Village subdivision and the University of Lethbridge campus. This 368 hectare area has been constructed on the Lethbridge Moraine, making till the major sediment underlying the study area. There are five water bodies (Figure 3.11) in Varsity Village including: Nicholas Sheran Lake, the University of Lethbridge irrigation reservoir (Aperture Lake), the campus wetland, Rotary Brook, and the Oldman River.

Lakeview study area lies in the southeast corner of Lethbridge. Covering 330 hectares, the study area is mainly constructed on glaciolacustrine sediments that overlie till. The glaciolacustrine sediments underlying Lakeview study area were deposited in Glacial Lake Lethbridge during the retreat of the Laurentide ice sheet. Henderson Lake (Figure 3.12) is the only water body within Lakeview study area.

Chapter 4

Methodology

4.1 Introduction

This section will discuss the techniques used in this study. The chapter will provide a discussion of data collection in the field, the use of this data to gain insight about the groundwater conditions in Lakeview and the methods used to compare the two study areas. Construction of a turfgrass irrigation model is discussed towards the end of this chapter.

4.2 Borehole and Well Installation

During a prior study, 54 wells were installed for the purpose of monitoring water table levels in Varsity Village subdivision and the University of Lethbridge campus (Berg, 1997). As part of this thesis research, an additional 23 wells were installed in Lakeview subdivision during August 1997 and five more were installed the following spring (May 6, 1998) in Henderson Lake Golf Course (Figure 3.12).

Drilling sites were selected to provide a near uniform distribution of well installations over the entire subdivision, with wells being positioned in a variety of representative land cover classes (Table 4.1). The near uniform distribution was used to ensure that there would be no areas of Lakeview subdivision that did not have water table data available from a nearby location. Accessibility was a consideration in the selection of borehole locations. Areas where drilling took place needed to be readily accessible for a large (5 ton) drilling truck (Figure 4.1) as well as remain available for long-term monitoring of water wells.

Land Cover Class	Description	Number of Boreholes Located in Class
Golf Course	Boreholes located in Henderson Lake Golf Course.	5
Residential	Green spaces/lawns maintained by city residents or other non-city employees.	3
Road	Boreholes located in the middle of roads or alleys (gravel/pavement surfaces).	6
Park	Boreholes located in green spaces maintained by the City of Lethbridge.	6
Vacant Lot	Boreholes located in unirrigated, open areas. Buildings or structures were sometimes located nearby.	8

Table 4.1 Land cover classes where boreholes were located.

The size of the drill truck made it difficult to drill boreholes near residential homes. As a result, only three boreholes were drilled in areas that were classed as residential. An

attempt was made however to place boreholes that were classed in other categories close to residential homes so that those would be represented as well as possible. Irrigated areas were still well represented however, since the golf course, residential, and park land cover classes represent 14 boreholes and the road and vacant lot land cover classes represent 14 boreholes that were placed in non-irrigated areas. The groupings of irrigated and non-irrigated land cover classes is later compared to water table depth using a Mann-Whitney test.



Figure 4.1 Drill truck and workers.

All boreholes were drilled using a 15 cm auger stem. The maximum depth drilled was 16.5 metres, with the average depth drilled being 7.5 m. Some boreholes were drilled to greater depths to see if the contact between the oxidized and unoxidized tills could be reached. Soil samples and well logs were obtained during drilling for the purpose of gravimetric soil moisture and soil texture analyses. The samples were typically collected at the 30 cm depth and then at one metre increments below the surface until drilling was

completed. All samples were immediately placed into zip lock freezer bags so that any moisture loss from the samples would be minimized. Figure 4.2 shows the drilling sites where soil samples were collected.

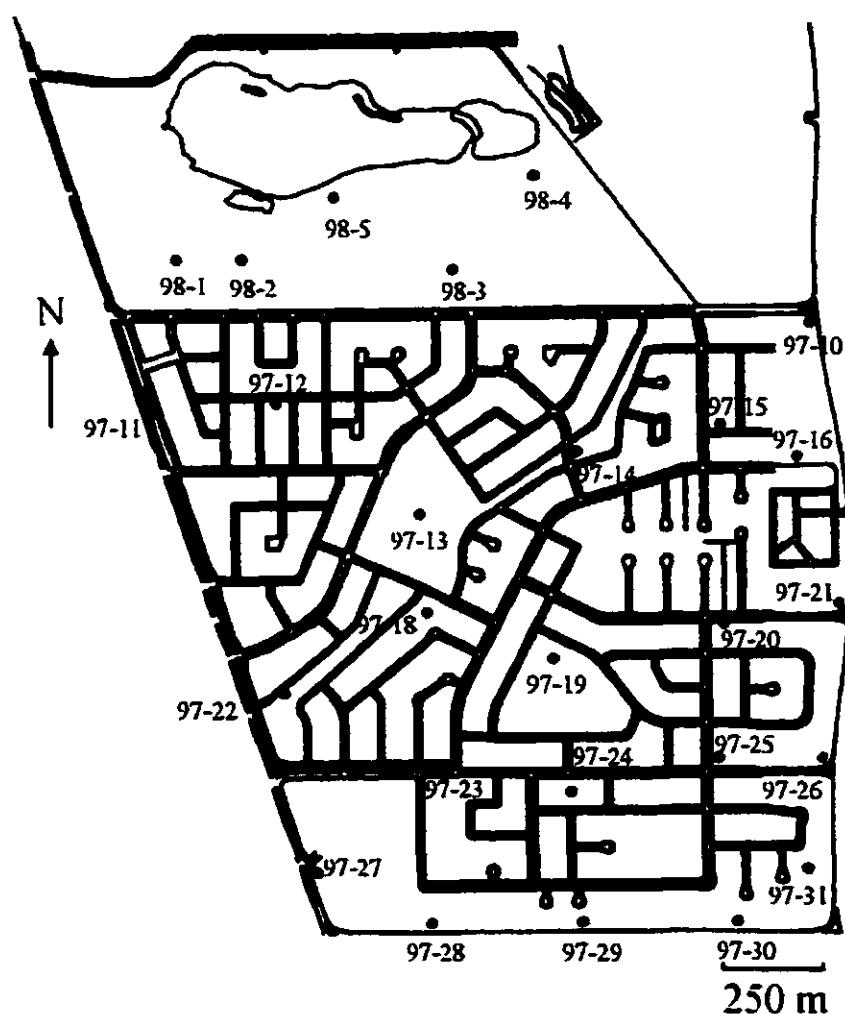


Figure 4.2 Soil sample sites and well locations, Lakeview study area.

Slotted PVC tubing was installed in each borehole. Slotting began one metre below the surface and continued at half-metre increments until the bottom of the hole was reached.

The PVC tube was slotted to allow water to flow freely from the subsurface into the tube where the water table elevation can be monitored. Following insertion of the PVC tube, pea grade gravel was used to fill the remainder of the hole to within 30 cm of the surface. Bentonite was used to fill the top 30 cm of the hole. The bentonite acts as a seal to prevent surface runoff from infiltrating directly down the borehole.

4.3 Soil Analysis

4.3.1 Texture Analysis

Sediment texture analysis was conducted on all samples collected from the 23 holes drilled in Lakeview subdivision. The hydrometer method as described in Bouyoucos (1962) and Day (1965) was used so that all soil texture data obtained would be comparable with soil texture data obtained by Berg (1997).

The samples (approximately 100 to 150 g each) obtained from Lakeview were air dried for four to five days and then a portion of this sample (approximately 60 g) was weighed, recorded and then broken up using a crucible. This was done carefully to minimize the chances of crushing a gravel size particle into smaller pieces. If a gravel sized particle was apparent, it was removed from the sample and set aside to be weighed later. A 2 mm sieve was used to separate the remaining gravel from the sample and this gravel was then weighed. Following removal of the gravel, the remaining sample was poured into a milk shake mixer cup and 40 ml of dispersing solution was added to the sample

along with distilled water. The dispersing solution was prepared by dissolving 38 g of calgon and eight grams of Sodium Carbonate (Na_2CO_3) in 1 L of distilled water. Once the dispersing solution was added the sample was agitated for 10 minutes using a milk shake mixer. Dispersion of the soil particles is necessary to ensure that the abundance of primary soil particles in the sample clay and silt size range are being properly measured. If the dispersion solution had not been used some soil particles may have remained aggregated and given an incorrect estimate of the proportions of clay, silt and sand. (e.g. many clay sized particles clumped together would register as a silt or sand sized particle).

Following agitation, the sample was sieved using a 63 micron (0.063 mm) sieve that separates the sand portion from the remainder of the sample. The use of the 63 micron sieve ensured that the soil texture data obtained would be usable in a comparison with that obtained by Berg (1997). The sand portion was then sieved through a 50 micron (0.05 mm) sieve to separate the medium and coarse grained sand from the fine textured sand. Drying tins were weighed and the coarse-medium and fine sand portions were added to the tins and dried in an oven at 105 to 110°C for 24 hours. Once dry, the tins containing the dried sand were weighed to determine their percentage of the total dried sample.

Following the removal of the sand fraction the remaining sample, along with the distilled water and dispersing solution, was poured into a one litre cylinder and distilled water was added until the solution had a volume of exactly one litre. The solution was then agitated

for an additional 30 seconds before the solution was allowed to begin settling. For this study, hydrometer readings were taken to measure the amount of sediment remaining in the solution after it had been left standing for 2 hrs.. Soil particles of different sizes require different periods of time to settle out, the larger particles requiring less time to settle out of the solution than the smaller soil particles. Readings taken at the 2 hr time period shown above were used to calculate the percentage of clay (2 hrs) remaining in the sample suspension (Palmer and Troeh, 1995).

A hydrometer reading was also taken from a control cylinder containing a 1 L mixture of dispersing solution and distilled water. This reading was used to calibrate the hydrometer for the dispersing solution being used. The reading taken from the control cylinder was recorded and used in later calculations.

Once all readings were recorded, the percentage of each soil particle size contained within the sample was calculated. The percentage gravel, coarse-medium sand, and fine sand were calculated by dividing the dried weight of each soil particle size by the total dried weight of the sample and multiplying by 100. The remaining soil texture classes were determined using the following equation :

$$W\% = 100 \left[\frac{H_x - H_D}{W_s} \right] V \quad (4.1)$$

Where: W% = Percentage of soil particles remaining in suspension at any given time

H_x = hydrometer reading at time x (gram/litre)

H_D = hydrometer reading for dispersing solution (gram/litre)

W_s = total dry weight of sample (grams)

V = volume of suspension (1 litre)

The percentage of clay remaining in the sample was determined by calculating the W% using the hydrometer reading taken at 2 hrs. Once the percentage of clay and sand were calculated, the remaining sample was considered to be silt.

4.3.2 Soil Moisture Content

Soil moisture analysis was conducted to gain insight into the variations of soil moisture content along a vertical borehole wall of the study area. Analysis of soil moisture was started two days after the soil samples were collected. It was necessary to start the soil moisture analysis soon after the samples were collected to minimize any loss of moisture from the samples. Drying tins were weighed and then approximately 55 - 65 grams of each sample was taken out of the zip lock freezer bags and placed into these tins. The wet sample and the tin were then weighed again. The weight was recorded and the samples were placed in a drying oven and dried at a temperature between 105 to 110°C for 24 hours (Brady and Weil, 1996; Tan, 1996; Topp, 1993). After the samples had been dried they were removed from the drying oven and let cool to room temperature. Once cool, the weight of the dried sample along with the tin were measured and recorded. Soil moisture (θ) was calculated from the collected data using the following equation:

$$\theta = 100 \left[\frac{m_m - m_d}{m_d - m_t} \right] \quad (4.2)$$

Where: m_m = mass of moist soil and tin
 m_d = mass of dry soil and tin
 m_t = mass of tin

This equation gives the percent mass of water compared to the mass of the total sample.

4.3.3 Soil-Stratigraphic Analysis

One of the objectives of this study was to determine whether substrate played a role in determining the elevation of water tables development. Variations in soil texture play a major role in determining the permeability (the ability of a soil to permit water to flow through it) and hydraulic conductivity of a soil (Brady and Weil, 1996; Saxton et al., 1986; Ward, 1975) and it was decided that by examining the distribution of soil texture throughout Lakeview, a correlation between these two variables may be determined. Saxton et al. (1986) even developed an equation to estimate the hydraulic conductivity of a soil using texture and found that it provided reasonable estimates when the soil textural range of percent sand was between 5% and 30% and percent clay was between 8 % and 58%. The equation also showed good estimates when percent sand was between 30% and 95% at the same time that percent clay was between 5% and 60 %.

Once analysis of soil texture was completed on all soil samples collected from Lakeview, the samples were used to examine whether boundaries or structures of coarser or finer sediments existed at particular depths. A boundary marking a transition from coarse to fine soil particle sizes could be a boundary where potential water build-up could occur. Structures of coarse sediments extending over a large area of Lakeview may have higher hydraulic conductivities than surrounding sediments, making these structures more effective as conduits of water transport.

Each soil sample was assigned a colour according to their measured soil texture and then arranged by sampling depth. The various colours were assigned to provide easy visual comparison between adjoining boreholes. When a yellow colour was used between the three and four metre intervals, this designates that a single clay textured sample was collected from three metres below the surface (Figure 5.5). This application of colour was done to allow for ease of comparison between adjoining boreholes and does not represent that all sediment found between three and four metres below the surface will have a soil texture of clay.

Once the colour scheme was applied to all soil samples the boreholes were arranged according to their proximity to other boreholes. Boreholes were arranged in this way so that soil textures of boreholes lying in close proximity to one another could be compared and any zones of similar soil texture could be identified. Each borehole was selected and concentric circles were drawn outwards from this borehole to determine the boreholes that were closest to and furthest from the selected borehole. This process was repeated for each borehole in Lakeview and the soil texture columns were arranged according to the distance that they were from the selected borehole. An example of this process is shown in figure 4.3.

Soil samples were also arranged according to their elevation above sea level. By arranging the samples in this way it was hoped that horizontal structures may be easier to identify. This was done by adjusting the top of the borehole to match the elevation of the surface where the borehole was originally drilled. The adjusted boreholes were then

arranged in a similar fashion to compare a selected borehole to those that lay in closest proximity to it.

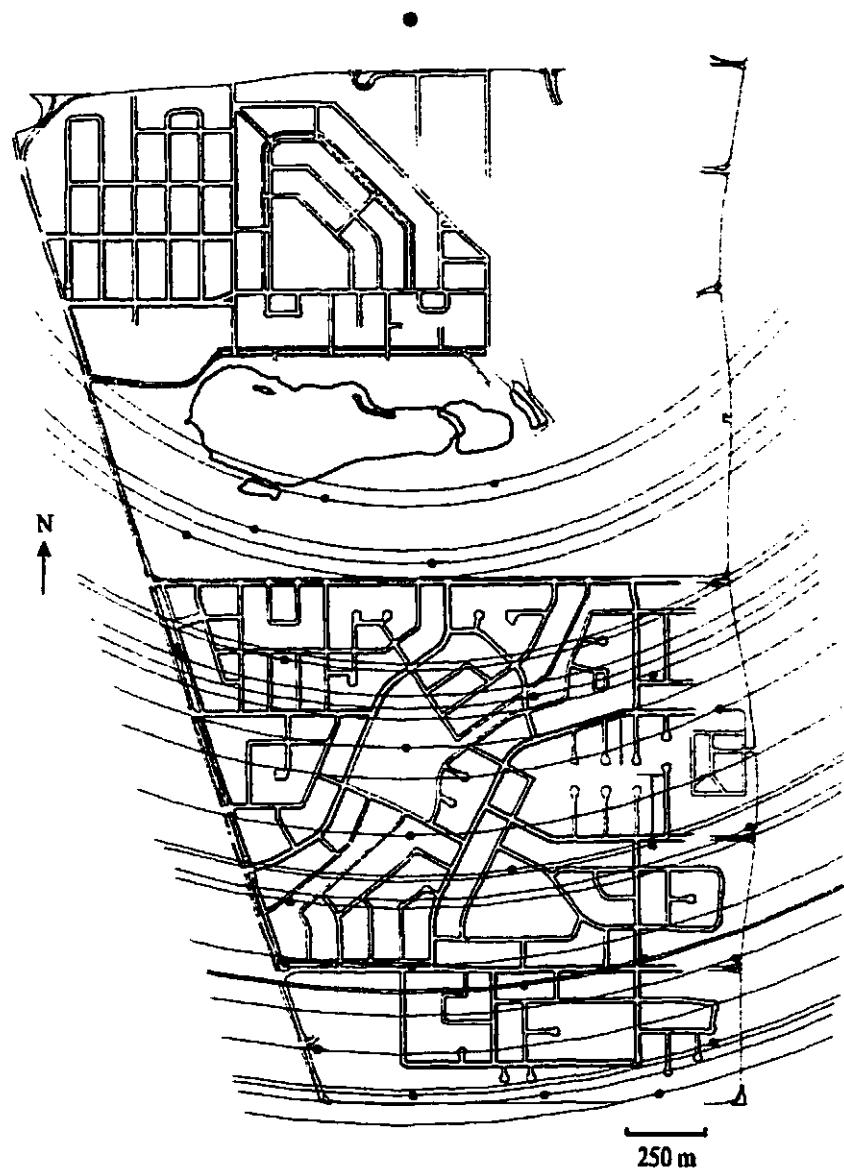


Figure 4.3 Proximity of boreholes to a selected point.

4.4 Water Level Monitoring

During the summer of 1998, water level monitoring was carried out on a weekly basis for all well installations in Lethbridge. Water table levels were measured using a water level indicator. To use the water level indicator, the probe was lowered down the well. The probe contained two separate wires connected to a battery, a buzzer and a small light. Once the probe reaches the water table surface, an electrical current passes from one wire to another, completing the circuit and setting off the buzzer and light. The light and buzzer alert the operator that the water table level has been reached.

Water table records are available for Varsity Village from 1994 to 1998. These records were monitored and recorded as part of Berg (1997) until the summer of 1997 when monitoring of these wells was continued as part of this thesis research. Records of water tables in Lakeview subdivision have only been available since installation in the summer of 1997 and spring of 1998. For both study areas, water table elevations were monitored on a weekly basis. Well installations monitored for water table levels in Lakeview and Varsity Village are shown in figures 4.4 and 4.5 respectively.

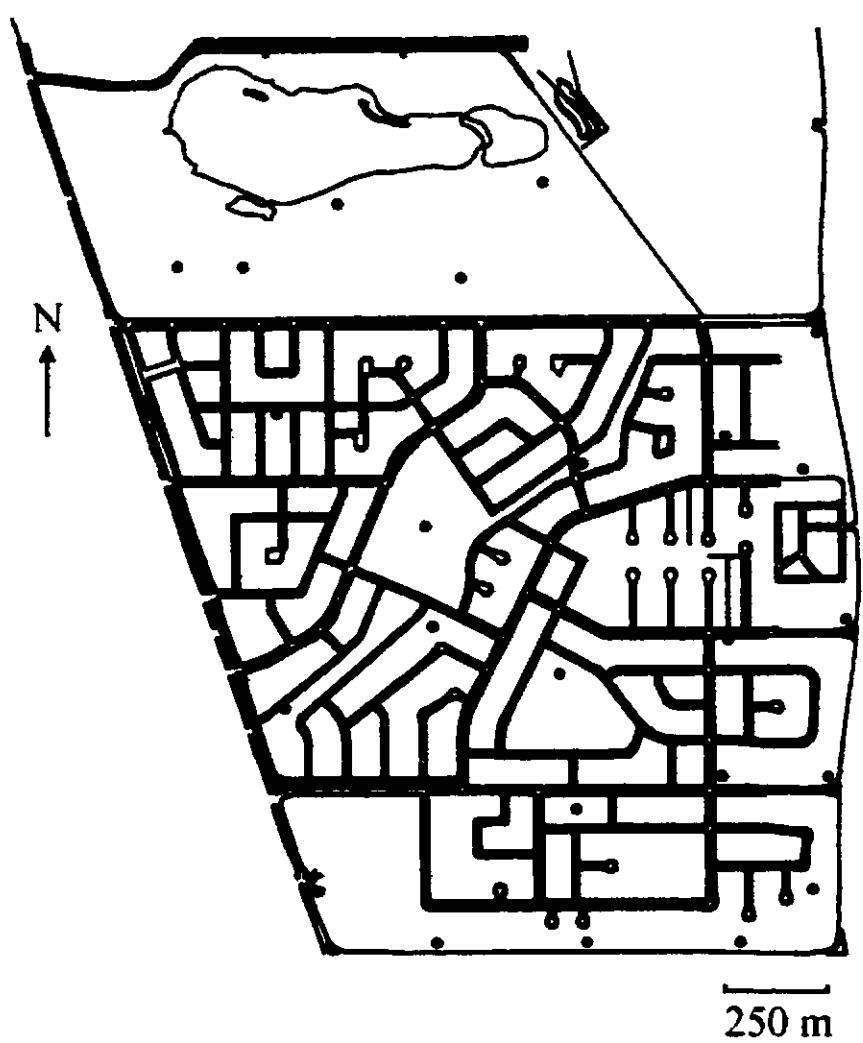


Figure 4.4 Location of well installations monitored in Lakeview study area.

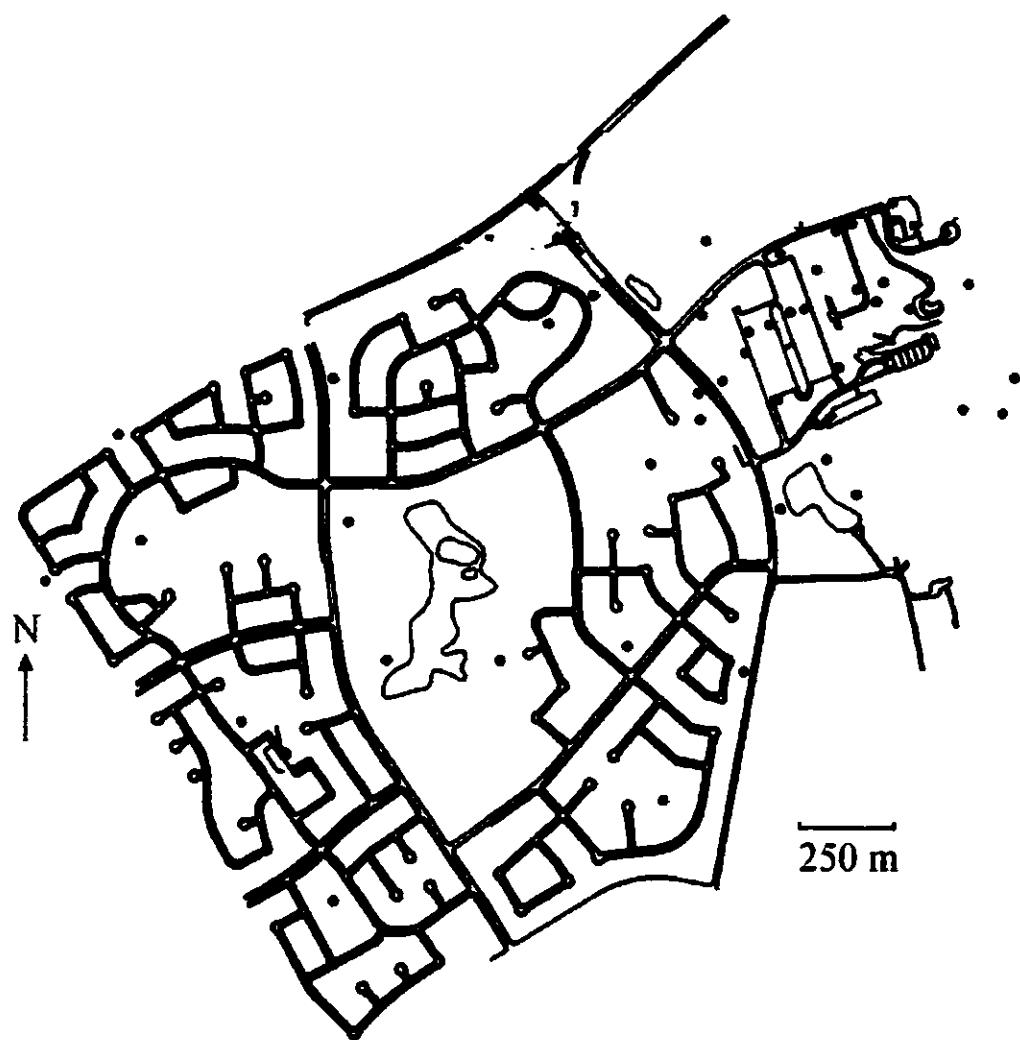


Figure 4.5 Location of well installations monitored in Varsity Village study area.

