URBAN IMPACTS ON A PRAIRIE GROUNDWATER SYSTEM: ESTIMATION OF ANTHROPOGENIC CONTRIBUTIONS OF WATER AND POTENTIAL EFFECTS ON WATER TABLE DEVELOPMENT

AARON ANDREW BERG
B.Sc University of Lethbridge, 1995

A Thesis
Submitted to the Council on Graduate Studies
of the University of Lethbridge
in Partial Fulfillment of the
Requirements for the Degree

MASTER OF SCIENCE

LETHBRIDGE, ALBERTA
May, 1997

ABSTRACT

In subhumid to arid climates throughout the world, recharge to groundwater in urban areas is often found to be higher than pre-urbanization rates, despite an increased percentage of impermeable surfaces. Groundwater recharge in the city of Lethbridge is substantially higher than recharge rates prior to urbanization, resulting in the formation of perched water table conditions. High perched water table conditions, typically at depths between one and 2.5 metres, have created problems for the City and University of Lethbridge, including the increased occurrence of slope failures along nearby coulees. This study estimates of the volume of excess water available for groundwater recharge through the practices of urban turfgrass irrigation, and water storage. Between May and September, 1990-1996 irrigation was applied far above evapotranspiration demands, resulting in large volumes of water available for groundwater recharge in the Varsity Village subdivision of the City of Lethbridge. The relationship between the amount of water applied and the development of perched water table systems was strong enough that equations between inputs and water table depth could be derived, and used to predict water table elevation.

ACKNOWLEDGMENTS

I would like to extend a sincere thank you to my supervisors Dr. J.Byrne and Dr. R. Rogerson. My work greatly benefited from helpful discussions, encouragement, and providing comments on my draft. A special thank you to Dr. J Byrne for all of his work to organize funding for this project, and providing helpful comments throughout my study. I would also like to thank my thesis committee members Dr. R. Barendregt from the University of Lethbridge, and Dr. D. Sauchyn from the University of Regina for their valuable recommendations.

I am also grateful to both the City of Lethbridge and the University of Lethbridge Physical Plant who provided funding for this project. I wish to thank individuals at both locations for discussions related to this project and who provided assistance with data collection. From the University of Lethbridge I wish to thank W. Stevens and B. Sullivan for their support of the project, D. Ross and D. Kunimoto for assistance in obtaining campus maps, I. Wells and H Overes for assistance with materials needed for this project.

From the City of Lethbridge I wish to thank H. Bosman and D. Stafford for their support of the project, B. Klima for providing city maps used in digitizing, I. Peterson and K. Verguitz for providing necessary data.

Several students from the University of Lethbridge took part in data collection for this project. Their input, discussions, and assistance with field work was greatly appreciated. I extend my gratitude to K. Dick, D. Greenfield, M. Gruninger, J. Kramer, J. Pennington, and C. Sweet.

I also wish to thank my family for their continued support in all my endeavors. Their support and encouragement is greatly appreciated.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION AND PROBLEM OVERVIEW

1.1 Introduction

Urbanization has extensive effects on the hydrology of a region. The most significant of these effects results from the situation where large tracts of land are rendered impervious to precipitation due to concrete or asphalt structures. It is therefore often suggested that recharge to groundwater in the urban environment should be markedly reduced compared to rural areas (Douglas, 1983). However in many urban areas recharge to groundwater is found to be higher than pre-urbanization rates (Lerner, 1990). High rates of recharge, combined with lower overall rates of actual evapotranspiration, result in an increase of groundwater tables in many urban locations (Lerner, 1990; Foster *et al.*, 1994; Greswell *et al.*, 1994; Karnieli *et al.*, 1984).

Lethbridge, Alberta not unlike many other urban areas has been affected by high water tables in recent years. High water table conditions have been observed in many areas on the west side of the City of Lethbridge and the University of Lethbridge campus (EBA Engineering Consultants Ltd. (EBA), 1996b; Stanley and Associates Engineering Ltd., 1993). These conditions have resulted in problems for Physical Plant operations on the University of Lethbridge campus. Observed problems include: road and parking lot maintenance, basement flooding, and flooding of buried utility corridors. Concern expressed among University maintenance engineers regarding the integrity of campus building foundations. Many of the problems are thought to be caused by excess water applied to the low permeability soils characteristic of the region. The result of the over accumulation of water from both natural and anthropogenic causes, combined with the low observed hydraulic conductivities, is the formation of perched water tables.

Of great concern to the Lethbridge region in general is the formation of high water table conditions above the river valley walls. Elevated water tables near valley walls have resulted in increased occurence of slope failures for river valleys in Southern Alberta (Thomson and Morgenstern, 1977; Ruban and Thomson, 1983). Perched groundwater conditions observed in the Lethbridge region have had a considerable effect on coulee slopes as an increased groundwater table results in an increase in porewater pressure, thereby reducing the effective stress within the soil itself (Ruban and Thomson, 1983). Progressive slope failures which have occurred in two Lethbridge neighborhoods have resulted in the need for very costly ameliorative measures, including the removal of affected homes, and extensive slope stabilizing procedures.

Potential sources of input to groundwater for most urban areas include: precipitation, water leakage from mains, sewers, and storage tanks, leakage from artificial lakes and reservoirs, and over irrigation of lawns and gardens (Lerner, 1990). Many of these potential sources have been identified in West Lethbridge. Consequently, water tables depths observed within many areas in the City of Lethbridge have been found to be at depths of one to two metres, often more than five metres above depths observed in non developed areas (EBA, 1996a; EBA, 1996b; Greiger, 1962; Ruban and Thomson, 1983).

The observation of high water table conditions throughout the City of Lethbridge, and the potential damage which can occur, has prompted a study supported by the University of Lethbridge, and the City of the Lethbridge. This study focuses on urban contributions to local groundwater due to the practices of turf grass irrigation and water storage. Interactions between the surficial geology of low hydraulic conductivity, and water recieved are examined and an attempt at modeling water table development is made.

The established objectives of this study are as follows:

- To examine the extent and occurrence of perched water tables in the Varsity Village subdivision of the City of Lethbridge.
- Through water balance modeling, quantify the amount of water available for groundwater recharge from various sources in the study area.
- To develop a model that will accurately forecast observed groundwater conditions in the study area.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The main concept utilized in this study to evaluate urban contributions to groundwater is the urban water balance equation. To better understand the application of this equation to the present study, discussion will focus on various components incorporated in the urban water balance equation. Discussion will also focus on the effects of water table development on urban areas, and on the City of Lethbridge itself.

2.2 The Urban Water Balance

The water balance equation is fundamental to the study of hydrology. The hydrologic equation allows researchers a quantitative means to evaluate flow of water through a system. This equation in its most basic form is represented in Fetter (1994):

$$\text{Inflow or Inputs} = \text{Outflow or Outputs} \pm \text{Changes in Storage.} \qquad (2.1)$$

The water balance equation has been utilized to quantify water flow in a number of applications. In agriculture it has been used to estimate evapotranspiration (Allen *et al.*, 1989; Jury and Tanner, 1975; Pescheke *et al.*, 1986; Pruitt and Lourence, 1985), soil moisture (Baier and Robertson, 1966; Belmans *et al*, 1983; Calder *et al.*, 1983; de Jong and Kabat, 1990; Jensen *et al* 1971), leaching fractions (Kincaid *et al*, 1979; Morton *et al.*, 1988), and infiltration and runoff (Hino *et al.*, 1987). The water balance equation is also of great importance in urban hydrologic studies. Use of the water balance equation can allow a researcher to:

-quantify amounts of water flow through a particular urban system,

-assess potential pollutant load passed through a urban system,

-quantify time period variations,

-assess landuse changes to the hydrologic system (van de Ven, 1990).

As reported in Grimmond and Oke (1986) and van de Ven (1990), urban water balances have been carried out throughout the world A summary of these studies is listed in Table 2.1.

The typical form of the urban water balance equation (used in urban settings) is:

$$P + I = r + E + \Delta S \qquad (2.2)$$

where:

P is precipitation,
I is the piped in water supply,
r is runoff,
E is evapotranspiration,
ΔS is the change in storage (Grimmond *et al*, 1986).

Table 2.1 Examples of Urban Hydrologic Balance Studies Throughout the World

Author	**Location**	**Purpose**
Aston (1977)	Hong Kong	Predict future water demands
Bell (1972)	Sydney, Australia	Prediction of future sewage system requirements
Berg et al. (1996)	Lethbridge, Canada	Predict urban lawn Over-watering
Campbell (1982)	Mexico City, Mexico	Assessment of Mexico City as part of the ecosystem
Grimmond and Oke (1986)	Oakridge, Vancouver, Canada	Gauge impact of irrigation input on the water balance
Lindh (1978)	Sweden	Hydrological research program
L'vovich and Chernogayeva (1977)	Moscow, Russia	Assess urban impacts
Peters (1994)	Denver, USA	Lawn irrigation return flow study
Zvi (1977)	Israel	Effects of urbanization on recharge to groundwater

Equation 2.2, although useful, is very simplistic. Urban areas have two distinct subsystems of water flow (Grimmond *et al*, 1986, van de Ven, 1990). These subsystems include an internal and external system (Grimmond et al., 1986). The internal system includes water directed into, and then from homes and businesses. Water in the internal system is not in contact with the outside environment. The external system includes water associated with the outside environment including: precipitation, irrigation, storage in irrigation lakes or reservoirs, and runoff diverted to storm sewers.

For water balances in urban areas where irrigation and pipe leakage are considered negligible, such as the study conducted by Uunk and Van de Ven (1984), the internal system is separate from the external system. However, in most urban areas there are several interconnections between the two subsystems including: irrigation, weeping tile connections to sanitary sewers, use of water in industrial cooling (vaporization), and pipe leakage. Important information can be obtained by a researcher if the subsystems can be considered separately. Separation of the subsystems, coupled with accurate information and the use of a modified water balance equation, allows researchers to quantify and examine the movement of water throughout the urban environment.

By comparing inflows, and outflows in the winter, and summer periods, separation between the subsystems can be completed. During the winter period, most urban flow is confined to the internal system [American Water Works Association, Committee on Water Use (AWWA-CWU), 1973]. However, during the summer period, there are many connections between the internal and external system. Volumes of water derived from the internal system but released into the external system can be estimated by subtracting the amount of water use in summer, by water use in winter. Similar calculations can be used to estimate the volume water leaving the external system and entering the internal system through connections such as household weeping tile hookups to sanitary lines. This type of estimation is applicable in suburban settings, due to low amounts of industry. Seasonal variations of water used by industry such as in the treatment and packaging of agricultural products, may result in overestimations of the amount of water used.

In order to better understand the urban application of equation 2.2, in the estimation of groundwater recharge, discussion below examines each of the variables involved in this equation.

2.3 Inputs

The input side of equation 2.2 contains the variables precipitation and the piped in water supply. Precipitation of course considers water derived from a precipitation event. Inputs derived from the piped in water supply include water applied as irrigation, pipe leakage, and water diverted to surface features. Inputs from each of these potential sources will be discussed with reference to recharge of groundwater in a urban setting.

2.2.1 Precipitation

In southern Alberta approximately 60% of the total annual precipitation falls between May and September (Canadian Climate Normals 1961-1990). Precipitation falling in the Varsity Village area or the University of Lethbridge campus will land on an impermeable surface such as roads, parking lots, and buildings, or on a permeable surface such as parks or domestic lawns and gardens. Water landing on roads will be diverted to storm water systems and carried to the Oldman river. The presence of cracks on a asphalt or concrete surface will allow for the infiltration of water Water entering cracks can be problematic in areas with slowly permeable soils. Water beneath asphalt or concrete will not be removed quickly due to an evaporative "cap" formed by the impermeable surface (Lerner, 1990; Stanley Associates, Engineering Ltd., 1993) Eventually the build up of water beneath these surfaces will diminish the load capacity of the surface itself.

Precipitation landing on building roofs is often directed onto nearby lawns or gardens. This practice was noticed extensively in the Varsity Village area of the city of Lethbridge (Berg *et al*, 1996). Higher rates of water input into lawns and gardens occurs in areas where this practice is evident.

An important variable in southern Alberta is winter precipitation. Snowfall or rain falling between October and April is very important to spring soil moisture. A study by Chang et al (1990) found that winter precipitation was highly correlated with spring soil moisture conditions in the Lethbridge region.

2.2.2 The Piped in Water Supply

The network of pipes throughout a city supply potable water, and allow for the transport of waste water out of the city. The pipe network is often seen as a separate internal system, not connected with the outside environment. However, in most cities, this internal system is connected to the environment in a number of ways. Three identified modes of connection include: pipe leakage, filling of water storage areas, and irrigation.

2.2.2.1 Pipe Leakage

Interconnections between the internal system and external system can occur through leakage of pipes. Discussion in Lerner (1990) identified that few municipal authorities can claim urban pipe leakage below 10% of supply. This source alone could be responsible for 100-300 mm/yr. of potential recharge (Lerner, 1990). Urban water networks are often a major source of groundwater recharge, especially water transported via pressurized water mains. In Britain it has been estimated that approximately 20-30% of water put into distribution is lost due to leakage (Foster et al., 1994). A similar study in Lima, Peru, conducted by Lerner (1986) found water loses from mains amounted to 44-60% of average flows. Lerner (1986) estimated 35% of losses occurred in the city distribution system, while 15% was lost on consumers' premises. In the City of Lethbridge leakage from water mains is consided to be low, as any breaks, or leaks, are rapidly apparent in the low permeabily clay, often breaking through asphalt surfaces (Bosman, pers. comm., 1995).

Studies conducted in Liverpool and Hong Kong has revealed that leakage from both storm and sanitary sewers occurs (Lerner, 1990, Lerner, 1986). However, since storm networks are used occasionally, and rarely under pressure, amounts of leakage are assumed to be low. Sanitary sewers are typically not under pressure, therefore overall leakage is expected to be much lower than leakage from pressurized water mains (Lerner, 1986).

2.2.2.2 Water Storage Areas

A second connection between the internal and external system is the filling of water storage areas such as lakes, ponds, or marshes. The presence of these surface water features may have a tremendous effect on water table elevations. The use of collection basins for disposal of urban storm water runoff in Nassau County, New York has resulted in water table increases of up to 1.5 metres above pre development levels (Ku *et al*, 1992). Where these basins were not used on Long Island, groundwater elevations were found to be approximately 1 metre lower than predevelopment levels (Ku *et al*, 1992).

2.2.2.3 Irrigation

The third connection between the internal system and the external system is the use of the piped in water supply for irrigation of parks or household lawns and gardens. It has been identified that irrigation of lawns and gardens is a potentially large source of water available for groundwater recharge (Foster *et al*, 1994; Lerner 1990; and Rushton and Al-Othman 1994). Irrigation events are often completed based on variables such as air temperature, number of days since last irrigation, or day of week (Grimmond and Oke, 1986). Often very little concern to the soil moisture status or moisture capacity of the irrigated soil is considered. The use of automated systems can cause extensive Over-watering since the system is often programmed to irrigate at rates selected to meet maximum evaporative demands (Morton *et al*, 1988).

Very little of water applied to lawn is lost to surface runoff as turf grasses possess great water holding capacities (Beard and Green, 1994). A study completed by Gross et al.

(1990) found that runoff from turfgrass averaged 0.15 mm ha^{-1}/wk^{-1}. A study conducted by Hino et al. (1987) found that during extremely intense rainfall events of 100 mm h^{-1}, no overland flow was observed from a grassed lysimeter. Hino et al. (1987) found that grass roots acted as "pipes of high conductivity" that allowed water to be moved downwards quickly. Beard and Green (1994) noted that the role turfgrass serves in groundwater recharge is enhanced by the abundant populations of earthworms which can be supported. Earthworms increase macropore space by burrowing, further increasing infiltration rates. Hamilton (1990) attributed spatial differences in lawn infiltration rates to earthworm activity.

2.4 Outputs

The output side of equation 2.2 includes the variables runoff, evapotranspiration, and change in storage. Change in moisture storage refers primarily to the enhancement of local soil moisture status, and the recharge of groundwater. Change in moisture storage and the processes affecting it will be discussed separately.

2.4.1 Evaporation and Transpiration

Evaporation is the conversion of molecules of liquid water on a surface into atmospheric water vapour (Fetter, 1994; Wilson, 1990). Water is evaporated from all surfaces in an urban environment including; open water, soil, vegetation, and impermeable surfaces such as roads and roofs. Transpiration like evaporation is the exchange of liquid molecules of water into water vapour, completed through the leaf area of a plant. All plants require vast quantities of water to support growth and development. It is estimated that approximately 1000 kg of water is required to make 1 kg of wheat (Hobbs and Krogman, 1983). The majority of water absorbed by plant roots is transpired to the atmosphere through stomata in the plant leaves. In a turfgrass the stomata comprise only 2 to 3 % of the entire leaf area, yet the stomata are responsible for approximately 90% of total transpiration (Beard, 1973).

The process of transpiration is completed by plants to aid in cooling the plant through the evaporative process, and for transport of nutrients essential in the process of photosynthesis. Differentiating between evaporation and transpiration in the field is nearly impossible (Wilson, 1990). Thus the cumulative amount of evaporation and transpiration are combined and termed evapotranspiration. On a soil covered by turf grass transpiration is the process most important in depletion of soil water, accounting for up to 85% of all moisture lost (Beard, 1973).

The actual amount of evapotranspiration is the amount of water the plant removes from the soil, plus the amount of water evaporated from the soil itself. The total amount of evapotranspiration from a vegetated surface is controlled by solar radiation, wind, relative humidity, temperature, and water supply available to the plant.

The exchange of water molecules between a liquid and vapour requires a source of energy. This source of energy is solar radiation. Evapotranspiration will occur most readily under direct solar radiation. Blockage of solar radiation will slow the process. In a urban environment blockage of solar radiation due to shading from trees or buildings will result in different levels of evapotranspiration across the area.

Wind is also very important in the process of evapotranspiration. A study conducted by Grace and Quick (1988) found that equations used to estimate potential evapotranspiration that did not include a wind parameter significantly underestimated evapotranspiration, in regions affected by frequent winds, such as in southern Alberta. In an urban environment the total amount of wind received in an area will be influenced by surface features, or vegetation. Results from numerous studies listed in Landsberg (1981) and Chandler (1976) conclude that on average wind speeds are reduced in urban areas. Total wind speeds are most significantly reduced during summer period, due to the affect of deciduous trees (Landsberg, 1981).

Relative humidity of the air is an important factor in the calculation of evapotranspiration. As the humidity of air rises, the ability of the air to absorb water vapour decreases. Evidence provided by Landsberg (1981) shows that humidity in the city is lower than humidity in the country side. The lower humidity observed, is due to a reduced amount of vegetation, and higher temperatures. The lower humidity values, coupled with higher observed temperatures serve to reduce average dew deposits detected within the built up environment (Landsberg, 1981).

Temperature is an important control over evapotranspiration. Temperature like solar radiation provides energy to evaporate water. A rise in temperature will increase the evapotranspiration potential, due to an increase in the amount of available energy. An increase in air temperature will also raise the water vapour holding capacity of the air thereby affecting how much water can be absorbed. Air temperature in an urban climate is affected by the urban heat island effect. The built up area of cities absorb heat throughout the day, this heat is then released after sunset, slightly raising overall temperatures observed. This affect is enhanced by the reduction of evapotranspiration. Diversion of precipitation water into sewers, and reduction of plant cover due to roads and buildings, reduce the amount of evapotranspiration, thereby lowering the evaporative cooling effects (Landsberg, 1981). Chandler (1976) has reported that on average temperature increases in medium to large size towns in mid-latitude suburban environments are approximately 0.7 °C warmer. The presence of high wind conditions or low sunlight will serve to reduce urban heat island effects.

The soil moisture status of the soil is another control over the amount of evapotranspiration that will occur. Plants with greater access to available water will transpire more throughout the growing season. Water is extracted from the soil with no restriction until the soil moisture falls to between 50 to 80 percent of field capacity depending on soil type (Shuttleworth, 1994). At this point the hydraulic conductivity of the soil begins to decline, due to fewer available saturated pores to facilitate water movement. As the hydraulic conductivity begins to decline, transpiration rates decrease because plants are able to extract less water from the soil. The rate of transpiration declines until the soil reaches a moisture level where the moisture tension of the soil surpasses the osmotic potential of the plant roots. The point at which no further water can enter the root, is referred to as the wilting point, the wilting point will vary with type of vegetation (Brady, 1990; Fetter, 1994). The amount of soil moisture will vary dramatically across a urban region depending on factors such as soil type, amount of irrigation or precipitation received, and type and amount of vegetation.

Estimation of potential evapotranspiration rate has been the subject of many studies (Allen et al, 1989; Baier and Robertson, 1965; Doorenbos and Pruitt, 1977; Foroud *et al,* 1989; Jensen and Haise, 1963; Jury and Tanner, 1975; Penman, 1948; Priestly and Taylor, 1972). The purpose of each of these studies was to derive estimations of evapotranspiration based on measured weather variables, or measured volumes of water evaporated from class A evaporation pans. Variables considered in these calculations include solar radiation, wind, relative humidity and temperature, the importance of each in the process of evaporation has been discussed above. Many of the equations used to estimate evapotranspiration require local calibration. One such equation which has been calibrated for the southern Alberta Chinook region is a modified version of the Jensen Haise equation. The original equation was modified by Foroud *et al* (1989) to include a wind parameter. This equation uses the meteorological variables of daily solar radiation (RS), average temperature (TAVE), and daily wind run (W) in its calculation of daily potential evapotranspiration (PE). Daily potential evapotranspiration can be determined by the equation:

$$PE=0.00824\,(RS)(TAVG+7.1)0.00304(W) \qquad (2.3)$$

The values 0.00824, 7.1, and 0.00304 are locally derived constants specific to the Lethbridge region determined through mean maximum and minimum temperatures, and corresponding saturated vapour pressures as calculated for the month of highest mean temperature (Foroud *et al*, 1989). The derived constants are also modified for area elevation and humidity.