4.5 Modelling and Comparison of Water Table Surfaces

A Geographic Information System (GIS) is an effective tool for integrating and comparing information from a variety of sources. GIS allows information to be digitized from maps or imported from another digital source. For this study, GIS was an essential tool since it was necessary to integrate data collected from the field with information and data provided by the City of Lethbridge. PAMAP was the GIS software chosen for this study. This particular package was a good choice for this study based on its availability, the softwares vector and raster data handling capabilities, and the author's previous exposure to PAMAP.

For this study, the City of Lethbridge was able to provide information that had been previously converted to digital format. The City of Lethbridge provided vector layers for both the Lakeview and Varsity Village subdivisions that included topographic features, contours, water features, roads, alleys, parking lots, building lots, and building easements. Vector layers provided by the City of Lethbridge were created from 1:10000 aerial photographs of Lethbridge taken in 1988. Accuracy of this data has been determined (ground truth) to be within 15 cm. Both the accuracy of the data and the vector layers were created by a company contracted by the City of Lethbridge.

The creation of digital elevation models (DEM) for both subdivisions was the first step of the project. The DEM was created using Surfer, a contouring and 3D surface mapping software package. Kriging (discussed below) was used to create a DEM for Varsity

Village using one metre contours provided by the City of Lethbridge for sections 23, 24, 25, 26 and 26 of township 8, range 22. The DEM for Lakeview subdivision was also created using kriging from one metre contours of sections 28 and 33 of township 8, range 21.

Water table surfaces and surfaces expressing depth to water table were also created using Surfer. The vector to raster transformation was done to allow for easier visual examination. Surfer uses a surface interpolation method called kriging. Kriging is one of the most widely used geostatistical estimation methods and attempts to express trends occurring in the data. Surfer generates a uniformly spaced grid from irregularly spaced data using kriging (Shan and Stephens, 1994). The 40 m grid was created using surfer to produce the water table surfaces and depth to water table surfaces. A 5 m grid was also created using kriging but took a significantly longer computing time to create while providing little change to the final surfaces. The equation used by kriging is:

$$Z(s_o) = \sum_{i=1}^n \lambda_i Z(s_i) \quad (4.3)$$

Where:
 $Z(s_o)$ = predicted value
 λ_i = weight applied
 $Z(s_i)$ = neighbouring data value
 n = number of neighbouring data values

In order for Surfer to create the necessary grid file, an XYZ file was required. X and Y projection coordinates of well locations were exported from PAMAP as an ASCII text file. Locations of the well installations were identified on the orthophoto maps and digitized into PAMAP using recognizable features such as roads, house lots, and house

numbers. Using this method it is expected that all well installations were located to within 1 to 2 m of their actual location. GPS was originally used to locate the well installations, however it was found that the projection coordinates that it provided were inaccurate when compared with maps of Lakeview study area. Z values used in the XYZ files consisted of water table elevations and depth to water table at each piezometer location. Surface elevations of the borehole installations were extracted from the DEM so that water table depths could be reported as elevation above sea level. Contours and surfaces for both subdivisions were derived for all days that water table readings were taken.

In Surfer, several factors are used in the kriging method: the Variogram Model, the Drift Type, and the Nugget Effect (Keckler, 1994). A variogram suggests how weight should be applied and which observations should be used in the calculation of the grid nodes. The linear variogram model with a scale of 1 was used during this study since this is suggested when little is known about the variogram of your data (Keckler, 1994). No Drift was applied to the data since the data points were evenly dispersed throughout the study area. A zero Nugget Effect was also used to avoid smoothing of the original data points and ensures that the original values used to create the grid are not changed.

As shown in Figure 4.6, the elevation of the Varsity Village area varies from a low of 840 m, in the lower slopes of The University of Lethbridge campus in the northeast corner, to elevations of over 930 m along the western edge. Lakeview (Figure 4.7) has surface

elevations ranging from 906 m in the northwestern corner of the subdivision while to the southeast, elevations are as high as 918 m.

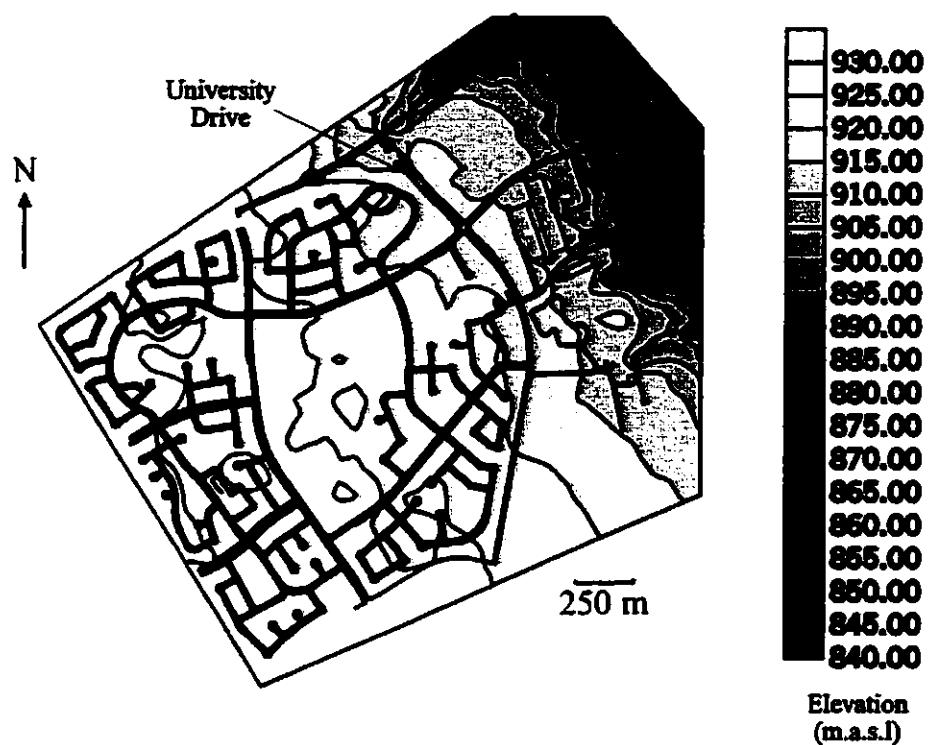


Figure 4.6 DEM of Varsity Village study area.

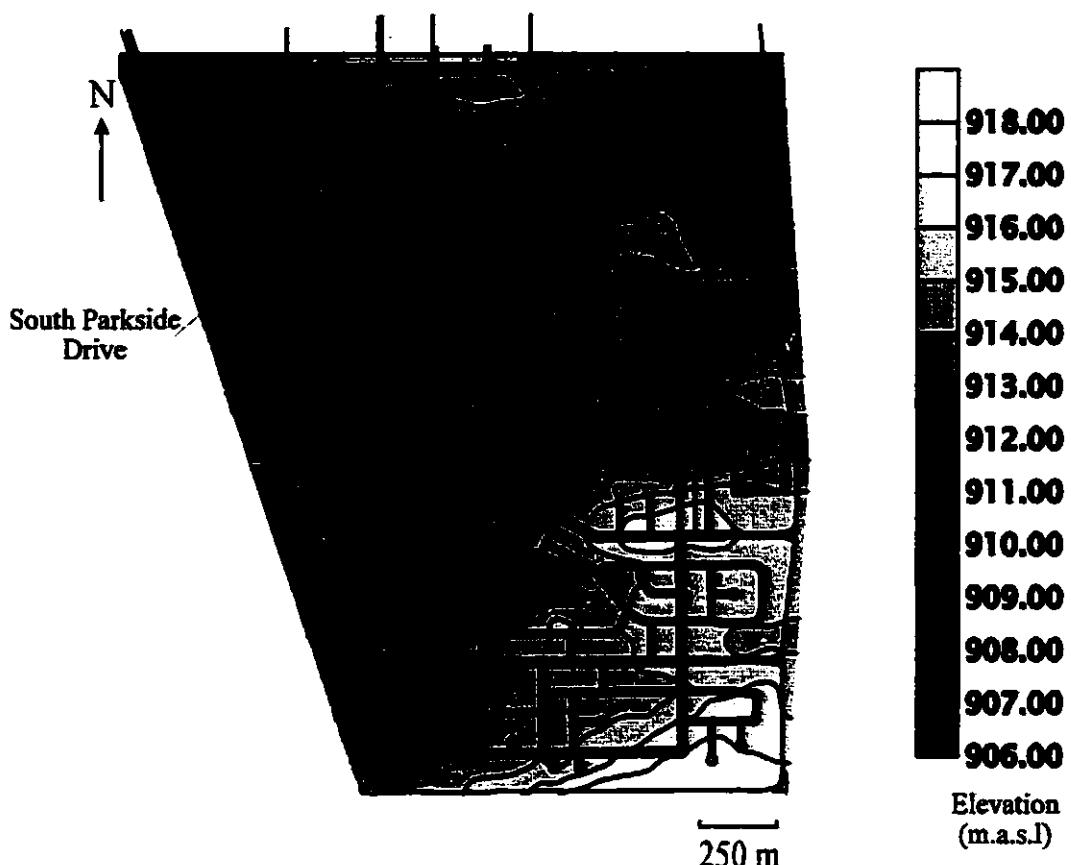


Figure 4.7 DEM of Lakeview study area.

4.6 Statistical Analyses

4.6.1 Water Table Depth vs. Sand and Clay Fractions

The possibility that there were substrate controls (soil texture and stratigraphy) on the depth of water tables can be tested. Sand lenses in particular were believed to play a

major role in the development of high water tables. In order to test the effect of soil texture on water table depth, the sand and clay fractions obtained from the sampled boreholes were compared with water table depth.

For each well installation in Lakeview subdivision, a linear regression was used to compare the mean sand and clay fractions to mean water table depth. Mean sand and clay fractions were calculated for each individual borehole that was drilled. Each borehole had three means of sand and clay fractions calculated. The first mean used all soil samples collected from a given borehole to calculate the mean sand and clay fraction for that hole. The other two means of both clay and sand fractions for each borehole were calculated using only the soil samples collected from the upper 2 and 4 m. These means calculated using only samples to a depth of 4 m was done since some holes were drilled to only 4.5 m while others were drilled to as deep as 16.5 m. A depth of 4 m ensured that all boreholes were equally represented to a particular depth. The 2 m depth was used to investigate if the mean sand and clay fractions closer to the surface impacted variations in water table depth greater than a mean calculated using samples deeper down. This was of interest since a large number of the water tables can be found within 1 to 2 m of the surface.

Linear regression attempts to determine whether there is a linear relationship between the two sets of data. If there is a linear relationship between the data, the graph of the data should be a straight line, defined by the equation:

$$y = \alpha + \beta x + e \quad (4.4)$$

Where: α = the y intercept
 β = the slope
 e = random deviation

Linear regressions also provide an estimate of r^2 . An r^2 value, also known as the coefficient of determination, can be interpreted as the proportion of y variation that is explained by the model relationship (Devore and Peck, 1994).

4.6.2 Water Table Depth vs. Irrigated and Non-irrigated Land Cover Classes

Irrigation is a probable control on water table depth. A comparison between the mean water table depth and well installations lying in irrigated and non-irrigated land cover classes was done using a Mann-Whitney test. A Mann-Whitney test is the non-parametric equivalent of a difference of means test (McGrew and Monroe, 1993). The Mann-Whitney test was chosen based on the belief that it was the best statistical test for comparison of classes containing non-ordinal data as well as the small values of n that could be obtained for both the irrigated and non-irrigated land cover classes.

Well installations from both study areas were grouped into irrigated and non-irrigated land cover class based on whether they received frequent applications of water during the irrigation period. Areas such as parks, residential areas, and golf courses were placed in the irrigation land cover class. The non-irrigated class included well installations located in parking lots, roads, or vacant lots. The irrigated land cover class is made up of areas receiving varying amounts of irrigation. While golf courses may receive much higher

irrigation inputs than parks or residential areas, possibly skewing the mean of this land cover class, it was expected that all three of these groups would receive markedly higher irrigation rates than those areas placed in the non-irrigated class and therefore the grouping would be appropriate. Grouping into the irrigated and non-irrigated land cover classes was done so that there would be a larger number of well installations in each group, making the statistical analysis more meaningful.

Performing the test for each study area separately, ranks were assigned to all mean water table depths in the experiment. The shallowest water table depth will receive a rank of one, the next shallowest a rank of two, and so on. In the event of a tie, the water table depths are assigned the mean of the ranks they would have received had there not have been a tie. An example of this process is shown in Table 4.2.

Water Table Depth (m)	Rank	Value Given
2.5	1	1
3.6	2	2
3.7	Tie (3 and 4)	$((3+4) / 2) = 3.5$
3.7	Tie (3 and 4)	$((3+4) / 2) = 3.5$
4.8	5	5

Table 4.2 An Example of the Process of Assigning Ranks.

Once the mean water table depths have been ranked, the ranks were summed for both the irrigated and non-irrigated land cover classes. From these sums, the Mann-Whitney U is calculated for each land cover class using the equation:

$$U_1 = (n_1)(n_2) + \frac{n_1(n_1+1)}{2} - \sum R_1 \quad (4.5)$$

Where:
 n_1 = the number of wells in the irrigated land cover class
 n_2 = the number of wells in the non-irrigated land cover class
 R_1 = the sum of the ranks for the irrigated land cover class

The equation above calculates the Mann-Whitney U for the irrigated land cover class.

To calculate the Mann-Whitney U for the non-irrigated land cover class, it is only necessary to substitute the necessary information for this class (ie. R_2 rather than R_1 , and n_2 rather than n_1). Once the U value has been calculated it is translated to a Z-value. The Z-value is used to compute a value for P, that will give an indication of whether the results that the test provides are significant.

4.7 Turfgrass Irrigation Modelling

Since irrigation has been identified as a major contributor to raised water tables within the City of Lethbridge (Berg et al., 1996; Berg, 1997; Berg and Byrne, 1998), problems arising from elevated water tables may be reduced through the design and implementation of a water scheduling program. This program would monitor the rate of turfgrass soil moisture depletion and encourage residents to water their lawns at a rate that matches the soil moisture depletion. By matching the irrigation application rate with the soil moisture depletion rate the amount of unnecessary water contributed to groundwater will be minimized. Less frequent and deeper water applications will

encourage the development of deeper rooting turfgrass that will be better equipped to remove water from deep in the soil profile.

A community water conservation program webpage was designed to address the water table problems within the City of Lethbridge. The author participated in the development of this webpage and was directly responsible for the page discussing some of the water table problems that occur within Lethbridge as well as the water scheduling page that was set up to aid in the appropriate application of irrigation to city parks and residential lawns. The community water conservation program webpage included:

- water scheduling - provided information on how much water should be applied to meet the evapotranspiration needs of turfgrass.
- water issues - discussed some of the problems the city of Lethbridge experiences due to high water tables.
- xeriscaping - the use of drought tolerant plants in parks and gardens.
- community involvement - discussion about how to best get the members of the community involved in conserving water.
- who we are - a page discussing the motivation behind developing the webpage and those involved in making it.

See Appendix B for pictures of the above webpages.

Using a water scheduling model in a webpage format allows a wide variety of people to have access to the model with a minimum amount of knowledge needed to run it. Most of the data input and database management can be controlled by a single operator on a remote computer, allowing users to concentrate their efforts on using the information effectively (applying appropriate amounts of water as required). Some of the data

needed to run the model can also be expensive to obtain (e.g. solar radiation). It is more cost effective to obtain the data and enter it at one location rather than requiring hundreds of users to obtain and enter it themselves. Finally, to provide the water scheduling model in a webpage format allowed it to be constantly updated and refreshed with new information at little cost to those who are running or using it. A dynamic webpage that can be accessed at any time is a more appealing option than a weekly newsletter or newspaper update.

4.7.1 Water Scheduling Model

When modelling the hydrological cycle within an area or watershed, changes in water volume inputs or outputs will result in a change of storage. A convenient way of ensuring that losses in water volume are accounted for is by utilizing the water-balance equation. The water-balance equation can be expressed in a simple form as:

$$\Delta S = I - O \quad (4.6)$$

Where: ΔS = change in storage
 I = inputs
 O = outputs

Each of these variables can be expanded to provide greater detail when examining a specific portion of the hydrologic cycle. If lake volume is of interest, inputs to the water-balance equation will become stream inflow, groundwater inflow, and precipitation onto the lake. Outputs from the lake can be expanded to include stream outflow, groundwater outflow, and evapotranspiration. Any change in lake storage can be monitored by measuring the change in lake elevation (rise or fall).

When examining the movement of water in and out of the soil system, the water-balance equation can be expanded to the following:

$$(P + I) - (ET + R + RR) +/- GR = +/- SM \quad (4.7)$$

Where:

P	= precipitation
I	= irrigation
RR	= roof runoff
ET	= evapotranspiration
R	= turfgrass runoff
GR	= groundwater recharge
SM	= soil moisture of the soil-turf system

In order to monitor the amount of soil moisture in the soil-turf system, it is necessary to measure or monitor both the inputs and outputs from this system. For this study, the high cost of weather monitoring equipment played a major role in deciding the variables that could be measured and the ones that needed to be estimated. SI (Système International) are used throughout.

Since soil moisture determination was important in the analysis for this thesis, each component of the water balance equation is examined in more detail in the following section.

4.7.1.1 Precipitation

For this study, residents who used the water scheduling page were encouraged to measure precipitation on a day to day basis themselves. This method was encouraged since the large convective storms that southern Alberta experiences during the summer cause precipitation to be extremely variable over small areas. During the summer months it

can be frequently observed that one area of Lethbridge will get a large precipitation event, while another area will not have any precipitation at all.

A webpage was provided as a link on the water scheduling page to describe what type of equipment residents needed to monitor rainfall. This page suggested that any deep, straight edged, cylindrical container (eg. coffee tin) could be used to collect precipitation and a ruler could be used to measure the precipitation collected. Also included on this page were instructions on how to use this equipment to measure the amount of precipitation falling on their lawn and when measurements should be taken. In the event that residents either could not or did not want to measure precipitation on their own, a default button could be used that provided precipitation measured in the Lethbridge area by Environment Canada. The recording station used by Environment Canada is at the Lethbridge Airport that lies approximately four kilometres south of Lethbridge. By using this value, the possibility of introducing water inputs to soil-turf system that did not actually occur was increased.

4.7.1.2 Water Scheduling

The purpose of the water scheduling page is to predict when and how much irrigation should be applied to park and residential turfgrass. Once the model requested the application of irrigation to the soil-turf system, and if the user applied this irrigation, it is necessary for the user to enter the date that the irrigation was applied and the amount applied. If this information is not provided, the model will be unable to account for these

water inputs. The model will continue to request that irrigation be applied in increasing amounts as water in the soil-turf system becomes further depleted. Irrigation applied prior to an irrigation request by the water scheduling page results in a later irrigation date for subsequent irrigation requests.

To ensure that water scheduling page users could monitor how much water they applied to their lawn, a webpage was provided with instructions on the instruments and methods necessary to measure irrigation. The instruments necessary to measure irrigation are no different from those needed to measure precipitation, namely a straight-sided, cylindrical container and a ruler.

To measure the amount of water a sprinkler is applying to their lawn, users are instructed to set out their measuring containers while watering and measure the amount of water that falls into the container over a specific period of time (eg. 1 hour). An improved estimate could be obtained by using several buckets placed under the sprinkler at the same time and calculating the average amount of water received by all buckets. The faucet must not be touched during the period of measurement so that an accurate estimate of water flow can be calculated. Marking the faucet will allow the user to return to the same calculated flow rate any time he/she wants, and will allow for the application of appropriate amounts of irrigation.

An example of a water flow calculation would be if 6 mm of water fell into the container over a 1 hour period, then the water was applied at a rate of $6 \text{ mm/hour} = 0.1 \text{ mm/min}$.

This means that in 20 minutes of watering, the lawn would receive 2 mm of water.

Sprinklers used in agricultural applications usually only bring 75-85 % of the water to the crops because of spray evaporation (Miller, 1994). Residents using sprinklers to irrigate their lawns may expect similar efficiency.

4.7.1.3 Roof Runoff

Another source of water to the soil-turf system is roof runoff. As mentioned earlier, Berg (1997) found that approximately 38% of an average sized lot was occupied by houses, garages, or other structures. He also showed that 85% of roof runoff was discharged by homeowners onto the turf, while the remaining 15% was discharged onto impermeable surfaces.

Berg determined the water inputs due to roof runoff using the equation (Berg, 1997):

$$I = ((P \times A)/IA) \times Di \quad (4.8)$$

Where:
I = total input from roof runoff
P = precipitation recorded over the study region
subtracted by 1 mm, which accounts for storage
on residential roofs
A = total roof area
IA = total irrigated area of residential area
Di = runoff discharge index

The 1 mm subtracted from recorded precipitation represents water that falls on household roofs and is stored or evapotranspired before being discharged onto residential lawns and was calculated during a rainfall simulation experiment conducted in Lethbridge (Berg, 1997). The runoff discharge index corrects for the proportion of water

that will be discharged onto impermeable surfaces. In the Varsity Village example shown above, the discharge index is 0.85. By conducting a survey of drainage characteristics, this index can be estimated for any subdivision.

4.7.1.4 Evapotranspiration

The largest soil moisture loss in the Lethbridge area is through evapotranspiration (ET). This model estimates potential ET (PET) using a modified Jensen-Haise equation (Foroud et al., 1989). The modified Jensen-Haise equation includes a parameter for wind, which is an important consideration in southern Alberta where higher winds and Chinook winds occur. Potential ET was calculated using the equation (Foroud et al., 1989):

$$PET = 0.00824 (RS) (TA + 7.1) 0.00304 (W) \quad (4.9)$$

Where: PET = potential evapotranspiration in mm per day
RS = total daily solar radiation in megajoules per m² per day
TA = daily average temperature in degrees Celsius
W = total wind run in kilometers per day

The values 0.00824, 7.1, and 0.00304 are locally derived and calibrated constants for Lethbridge, that were calculated using Lethbridge weather data (Foroud et al., 1989).