The resulting value of potential evapotranspiration must then be multiplied by a coefficient representative of the water usage of the crop, or plants, since these water usage rates differ between plant varieties depending on factors such as rooting depths and stage of growth (Hobbs and Krogman, 1983). A crop coefficient curve representing water usage of grass has been included as Figure 4.6

Despite the number of variables used in the calculation of evapotranspiration, estimates are subject to errors due to complexities involved in the process (Foroud et al., 1989). The actual amount of evapotranspiration is influenced by factors such as: aspect, vegetation type, and influence from surrounding areas.

Aspect alters the amount of evapotranspiration observed. Generally in southern Alberta, south facing slopes receive more intense solar radiation than north facing slopes, as observed by vegetation characteristics. Evapotranspiration in areas with this aspect (south facing slope) will be higher. Aspect is a factor which will vary spatially throughout a region, and thus have to be accounted for throughout the region of interest.

Vegetation also has a tremendous effect on the amount of evapotranspiration. Different types of vegetation will transpire water to the atmosphere at different rates (Hobbs and Krogman, 1983). Even among turfgrass species transpiration rate is variable (Beard, 1973). Transpiration from a vegetated surface has been shown to be proportional to the stomatal conductance and the vapour pressure deficit of the air (Jarvis, 1981). However, during extreme temperatures events the stomata may close thereby reducing transpiration rates (Beard, 1973).

A wide variety of vegetation exists in a urban area, however the dominate vegetation types are turf grasses and trees. The majority of the evapotranspiration models derived have been calibrated for grasses, and agricultural crops. Research has revealed that many of these equations cannot be applied to modelling evapotranspiraton loses from trees (Shuttleworth and Calder, 1979). Generally an area covered with trees will evapotranspire more water than an equally sized turfgrassed area, however the magnitude of this difference has not been determined (Calder, 1979). Modelling of transpiration and interception losses in forests has been completed by several researchers, (Calder, 1977; Calder, 1978; Pearce *et al*, 1980; Shuttleworth and Calder, 1979) however, the application of transpiration values recorded for a closed canopy forest could not be applied to an urban environment where the tree canopy is not closed. The canopy in a urban environment is better defined as a heterogeneous community where tree spacing is variable.

Surrounding areas may have a considerable impact on the amount of evapotranspiration. Estimations of evapotranspiration in urban areas may be under-represented due to "oasis" type advection (Grimmond et al., 1986). A study conducted by Oke (1979), suggested that urban evapotranspiration is increased due to advected energy from dry surfaces. The amount and variability of evapotranspiration affected by advected energy is very difficult to account for in a estimation of overall evapotranspiration.

2.4.2 Runoff

During a precipitation or irrigation event, the rate of water application may exceed the combined rates of interception, infiltration, and evaporation. Exceeding these rates will result in overland flow of the surplus water. Some of this overland flow will fill depressions, but the majority of flow, obeying laws of gravity, will be directed to the nearest stream channel. In an urban environment the overland flow is directed towards the storm sewer network.

In an urban setting the method widely used to evaluate overland flow is the Soil Conservation Service (SCS) Method (Pilgrim and Cordery, 1994). The SCS method has been adopted as the required procedure by many municipalities in the United States. For this procedure no runoff is assumed to occur until the initial abstraction capability of the surface in question is exceeded by the precipitation rate. Initial abstraction is all water loss before runoff will begin, these losses include: water detained in surface depressions, interceptions by vegetation and other surfaces, evaporation, and infiltration (SCS, 1986). Through experimentation it was determined that the initial abstraction could be correlated with soil and land cover parameters, and empirical equations could be adopted (SCS, 1986).

2.5 Storage

Water entering the soil system not lost as runoff or evapotranspiration will be stored. Storage first will occur in the rooting depth of the vegetation entering the soil through the processes of infiltration. Water contents in this root zone above the field capacity of the soil will be free to drain below the root zone. Water draining below the root zone is available for water table recharge. These processes are discussed below.

2.5.1 Infiltration and Soil Storage

Water enters the soil through the process of infiltration. The infiltration capacity of the soil is controlled by the rate at which water can be absorbed by a soil (Ward, 1975). It is the movement of soil water that ultimately controls the amount of water available for plants, runoff, and groundwater recharge (Rawls *et al,* 1994).

The rate at which water will move into a soil has been examined by Horton (1940). If a soil is dry, initial movement of water into a soil is high. The low moisture content of a dry soil facilitates the rapid movement into the soil through a labyrinth of relatively dry capillary passages. This process is termed the initial infiltration capacity (f_o) (Fetter, 1994). As soil moisture increases, and interstitial passages become filled with water, forces acting to draw water into soil will diminish until an equilibrium infiltration capacity (f_c) is reached. An equation to estimate this process was proposed by Horton (1940), reported by Fetter (1994) as:

$$f_p = f_c + (f_o - f_c)\, e^{-kt}$$

where

f_p is the infiltration capacity at time t
k is a constant representing the rate of decreased infiltration capacity with time.

Following a large infiltration event there will be relatively rapid downward movement of water for approximately two to three days, due to the hydraulic gradient (Brady, 1990). At the end of this two to three day period water has predominately moved out of the larger macropore spaces, and is held in the micropores. Water flow from a soil continues until no further water will drain due to the forces of gravity, this moisture condition is specified as field capacity. Water is held in a soil against the forces of gravity due to the forces of adhesion and capillarity collectively termed matric potential (Brady, 1990) or moisture potential (Fetter, 1994). Adhesion is related to attraction or absorption of water by soil solids causing a matric force (Brady, 1990). Capillarity is related to adhesion; as water molecules are pulled to soil solids, additional water molecules are pulled along due to the attraction of water molecules for each other. Together these forces act to hold water in the soil.

Water held in the soil against the force of gravity is eventually removed due to uptake from plant roots. As water content of the soil diminishes, the ability of plants to extract this water is impaired. In an attempt to conserve water, plants will wilt. The moisture content of the soil at which plants will wilt is not constant, but related to type of plant and soil hydrologic condition (Ward, 1975).

Water not available to plants is held very tightly, bound to soil solids. Soil water of this type is referred to as hygroscopic water. Hygroscopic water often exists in a soil in a non fluid state, moving through soils as a vapour (Brady, 1990).

2.5.2 Factors Affecting Infiltration Rates

The rate at which water can enter a soil is controlled by a number of factors including: pore size, antecedent moisture content, organic matter content, soil cover, surface sealing, and treatment of site (Hamilton, 1990; Partsch, 1992).

2.5.2.1 Pore Size

Pore size or pore space is the portion of soil that is occupied by air or water. It is determined by the arrangement of soil particles (Brady, 1990). Pore size is determined by particle size, and the degree of soil aggregation (Partsch, 1992). In a soil there are two types of pore sizes: micropores, and macropores. Micropores having a space less than about 0.06mm in diameter, are typically filled with water (Brady, 1990). In a fine textured, poorly structured soils, micropores will often dominate total amount of pore space. This can lead to problems with aeration as these water filled pores will not allow enough air through for root development and microbial activity (Brady, 1990).

Only through loosening of the soil, and increasing the total volume of macropores can better aeration be facilitated.

Macropores allow for the relatively rapid movement of air and water into the soil. Coarse textured soils such as sandy soils have rapid movements of air and water due primarily to the occurrence of macropores. Macropore spaces created by earthworm burrows have been attributed to wide variations of infiltration rates across a residential lawn (Hamilton, 1990).

2.5.2.2 Antecedent Moisture Content of the Soil

Antecedent moisture content of the soil is also very important to infiltration rates of the soil. Hino *et al.* (1987) demonstrated that the amount of runoff depended upon the initial moisture content of near surface soils. Similar results were obtained by Istok and Boersma (1986), this study demonstrated that the reliable prediction of runoff depended upon initial soil moisture content.

2.5.2.3 Organic Matter

Organic matter has a very important effect on soil infiltration rates. Numerous studies reported in Partsch (1992), have shown that infiltration rates are directly proportional to the amount of organic matter applied to the soil. Organic matter affects infiltration by impacting soil structure, soil porosity, and water holding capacity. Hino *et al.*(1987) found that development of roots affected macropore structure, developing a vertical pipe system along root surfaces.

2.5.2.4 Amount and Type of Vegetation

Vegetation is important to infiltration rates. Bare soils have lower infiltration rates due to plant roots or "pipes" of high conductivity (Hino et al. 1987). Vegetation that provides continuous cover over the soil, such as turfgrass, have a dramatic affect on infiltration rates. Runoff for a tobacco crop (providing incomplete ground coverage) averaged 6.7 mm ha^{-1} 4 $week^{-1}$; whereas runoff collect for turfgrass grown on the same site averaged only 0.6 mm ha^{-1} 4 $week^{-1}$ (Beard and Green, 1994). Higher amounts of vegetation in soils adds organic matter which aids in the vertical movement of water into the soil profile.

2.5.2.5 Surface Sealing

Surface sealing of a bare soil can effect infiltration characteristics of a soil dramatically. Intense rainfall can cause considerable compaction to an exposed soil, preventing the infiltration of water. This effect is enhanced by the tendency for small particles to be washed into void spaces (Wilson, 1990).

2.5.2.6 Treatment of the Site

The treatment of the site can be very important to infiltration characteristics. Often during construction the topsoil is removed prior to building excavation. Upon completion of the project the topsoil is reapplied. During construction of the site the soil is compacted by heavy machinery required for construction. The result of these building techniques is a disruption in soil profile (Partsch et al., 1993). Hamilton (1990) found that newly constructed lawns had the slowest infiltration rates due to disruption of soil profiles, and compaction of subsoil by heavy machinery. Older lawns that have had many years to develop have much faster infiltration rate due to such factors as; higher earthworm populations, better developed soil profile, increased macropores due to the development of turf rooting systems (Hamilton, 1990).

2.5.3 Percolation Beyond the Root Zone and Groundwater Storage

Water flow beyond the root zone is due to both gravity potential and moisture potential (Fetter, 1994). Most of moisture flow is due to gravity flow through interconnected pores or as films of water flowing along a particle surface (Fetter, 1994).

Flow due to moisture potential is due to gradients. Flow is directed from areas of high potential or high moisture to areas of low potential. Water flow is higher in moist soils as the gradient between moist and dry zones is greater (Brady, 1990). Overall, flow in soils is oriented in the direction of greatest potential. In dry soils, soil moisture potential may be far greater than the gravity potential.

The rate of water movement through a soil is controlled by the hydraulic conductivity. A complicating factor in the flow of water through a soil is that the hydraulic conductivity of the soil is dependant upon the moisture content of the soil. At saturated conditions soils take on a maximum value of hydraulic conductivity, with increasing air spaces, or a reduction in the overall moisture storage, the value of unsaturated hydraulic conductivity decreases (Domenico and Schwartz, 1990; Fetter, 1994). At low moisture storage values, the unsaturated hydraulic conductivity of a sand may be lower than that of a clay, as the particles of sand drain quickly leaving large pore spaces, whereas the clay particles may still have the majority of pores still in a saturated state (Fetter, 1994).

An unsaturated zone which extends from the ground surface to phreatic surface or water table is termed the unsaturated or vadose zone. Water movement through the vadose zone can take a couple hours, in the case of rainy areas with high water tables, to a number of years, for dry areas with low water table depths (Fetter, 1994). The rate of groundwater recharge in a area is highly variable due to the variability of hydraulic conductivity, and the size and moisture status of the vadose zone (Dagan, 1986; Dagan, 1982; Keller et al., 1988; Romeu and Noetinger, 1995; Rubin, 1995). Where the thickness of the unsaturated zone is lowest, such as in topographic lows, recharge can reach groundwater quickly, often resulting in groundwater mounds (Fetter, 1994).

Below the vadose zone and above the phreatic zone a near saturated zone of capillary water is found. The capillary fringe resulting from water rising from the water table due to capillary forces results in near saturated conditions of the soil above the water table itself. The movement of water through the capillary fringe displaces air in the pore spaces and results in a rise in water table elevation (Fetter, 1994).

Potentially, water moving through the vadose zone will encounter lenses or deposits of lower permeability amongst the surrounding material of higher hydraulic conductivity. These low hydraulic conductivity zones will intercept downward flow, causing accumulations of water. Water stoppage by clay pans is obvious, however any type of stratification in a soil will impede flow. Lenses of sands will also slow downward movement as the macropores of the sand will offer less attraction than the pores of a fine textured material (Brady, 1990). Any saturated layer above the main water table is termed a perched water table.

2.6 Urban Groundwater Problems

Despite the amount of area left impermeable due to urban development, the presence of high groundwater conditions has been well documented in many urban areas. A few of these problem areas identified are: Nassau County, New York (Ku et al, 1994), Riyadh, Saudi Arabia (Rushton et al, 1994), Domona, Israel (Karieli et al, 1984), several urban areas in the Netherlands (van de Ven, 1994), and Birmingham, Britain (Greswell et al, 1994). Groundwater problems in urban areas are due primarily to the impact urbanization has on the hydrologic cycle. Urbanization of an area results in (a) a large area of land becoming impermeable while (b) large volumes of water are imported from outside the region itself (Foster, 1990). Lerner (1990) identified that for drier climates with large imports of water, recharge to groundwater is likely to exceed that in rural areas. Recharge to groundwater can occur from a variety of sources typical of many urban areas. These sources identified by Rushton et al (1994) include: losses from water mains, underground reservoirs, surface reservoirs, lawn and garden irrigation, and rainfall.

High water table levels can have a dramatic effect on subsurface and surface structures in an urban environment. Groundwater levels above structure basement levels increases building cost dramatically. Johnson (1994) has identified construction problems associated with high water tables:

1. a reduction in soil bearing capacity
2. uplift water pressures under foundations and surfaces
3. swelling of clays
4. expansion of materials used in fill
5. leakage of water into basements and service conduits
6. loose material compaction and settling
7. load increase on basement walls
8. increased potential for chemical reactions on structures such as building pilings.
9. potential entrapment of hazardous gases
10. increased instability of excavations.

Solutions to each of these problems must incorporated into building design. Failure to consider any of these potential problems can result in expensive ameliorative measures. In the case of rising water tables, many of these problems are not foreseen, and are therefore not incorporated into building design.

2.6.1 Groundwater Problems Observed Within the Lethbridge Region

In the City of Lethbridge water tables measured prior to development are often dry well below 7 metres (Agra, 1995; EBA, 1996b; EBA, 1995; EBA, 1991; EBA, 1990; EBA, 1986). However after development water table depths are observed between

0.5 to 2.5 metres (EBA, 1996b; Ruban and Thomson, 1983). The high water tables observed have caused a number of problems throughout the area including: basement and corridor flooding, asphalt instability, increased flow to the waste water treatment plant, and slope instability

2.6.1.1 Flooding

High water tables surrounding Lethbridge buildings have resulted in flooding of basements and sub-surface corridors such as telephone and electrical conduits. Problems with basement flooding have prompted the city to enforce the installation of sump pumps to discharge water into storm sewers or foundation drainage collectors on all subdivisions constructed after December 31st 1994 (Environmental Utilities, 1994).

2.6.1.2 Asphalt Instability

High water tables have been observed beneath asphalt surfaces within the Lethbridge region. During a 1991 paving attempt of two University of Lethbridge parking lots, saturation of sub-base gravels and underlying till deposits prevented the use of heavy equipment.

2.6.1.3 Increased Discharge to Waste Water Collection System

Problems with increased flow to the city of Lethbridge waste water treatment plant have been attributed to elevated water table conditions. Prior to February 28, 1994, household weeping tile connections were connected to the waste water collection system. These connections are expected to be the cause of high discharges, especially evident during substantial precipitation events. High flow conditions in the waste water collection system are also responsible for basement flooding due to sanitary sewer backup.

2.6.1.4 Slope Instability

High water tables on sloping surfaces has caused significant damage through problems with slope instability. In the Lethbridge region problems with slope instability have been observed with increasing development adjacent to coulee walls (Ruban and Thomson, 1983; Thomson and Morgenstern, 1977). Figure 2.1 illustrates the result of excess water applied to a coulee slope. Coulee slope instability has been observed to occur as a result of:

-Overwatering of lawns and gardens

-leakage from subsurface water-carrying infrastructure

Figure 2.1: Coulee Slope Failure Due to Excess Water Application

-irrigation of farmland

-excessive placement of fill along coulee walls

-discharge of surface runoff water onto slopes

-ponding of water at top of slopes (Ruban and Thomson, 1983).

Excessive water along coulee slopes causes considerable problems because infiltrating water increases weight of the soil, and increases pore water pressures (Sidle et al, 1985). These processes serve to reduce the stability of the slope, by effecting forces involved in soil cohesion.

2.7 Summary

This chapter has examined the use of the urban water balance equation with particular attention to the components involved in the equation itself. These components consisted of inputs, outputs and change in storage. This chapter also discussed the implications of water table development on an urban area with emphasis on problems observed within the City of Lethbridge.

Chapter 3

STUDY AREA

3.1 Introduction

This section will describe the study area, providing insight into characteristics of the region potentially having an impact on many of the problems described in chapters 1 and 2.6.1. Of particular concern to the study of elevated groundwater tables is the local surficial geology, surface hydrology, hydrogeology, and land use. These topics and other relevant features will be examined to better understand the characteristics important to the region and the problems observed within.

3.2 Location

The location of the study area as depicted in Figure 3.1 lies on the west side of the Oldman River in the City of Lethbridge, Alberta. The study area includes the Varsity Village subdivision, and the University of Lethbridge campus. The area is approximately 450 ha, encompassing sections 22 through 27 in Township 8 Range 22 west of the Fourth Meridian. Varsity Village is surrounded by other subdivisions to

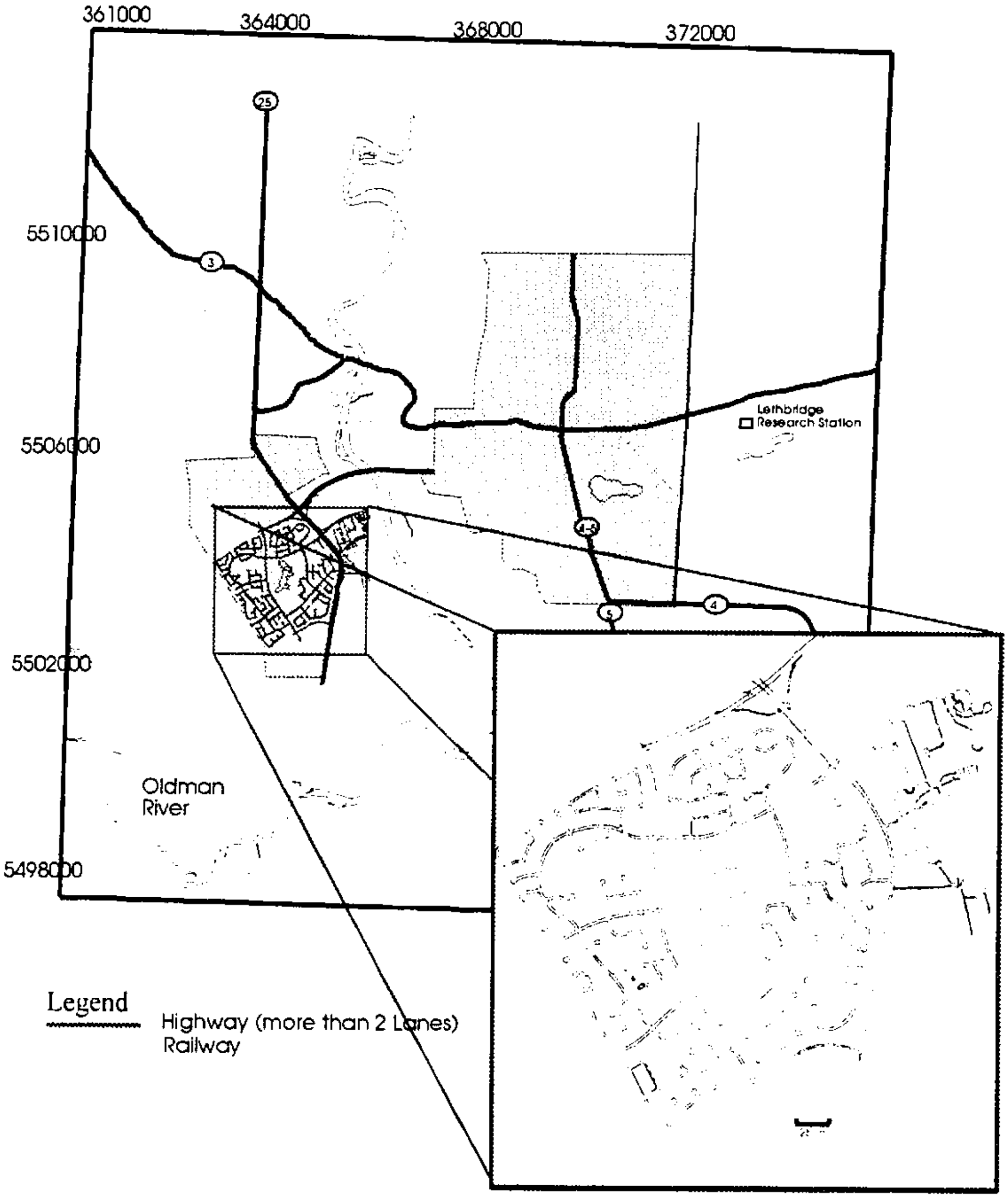


Figure 3.1: Study Area: Varsity Village Subdivision of the City of Lethbridge.

Projection: UTM
Scale: 1: 115 000 inset 1: 35 000

the north and south, and by the University of Lethbridge campus to the east. The area to the west of the study area is devoted to dryland agriculture.

The University of Lethbridge campus is located east of Varsity Village and west of the steep walled coulees of the Oldman River Valley. The main campus buildings have all been constructed directly on or near the coulee slopes leading towards the river.

3.3 Climate

The climate of southern Alberta is continental, with relatively hot summers, cold winters, and low annual precipitation (Dzikowski and Heywood, 1990) (BSk, Cold Steppe, in the Koeppen-Geiger system). The frost free period in Lethbridge region is typically above 115 days, with a growing season of approximately 185 days (Dzikowski and Heywood, 1990). Average annual precipitation in Lethbridge is 386.5 mm with approximately 62 percent of the total precipitation falling between May and September (Canadian Climate Normals 1961-1990). Approximately 40 percent of summer precipitation in the Lethbridge region is due to convective storms (Dzikowski and Heywood, 1990).