Total daily solar radiation, daily average temperature, and total wind run were all obtained from Environment Canada. Along with precipitation, these variables were measured at the Lethbridge airport. In the absence of equipment to measure these three variables, the data for daily average temperature and wind run can be calculated. Daily average temperature can be determined from the maximum and minimum temperatures for the day, while wind run can be calculated using the average wind speed (km h⁻¹) and

multiplying by 24 hours. Equipment to measure total daily solar radiation is expensive but calculations of daily solar radiation can be made using more easily measured variables. A method to calculate the total daily solar radiation is provided in Appendix C.

By using the derived potential ET, an estimate of actual ET can be calculated. This is done by multiplying the potential evapotranspiration (mm day⁻¹) by a crop coefficient representing stages of the turfgrass growth cycle. The equation necessary to calculate the estimate of actual ET is shown in equation 4.17.

$$ET = K \times PET \quad (4.10)$$

The K-coefficient is derived using a third degree polynomial equation (Hobbs and Krogman, 1983) and is largely dependent on the Julian date. Julian date is used to generate the stage of plant development for agricultural grass. This equation was used to calculate the K-coefficient for turfgrass (Hobbs and Krogman, 1983):

$$K = -1.003 + (-2.547 E-03 \times J) + (1.722 E-04 \times J^2) + (-5.494 E-07 \times J^3) \quad (4.11)$$

4.7.1.5 Turfgrass Runoff

As discussed earlier, turfgrass has been shown to have an extraordinary ability of trapping surface water and causing infiltration. Since turfgrass has a high capacity for infiltration and thus creates so little runoff, all precipitation falling over a turfgrass covered area is assumed to infiltrate the soil-turf system for the model used in the water scheduling page.

4.7.1.6 Groundwater Recharge

Here the term groundwater recharge is used to refer to deep percolation of water to the regional groundwater table. This is in contrast to contributions to the perched water tables that are found in Lethbridge. Perched water tables found in the City of Lethbridge are considered to be part of the soil-turf system in this model.

As discussed earlier, the City of Lethbridge overlies till and glacial lake deposits. Glacial Lake silt and clays are known to have very low hydraulic conductivity, but the till has also been found to have very low hydraulic conductivities. Work by Hendry (1988) in three study areas near Taber, Alberta (approximately 50 km east of Lethbridge) revealed groundwater velocities for the oxidized and unoxidized tills. In his paper Hendry referred to the tills as the weathered (oxidized) and nonweathered (unoxidized) till. The bedrock of the area was of the Judith River Formation (Hendry, 1988). This formation consists of interbedded bentonitic sandstones, carbonaceous shales, mudstone, siltstone and coal layers. To the north of these study areas bedrock becomes younger and changes to the Bearpaw Formation, the bedrock that can be found underlying Lethbridge. The nonweathered (unoxidized) till in this study revealed groundwater velocities as slow as 2 to 6 metres per 1000 years (6 mm/year) and lateral velocities of 9 metres per 1000 years (9 mm/year). The vertical groundwater velocity of the weathered (oxidized) till was faster but still very low compared to the infiltration rates on turfgrass covered areas (Berg, 1997). Groundwater velocities of the weathered (oxidized) till examined by Hendry (1988) were reported to be around 0.1 metres per year.

Hydraulic conductivity of the oxidized and unoxidized tills in the Lethbridge were assumed to be similar to those examined by Hendry (1988). Due to the low hydraulic conductivities reported by Hendry (1988), water contributions to the regional water table were assumed to be small. Hence, the analyses herein did not include groundwater recharge as a variable.

4.7.1.7 Soil-Turf System

The soil-turf system defines the zone in which soil moisture storage occurs. Water stored in the soil-turf system is necessary to ensure the health and survival of the turfgrass. Excess water in this system contributes to the development of raised (perched) water tables in the City of Lethbridge.

The soil-turf system has the ability to accept water until the soil becomes saturated. Water applied to the soil, after saturation is reached, contributes to overland flow or runoff since all soil pore spaces are occupied by water. Irrigating a soil until it is saturated allows for the drainage of the soil by gravity, contributing directly to the water table. Field capacity defines the approximate depth of water that a soil can hold against gravity drainage. This water is held in pore spaces and when hygroscopic water is subtracted, the water remaining is what is available for plant use. Hygroscopic water is held very tightly by the soil particles making this water unavailable for use by plants.

The depth of water available to turfgrass is also dependent on rooting depth. Rooting depth is a good indicator of the storage capacity of the soil-turf system. A turfgrass with a deeper root system will have an increased ability to draw water from the soil, while a shallow root system will have a small capacity for water absorption. The rooting depths of the turfgrass will differ according to the species. Species such as centipedegrass, bahiagrass, and Bermudagrass have been found at depths from 1.5 to 2.1 metres (Beard, 1973). Kentucky bluegrass is a commonly used species of grass in the Lethbridge area and is seldom observed to have roots at depths greater than 0.6 metres (Beard, 1973). Water available for turfgrass use is a function of field capacity, wilting point and rooting depth.

This model attempts to maintain the soil moisture in the soil-turf system below field capacity and above a level that would compromise turfgrass health. Plant available moisture was calculated according to the soil texture using a chart from Hansen et al (1980). Part of this chart is recreated in Table 4.3.

Rooting depth was then used to determine the total depth of water (mm) available to the plant. Irrigation was applied to maintain the soil moisture between 56 and 90 % plant available soil moisture. The upper limit of 90 % soil moisture was chosen to allow for water storage during a precipitation event. A lower limit of 56 % plant available soil moisture was used since this amount of depletion imposes moderate to moderately severe stress on the turfgrass without causing serious damage (Carrow, 1995). This amount of

		Total Available Moisture			
Soil Texture	Apparent Specific Gravity As	Field Capacity (%) FC	Permanent Wilting (%) PW	Dry Weight (%) Pw = FC-PW	mm/m d = $\frac{Pw}{1000} \cdot AsD$
Sandy	1.65	9	4	5	80
Sandy loam	1.50	14	6	8	120
Loam	1.40	22	10	12	170
Clay loam	1.35	27	13	14	190
Silty clay	1.30	31	15	16	210
Clay	1.25	35	17	18	230

Table 4.3 Chart Used to Calculate Plant Available Moisture (after Hansen et al., 1980).

stress encourages a deeper rooting turfgrass, creating an increased capacity for water absorption and wilt tolerance.

4.8 Summary

The above discussion provides information about the techniques used in this study. Methods used in the collection of field data in Lakeview study area were outlined and the analysis of this data was discussed. Soil texture analysis and soil moisture analysis were done in the lab on all soil samples collected from Lakeview study area. Analysis of texture will provide data for use in the construction of soil texture profiles as well as comparisons between mean clay and sand fractions to mean water table depth using linear regression analysis. Mean clay and sand fractions can be determined for each

individual borehole and compared with the mean water table depth observed at that location. This comparison was used to examine whether variations in mean clay and sand fractions over Lakeview study area play a role in determining variations in mean water table depth.

The Mann-Whitney test is described, as well as a way that it can be used to compare the mean water table depths of irrigated and non-irrigated land cover classes in both Lakeview and Varsity Village study areas. Whether there is a significant difference between the mean water table depths of the two land cover classes in both study areas is important in identifying differences between them.

A turfgrass irrigation model was also discussed. The layout, equations, and necessary data to be used in the model are identified and described. This model is an attempt at providing city residents a tool for the appropriate application of water to the turfgrass used in their gardens. It is hoped that through the use of this model water will only be applied to turfgrass at a rate that the plant requires, reducing the amount contributed to the water table.

Chapter 5

Results and Discussion

5.1 Introduction

Discussion in this chapter reveals the findings of this study. Current groundwater conditions in Lakeview subdivision are addressed in this chapter. Results and analysis of soil texture are reported and are compared with water table depth. Lakeview and Varsity Village subdivisions are also compared in this chapter. The implementation of a turfgrass irrigation model webpage is also discussed.

5.2 Soil Analysis

5.2.1 Texture Analysis

Soil textures of all samples collected from Lakeview study area are shown in figure 5.1. This figure reveals that soil textures within the study area are rather similar, the major soil texture class being clay loam, representing about 59 % of all the samples collected. Following clay loam the next most frequently occurring soil texture class is clay.

representing 30 % of the collected samples. The remaining 11 % of the samples consist of soil textures from the following classes: silty clay, silty clay loam, sandy clay, sandy clay loam, loam, sandy loam, and loamy sand.

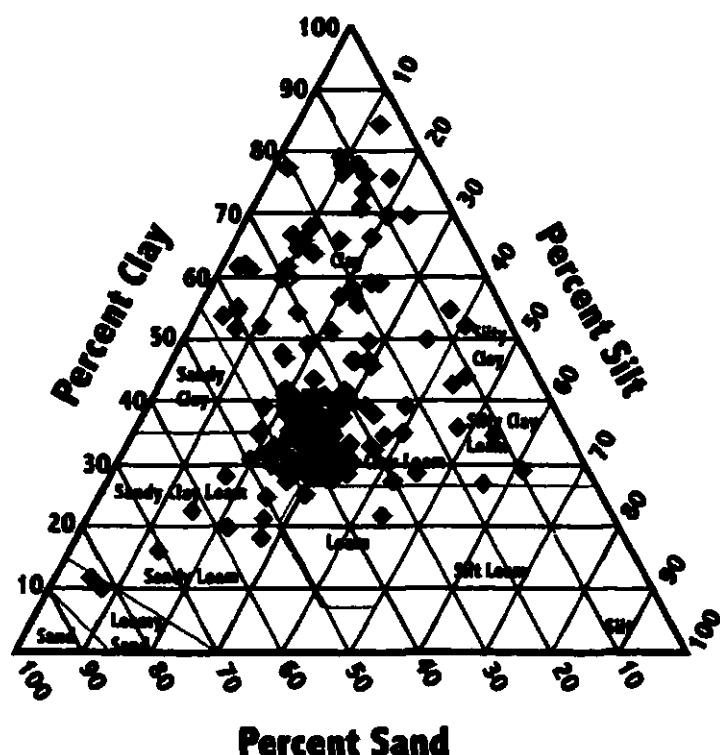


Figure 5.1 Soil texture of samples collected from Lakeview study area.

Comparison with soil texture data from Varsity Village by Berg (1997) reveals that the clay loam and clay soil texture classes were predominant in that area as well. These two soil texture classes made up 76 % of the 55 samples analyzed by Berg, each class making up 38 % of all the samples analyzed. The remaining soil texture classes analyzed by Berg in Varsity Village represented a larger portion of the soil samples compared to

those collected in Lakeview. Loam, sandy clay loam, silty clay, and silty clay loam soil texture classes made up 24 % of the soil samples analyzed in Varsity Village. There was also a very slight difference in the variety of soil textures represented in the soil sampling of Varsity Village compared to that of Lakeview subdivision. Soil sampling in Lakeview subdivision revealed samples from nine different soil textures, while sampling from Varsity Village represented only six. The percentage of each soil texture class found in both subdivisions is shown in table 5.1.

Soil Type	Soil Samples in Each Soil Texture Class (%)	
	Varsity Village	Lakeview
Clay	38	30
Clay Loam	38	59
Loam	3	1
Loamy Sand	0	1
Sand	0	0
Sandy Clay	0	1
Sandy Clay Loam	13	4
Sandy Loam	0	1
Silt	0	0
Silty Clay	2	1
Silty Clay Loam	1	2
Silt Loam	0	0

Table 5.1 Summary of Sampled Soil Textures in Varsity Village and Lakeview Subdivisions.

Major differences between the two subdivisions are the decrease in proportion of soil samples represented by the clay loam and clay soil textures between Lakeview and Varsity Village, 89 % to 76 % respectively, and the decrease in the variety of samples represented. Both of these differences could be the result of collecting samples from both glacial and glacio-lacustrine deposits in Lakeview, while sampling in Varsity Village did not include any lacustrine sediments (Berg, 1997).

The larger variety of soil texture classes represented in Lakeview may best be explained by the differences in sampling size between Varsity Village and Lakeview. The three soil texture classes reported in Lakeview but not in Varsity Village represent only three percent of the total sample, a proportion that would only be 1.6 samples from the sample size collected in Varsity Village, a size that could have easily been missed during sampling. Subsequent sampling in either study area would likely not reveal the same proportions of the smaller classes of samples, but it is expected that a further sampling from either subdivision would reveal similar high proportions of clay and clay loam samples as shown in the above table.

Regardless of the above discussion, the differences between soil texture of the two subdivisions is relatively small. Both Varsity Village and Lakeview have soil textures that are predominantly clay loam or clay, and the occurrence of sand lenses and coarser soil texture classes are found dispersed throughout both subdivisions. These sand lenses can be quite large and can act as storage compartments for water.

5.2.2 Soil Moisture Content

Results for the soil moisture analysis are presented in figures 5.2 through 5.4. The graphs show the soil moisture (%) with depth for each borehole. The highest water contents are generally observed above two to three metres depth and the water content decreases at greater depths. As Berg (1997) found in Varsity Village, this type of relationship is observed in soils in irrigated areas. In Lakeview the holes that best display the trend are: 98-1, 98-2, 98-3, 98-4, 97-11, 97-12, 97-13, 97-14, 97-15, and 97-20. For the locations of these boreholes see figure 4.2. The majority of these boreholes are found in areas that were classed as golf course, parks, or residential land cover areas.

Data from boreholes found in non-irrigated areas do not show a well defined pattern as can be seen in the graphs of soil moisture content versus depth. In some cases, the non-irrigated areas display high water contents in the top two or three metres of the sampling depth and then the soil moisture decreases as depth increases. In other locations, there were no soil samples found that displayed soil moisture contents that were remarkably higher than others, and in still other locations the graphs revealed several samples that had higher soil moisture content. The samples where higher soil moisture content was displayed did not necessarily occur in the upper two or three metres of the hole.

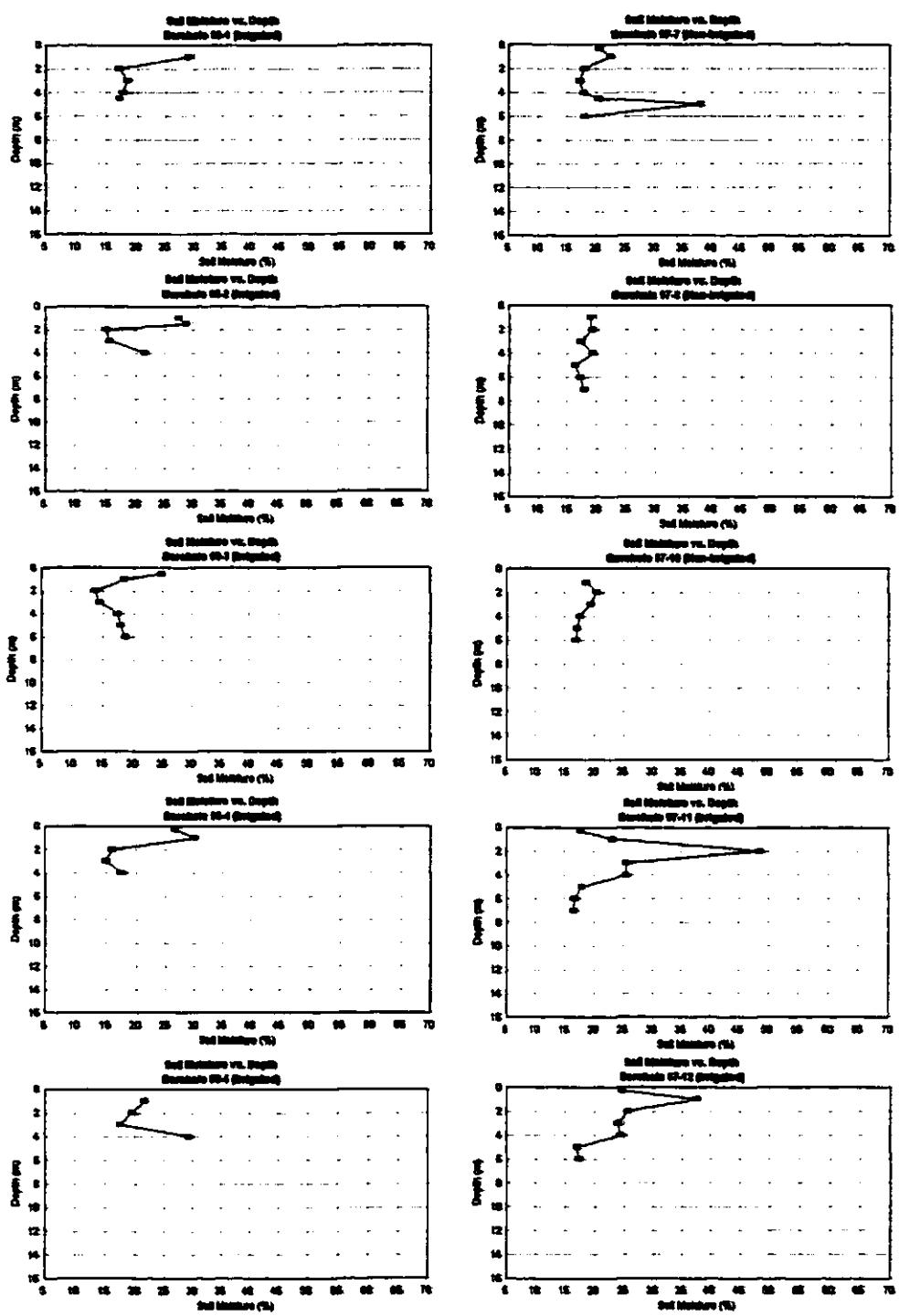


Figure 5.2 Mass water content vs depth for samples from boreholes 98-1 through 97-12.

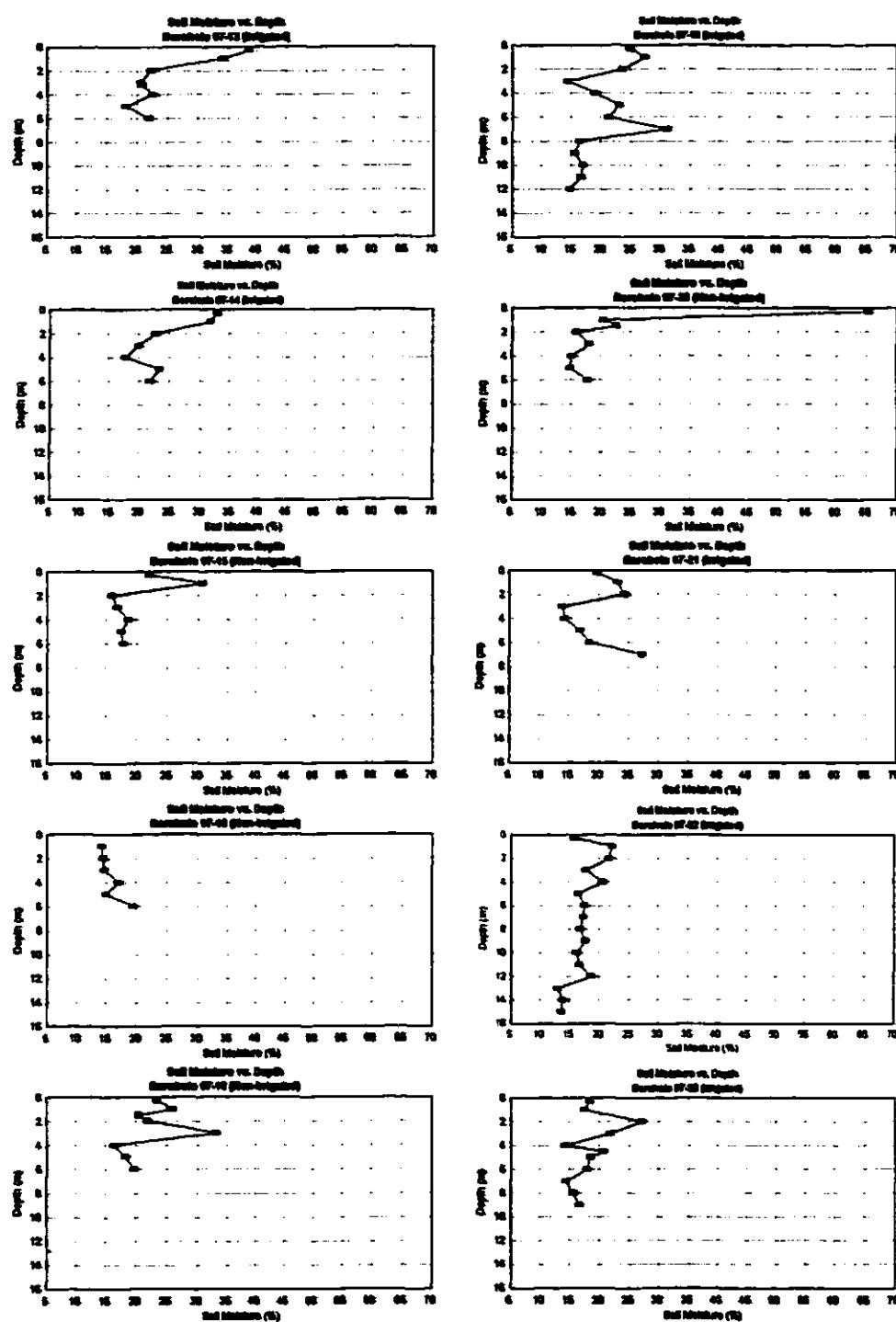


Figure 5.3 Mass water content vs depth for samples from boreholes 97-13 through 97-23.