Despite maximum precipitation occurring during the summer period, as illustrated in the climograph included as Figure 3.2, hot summers with consistent dry Chinook winds result in moisture deficits throughout the summer months. The total class A pan evaporation from April to October is over 1300mm (Chang et al, 1990). Due to

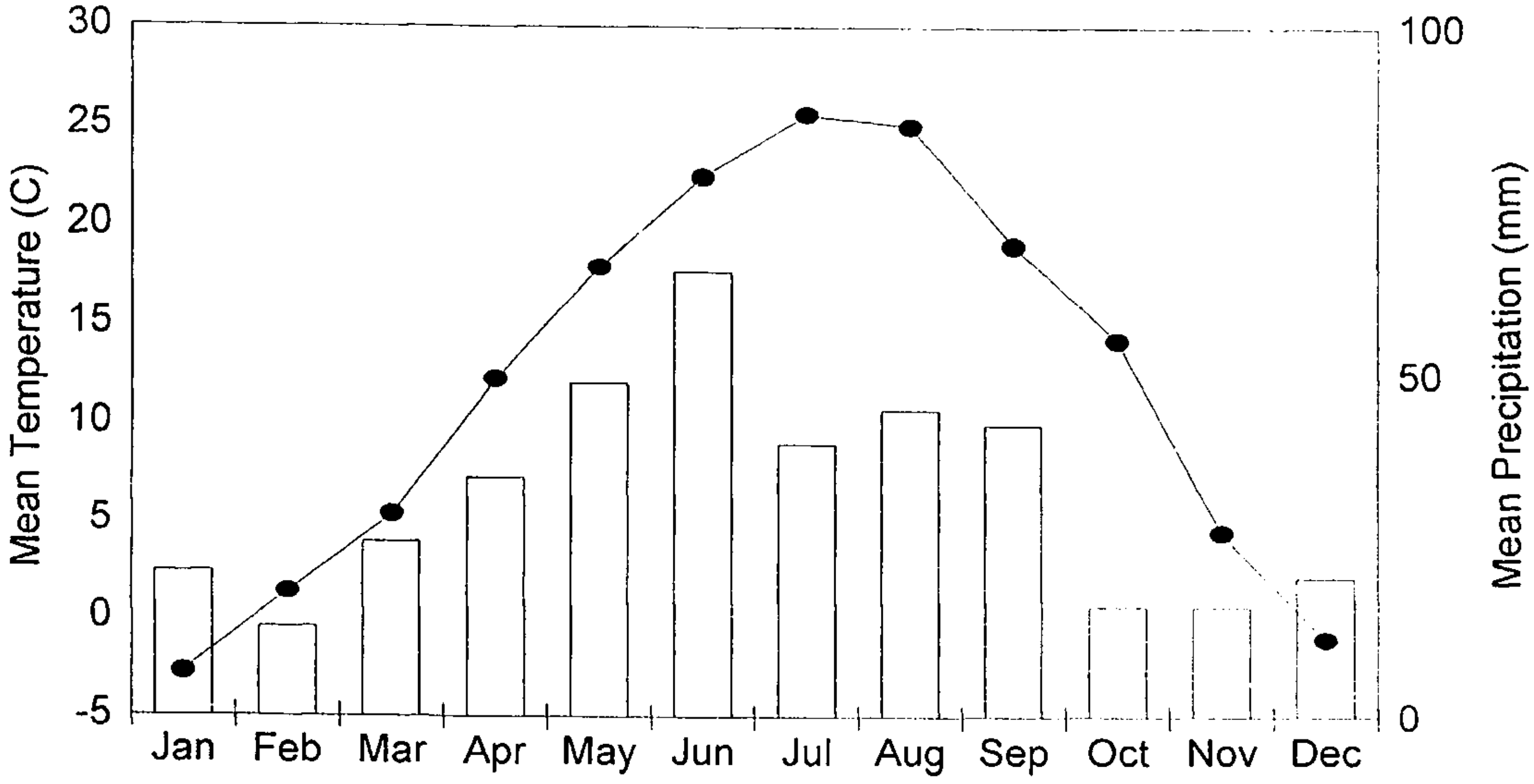


Figure 3.2 Climograph for the Canada Agricultural Research Station at Lethbridge, Alberta. Derived from Canadian Climate Normals, 1961-1990.

moisture deficits, irrigation is very important to the region for maintaining lush lawns and gardens.

3.4 Physiography

The area lies in the Alberta plains physiographic region. There are two main physiographic features in the study area, plains and valley slopes. The glaciated prairie flatland is gently undulating to flat. The region according to Kocaoglu and Pettapiece (1980) is morainal, gently undulating, and hummocky. The overall slope of the prairie in the study area is approximately 96H:1V. The prairie flatland in the study area has been altered to accommodate housing, roads, and parks.

Coulee formations of the Lethbridge region are illustrated as Figure 3.3, they consist of dry gullies which slope down from the prairie flatland to the river bottom, approximately 90 metres below. These valley slopes occupy approximately seven percent of the total study region. The steep walled valleys typically from 1.5H:1V to 2.0H:1V are ordinarily dry, occasionally carrying runoff water during periods of high precipitation or substantial snowmelt (Sladen and Joshi, 1988). Two forms of valley walls are apparent in the Lethbridge area: a main coulee system where the Oldman River is found, and dry tributary coulees. The main valley wall was formed as a result of high volumes of discharge associated with glacial meltwater. The tributary valleys

Figure 3.3 Aerial Photograph of the Study Area, Illustrating Coulee Formations East of the Region of Study.

Date of Photograph: October 1995
Scale: 1: 20 500

were formed due to drainage of various glacial lakes, and snow melt and runoff during wet periods of the Holocene.

The tributary coulees generally run parallel or subparallel, tributary to the Oldman river (Ruban and Thomson, 1983). The alignment of the dry relatively steep tributary coulees is typically N 70° E. This orientation suggests that although the coulee formations are related to the large quantities of meltwater available as Laurentide glaciers retreated from the area, coulee alignment is strongly influenced by the powerful Chinook winds characteristic of the region. The following model for coulee development was proposed by Beaty (1975).

(1) Current drainage patterns were established 14 000 to 12 000 years ago, the deep valleys had sufficient relief for initiation of coulee development.

(2) Powerful southwesterly winds affected windward topographic surfaces by: retaining less snow, and creating a microclimate within a few centimetres of the surface that is considerably drier than leeward slopes due to solar radiation and high wind conditions. These two effects result in a significant reduction in vegetation, thereby allowing these surfaces to be more susceptible to erosion.

(3) Narrow, shallow surface furrows carved by wind driven snow and rain were enlarged by surface runoff on southwesterly facing valley walls. This condition is suspected to be enhanced during the fall and spring when vegetation is dead or dormant offering very little surface protection against erosive disturbances.

(4) Enlargement of the coulees is expected to continue due primarily to occasional surface runoff from summer storms, and periodic slumping.

The present day shape of local coulees is being affected by mass failure events observed on coulee slopes along Oldman River valley walls, or among coulees draining into the River valley itself. Typical failures occurring along the Oldman River are due to erosion of material at the toe of the slope primarily due to river meanders (Thomson and Morgenstern, 1977).

Failures along coulees tributary to the main river valley in the Lethbridge area can be attributed to anthropogenic interference (Ruban and Thomson, 1983). Rise of groundwater levels adjacent to coulee slopes due to application of water from irrigation results in an increase of soil weight, and an increase in pore water pressures thereby reducing the effective stress within the soil.

The amount of available moisture provides an important control over slope failures in the Lethbridge region. Prevailing westerly winds which allow for the accumulation of snow drifts on slopes of northeasterly, easterly, and southeasterly aspect, and minimal insolation receipt on slopes of northerly aspect results in the concentration of moisture on slopes of northerly, northeasterly, easterly, southeasterly aspect (Beaty, 1972). Due to the concentration of moisture on these slopes, landslide activity in the Lethbridge region has predominately occurred on slopes with a northerly, northeasterly, easterly, and southeasterly aspect (Beaty, 1972).

A physiographic feature common to area coulees is the development of terracettes along steep coulee slopes. These step-like features are approximately 50 cm to one metre in width, and vary from centimetres to two metres in height (Ruban and Thomson, 1983). It is expected that the development of terracettes may enhance slope stability by providing a toe load (Thomson and Morgenstern, 1977). They are preferentially developed on the cooler, and wetter north-facing slopes of tributary valley walls.

3.5 Vegetation and Soils

The natural vegetation as classified by Dzikowski and Heywood (1990) is Prairie Grassland. Prior to farming in the region, and later urban development, typical vegetation was short prairie grasses. Before construction of the University of Lethbridge an ecological survey was carried out along the coulees in west Lethbridge. Grass types observed in undisturbed coulees and prairie flatland in the study area included: *Stipa comata* (Needle and Thread), *Poa secunda* (Sandberg Bluegrass), *Koeleria cristata* (June-grass), *Agropyron smithii* (blue-joint), and *Bouteloua gracilis* (Blue grama grass). A number of low growing forbs were also noted: *Hymenoxys acaulis* (Butte marigold), *Cerastium arvense* (Field chickweed), *Musineon divaricatum* (Leafy musineon), *Pentstemon nitidus* (Smooth pentstemon), and *Artemisia frigida* (pasture sage). Two cactus were also identified in the study: *Opuntia polycantha* (Prickly Pear), and *Mammalari viparia* (Purple cactus). Cactus are typically found on the drier south facing slopes of area coulees.

On valley slopes small trees and shrubs are abundant in areas of higher soil moisture content. Shrubs observed included: *Prunus virginiana melanocarpa* (Western Chokecherry), *Amelanchier alnifolia* (Saskatoon), *Symphoricaros occidentalis* (Western Snowberry), and *Ribes aureum* (Golden Currant). These areas of high soil moisture are often found in locations of groundwater discharge, areas where surface runoff may be ponded, or areas of snow drift accumulation (Ruban and Thomson, 1983). In the river valley stands of cottonwood trees (*Populus sargenti* and *Populous angustifolia*) are common.

The farmland area directly west of Varsity Village is typically planted with wheat, barley or canola crops. Vegetation common to the urban area includes: various turf grasses, vegetable gardens, ornamental bushes, coniferous and deciduous trees.

Soils of the region are typically Dark Brown Chernozemic soils developed on glacial till material. The soils of the study area are composed of fine loamy morainal material, and fine loamy to fine silty lacustrine veneer (Kocaoglu and Pettapiece, 1980). Area soils are classified as "readymade" as the lacustrine mantle is very thin or not present, due to frequent outcrops of the underlying till. Readymade-Lethbridge soils generally occur along the Lethbridge end moraine which is described and illustrated below.

3.6 Surface Hydrology

The study area contains five surface water features illustrated in Figure 3.4. These water features include: the Oldman River (the only naturally occurring surface water feature), University of Lethbridge irrigation reservoir, campus wetland, Nicholas Sheran lake, and Rotary Brook (irrigation canal flowing from Nicholas Sheran lake to the campus irrigation reservoir). With the exception of the Oldman River, water bodies within the study area are not considered natural as they require periodic inputs of water to sustain consistent levels. Each of these water features may have an influence on water table elevations in adjacent areas.

The Oldman River is situated approximately 65 metres below the campus. The river does not have a substantial impact on groundwater levels in the study area as the water level is far below the elevation of Varsity Village. However, water diverted from the river is the source of the water stored and applied in Lethbridge.

The University of Lethbridge irrigation reservoir is located in the south-east of the study area, approximately 150m from the valley wall. It was created in 1971 during construction of the campus. The reservoir is reported to be lined (Wells, pers. comm., 1994). Potential leakage from this reservoir may cause instability to local coulees, eventually impacting housing constructed directly east, above the coulee.

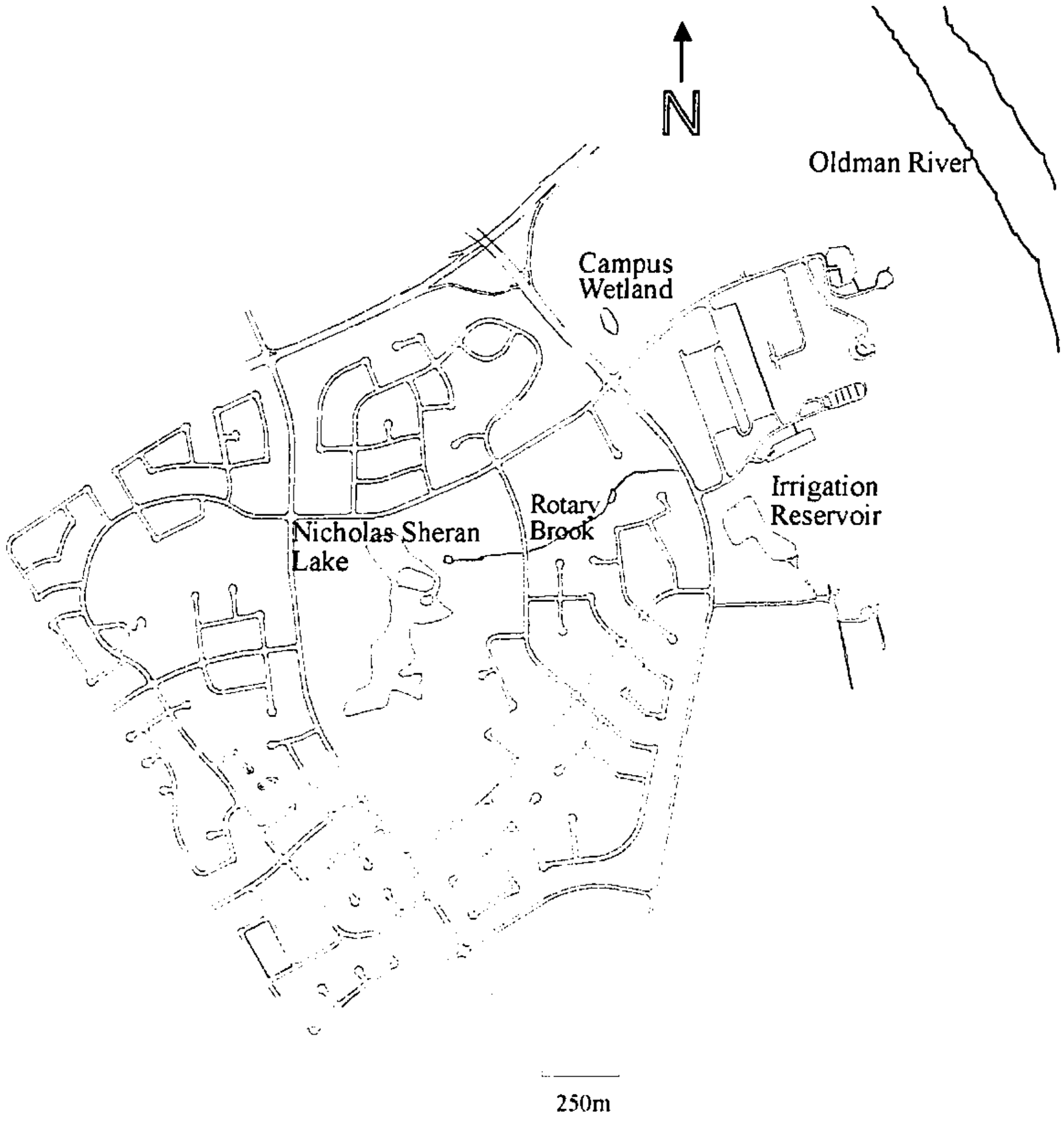


Figure 3.4: Water Features Within the Varsity Village and University of Lethbridge Campus Area

Scale: 1:20 500

The campus wetland is located on the corner of Valley road and University drive in the north of the study area. Water elevation in the wetland is maintained by an irrigation pipe flowing into the area. This water body is not lined.

Nicholas Sheran Lake is located in the centre of the study area. The lake was created in the mid 1970's for use as a recreational area, and as a source for irrigation water for local parks. The lake level is maintained by water inflows from the Lethbridge Northern Irrigation District. The lake has not been lined to prevent water flow.

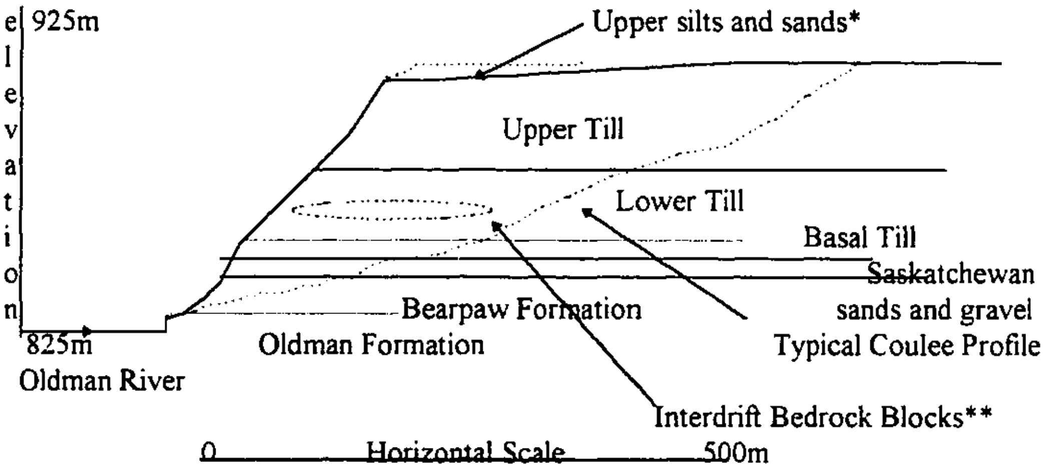
Rotary Brook is an irrigation canal that flows between Nicholas Sheran Lake and the campus irrigation reservoir. The lined canal is in use throughout the irrigation season.

3.7 Regional Geology

Downcutting by the Oldman River at Lethbridge has resulted in an almost continuous exposure of glacial deposits. The exposures offered by the steep valley walls have allowed geologists in the Lethbridge region to describe both glacial, and preglacial deposits (Horberg, 1952; Stalker, 1963; Stalker, 1968; Stalker, 1975). Along the steep walled coulees deposits of Cretaceous, Tertiary, and Quaternary age, are exposed. Rich exposures of the Lethbridge Coal Member allowed for the early development of the settlement at Lethbridge. This section will describe the geology of the region based on the findings of numerous studies in the region and field work.

3.7.1 Bedrock Geology

This section will discuss bedrock exposed along the banks of the Oldman River as observed east of the University of Lethbridge, and therefore expected below the study region. Bedrock below river level will not be discussed in this paper as these deposits do not have an impact on the development of perched water table conditions observed in the upper till sediments, detailed discussion of deposits below river valley level in the Lethbridge area is available in Irish (1967), Nielsen (1971), Scracek (1993), and Tokarsky (1974). A cross section of the deposits observed below the University of Lethbridge can be seen below as Figure 3.5.



*The upper silts and sands (lacustrine deposits) observed extensively in eastern Lethbridge was only observed in isolated pockets, or not at all in Varsity Village.
** Interdrift bedrock blocks do not appear in the section analysed below the University of Lethbridge, but may be present elsewhere in the Lower Till.

Figure 3.5 Regional Surficial Geology Adapted from Sladen and Joshi (1988), and Field Work.

Bedrock outcropped along the banks of the Oldman River below the University of Lethbridge is of Upper Cretaceous age, a photo of the section analysed below the University has been included as Figure 3.6. It is composed of light gray sandstones belonging to the Dinosaur Park Formation, and the overlying dark gray friable marine shales of the Bearpaw formation (Barendregt, 1997). The Dinosaur Park Formation termed the Oldman Formation in Nielsen (1971) and Tokarsky (1974) is composed of interbedded light gray to white weathering sandstones, with thin ironstone and limestone bands in some areas. The Dinosaur Park Formation was deposited in fresh water by numerous rivers emptying into a large inland sea. In the upper part of this

Figure 3.6: Coulee Section Below the University of Lethbridge Campus

formation coal beds and carbonaceous shale are observed, including the Lethbridge Coal Member or the Galt seam (Ruban and Thomson, 1983; Scracek, 1993). At the section examined below the University of Lethbridge deposits of the Dinosaur Park Formation were observed approximately 2 metres above river level, overall deposit thickness as reported in Scracek (1993) is up to 210 metres.

Directly above the Dinosaur Park Formation or the Oldman Formation lie the beds of the Bearpaw Formation. This formation was deposited in marine conditions under the fluctuating Bearpaw Sea during the late Cretaceous. The Bearpaw Formation is composed of dark gray weathering shale and silty shale, clayey sandstone, with spheroidal ironstone concretions and thin bentonite beds (Irish, 1967). Deposits of bentonite in the formation point to evidence of volcanism during the period of deposition. Chemical weathering of the ash through denitrification, oxidation and reduction and through the process of hydrolysis have resulted in the bentonite deposits observed.

Much of the Bearpaw Formation outcropping below the University of Lethbridge was weathered and breaks up into small angular fragments. Reducing conditions at the time of sedimentation have resulted in a very soft formation, with evidence of pyrite (Scracek, 1993). The high amount of weathering associated with this deposit may also be related to the very long period of exposure (Upper Cretaceous to Oligocene) associated with this deposit (Scracek, 1993). Thomson and Morgenstern (1977) identified that many of the landslides observed along the banks of the Oldman River had been initiated in the soft, marine deposited Bearpaw Formation. The Bearpaw Formation represents the upper-most layer of the bedrock formation, outcropping along the coulee slopes below the University of Lethbridge Campus. At the outcrop observed below the University of Lethbridge the thickness of this deposit was approximately 10 metres.

Deposited above the bedrock in the Lethbridge region are the Saskatchewan Sands and Gravels. These sands and gravels are the oldest surficial deposit of the region, composed of loose, clean, well-sorted river gravels and sands (Stalker, 1963) The Saskatchewan Sands and Gravels have been described by Horberg (1952) as being composed mainly of quartzite and chert with smaller amounts of argillite, limestone, Crowsnest Volcanics, and Cretaceous sandstones and shales. Preglacial rivers flowing eastward, and northeastward, from the emerging Rocky Mountains deposited these preglacial gravels and sands beginning in the Oligocene (Stalker, 1968). Deposition continued through the Tertiary into the Quaternary until interrupted by the advent of the first Laurentide ice sheet (Stalker, 1968). Presently, the City of Lethbridge sits directly above a 10 to 16 km wide preglacial river valley (Ruban and Thomson, 1983). The thalweg of this preglacial river system, defined by Geiger (1965) as the Lethbridge Valley, runs directly below the study area. At the section observed below the University of the Lethbridge the thickness of this deposit is approximately 3 metres.