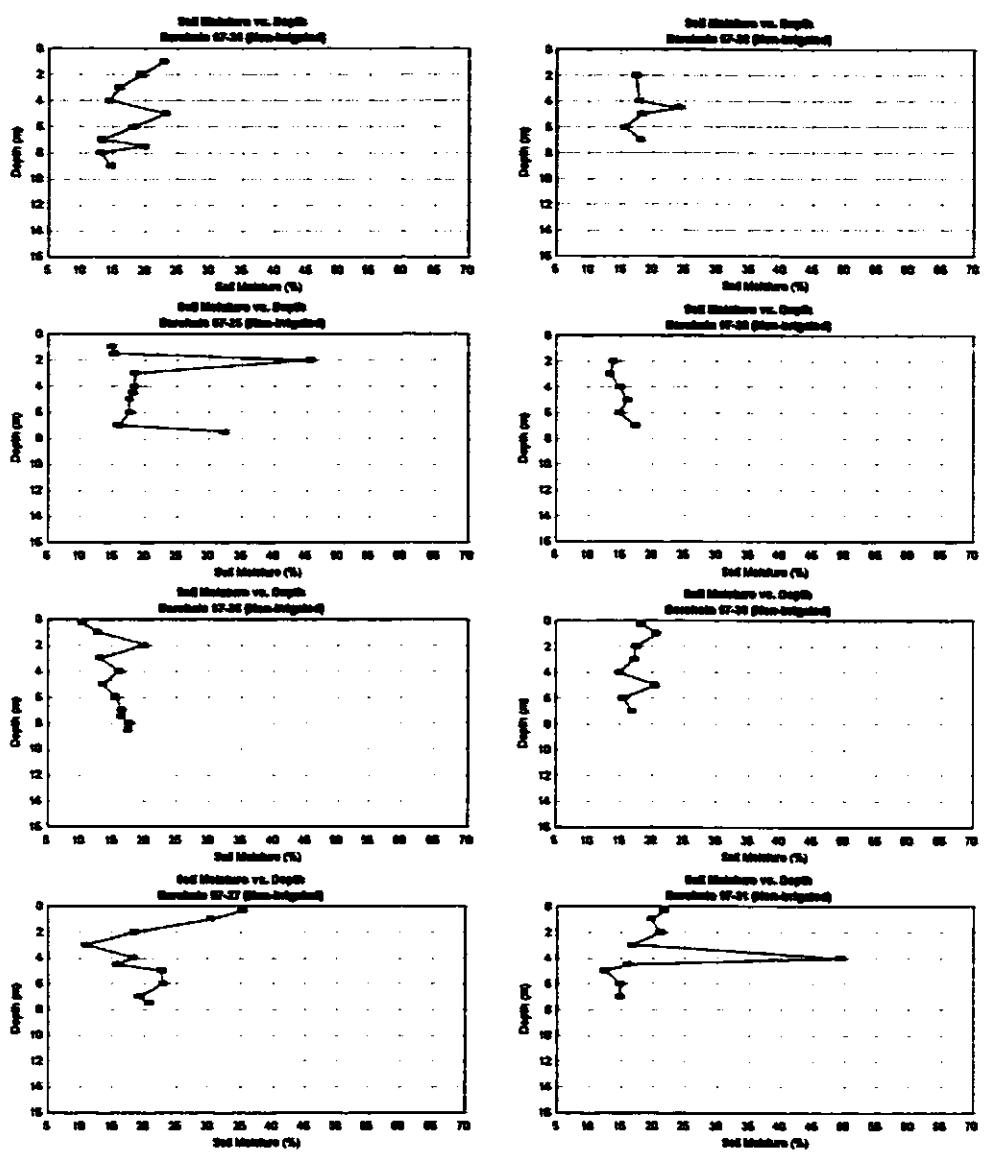


Figure 5.4 Mass water content vs depth for samples from boreholes 97-24 through 97-31.

5.2.3 Stratigraphic Analysis

Figure 5.5 shows the arrangement of soil textures with depth for each borehole in Lakeview subdivision. Boreholes in Figure 5.5 were arranged according to their distance from a selected point outside of Lakeview subdivision, boreholes on the left being the closest to this point and those on the right being the furthest. The location of this point and the lines used to determine whether one hole was closer than another is shown in figure 4.3. Figure 5.5 and others were used as a precursor to fence diagrams in an attempt to identify structures of coarse textured material or boundaries marking a transition from coarse to fine or fine to coarse. Such boundaries help in the identification of locations where perched water tables could develop or locations where higher hydraulic conductivities occur. Such locations probably play a role in the transport of water and the elevation of water tables.

Figure 5.5 shows little correlation between borehole soil textures. Soil texture samples coarser than clay or clay loam are scattered anywhere from 30 cm to 16 m. A distinct boundary between one soil texture class and another is not apparent although 20 boreholes reveal a tendency of clay samples overlying clay loam. A concentration of clay samples occurs above a depth of four metres. Below four metres, clay loam becomes the dominant soil texture class. This trend seems to indicate that the soil is becoming slightly coarser below four metres. Soil below this depth would only be slightly coarser since both clay and clay loam are relatively fine soil texture classes. Another interesting observation is that only two samples contained sand within 2 m of the surface while 6 others had sand at greater depths. Appendix D shows other

arrangements of borehole soil texture with depth using various boreholes as the center of the concentric circles.

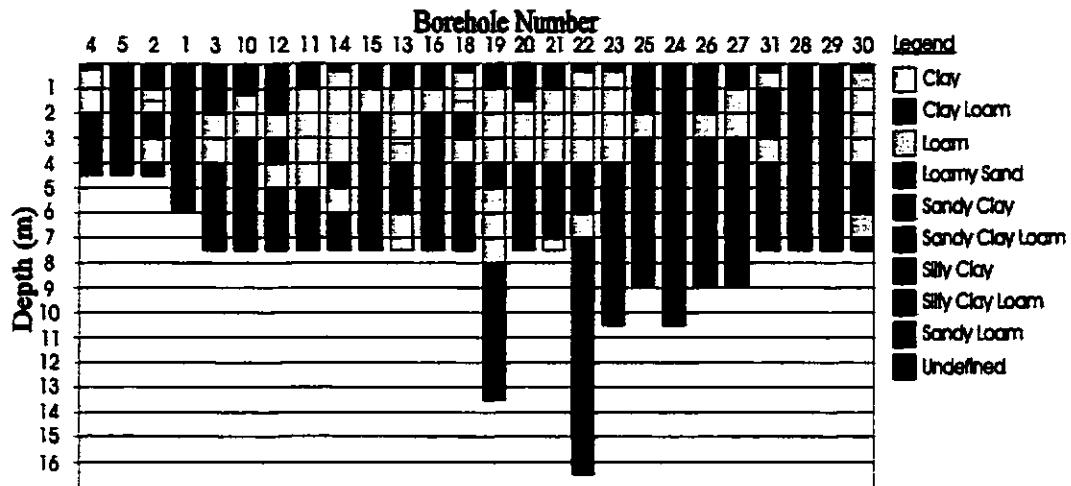


Figure 5.5 Soil texture samples arranged according to distance from a selected point.

Figure 5.5 was rearranged according to the elevation of soil samples above sea level. It was thought that this arrangement may allow for better identification of continuous units not apparent in Figure 5.5. A figure showing the elevation of soil samples above sea level has an advantage over one that shows only the depth from which samples were obtained because the latter includes the effects of surface relief. The elevation of soil samples above sea level is shown in figure 5.6. Elevations of the boreholes were determined by surveying from known benchmarks.

Figure 5.6 shows even less correlation of soil textural properties versus depth between boreholes than figure 5.5. These results seem to indicate that soil texture does not play a major role in determining any consistent trends in water table elevation for Lakeview. Only if the water table is similarly incoherent can correlation be suggested. No

significant zones of higher hydraulic conductivities were identified. Since little systematic continuity between textures in boreholes could be identified using the above methods, it was decided that the use of fence diagrams would provide little more information.

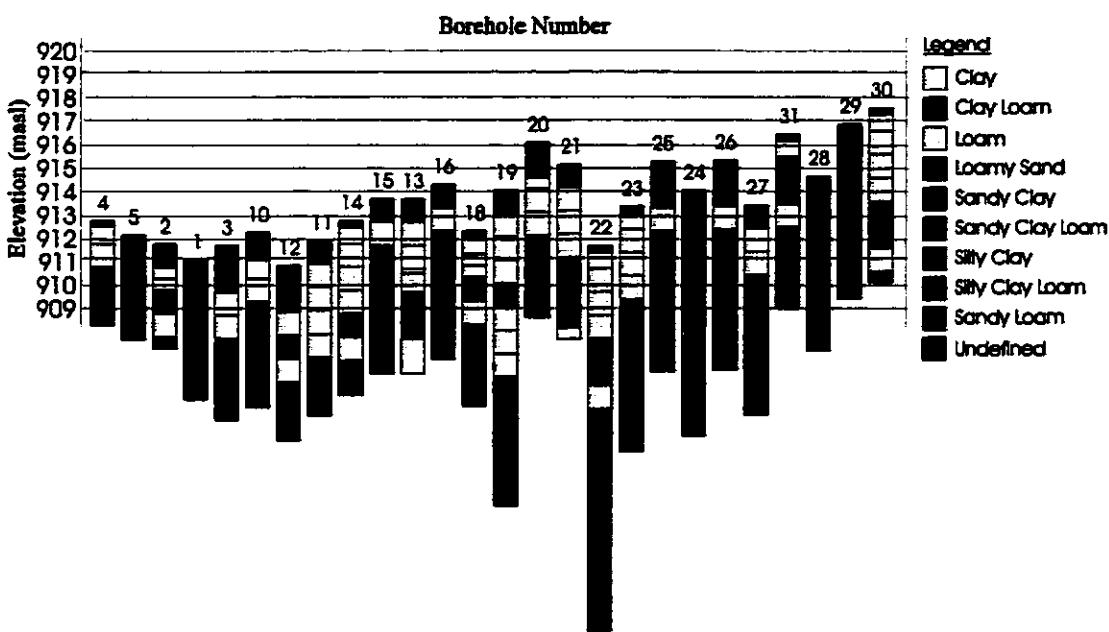


Figure 5.6 Soil texture samples arranged according to elevation above sea level.

5.3 Modelling and Comparison of Water Table Surfaces

The Surfer software was used to create surfaces of water table elevation and depth to water table for the Lakeview and Varsity Village study areas on May 8, June 11, July 6, August 13, and September 28, 1998. These dates provide a cross section of the irrigation season. Figure 5.7 shows the water table elevations for Lakeview, while Figure 5.8 shows the depth to water table. Water table elevations and depth to water table for Varsity Village are shown in Figures 5.9 and 5.10 respectively.

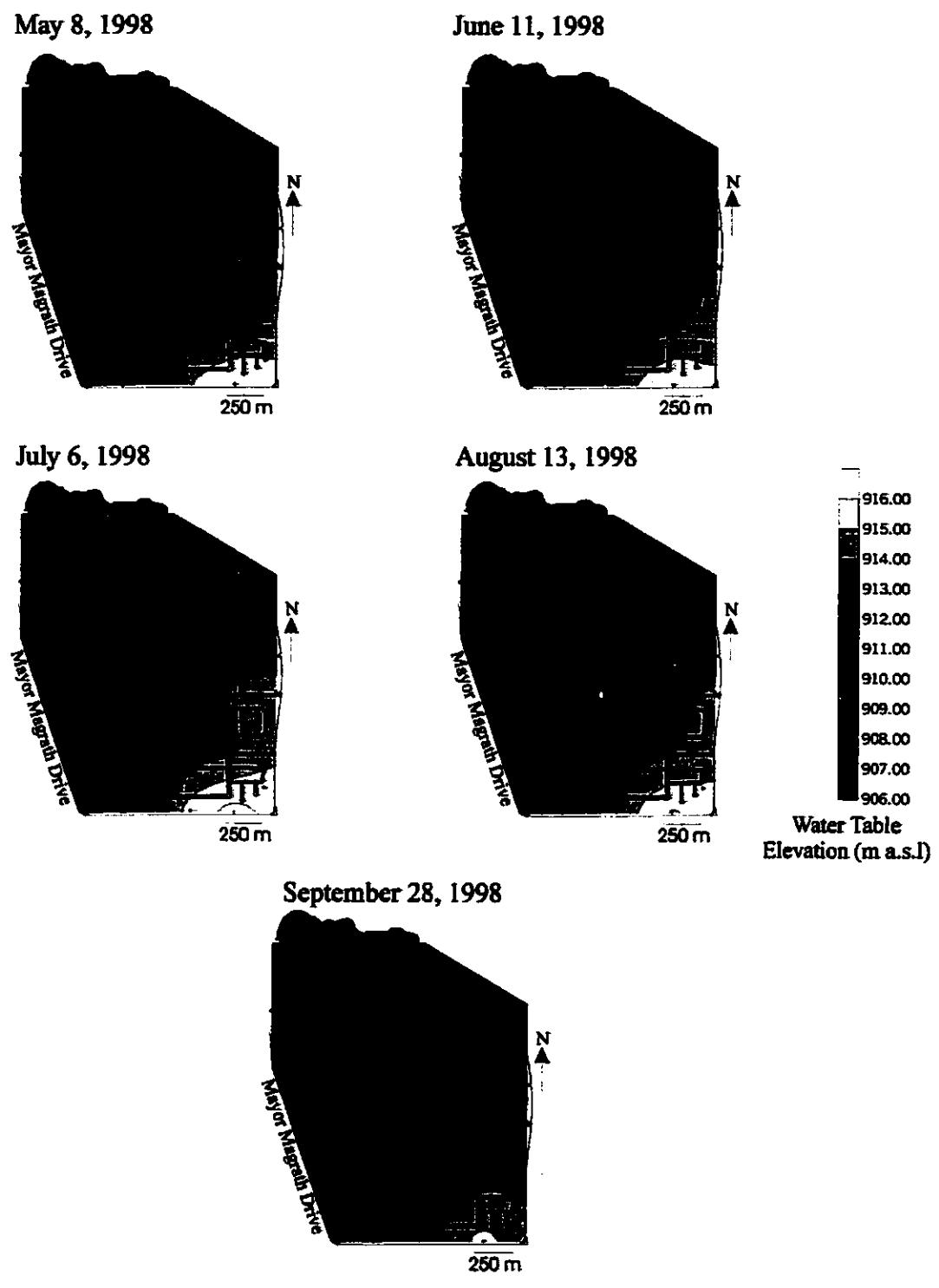


Figure 5.7 Water table elevation surfaces for Lakeview study area.

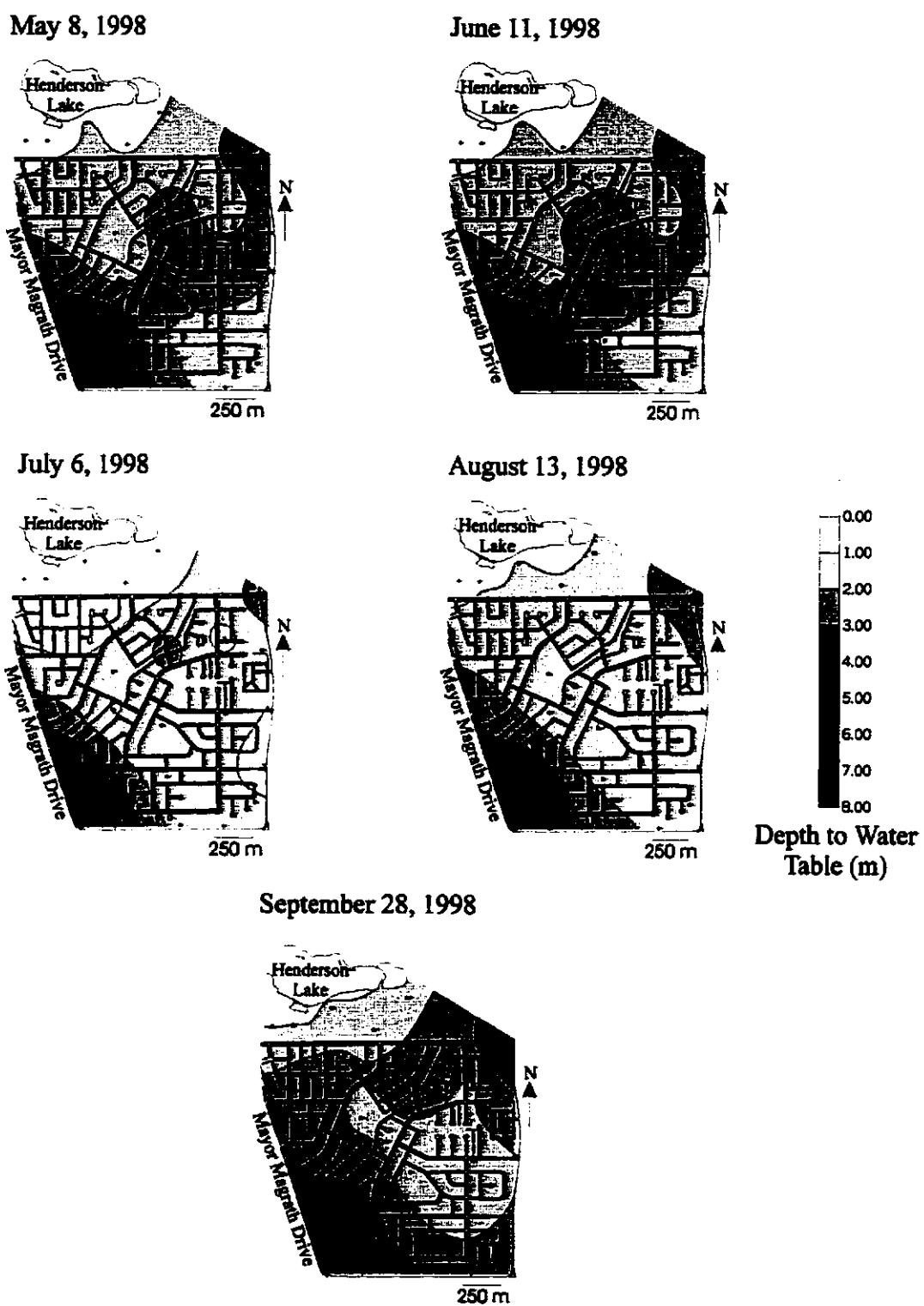


Figure 5.8 Water table depth surfaces for Lakeview study area.

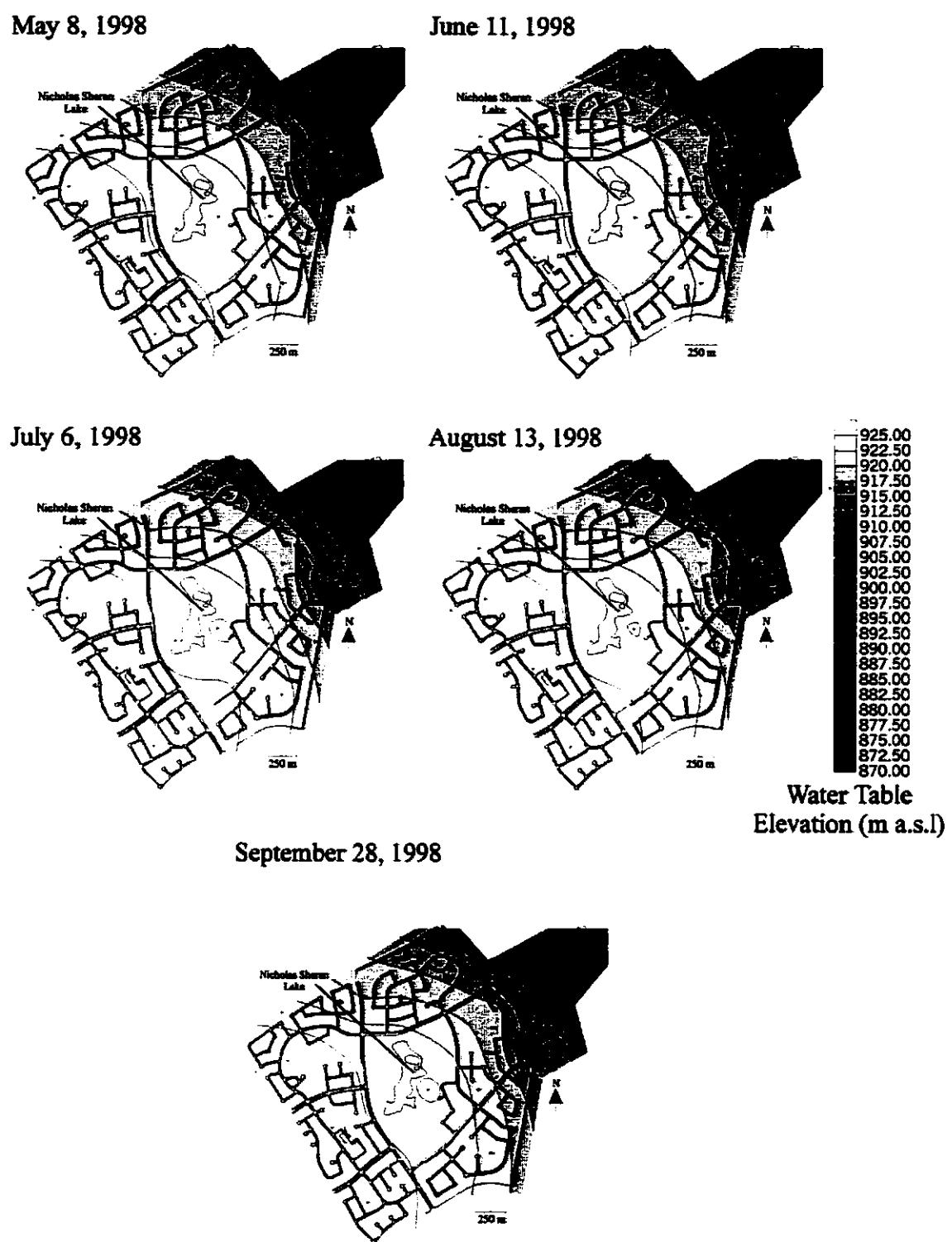


Figure 5.9 Water table elevation surfaces for Varsity Village study area.

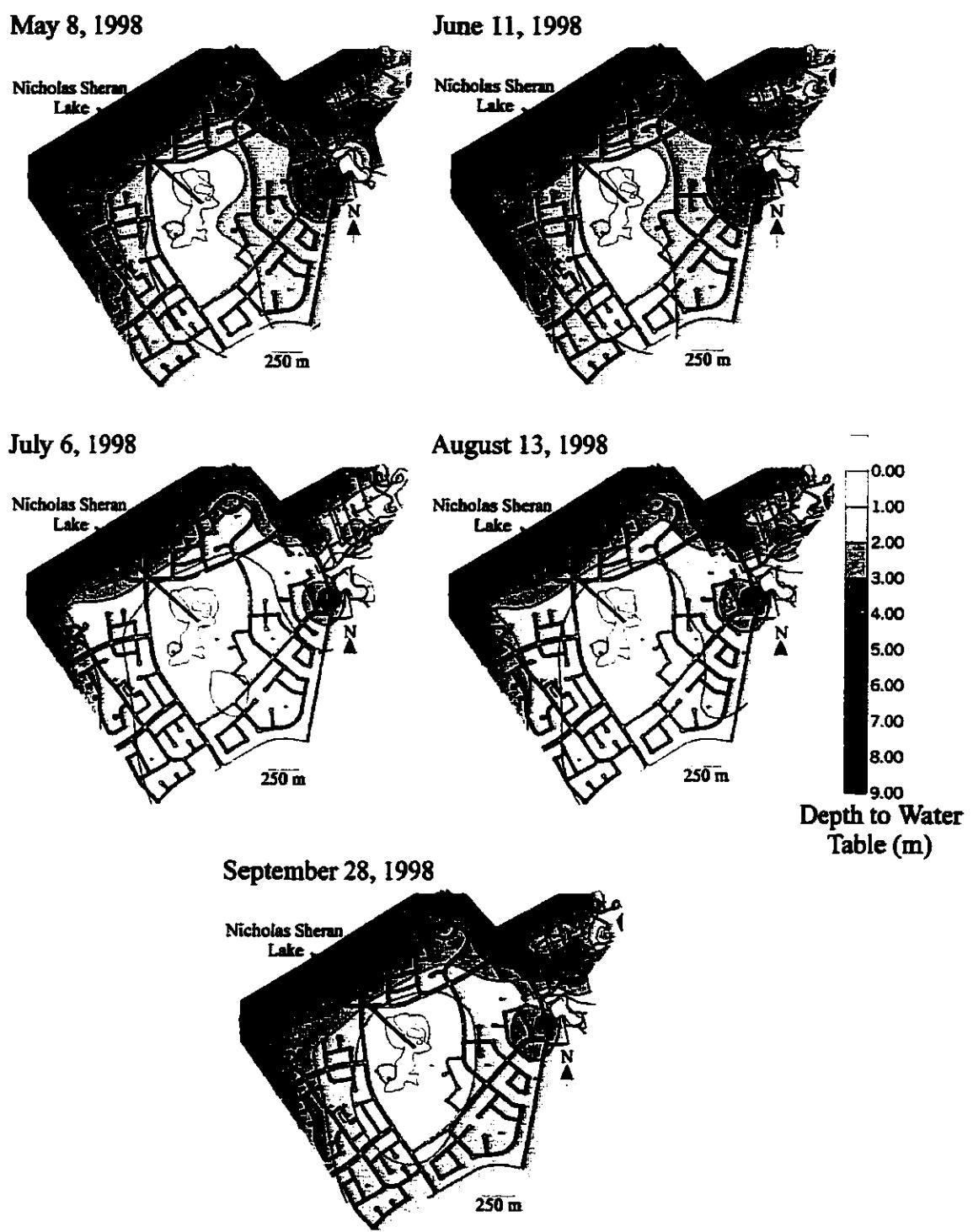


Figure 5.10 Water table depth surfaces for Varsity Village study area.