Approximately 2000-2500 years ago this deposit was exposed due to downcutting of the Oldman River. Once this deposit was exposed significant dewatering of the aquifer took place (Scracek, 1993). Dewatering of this aquifer would have resulted in additional water available to the Oldman River and consequently rapid downcutting occurring during this period.

The presence of gravels above the bedrock has been observed to have an overall stabilizing effect on coulee slopes. Thomson and Morgenstern (1977) observed that the presence of preglacial river valleys allowed for drainage through the gravels thereby lowering water tables, decreasing porewater pressures, and therefore increasing overall slope stability. The ability of this deposit to act as an effective drain has made the deposit useful as an aquifer, known locally as the Lethbridge Aquifer. In the Lethbridge area, the aquifer is dry in many zones. This can be attributed to discharge into the Oldman River, and drainage into mine works (Sracek, 1993). Conditions of this aquifer below the study area has not been studied, however the depth to this aquifer is far below the deposits affected by perched water table development. The extent, thickness, and hydrogeology, of the buried preglacial valleys in the Lethbridge area has been examined by Geiger (1965), Nielsen (1971), and Sracek (1993).

3.7.2 Glacial Geology

The presence of a preglacial river valley below the study area allowed for deep drifts of glacial till to be deposited. Today these glacial till deposits form the ground surface, ultimately controlling present water table conditions observed within the study area. This section will present the glacial history of the study area providing insight into geologic conditions affecting the developmert of perched water table conditions.

Although is has not been determined unequivocally, it is expected that the study region was covered by great ice masses at least twice, and the thick deposits of tills were laid down as a result (Barendregt, 1997). The first glacier to advance into the region was of Illinoian age. The deposits left by this glacier lie directly above the Saskatchewan Gravels in the study area. The deposit, named the Basal till by Horberg (1952), and the Labuma Till by Stalker (1962), was also described by Nielsen (1971) as a thin highly indurated till. The Basal till is very hard, and columnar in structure. In many locations it is harder than the Oldman or Bearpaw Formations below (Nielsen, 1971). The Basal till was subjected to great consolidation pressures due to the weight of the overlying ice. Upon dewatering of the till, high calcium carbonate concentrations resulted in a very hard, massive till, cemented with a calcareous material. Below the University of Lethbridge the thickness of this deposit is approximately 2 metres.

Deposited above the Basal Till in the study area is the Lower Till (Nielsen, 1971) referred to as the Maunusell Till by Stalker (1963). It is expected that ice advances into the region filled preglacial valleys with this deposit (Nielsen, 1971). The Lower till forms the main body of till material deposited in the region (Horberg, 1952). The Lower Till was possibly deposited during the same glaciation that deposited the Basal till, since it is very similar: very dense, jointed, indurated, calcareous, and high in clay (Horberg, 1952). The upper part of this till sheet is a brownish gray or buff color (Nielsen, 1971). The colors observed in the upper part of the till sheet are due to oxidation. Typically, oxidation of this till sheet is observed to an average depth of three metres (Horberg, 1952). Oxidized zones within the till sheet are most likely due to groundwater flow, especially groundwater flow through fractures as examined by Hendry *et al* (1986). The lower part of the till is un-oxidized and dark gray in color.

The Lower Till has been subdivided into a Number 1 and Number 2 till (Ruban and Thomson, 1983). Subdivision of this till is based on the occurrence of large discontinuous blocks of Cretaceous bedrock in some areas of Southern Alberta. However, subdivision of the Lower Till in absence of the interdrift bedrock blocks has proved quite difficult (Nielsen, 1971).

A massive interdrift bedrock block has been studied by Stalker (1975) at Laundry Hill, Lethbridge, located approximately 1 km east of the study area on the opposite bank of the Oldman River. The bedrock block is of the Oldman formation, composed of a soft sandstone, with lignite and bentonitic clay. The massive block is observed on many tributary coulee faces on both the east and west side of the river valley. Below the study area sheets of interdrift bedrock blocks could be present, however no such block was observed at the exposure examined below the University of Lethbridge, or in drill holes.

The large sheet of bedrock between the till deposits at Laundry Hill in Lethbridge was removed from a deposit somewhere north or northeast of the city and carried by glacial ice to its present location (Barendregt, 1997). The occurrence of this bedrock sheet on both sides of the river indicates that the deposit may have been over one square kilometer in size, potentially weighing greater than 25 000 000 tons (Stalker, 1975). The occurrence of the bedrock block between sheets of the same till indicates that the block was transported by a readvance of the glacier.

Deposited above the Lower Till in most regions in the Lethbridge area are the Lenzie Silts. The Lenzie Silts composed predominately of sand, were deposited in a cold sterile lacustrine environment as the sediments are devoid of any plant material or fossils. This stratified ice marginal deposit forms the boundary between the Upper, Wisconsin age tills and the Lower Illinoian tills. It was deposited in front of an advancing, oscillating, or retreating ice mass. However, it is not yet certain whether these sediments were deposited at the retreat of the Illinoian glaciation, or during the advance of the Wisconsin glaciation. Thickness of the deposit varies between 3 and 10 metres (Nielsen, 1971). Thin deposits of the Lenzie Silts occur in areas where the surface of the Lower Till is higher. The deposit was not observed in the section studied below the University of Lethbridge. The lack of Lenzie Silts at this section could be due to a pre-last glaciation high point in the lower till, or to removal of the deposit by subsequent glacial events.

The final till deposits observed in the Lethbridge region are the Upper Tills (Nielsen, 1971) referred to as the Buffalo Lake Tills by Stalker (1962). These tills were deposited during the late Wisconsin. Upper Till deposits have a maximum thickness in the Lethbridge region of 40 metres (Nielsen, 1971). The Upper Till consists mostly of clays and silts. It includes all the till of the Lethbridge end moraine (Horberg, 1952). The Lethbridge end moraine, which forms the present ground surface beneath the study area, represents the maximum extent of the glacial ice which deposited the Upper Till in the Lethbridge area. The location of the Lethbridge moraine in relation to the study area and the city of Lethbridge has been provided as Figure 3.7.

The Upper till differs from the Lower Till as it is more bouldery in composition, and less compact or jointed (Horberg, 1952). The oxidized portion of the surface till is buff in color. Where the till is not oxidized its color is dark gray. Sand and gravel units are present within the till, found predominately near the base and top of the till (Nielsen, 1971).

In the study area the Upper Till forms the ground surface except in isolated locations where it has been buried by the Upper Silts and Sands. Deposition of the Upper Silts and Sands is related to proglacial lake Lethbridge formed in front of the retreating ice. Deposition of the Upper Silts and Sands on the Lethbridge moraine is isolated to lower pockets or sections. Proglacial lake Lethbridge rose before the retreating glacier until a meltwater channel developed, draining the lake. The melt water channel

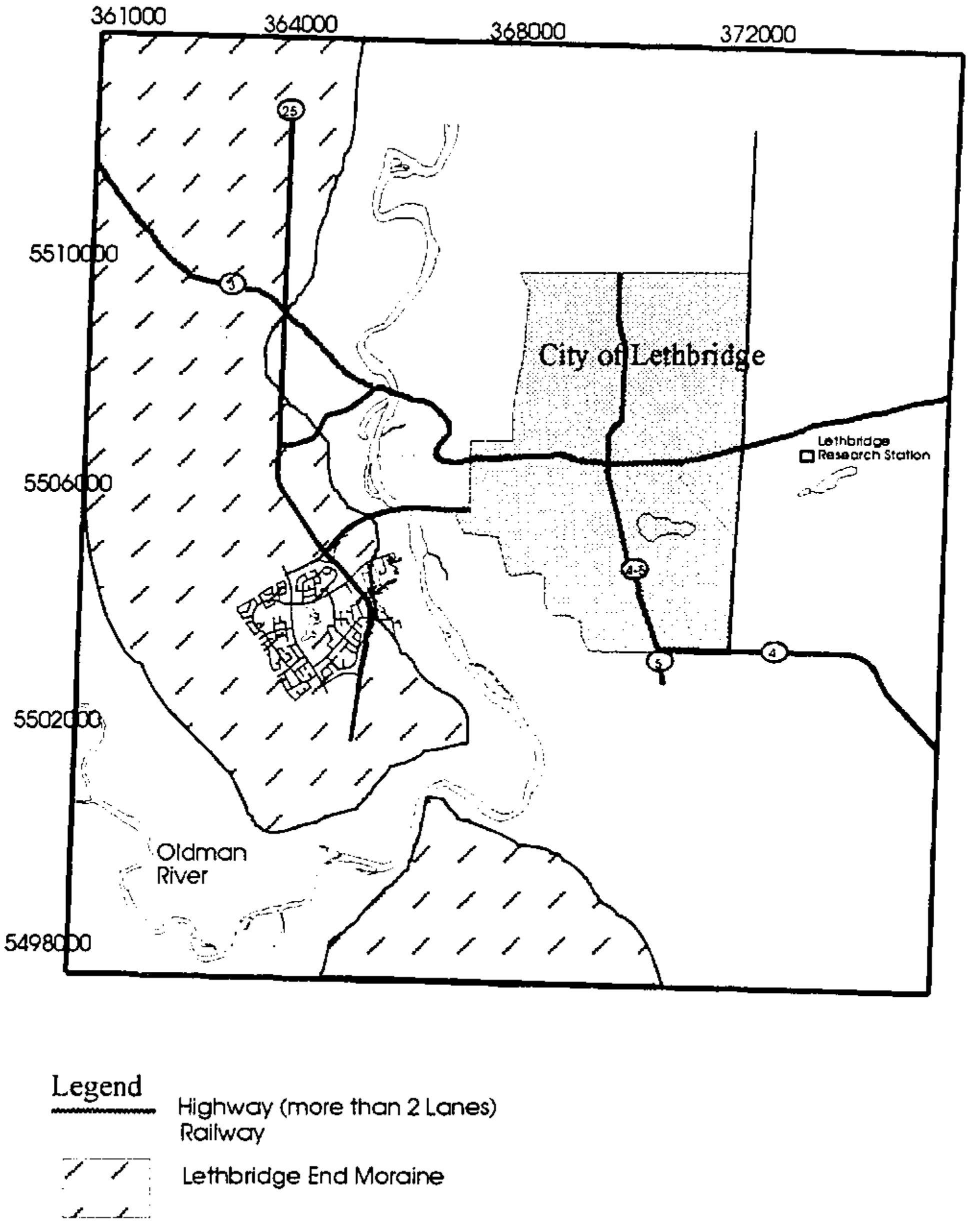


Figure 3.7: Location of the Lethbridge End Moraine in Relation to the Study Area

Projection: UTM
Scale: 1:115 000

was formed in what is now the southern portion of the Oldman Valley in Figure 3.7, dividing the Lethbridge moraine along this route (Stalker and Barendregt, 1988). Flow at this time was opposite to present-day flow of the Oldman river. As the lake was drained away the Oldman river appropriated this segment, reversing flow to follow the regional slope, draining northerly along the moraine and further deepening the channel observed near Lethbridge.