In Varsity Village subdivision, water table depths are generally shallowest around the water bodies in the study area. Depth to water table increases in areas where urban development has not yet occurred. This phenomenon is best shown by the increasing depth to water table as one moves towards the northwestern edge of the subdivision. Water table elevation within Varsity Village decreases as one approaches the coulee edge. A decrease in water table elevation in this direction reveals that groundwater in this subdivision flows towards the river valley. The movement of groundwater towards the coulee edge is probably a function of relief and is illustrated by the DEM of Varsity Village (figure 4.6). Two possible flow directions of water across Varsity Village on July 6, 1998 are shown in Figure 5.11. The lines of flow in Figure 5.11 illustrate the general direction of flow in Varsity Village and were drawn onto the figure normal to the water table contours.

July 6, 1998

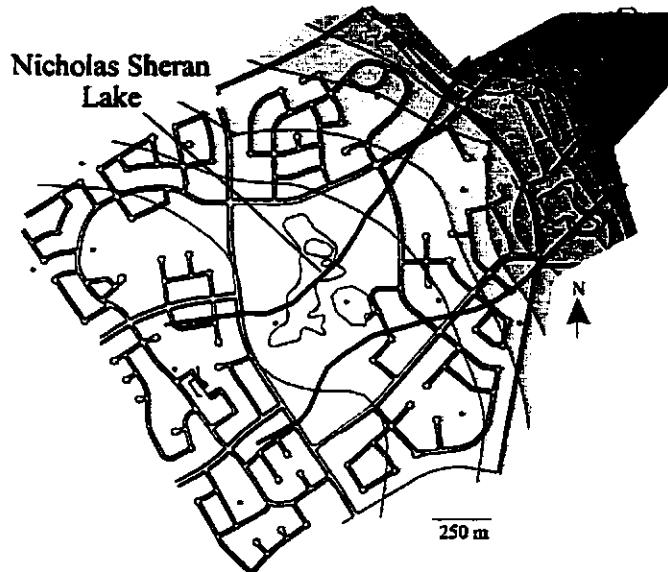


Figure 5.11 Two possible directions of water flow through Varsity Village study area on July 6, 1998.

Shallow water table depths (< 1 m) are shown to be most widespread on the diagrams of July 6 and August 13, 1998. Surfaces of water table depth for May 8 and June 11, 1998 are similar and show that a smaller area of Lakeview experiences water table depths of a metre or less compared to that on July 6 and August 13, 1998. The surface derived from data for September 28, 1998 reveals that the area where water table depths of less than a metre occur has once again decreased and is at the lowest of any of the five different dates.

Prior to this study, it was believed that Henderson Lake was a major contributor of water to Lakeview study area. While water contributions to Lakeview may occur from Henderson Lake, the southeast corner of Lakeview has been identified as another possible source of water. Figure 5.7 shows that high water table elevations occur in the southeast corner. The physiographic high for this study area also occurs in the southeast corner (see figure 4.7 for a DEM of Lakeview), but figure 5.8 shows that the depth to water table in this corner is very shallow, similar to shallow water tables that occur in the heavily irrigated Golf Course to the south of Henderson Lake.

As discussed earlier, water flows from areas of high elevation to areas of lower elevation in an attempt to minimize the mechanical energy it possesses. Therefore, water originating in this corner of Lakeview subdivision will flow from the southeast corner in a northwesterly direction before turning towards the southwest. A gradient also occurs from near Henderson Lake with flow of water originating from this source and moving in a southwesterly direction. Figure 5.12 shows several possible water flow directions on

July 6, 1998. Once again, these lines are meant to show the general movement of water in Lakeview and were drawn onto the figure normal to water table contours. There may be other directions of flow that also occur in Lakeview study area.

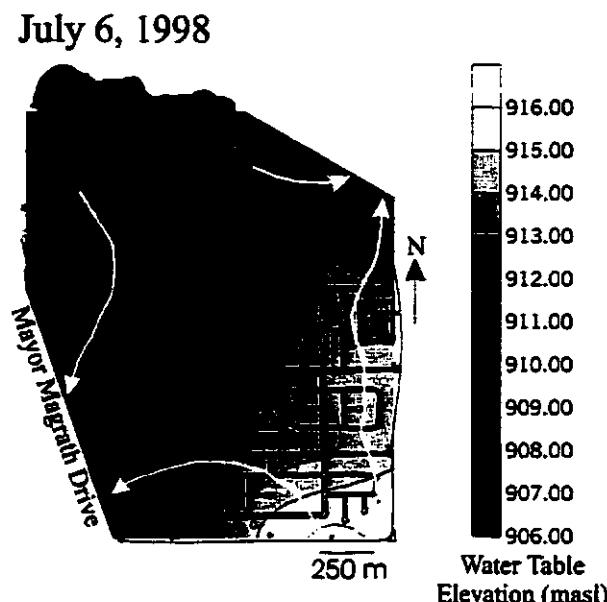


Figure 5.12 Several possible flow directions in Lakeview study area on July 6, 1998.

Surfaces of water table depth for Lakeview show that depths of less than a metre are most widespread on July 6, 1998. Water table depths for May 8 and June 11, 1998 are very similar. On August 13, 1998, the area where water tables less than one metre deep occur is not as large as that on July 6, however the area where water tables less than two metres deep are very widespread, much more so than on May 8 or June 11. Like Varsity Village, water table depths in Lakeview on September 28 are deeper than those on July 6 or August 13.

Water table elevations are consistently highest in the southeast corner of Lakeview for all dates examined. The highest water table elevation that occurs in this corner is 916 metres on July 6 and August 13, 1998. May 8, June 11, and September 28 all show elevations of 915 metres in this corner, with this elevation covering the smallest area on September 28, 1998.

Both study areas show that the shallowest water tables occur mainly around the water bodies. Water tables occurring less than 1 metre below the surface were most widespread on July 6, 1998 for both Varsity Village and Lakeview. Likewise, water tables occurring within one metre of the surface in both subdivisions, covered the smallest area on September 28, 1998.

The high water tables that occurred on July 6 are likely due to a combination of the increasing irrigation application as the summer progresses along with the high amounts of precipitation that historically fall in June (Canadian Climate Normals, 1961-1990). In June 1998, 148 mm of precipitation was recorded at the Lethbridge Research Centre, 44% of all precipitation that fell between the months of May and September. The high irrigation rates continue through the summer, maintaining the high water table levels through the summer.

By the end of September water table elevations appear to be decreasing. This is likely due to decreases in both precipitation and irrigation while evapotranspiration remains

high. Lethbridge only received approximately 10 mm of rain during September, 1998 while the average temperature remained at about 16 °C.

5.4 Statistical Analyses

5.4.1 Water Table Depth vs. Sand and Clay Fractions

All linear regressions comparing the mean clay and sand fractions to mean water table depth revealed that there was no statistical correlation between the variations in mean clay or sand fractions and variations in mean water table depth. Comparison of the mean clay fraction for the entire borehole to mean water table depth revealed that $r^2 = 0.046$ ($\alpha = 0.05$, $n = 24$). The linear regression analysis between mean clay fraction of samples in the upper 2 and 4 m of each borehole to the mean water table depth of these boreholes revealed that $r^2 = 0.039$ ($\alpha = 0.05$, $n = 24$) and $r^2 = 0.004$ ($\alpha = 0.05$, $n = 24$) respectively.

Similar linear regression analysis comparing the mean sand fractions of all samples collected from the well installation sites to mean water table depth showed that $r^2 = 0.034$ ($\alpha = 0.05$, $n = 24$). When the mean sand fractions of samples in the upper 2 and 4 m of each borehole were compared to the mean water table depth, the linear regression analysis revealed that $r^2 = 0.026$ ($\alpha = 0.05$, $n = 24$) and $r^2 = 0.001$ ($\alpha = 0.05$, $n = 24$) respectively. These results demonstrate that variations in mean soil particle size has no statistical correlation to observed variations in mean water table depth in Lakeview study area. This suggests that while the widespread clay rich sediments of the Lethbridge area

play a direct role in the creation of perched water tables, variations in mean soil texture does not systematically explain variations in water table depth.

5.4.2 Water Table Depth vs. Irrigated and Non-irrigated Land Cover Classes

Installation of wells in areas where irrigation would or would not be expected was investigated as the next most likely determining factor of water table depth. Berg (1997) observed that wells installed in areas not currently under irrigation in Varsity Village had a water table that was significantly deeper than those observed at wells installed in areas currently under irrigation and in some cases, no recordable water table at all since the wells were dry. A Mann-Whitney test was used to compare whether there was a significant difference between the mean water table depths of wells installed in irrigated and non-irrigated areas in Varsity Village. The Mann-Whitney test for Varsity Village revealed that there was a significant difference (significance = 0.00) between the mean water table depths of the irrigated and non-irrigated classes (irrigated areas n = 30, mean = 257cm; non-irrigated areas n = 8, mean = 557cm).

A similar test was performed on wells installed in Lakeview study area. Wells were classed into irrigated and non-irrigated land cover classes and the mean water table depths for these two classes were compared using the Mann-Whitney test. This test revealed that there was no significant difference (significance = 0.06) between the mean water table depths for the irrigated and non-irrigated classes (irrigated areas n=13, mean=152cm ; non-irrigated n=11, mean =237cm). While the difference between the

mean water table depths of the irrigated and non-irrigated classes appears to be fairly large, the fact that they were found to be not significantly different shows that the difference is not large enough to eliminate the possibility that the difference is not simply due to sample variability. It is saying that the possibility remains that during a different sampling of water tables in irrigated and non-irrigated areas in Lakeview study area, the difference in the means may be smaller than was found in this particular sample.

This result was surprising given the results of the Mann-Whitney test performed on data from Varsity Village and other results from Berg (1997). There are two possible explanations for the discrepancy of results between the two subdivisions. The first is the differing ages of the two subdivisions. Development of Lakeview began in approximately 1957, while development in Varsity Village Subdivision did not begin until about 1974. While hydraulic conductivities underlying the City of Lethbridge are very low, Lakeview has been irrigated by residents of Lakeview for nearly 20 years longer than Varsity Village. Since Lakeview has been irrigated for an additional 20 years, this has allowed water to diffuse to non-irrigated areas, possibly reducing the difference in mean water table depth for the irrigated and non-irrigated land cover classes. Hydraulic conductivities as low as 2 to 6 m every 1000 years and 0.1 m per year have been reported for unoxidized and oxidized tills respectively. With hydraulic conductivities this low, it would take several years before irrigation water applied on a residential yard would reach a well installation only 5 m from that yard. Fracturing of the till greatly increases the hydraulic conductivity, in some cases as much as 1000 times (Hendry, 1988), meaning water does have the capacity to move much faster through tills

when these fractures are present. There has been no long term analysis or data collection from other parts of the city to aid in the determination of how quickly water may be able to move from one area to another.

A second possible explanation for the lack of a significant difference between mean water table depths for the two classes is that masking of the difference has occurred due to inputs of water from some source to the east of Lakeview subdivision. As shown in the previous section, high water table elevations occur in the southeast corner of Lakeview. This corner of the subdivision lies in close proximity to an irrigation canal of the St. Mary's irrigation district. Water leaking from this irrigation canal may represent sufficient water inputs to enhance water table elevations above those that would occur if Lakeview subdivision only received inputs from precipitation, irrigation, and roof runoff. These inputs may enhance water table levels of non-irrigated areas above what they would be if only subjected to inputs from precipitation, regular irrigation and roof runoff. If water tables in non-irrigated areas have been enhanced due to inflows from this irrigation canal, it would be difficult to differentiate this from water tables enhanced through over-irrigation.

More evidence must be collected to determine whether the age of the subdivision or inputs from the irrigation canal are contributing to the lack of significant differences between water table depths of irrigated and non-irrigated land cover classes in Lakeview subdivision. Boreholes must be installed to the east and south of Lakeview to determine if the rising trend of water table elevations continue in those directions. Instrumentation

to monitor water elevation of nearby irrigation canals will also be necessary to determine if periods of high water flow through this canal corresponds with higher water table conditions in nearby well installations. Until this work has been completed it is difficult to suggest whether one of the above factors or possibly another factor is contributing to the above results.

5.5 Water Scheduling Model

The water scheduling webpage has been designed with the idea that a large number and variety of users would be interested in using it to monitor how much water they are applying to their lawns and when they should apply more. In order to allow multiple users to access and store information on the page, a database is needed to store the information of each individual user. A programmer assisted in the development and implementation of the water scheduling page (Figure 5.13), since the expertise needed to create such a database as well as allow the information to be accessed by a large number of users over the internet is not the main focus of this thesis research. Much interaction between the programmer and the author was necessary to ensure that the information provided by the users as well as weather data added to the model were used correctly.

To provide security for user information, each user is required to provide a username and the location of their home in Lethbridge. This username could have been anything the user wants and does not have to be his/her actual name. The location of a persons home is necessary to help differentiate between users who are using the same username in

other parts of the city, as well as to allow an appropriate soil texture class to be used in soil moisture calculations for that location. It is also recommended to users that a password be used when setting up their account to make it more difficult for others to access. Whether a password is used is left up to the user. A username and location

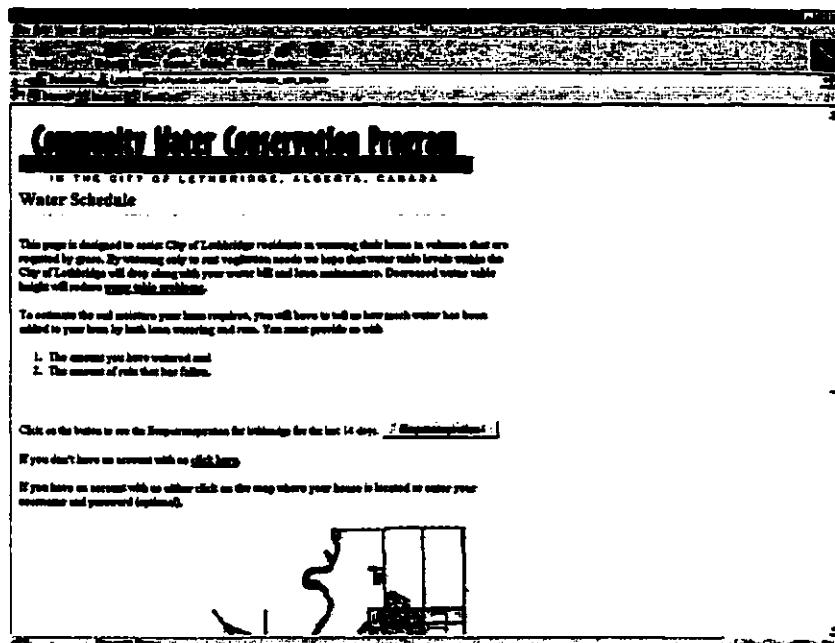


Figure 5.13 Water Scheduling Page.

are required before a user can use the water scheduling page. Once these are provided, users can access the page any time they want by clicking on the location of their home and entering their username.

Once a user enters their account, they would find themselves on the data entry page (Figure 5.14). This page includes a brief description of the data users are required to provide (irrigation and rainfall), a description of how the user can monitor these data, information on how much soil moisture there currently is, when and how much the user needs to irrigate his/her lawn, boxes where data can be entered, and a box where the user

can change their username, password, and enter their email address. The data entry page is where the model obtains data from the user. These data are necessary to monitor how closely the user is following the models suggested irrigations and account for inputs of water that either the users themselves are applying or that is being received by the soil through precipitation.

Community Water Conservation Program
IN THE CITY OF LETHBRIDGE, ALBERTA, CANADA

Water Schedule - Data Entry

Thursday November 25, 1999

Watering status:

Please enter all recent lawn watering and rainfall volumes that your lawn has received. This means that you must measure the amount of water that you have applied to your lawn. You can also measure your own precipitation, but a default generalized rain value is available for the City of Lethbridge. Measuring your own rainfall will ensure greater accuracy in determining the amount of water to apply to your lawn, as rainfall levels can vary between different areas of the city. For an explanation of how to measure the amount of irrigation or rainfall that your lawn has received click here.

The current soil moisture for your lawn is 300 mm.

You do not need to water your lawn at this time.

To change your username and password enter below:	If you don't know how much rain your lawn has received you can use a rainfall value measured as an average for the City of Lethbridge. To use the rain average result as the rain your lawn has received, click on the button below.
User:	<input type="text"/>
Password:	<input type="password"/>
Date:	<input type="text"/>
Amount of Rain:	<input type="text"/>
Amount of Irrigation:	<input type="text"/>

Figure 5.14 Water Scheduling Data Entry Page.

When the users enter water inputs, they specify whether these inputs come from watering their lawn or from rain. The model allows the user to see five of the last water inputs that occurred on their lawn by displaying these inputs at the bottom of the page. These values are displayed to minimize the chances of irrigation inputs being entered twice. Water inputs from rain can only be entered once a day and if more than one input of rain occurs on any given day an error message will appear.

Climate data was entered using a password protected administration page (Figure 5.15). Wind run (total wind measured in km/day), solar radiation, and average temperature are entered on a daily basis. The administration page also allows for changes to peoples accounts, the application of particular soil texture classes in different areas of Lethbridge, as well as changes to the field capacity, and the upper and lower percentage of field capacity that soil moisture will be maintained by the irrigation model.

Date	Total Irrigation Demand	Average Temperature	Wind Run	Average Rain
November November 25, 1999	0.00	10.00	0.00	0.00
December December 12, 2000	0.00	10.00	0.00	0.00
December December 13, 2000	0.00	10.00	0.00	0.00
December December 14, 2000	0.00	10.00	0.00	0.00
December December 15, 2000	0.00	10.00	0.00	0.00
December December 16, 2000	0.00	10.00	0.00	0.00
December December 17, 2000	0.00	10.00	0.00	0.00
December December 18, 2000	0.00	10.00	0.00	0.00
December December 19, 2000	0.00	10.00	0.00	0.00
December December 20, 2000	0.00	10.00	0.00	0.00
December December 21, 2000	0.00	10.00	0.00	0.00
December December 22, 2000	0.00	10.00	0.00	0.00
December December 23, 2000	0.00	10.00	0.00	0.00
December December 24, 2000	0.00	10.00	0.00	0.00
December December 25, 2000	0.00	10.00	0.00	0.00
December December 26, 2000	0.00	10.00	0.00	0.00
December December 27, 2000	0.00	10.00	0.00	0.00
December December 28, 2000	0.00	10.00	0.00	0.00
December December 29, 2000	0.00	10.00	0.00	0.00
December December 30, 2000	0.00	10.00	0.00	0.00
December December 31, 2000	0.00	10.00	0.00	0.00

Figure 5.15 Administration Page

The water scheduling page along with the other information provided on the “Community Water Conservation Program” webpage is a first attempt at involving the community in correcting the problem of raised water tables. It provides some information about the problems caused by these water tables and offers techniques, information, and tools on how to minimize the amount of water contributing to their development. See Appendix B for other pictures of the “Community Water Conservation Program” webpage.

The “Community Water Conservation Program” webpage first went online during July, 1999. The number of users were monitored for the first few days with over 200 people visiting the site. There are no further plans to improve the site at this time, but it is hoped that the site can be linked with other community webpages in order to increase the number of people that are exposed to the site and the information that it provides.

5.6 Summary

This chapter discussed the findings of this study. The soil texture analysis conducted in Lakeview revealed that soil texture in this area largely lies in the clay and clay loam soil texture classes. Data derived from the soil texture analysis was used to create soil texture profiles of boreholes in Lakeview. These profiles revealed that there were no major boundaries or structures that could be identified, using soil texture alone, that would affect the depth of water tables. Soil texture data was further used in linear regression analysis comparing the mean sand and clay fractions of samples collected from the entire hole and the upper 2 and 4 m of each borehole, to the mean water table depth. This analysis showed no statistical relationship between any of the mean sand and clay fractions to water table depth. Variations in mean sand and clay fractions do not appear to explain variations in mean water table depth in Lakeview.

The Mann-Whitney test was used to compare the mean water table depth of irrigated and non-irrigated land cover classes in both Varsity Village and Lakeview study areas. While Varsity Village showed a strong statistical difference between mean water table depth of

the two land cover classes, Lakeview did not show the same statistical difference. Possible explanations for the discrepancy between these results may be longer exposure of Lakeview to urban irrigation practices or inputs of water into Lakeview from nearby areas.

A Community Water Conservation Webpage was further discussed. This page has been implemented in an attempt to reduce the amount of water contributing to the high water tables in Lethbridge. This Webpage is a good first step in the education of the public regarding water use and the problems that can develop.

Chapter 6

Conclusions and Further Research

6.1 Conclusions

This study examined the development of raised (perched) water tables in two study areas that included residential subdivisions within the City of Lethbridge. Varsity Village and the University of Lethbridge were the location of a previous study of perched water tables (Berg, 1997). That study identified irrigation application in excess of plant requirements as the main contributor to the development of these water tables.

Lakeview, the second subdivision used in this study, had been identified as an area where basement flooding due to high water tables was a concern. Speculation regarding the main contributor to these water tables had centred around contributions from Henderson Lake, lying to the north end of the subdivision. No previous study characterizing water table conditions in Lakeview subdivision had been undertaken. Establishing the water table conditions that existed in Lakeview subdivision was a primary goal of this study.

The surficial geology of the two study areas was reviewed. Varsity Village has been built on an area of hummocky moraine while Lakeview was constructed on an area of

glacio-lacustrine sediments. The different lithologies that underlie these two subdivisions prompted the comparison between them to determine whether surficial geology affected groundwater in different ways. The soil texture analysis revealed only minor differences between Varsity Village and Lakeview subdivisions. Comparison of the two subdivisions also provided an opportunity to see whether groundwater conditions changed over time. Lakeview was constructed 15-20 years prior to Varsity Village, providing a much longer time for water to accumulate in the soil due to irrigation.

Finally, since irrigation applied in excess of plant evapotranspiration has been identified as the main source of water contributing to high water tables (Berg et al., 1996 ; Berg, 1997), a water management program was designed and introduced to the public. This program was aimed at reducing the amount of water that city residents applied to their lawns and gardens. If residents reduce the amount of water they apply to their lawns, water table build up may be decreased or reversed.

6.1.1 Geology and Hydrogeology

Wells were installed in Lakeview subdivision to aid the characterization of water table conditions in this study area. While water tables around Henderson Lake were high, much higher elevations were found in the southeast corner of the subdivision. This suggests that the main flow of water into Lakeview is not from Henderson Lake but from this southeast corner. An irrigation canal in the nearby St. Mary's Irrigation District may be a possible source of water entering the southeastern part of the study area. Further

study would be necessary to establish whether this trend of rising water table elevations continues to the east of the subdivision, towards the irrigation canal. The installation of wells to the south and east of Lakeview would permit a better understanding of the flow of groundwater into Lakeview from these directions.

Soil texture data for Lakeview subdivision revealed no distinct boundary between glacio-lacustrine and till sediments in this area. There was however, a higher concentration of clay textured soil samples in the upper four metres of the boreholes, while clay loam samples became dominant below this depth.

It has been suggested that there are geologic controls over the depth of observed water tables in Lethbridge. To test this statement a linear regression analysis was used to compare the clay and sand fractions to observed water table depth in Lakeview subdivision. Comparison using linear regression analysis between mean water table depth and the mean clay fraction of all samples from the borehole revealed that $r^2 = 0.046$ ($\alpha = 0.05$, $n = 24$). Mean water table depth was also compared to the mean clay fraction of samples in the upper 2 and 4 m of each borehole, showing $r^2 = 0.039$ ($\alpha = 0.05$, $n = 24$) and $r^2 = 0.004$ ($\alpha = 0.05$, $n = 24$) respectively. When mean water table depth was compared to the mean sand fraction of all samples from the borehole it revealed that $r^2 = 0.034$ ($\alpha = 0.05$, $n = 24$). As was done with the clay fractions, mean sand fractions were calculated for samples that were found within 2 and 4 m of the surface for each borehole. These mean sand fractions were compared to the mean water table depth for that location using linear regression and showed that for samples above

2 m, $r^2 = 0.026$ ($\alpha = 0.05$, $n = 24$) and for samples above 4 m, $r^2 = 0.001$ ($\alpha = 0.05$, $n = 24$). These results suggest that variations in soil texture have no statistical relationship to variations in water table depth.

In both Lakeview and Varsity Village, a Mann-Whitney test was used to compare mean water table depth to irrigated and non-irrigated land cover classes. Analysis in Varsity Village showed a significance of 0.00, revealing a significant difference between the mean water table depth of the two land cover classes. The same analysis in Lakeview revealed a significance of 0.06, suggesting there was no statistically significant difference between the mean water table depth for irrigated and non-irrigated land cover classes in this subdivision. The discrepancy between these results may be due to the difference in time the two subdivisions have been exposed to excessive water accumulation due to irrigation. Lakeview has existed for nearly 20 years longer than Varsity Village subdivision, allowing a longer period of time for accumulated water to flow to areas where irrigation is not directly applied. Another possible explanation for the lack of difference between mean water table depths of the two land cover classes in Lakeview is that the water table differences are being masked by water inputs coming from the southeast corner. Once again, wells installed to the south and east of Lakeview would provide more information on the water table conditions in this area.

6.1.2 Water Scheduling Model

The water scheduling page in conjunction with the community water saving program webpage was designed with the idea of making the public more aware of the amount of water they are applying to their lawns and educating them about water conservation practices and techniques. By putting the water scheduling page on the internet, it allows a wide variety of users to have access to the information, while allowing the database to be controlled and maintained by a single operator. Climatic data are often difficult and expensive to measure, but in this case climate data can be added to the database without burdening the users with the expertise or expense necessary to obtain such data. With the data that the users provide, the water scheduling page is able to relay information back to the user concerning the amount of water that he/she should be providing to their lawn or whether water should be applied at all. The community water saving program is the first step in the process of making the residents of Lethbridge more aware of the problems resulting from high water tables and what they can do to reduce some of these problems.

6.3 Suggestions for Future Research

As discussed earlier, further study is necessary to determine whether water is being contributed to water tables in Lakeview subdivision from irrigation canals to the east. An irrigation canal from the St. Mary's Irrigation District runs in a north-south direction to the east of Lakeview. Wells installed around the southeastern corner of the

subdivision and extending to the canal would help to identify whether water from this canal is contributing to the high water table conditions that are found in Lakeview subdivision or whether the high water tables in the southeast corner identified in the water table elevation surfaces (figure 5.14) come from a different source. Monitoring of water elevation in the canal would allow for comparison with elevations of water tables monitored at nearby well installations. This would also help identify whether water is flowing from the canal into Lakeview subdivision.

Analysis of water table conditions in a subdivision immediately prior and subsequent to development would be a useful undertaking. If high water tables were absent from the area prior to development, monitoring water table conditions in such an area following development would provide useful data on how quickly water tables responded to increases in water application to the soil. Continued data collection from such an area would provide data on how water table conditions in a subdivision change over time with respect to continued exposure to current irrigation practices. Heritage Heights subdivision, located in west Lethbridge, may be an appropriate location for such a study.

A group of city residents could be recruited to participate in a program that would test operation of the water scheduling program. Such a group may involve individual households following the prescribed inputs of water to their lawns as required by the water scheduling program over a period of two or three months. Several things can be tested by gathering such a group. The water scheduling program could be tested to ensure that it maintained the health of the turfgrass (ie. the turfgrass did not burn or turn

brown). Water tables can be monitored in the yards of participants to determine whether water table elevations will respond (drop) to a decrease in irrigation inputs using well installations or other equipment to measure soil moisture directly (ie. Neutron Probe to measure soil moisture). Measuring individual yards of participants would be a difficult task since inputs of water from neighbouring yards may skew the results. Blocks of homes may be needed to participate in order to minimize these inputs. Participating households can also be asked whether they liked the way the program was setup and provided information. This way the layout of information provided back to users by the water scheduling page can be altered to provide the most appropriate information for users.

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Appendix A: Well Logs

Well # and Sample Depth (m)	Water Content (%)	Sample Description	Lab Texture Analysis (Percentage)			
			Sand	Silt	Clay	Classification
1-1	28.89	some stones (2cm diam) dark grey patches	35.69	23.95	40.36	clay loam
1-2	16.98	small sand lenses clasts, oxidation	39.48	29.55	30.97	clay loam
1-3	18.37	coal clasts, pebbles	36.37	24.78	38.84	clay loam
1-4	17.62	—	41.48	27.61	30.91	clay loam
1-4.5	17.05	coal, sand lenses, clasts	40.68	29.41	29.91	clay loam
2-1	27.34	no clasts	9.81	12.18	78.00	clay
2-1.5	28.69	no clasts	9.93	8.99	81.07	clay
2-2	15.00	some clasts small sand lenses	36.87	24.58	38.55	clay loam
2-3	15.53	clasts, sand lenses	38.51	17.45	44.04	clay
2-4	21.44	clasts, oxidation	35.06	27.89	37.04	clay loam
3-50	24.68	no clasts	38.23	28.52	33.25	clay loam
3-1	18.49	clasts (1 cm), coal	36.64	28.80	34.56	clay loam
3-2	13.76	clasts	39.32	19.79	40.89	clay
3-3	14.39	clasts (3cm), oxidation small sand lenses	25.12	8.11	66.78	clay
3-4	17.33	clasts, oxidation	40.12	25.08	34.80	clay loam
3-5	17.75	clasts, coal	41.57	23.66	34.77	clay loam
3-6	18.61	darker bands of sediment —	36.99	24.69	38.32	clay loam
4-30	26.59	no clasts	9.86	20.56	69.58	clay
4-1	29.90	clasts	10.04	13.83	76.13	clay
4-2	16.02	small sand lenses	38.42	21.93	39.65	clay loam
4-3	14.88	clasts, sand lenses coal, oxidation	40.72	25.24	34.04	clay loam
4-4	17.48	dark patches ----	33.01	29.58	37.41	clay loam
5-1	21.45	few clasts	39.54	24.66	35.80	clay loam
5-2	19.43	few clasts	40.08	20.77	39.15	clay loam
5-3	17.42	sand lenses	38.08	22.71	39.20	clay loam
5-4	29.04	clasts (various sizes) coal, clasts (1 to 3 cm)	—	—	—	—

Well # and Sample Depth	Water Content	Sample Description	Lab Texture Analysis (Percentage)			
			Sand	Silt	Clay	Classification
7-30	20.45	—	41.05	23.87	35.08	clay loam
7-1	22.27	oxidation, clasts (more than above)	40.52	21.64	37.85	clay loam
7-2	17.77	—	38.87	19.31	41.82	clay
7-3	17.03	few clasts	43.04	23.53	33.43	clay loam
7-4	17.69	coal and clasts	38.67	24.04	37.29	clay loam
7-4.50	20.36	oxidation, coal	32.57	27.60	39.83	clay loam
7-5	38.05	mottled, oxidation	11.16	44.76	44.08	silty clay
7-6	17.91	—	37.98	20.87	41.15	clay
8-1	18.86	clasts, some banding	27.66	34.48	37.86	clay loam
8-2	19.11	small sand lenses, coal	42.04	4.23	53.73	clay
8-3	17.19	—	38.46	19.53	42.00	clay loam
8-4	19.11	larger sand lenses, clasts	39.03	26.14	34.83	clay loam
8-5	16.25	frequent small sand lenses	38.59	25.99	35.42	clay loam
8-6	17.11	sand lense (water)	44.20	26.45	29.34	clay loam
8-7	17.75	sand lense	41.83	20.39	37.78	clay loam
10-1.2	18.58	—	3.70	12.05	84.25	clay
10-2	20.41	clasts, calcite	23.53	12.79	63.67	clay
10-3	19.23	sandy	32.11	29.19	38.71	clay loam
10-4	17.42	fewer clasts than at 3 m bands of colour (10 YR 4/3 wet)	37.95	30.92	31.13	clay loam
10-5	16.98	clasts, oxidation, calcite	38.45	27.27	34.28	clay loam
10-6	16.79	—	43.81	27.70	28.50	clay loam
11-30	17.68	—	46.05	18.88	35.06	sandy clay loam
11-1	23.04	—	20.82	21.10	58.08	clay
11-2	48.56	coal	20.64	1.85	77.51	clay
11-3	25.47	—	21.06	21.76	57.19	clay
11-4	25.41	oxidation	24.22	29.25	46.53	clay
11-5	17.83	more clasts than above no banding, oxidation	39.18	29.15	33.69	clay loam
11-6	16.56	sandy, coal, clasts	37.16	29.15	33.69	clay loam
11-7	16.48	—	36.20	35.21	28.59	clay loam
12-30	24.55	—	44.80	22.35	32.85	clay loam
12-1	37.52	sand lense (~ 1.5 m)	—	—	—	—
12-2	25.60	clasts, coal	36.08	16.84	47.08	clay
12-3	23.90	large coal clast	37.82	22.34	39.84	clay loam
12-4	24.29	coal clasts (~ 5 cm)	21.41	23.08	55.51	clay
12-5	17.06	small sand lenses	40.55	30.59	28.86	clay loam
12-6	17.23	—	42.96	22.47	34.58	clay loam

Well # and Sample Depth (m)	Water Content (%)	Sample Description	Lab Texture Analysis (Percentage)			
			Sand	Silt	Clay	Classification
13-30	38.56	—	6.84	23.82	69.34	clay loam
13-1	33.92	—	13.10	10.21	76.69	clay
13-2	22.21	a few clast, clay matrix coal	34.27	4.65	61.07	clay
13-3	20.58	—	31.11	27.81	41.08	clay
13-3.2	20.79	coal clasts, banding	30.71	28.78	40.51	clay
13-4	22.51	no banding, clasts	22.25	38.55	39.19	clay loam
13-5	18.15	oxidation, sand lenses	40.21	26.14	33.65	clay loam
13-6	21.82	—	30.24	9.71	60.05	clay
14-30	32.88	—	6.61	23.54	69.86	clay
14-1	31.69	stones, some coal	12.26	8.73	79.00	clay
14-2	22.65	few clasts, coal, small sand lenses	33.61	25.34	41.05	clay
14-3	19.99	clasts	13.23	15.92	70.85	clay
14-4	17.70	oxidized, banding sand lenses, coal, clasts	41.12	30.64	28.24	clay loam
14-5	23.31	—	25.51	21.12	53.37	clay
14-6	21.81	oxidation, mottled	32.43	30.20	37.36	clay loam
15-30	22.02	—	32.43	30.20	37.36	clay loam
15-1	30.74	—	18.71	15.27	66.02	clay
15-2	15.98	oxidation	40.53	21.58	37.89	clay loam
15-3	16.72	—	36.46	29.94	33.60	clay loam
15-4	18.57	small coal clasts, small sand lenses	41.79	29.67	28.53	clay loam
15-5	17.35	a few clasts, banding	40.24	29.32	30.45	clay loam
15-6	17.75	oxidation, mottled	40.19	28.58	31.23	clay loam
16-1	14.11	coal	35.96	2.27	61.76	clay
16-2	14.49	mottled, oxidation, clasts	40.51	21.45	38.04	clay loam
16-3	14.65	small coal clasts	45.07	22.91	32.02	clay loam
16-4	17.02	sand lens	40.02	27.51	32.47	clay loam
16-5	14.95	sandy, mottled	37.87	25.74	36.39	clay loam
16-6	19.38	small sand lense	37.10	29.77	33.13	clay loam
18-30	23.34	—	11.66	14.86	73.49	clay
18-1	25.81	—	27.08	21.71	51.21	clay
18-1.5	20.32	—	29.27	10.99	59.73	clay
18-2	21.77	oxidation, clasts	35.17	30.20	34.63	clay loam
18-3	33.20	clasts, coal	26.20	27.03	46.77	clay
18-4	16.30	clasts, calcareous	38.34	31.45	30.21	clay loam
18-5	18.16	clasts	39.77	29.76	30.47	clay loam
18-6	19.58	oxidation	38.57	33.82	27.61	clay loam

Well # and Sample Depth (m)	Water Content (%)	Sample Description	Lab Texture Analysis (Percentage)			
			Sand	Silt	Clay	Classification
19-30	24.86	—	33.33	28.18	38.49	clay loam
19-1	27.28	—	13.89	19.78	66.33	clay
19-2	23.56	coal clasts	23.07	20.09	56.83	clay
19-3	14.41	—	21.91	10.05	68.04	clay
19-4	19.02	coal clasts, oxidized slightly calcareous	36.59	30.22	33.19	clay loam
19-5	23.02	small coal clasts	6.30	17.90	75.80	clay
19-6	21.18	—	28.71	24.03	47.26	clay
19-7	31.11	clasts (up to 3 cm)	17.45	23.66	58.89	clay
19-8	16.43	coal clasts, small sand lenses	45.99	26.83	27.19	sandy clay loam
19-9	15.58	—	28.12	37.52	34.36	clay loam
19-10	16.96	clasts, coal clasts (very small - 2 mm)	11.70	53.53	34.77	silty clay loam
19-11	16.62	clasts, coal	35.00	33.11	31.89	clay loam
19-12	14.73	—	36.79	29.98	33.23	clay loam
20-30	65.28	—	42.37	27.29	30.34	clay loam
20-1	20.48	—	35.56	28.72	35.72	clay loam
20-1.5	22.49	—	8.23	36.92	54.85	clay
20-2	15.96	—	37.22	10.56	52.22	clay
20-3	18.03	coal	39.16	5.85	55.00	clay
20-4	15.05	some clasts	38.66	23.53	37.82	clay loam
20-5	14.78	—	38.26	26.38	35.36	clay loam
20-6	17.65	small coal clasts small sand lenses	42.49	28.70	28.81	clay loam
21-20	19.77	—	23.84	21.24	54.91	clay
21-1	23.19	stones	24.22	30.01	45.76	clay
21-2	24.24	distinct colour change at 2.5 m	16.56	24.45	58.99	clay
21-3	13.92	—	14.01	36.07	49.93	clay
21-4	14.30	more stones than above	39.98	24.12	35.90	clay loam
21-5	16.81	—	37.30	30.13	32.57	clay loam
21-6	18.45	sand lense very plastic	39.58	29.19	31.22	clay loam
21-7	27.24	—	4.94	27.74	67.32	clay

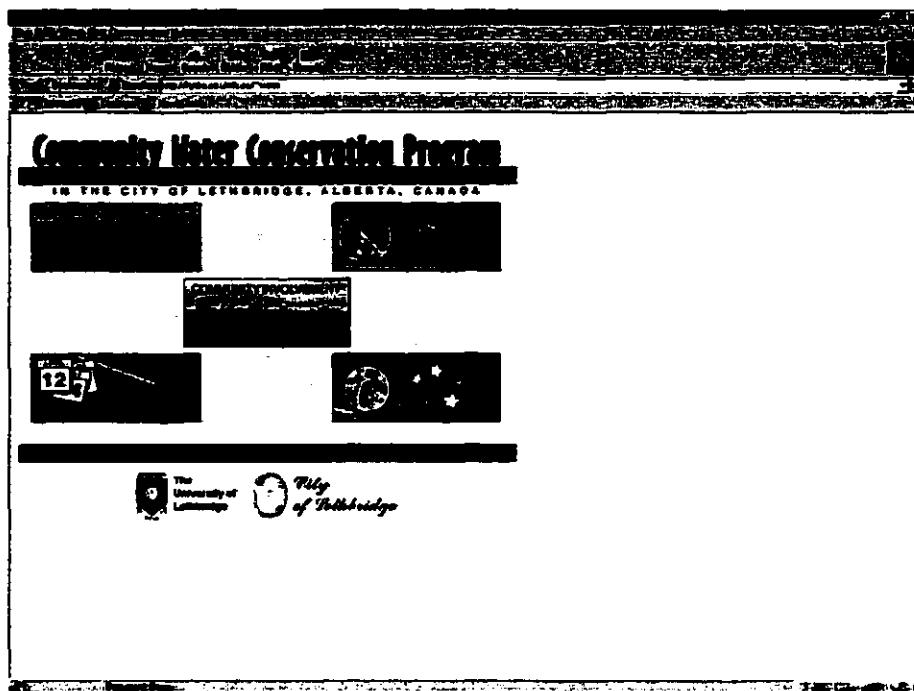
Well # and Sample Depth (m)	Water Content (%)	Sample Description	Lab Texture Analysis (Percentage)			
			Sand	Silt	Clay	Classification
22-30	15.82	stones slightly calcareous sandy matrix sandy matrix sandy matrix fewer clasts than above	29.89	28.08	42.03	clay
22-1	22.14		25.36	10.02	64.63	clay
22-2	21.57		28.50	9.81	61.70	clay
22-3	17.71		25.87	23.91	50.22	clay
22-4	20.55		30.24	29.75	40.01	clay loam
22-5	16.40		40.15	28.39	31.46	clay loam
22-6	17.49		36.51	15.82	47.67	clay
22-7	17.24		37.75	27.91	34.33	clay loam
22-8	16.72		34.84	27.80	37.35	clay loam
22-9	17.60		16.34	47.90	35.77	silty clay loam
22-10	16.12		39.60	32.21	28.19	clay loam
22-11	16.58		39.84	32.63	27.53	clay loam
22-12	18.69		40.55	29.53	29.91	clay loam
22-13	13.08		48.76	21.23	30.02	sandy clay loam
22-14	13.86		54.76	17.11	28.13	sandy clay loam
22-15	13.62		45.42	19.29	35.29	sandy clay
23-30	18.41	fine stones calcareous non-calcareous oxidized calcareous calcareous, more oxidation than above	22.55	27.87	49.58	clay
23-1	17.47		21.97	10.01	68.02	clay
23-2	27.04		12.30	9.94	77.76	clay
23-3	21.77		26.06	27.28	46.66	clay
23-4	14.21		46.69	21.73	31.58	sandy clay loam
23-4.5	20.64		9.82	61.07	29.11	silty clay loam
23-5	18.44		16.89	56.14	26.98	silty clay loam
23-6	17.90		26.12	45.11	28.77	clay loam
23-7	14.41		33.40	33.34	33.26	clay loam
23-8	15.62		38.21	31.76	30.02	clay loam
23-9	16.59		34.67	34.99	30.34	clay loam
24-1	22.73	sandy (water) sand lens	35.58	27.26	37.16	clay loam
24-2	19.28		37.58	29.12	33.30	clay loam
24-3	15.88		46.80	23.54	29.66	sandy clay loam
24-4	14.39		42.25	21.56	36.19	clay loam
24-5	23.08		49.58	19.61	30.81	sandy clay loam
24-6	18.10		81.98	8.03	9.98	loamy sand
24-7	13.34		42.26	29.17	28.57	clay loam
24-7.5	19.79		82.88	5.46	11.66	loamy sand
24-8	13.01		40.82	25.91	33.26	clay loam
24-9	14.60		43.04	26.15	30.81	clay loam

Well # and Sample Depth (m)	Water Content (%)	Sample Description	Lab Texture Analysis (Percentage)			
			Sand	Silt	Clay	Classification
25-1	14.79	—	62.33	15.14	22.54	sandy clay loam
25-1.5	15.19	—	40.77	23.37	35.86	clay loam
25-2	45.49	coal	30.66	15.22	54.12	clay
25-3	18.43	coal	43.44	17.38	39.18	clay loam
25-4	18.35	oxidized	39.25	25.44	35.31	clay loam
25-4.5	18.07	—	38.29	24.50	37.21	clay loam
25-5	17.55	sand lens	40.33	27.74	31.93	clay loam
25-6	17.56	sand lens (water)	50.31	25.03	24.67	sandy clay loam
25-7	15.86	large coal clast, sand lens	44.03	26.60	29.37	clay loam
25-7.5	32.26	—	41.17	23.33	35.50	clay loam
26-30	10.35	—	33.73	28.17	38.10	clay loam
26-1	12.74	calcite crystals, oxidation clasts	35.70	26.20	38.10	clay loam
26-2	19.87	—	21.18	36.54	42.28	clay
26-3	13.05	—	16.34	47.90	35.77	silty clay loam
26-4	16.02	—	38.20	26.41	35.38	clay loam
26-5	13.46	dry, stiff	30.56	36.78	32.67	clay loam
26-6	15.47	—	35.69	28.64	35.68	clay loam
26-7	16.46	—	37.29	30.23	32.48	clay loam
26-7.5	16.31	—	37.31	27.40	35.29	clay loam
26-8	17.55	—	36.47	25.09	38.44	clay loam
26-8.5	17.43	—	24.89	39.93	35.18	clay loam
27-30	35.23	unoxidized, calcareous	28.29	32.30	39.41	clay loam
27-1	30.40	—	9.75	13.95	76.30	clay
27-2	18.46	—	31.80	19.04	49.16	clay
27-3	10.90	sand and gravel	52.27	26.35	21.39	sandy clay loam
27-4	18.18	sand	45.37	26.19	28.43	clay loam
27-4.5	15.69	—	38.14	22.38	39.48	clay loam
27-5	22.62	sand	70.75	13.16	16.10	sandy loam
27-6	22.89	sand	58.29	21.69	20.03	sandy loam
27-7	19.12	—	54.03	27.65	18.32	sandy loam
27-7.5	20.64	—	36.02	33.47	30.51	clay loam
28-2	17.32	calcareous	35.73	28.20	36.07	clay loam
28-4	17.83	—	35.26	29.40	35.34	clay loam
28-4.5	23.92	—	13.75	43.75	42.50	silty clay
28-5	18.12	oxidized	35.06	32.86	32.08	clay loam
28-6	15.53	oxidized	37.01	27.09	35.90	clay loam
28-7	17.99	oxidized	38.40	32.28	29.31	clay loam

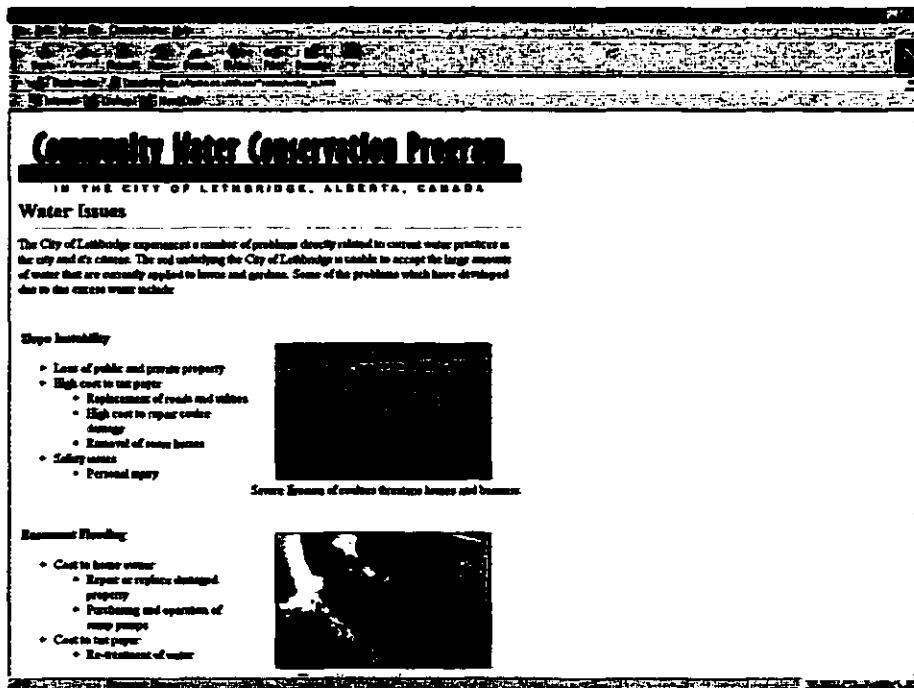
Well # and Sample Depth (m)	Water Content (%)	Sample Description	Lab Texture Analysis (Percentage)			
			Sand	Silt	Clay	Classification
29-2	13.79	oxidized	43.26	27.72	29.02	clay loam
29-3	13.25	oxidized	38.83	27.21	33.96	clay loam
29-4	14.88	—	41.01	29.41	29.58	clay loam
29-5	16.06	—	41.80	29.32	28.88	clay loam
29-6	14.75	—	43.75	25.45	30.80	clay loam
29-7	17.25	sandier than above sand lenses	41.76	29.82	28.42	clay loam
30-30	18.25	—	34.66	43.70	21.65	loam
30-1	20.63	oxidized	34.31	3.52	62.17	clay
30-2	17.42	—	39.62	5.87	54.51	clay
30-3	17.13	—	33.67	22.84	43.49	clay
30-4	14.76	clasts, banding, oxidation	38.26	32.69	29.05	clay loam
30-5	20.40	oxidation	30.39	37.34	32.27	clay loam
30-6	15.39	banding	44.06	30.91	25.03	loam
30-7	16.79	banding	37.11	30.30	32.59	clay loam
31-30	21.77	—	17.51	17.49	65.00	clay
31-1	19.69	small stones, calcareous	6.88	40.76	52.35	silty clay
31-2	21.15	—	30.40	42.46	27.13	clay loam
31-3	16.71	banding more stones to bottom	41.39	6.99	51.62	clay
31-4	49.26	—	37.13	26.13	36.74	clay loam
31-4.5	15.96	oxidized	35.15	28.99	35.86	clay loam
31-5	12.34	oxidized	36.46	28.09	35.45	clay loam
31-6	14.83	oxidized	39.21	23.52	37.28	clay loam
31-7	14.73	oxidized, mottled	38.64	25.80	35.56	clay loam

APPENDIX B

Community Water Conservation Program Home Page



Water Issues Page



Xeriscaping Page

The screenshot shows a web page titled "Community Water Conservation Program" under "IN THE CITY OF LETHBRIDGE, ALBERTA, CANADA". A sub-section titled "What is Xeriscaping?" is visible. Below it is a bulleted list of tips for xeriscaping:

- Knowing Your Soil
 - select appropriate plants and material for your soil.
- Planning And Design
 - know the climate around your yard and select plants which do well in those areas
(See "For More Information" at the bottom of this page)
- Efficient Irrigation
 - group plants with similar water needs
 - always water in the most conservative way (sometimes drip irrigation, sometimes sprinkler irrigation)
 - do not water during the hottest part of the day (drip irrigation uses water)
- Proper Plant Selection
 - best to use native and drought tolerant plants
- Practical Grass Areas
 - minimize lawn area of yard
 - use grass only in high activity areas
- Mulching
 - leaves, leaves or wood shavings used around shrubs, or flower beds
 - holds moisture in the soil
- Maintenance
 - weed, prune, mow, and irrigate only when needed

At the bottom of the page, there is a link labeled "Why Xeriscaping?"

Community Involvement Page

The screenshot shows a web page titled "Community Water Conservation Program" under "IN THE CITY OF LETHBRIDGE, ALBERTA, CANADA". A sub-section titled "Community Involvement" is visible. It includes a paragraph about the goal of bringing the community together to share and explore various water reduction and landscaping strategies, followed by a list of implementation projects:

- Collaborations - a) school and city demonstration gardens
- Economic Initiatives - a) rebates on products
- Education - a) public service announcements
- Infrastructure Improvement - a) water audits
- Public Laws (ordinances) - a) water scheduling

Below this, there is a note about the 1999 Lethbridge Better and Greener year show, and a contact section for further information:

For further information regarding future activities and projects or the discussion groups please phone or email Dawn or Jennifer at: Phone: (403) 329-2225
Email: wmcp@lethbridge.ca

Please provide us your name, telephone number and your email address if you have one.

Who Are We?

Community Water Conservation Program
IN THE CITY OF LETHBRIDGE, ALBERTA, CANADA

Who Are We?

We are a multi-disciplinary group of earth scientists, environmental scientist and environmental managers, dedicated to a high standard of living of all citizens through continued maintenance and care of our environment.

This team strengthens both pure and applied research related to our water, land, geographic resources and social systems. As designers we offer and implement strategic and practical concepts to maximize our components and resources. We are educating the citizens of Lethbridge about the water issues that exist as well as providing them with watering and landscape design strategies that, when implemented, will reduce unnecessary water consumption.

For more information on our program or our services please contact us water@cityoflethbridge.ca.

The University of Lethbridge City of Lethbridge

Water Scheduling Page

Community Water Conservation Program
IN THE CITY OF LETHBRIDGE, ALBERTA, CANADA

Water Schedule

This page is designed to assist City of Lethbridge residents in watering their lawns in volumes that are required by grass. By watering only in set vegetable areas we hope that water bills levels within the City of Lethbridge will drop along with your water bill and lawn maintenance. Overused water usage height will reduce water table problems.

To estimate the soil moisture your lawn requires, you will have to tell us how much water has been added to your lawn by both lawn watering and rain. You must provide us with:

1. The amount you have watered and
2. The amount of rain that has fallen.

Click on the button to see the Supersoaker for Lethbridge for the last 14 days.

If you don't have an account with us click here.

If you have an account with us click on the map where your house is located or enter your username and password (optional).

APPENDIX C - Method for calculating daily solar radiation

Net radiation received by the earth's surface can be calculated using the following equation (Shuttleworth, 1993):

$$NR = (0.25 + 0.5(C)) \times So - (0.9 \times C + 0.1) \times (0.34 - 0.14/(VP) \times 4.903 \times 10^{-9} \times T^4)$$

Where: NR = net radiation (MJ/m²/day)
C = cloudiness fraction
VP = vapour pressure (kPa)
T = average air temperature (°C)
So = extraterrestrial solar radiation (MJ/m²/day)

The cloudiness fraction for the above equation is estimated from the percentage of clear sky for the day, while vapour pressure is derived using (Shuttleworth, 1993):

$$VP = 0.6108((17.27 \times T)/(237.3 + T)) \text{ kPa}$$

Net radiation can be converted from MJ m⁻² day⁻¹ to mm day⁻¹ by multiplying net radiation by the equation for latent heat of vapourization (Shuttleworth, 1993):

$$\lambda = 2.501 - 0.002361(T_s)$$

Where: λ = latent heat of vapourization (MJ kg⁻¹)
 T_s = surface temperature of the soil (°C)

Extraterrestrial solar radiation represents the total solar radiation received at the top of the Earth's atmosphere and is calculated using the equation (Shuttleworth, 1993):

$$So = 15.392 dr (\omega s (\sin \phi) (\sin \delta) + (\cos \phi) (\cos \delta) (\sin \omega s)) \text{ mm day}^{-1}$$

Where: dr = relative distance between the earth and sun
 ωs = sunset hour angle (radians)
 ϕ = latitude of the site
 δ = solar declination (radians)

Due to atmospheric attenuation and scattering, radiation reaching the Earth's surface is less than that received at the top of the atmosphere. The calculation of net radiation above corrects the calculated extraterrestrial solar radiation for these atmospheric effects. Once derived in mm day^{-1} , the extraterrestrial solar radiation must be converted to $\text{MJ m}^{-2} \text{ day}^{-1}$ by dividing by the latent heat of vapourization. This allows the calculated extraterrestrial solar radiation to be used in the equation for net radiation.

There are several variables needed to derive extraterrestrial solar radiation that must be calculated as well. Relative distance between the earth and sun can be calculated using the equation (Shuttleworth, 1993):

$$dr = 1 + 0.033 \cos ((2\pi/365) \times J)$$

Where: J = Julian date.

The equation used to derive the sunset hour angle is (Shuttleworth, 1993):

$$\omega_s = \arccos (-\tan \varnothing \tan \delta)$$

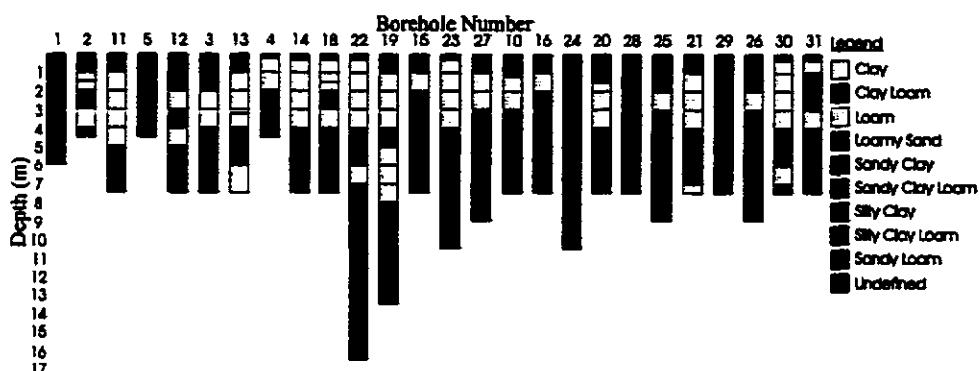
where \varnothing is the latitude of the sight (Northern hemisphere is positive, Southern hemisphere is negative) and solar declination (δ) is provided by the equation (Shuttleworth, 1993):

$$\delta = 0.4093 \sin ((2\pi/365) \times J - 1.405) \text{ (radians)}$$

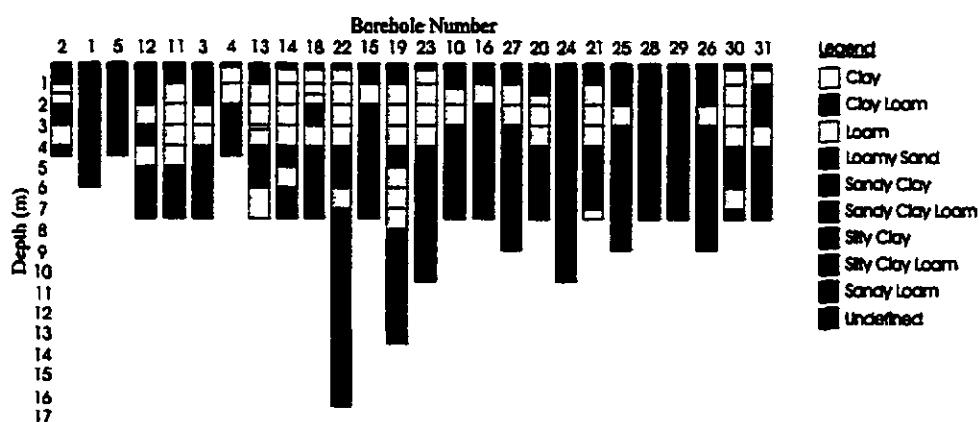
APPENDIX D

Soil Texture Profiles - The title given to the profiles shown below represent the borehole used as the center of the concentric rings and the profile is arranged from the closest borehole to the furthest on the far right.

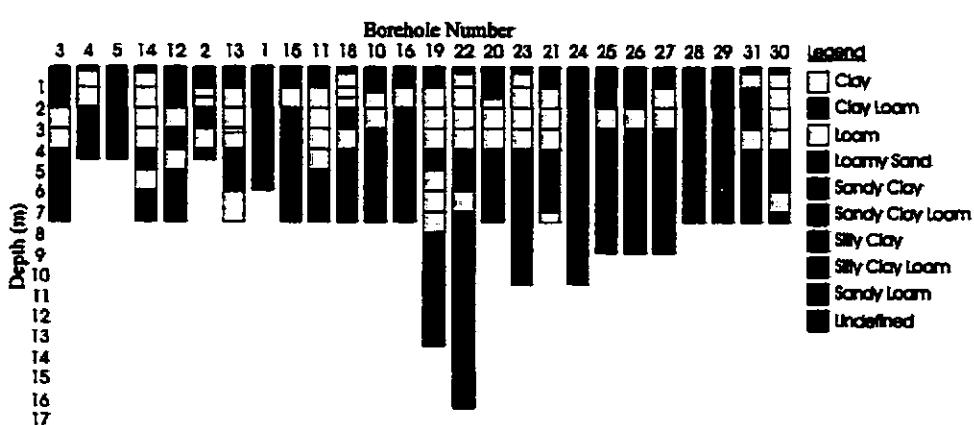
Borehole 1



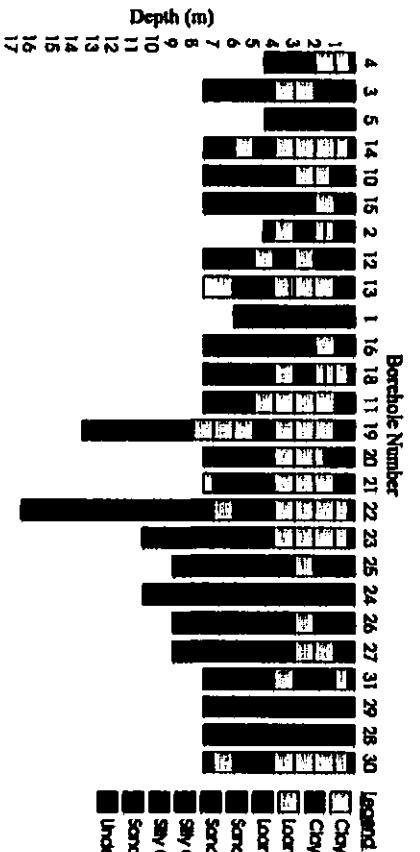
Borehole 2



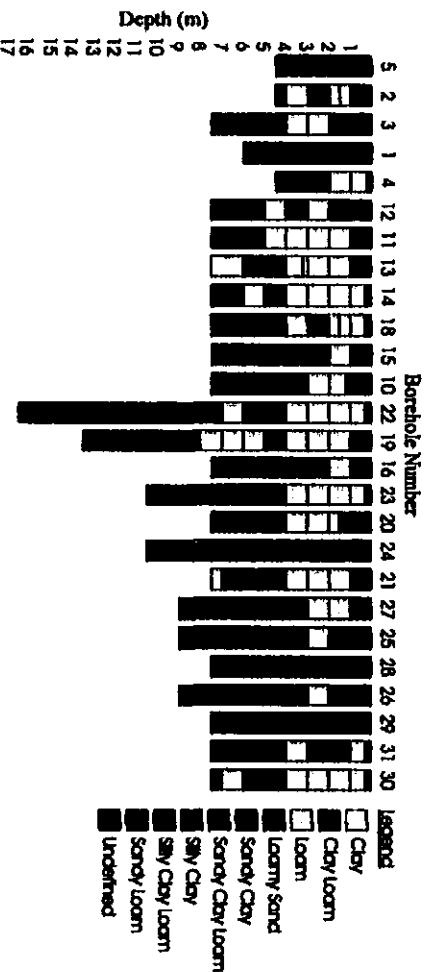
Borehole 3



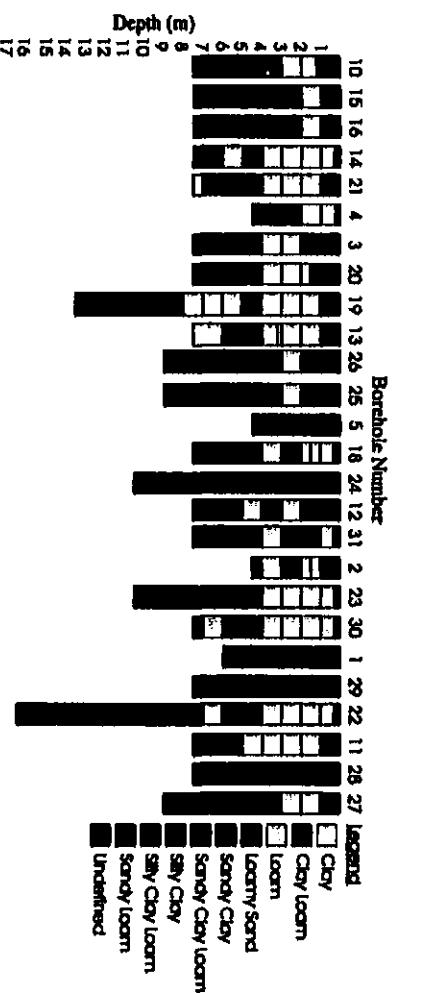
Borehole 4



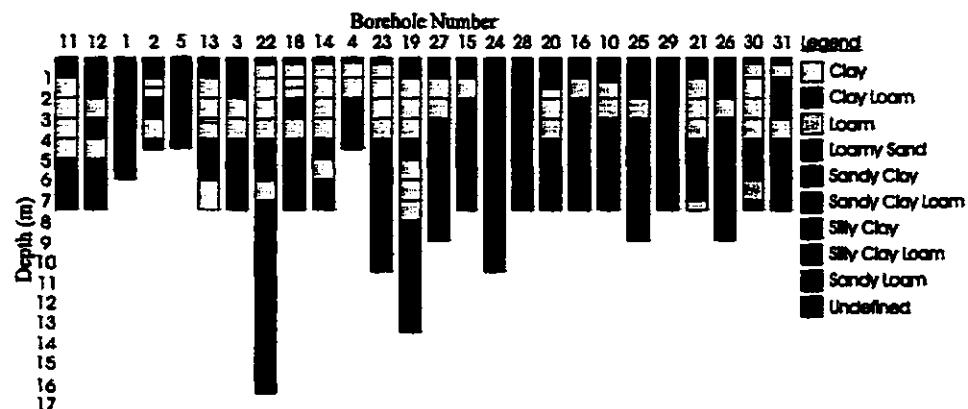
Borehole 5



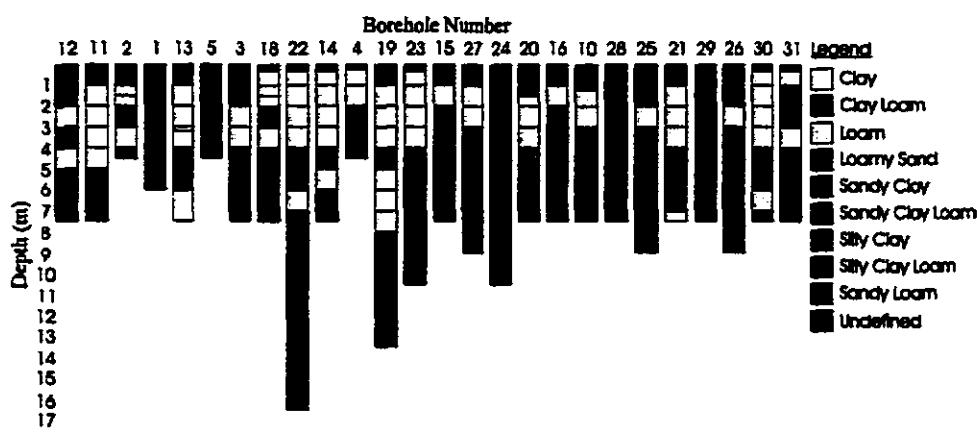
Borehole 10



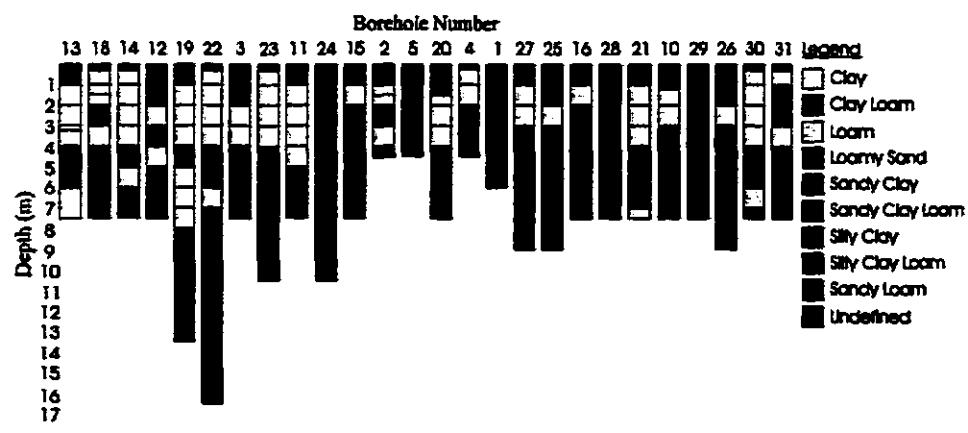
Borehole 11



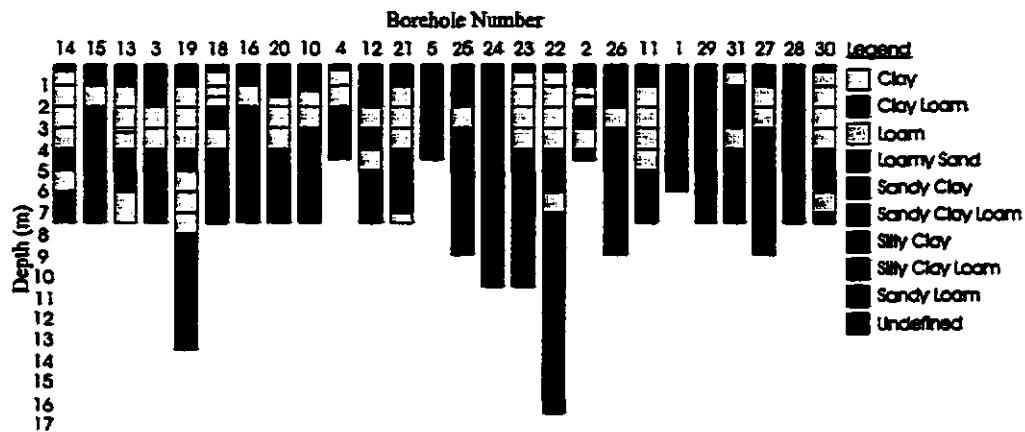
Borehole 12



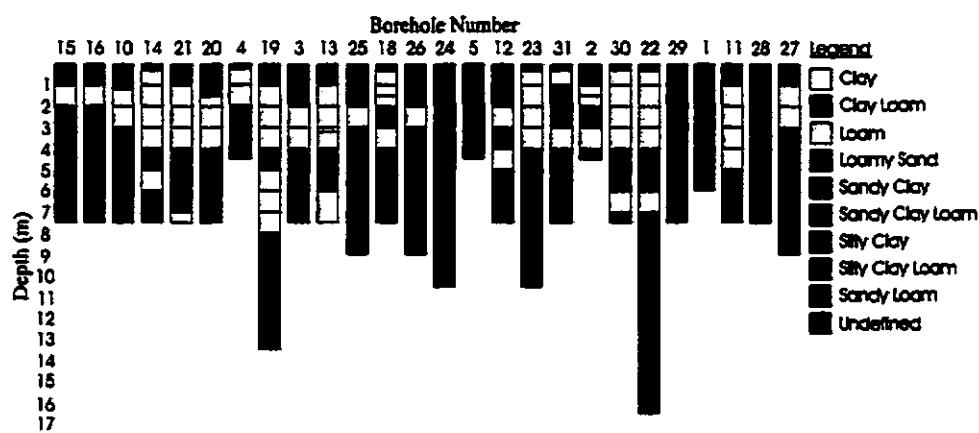
Borehole 13



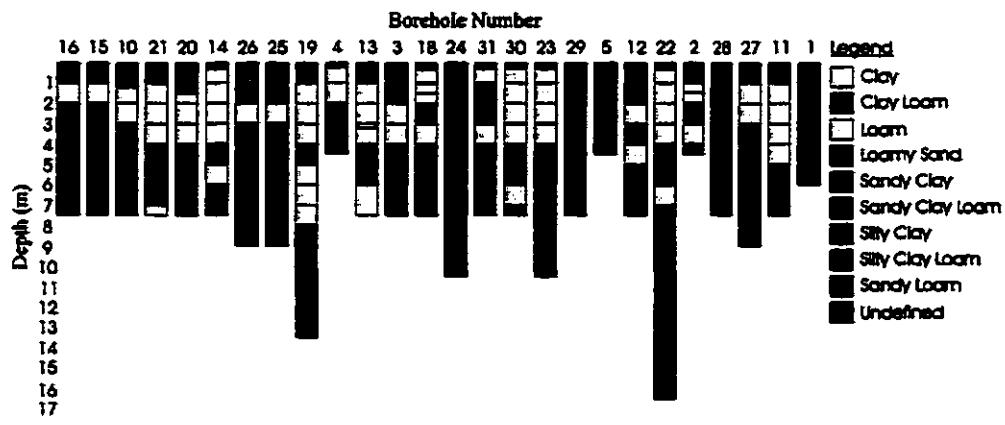
Borehole 14



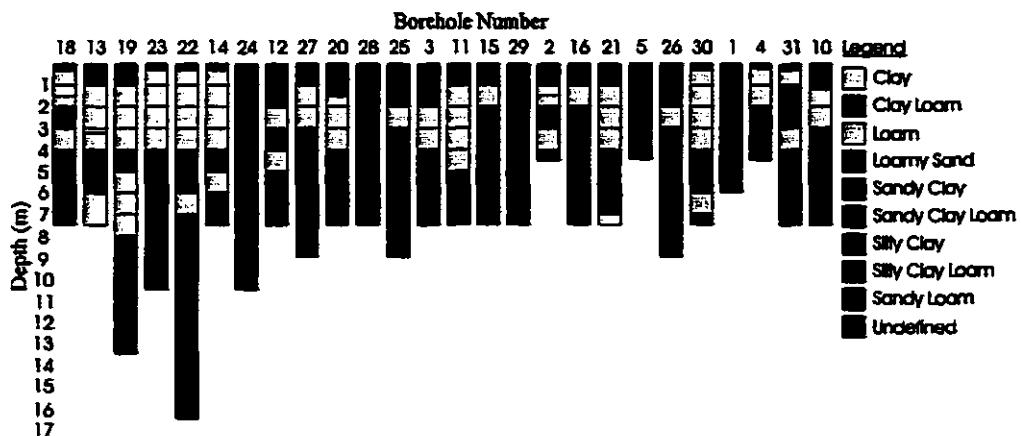
Borehole 15



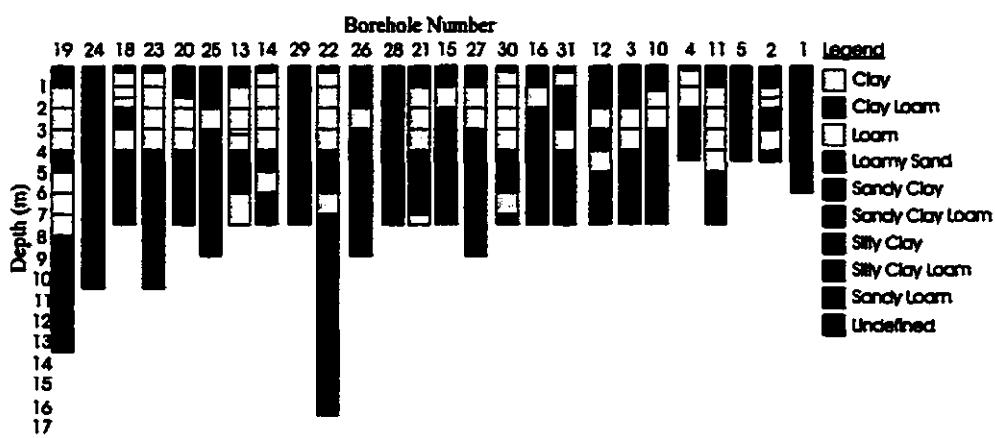
Borehole 16



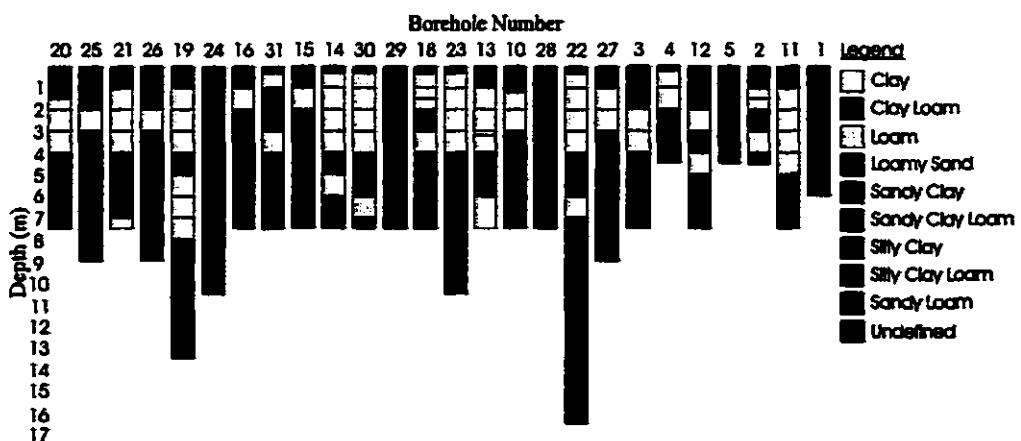
Borehole 18



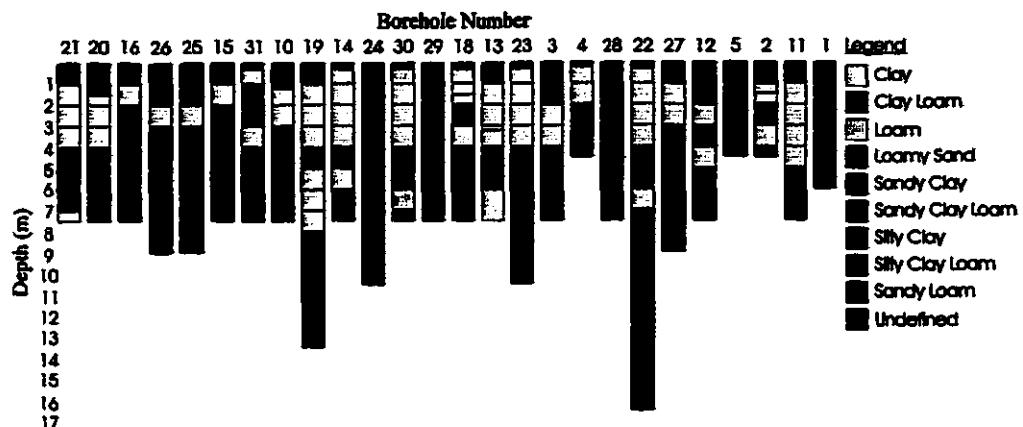
Borehole 19



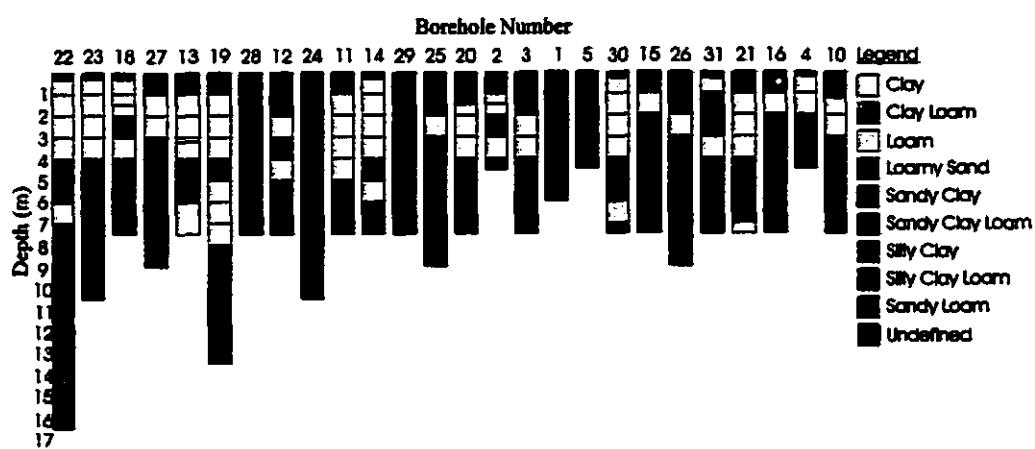
Borehole 20



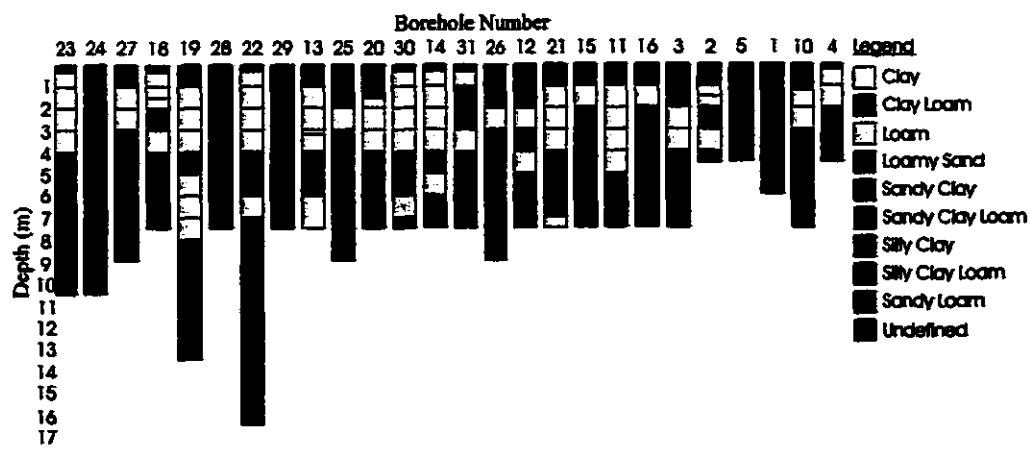
Borehole 21



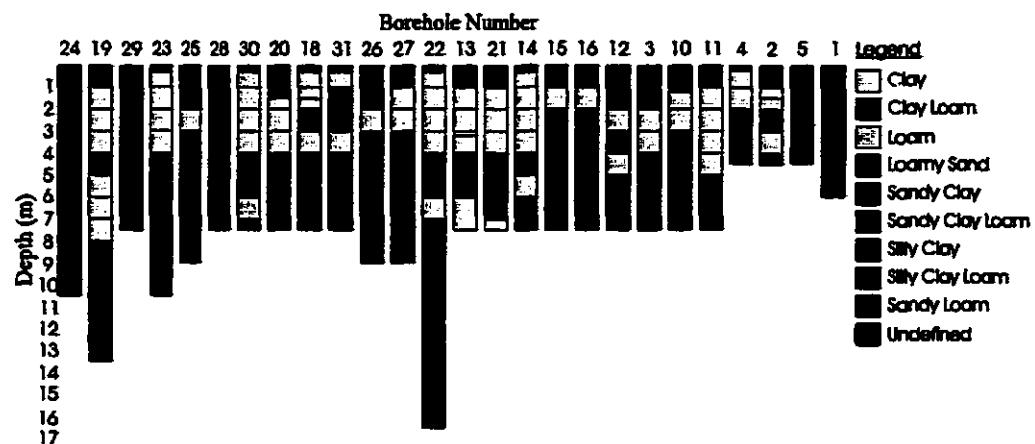
Borehole 22



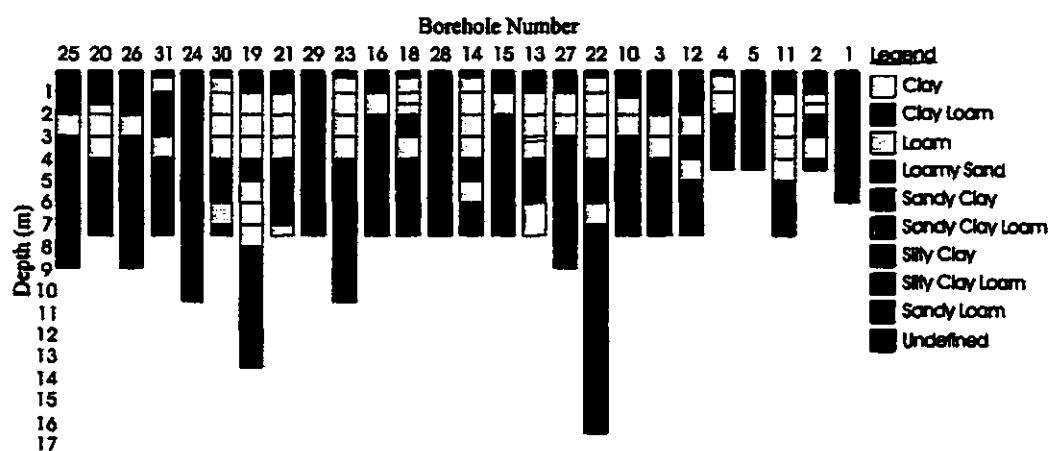
Borehole 23



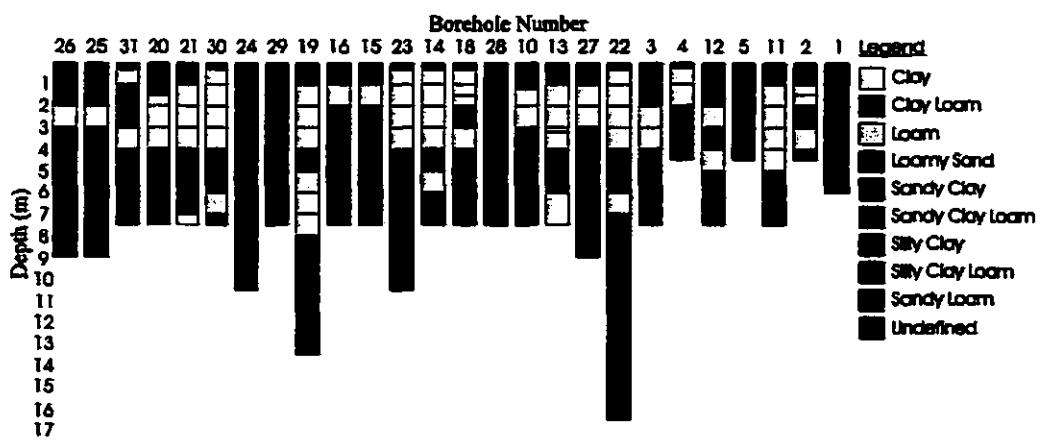
Borehole 24



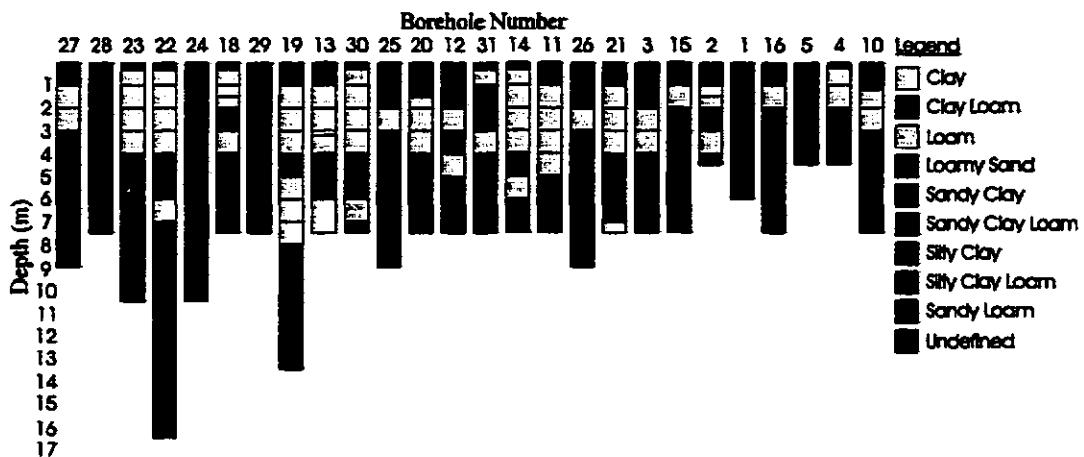
Borehole 25



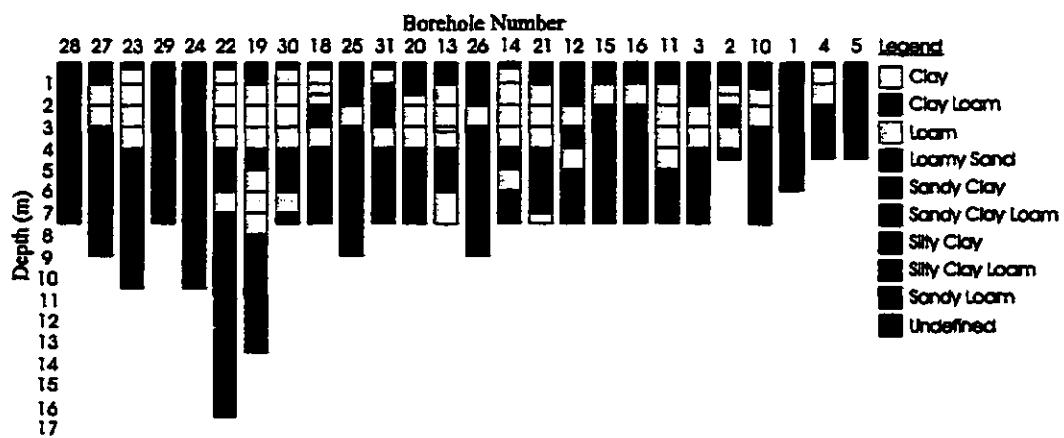
Borehole 26



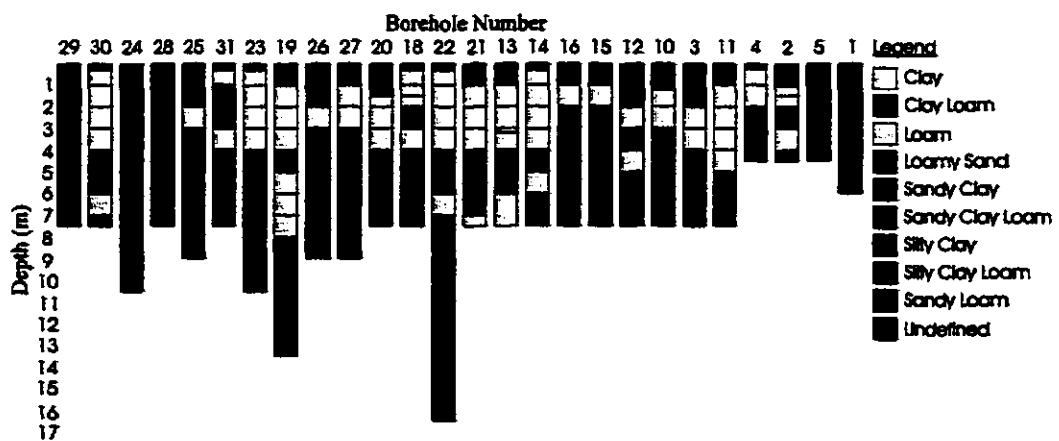
Borehole 27



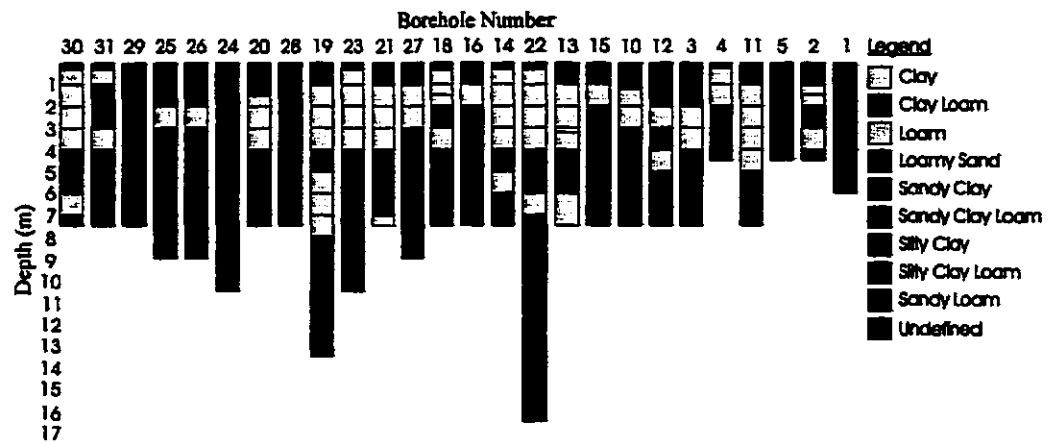
Borehole 28



Borehole 29



Borehole 30



Borehole 31