3.8 Regional Surficial Hydrogeology

Generally groundwater studies in southern Alberta divide the observed till into two hydrogeological units, an upper weathered unit, and a lower non-weathered unit (Hendry, 1982; Hendry, 1988; Sracek, 1993). The lower non-weathered unit has a very low hydraulic conductivity. Vertical water movement in the lower unit was estimated at approximately 2 to 6 m per 1000 years (Hendry, 1988). Therefore for the purposes of most groundwater studies, the lower nonweathered unit is assumed to act as an impermeable boundary (Hendry, 1988).

In the Upper weathered unit, vertical groundwater velocities from three sites in southern Alberta were calculated to be approximately 0.1 m yr^{-1} (Hendry, 1988). Several studies (Keller et al, 1988; Keller et al, 1989; Keller et al, 1991; and Schwartz et al, 1987) have discussed the spatial variability of permeability due in part to till fracturing discussed in Hendry et al (1986), and Grisak et al (1976). Occurrence of fractures has been shown to provide conduits for water to be transmitted relatively quickly through the unsaturated and saturated zones (Hendry, 1983). The occurrence of fractures has potentially allowed for long term irrigation in southern Alberta, with few overall problems with salinization, or perched water tables in the root zone (Hendry, 1982).

Groundwater movement in the upper weathered till unit at Lethbridge is not expected to be high, due to the presence of high perched water tables noticed throughout the city of Lethbridge (Berg *et al.*,1996; EBA Engineering Consultants Ltd., 1996a, 1996b; and Geiger, 1962). In a study conducted by Geiger (1962) perched water table conditions in a southside area of the city were blamed on inputs from nearby irrigation, low soil permeability, and low relative surface relief of the area.

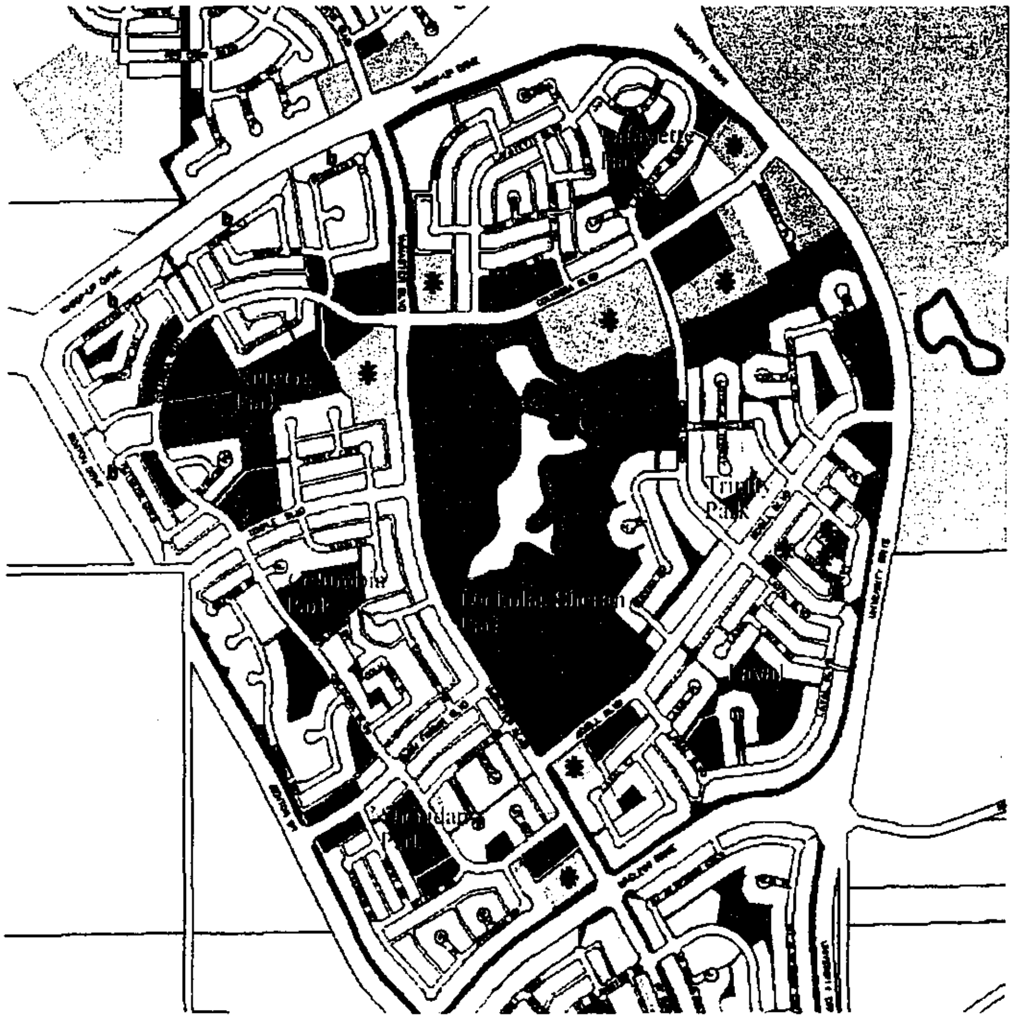
Lateral movement of groundwater in the Lethbridge area is very slow. Studies by Hendry (1988), and Sracek (1993) found that lateral groundwater movement in southern Alberta tills to range from 1 to 9 metres per 1000 years, although lateral flow may occur relatively quickly through isolated sand lenses. The importance of lateral flow in tills of the study area has not been studied. However, the majority of flow in southern Alberta tills is expected to be downwards related to fractures, and intergranular flow.

Recharge to groundwater through percolation of water through the root zone is most evident during the spring in the Lethbridge area. Sommerfeldt and MacKay (1982) found strong evidence for downward movement of water to 1.2 m in an area 20 km north of Lethbridge. In this study, soil at a 1.2 metre depth was at field capacity every spring between 1964 and 1977, even during dry years. A study by Chang *et al.* (1990) demonstrated that winter precipitation is highly correlated with spring soil moisture conditions in the Lethbridge region.

Land use practices such as cultivation also have a dramatic effect on the amount of recharge that can occur. A study by Christie *et al.* (1985) demonstrated that cultivation practices significantly increase the amount of moisture observed in the upper three metres of the soil profile, as compared to natural prairie.

3.9 Land Use

Land use in the Varsity Village area is illustrated in Figure 3.8. Land usage in Varsity Village is primarily low density housing, with an average lot size of 572 m^2. Total land usage of the Varsity Village is summarized in Figure 3.9. Of individual lots, it was determined that approximately 52% of the lot area was covered by lawns or gardens, and under irrigation. The total area within Varsity Village irrigated by households (the total area of lawns and gardens) was 55.5 ha.



Low Density Residential
▨ Medium Density Residential (between 37 and 75 dwelling units / ha)
■ High Density Residential (Over 100 dwelling units / ha)
■ Parks
Comprehensively Planned Medium Density Residential (37 dwelling units / ha)
■ Public Building District (eg. Education, Religious Assembly, Government Services)
■ Local and Neighbourhood Commercial Districts
☐ Roadways and Alleys
■ Lakes

Figure 3.8: Land Use in the Varsity Village Area

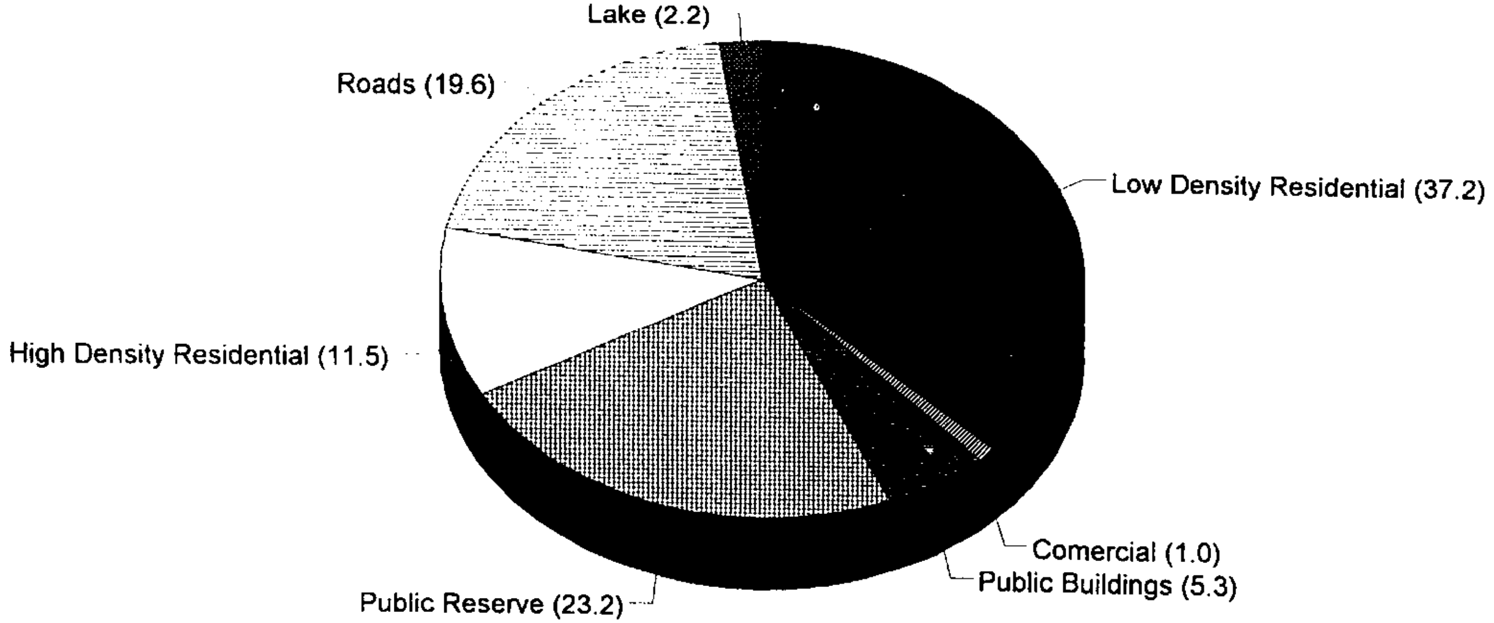


Figure 3.9 . Land Use in Varsity Village, West Lethbridge. Values represent percentage of total land area (287.4 ha)

Table 3.1. Amount of Lawn Coverage for Each Zone in Varsity Village

Zone	*Lawn Coverage (ha.)*
Low Density Residential	55.5
High Density Residential	6.9
Public Buildings	9.5
Public Reserve	66.1
Commercial	0.1
Roads	0.0
Total Lawn Coverage	138.25

Land usage at the University of Lethbridge is primarily undeveloped, and non-irrigated land. Irrigated turf grass is found around the campus buildings, on the athletic field, and at Devonian Park. Areas to the north and south of the campus are not under irrigation.

3.10 Summary

This chapter has detailed characteristics of the region potentially having an impact on development of perched water table conditions currently evident. Notable attributes of the study region potentially impacting the conditions observed are: surficial water bodies present, low hydraulic conductivity of surficial deposits, and landuse characteristics. Further focus on these attributes is detailed in chapter four below.

CHAPTER FOUR

METHODS OF STUDY

4.1 Introduction

This chapter will review the techniques utilized to evaluate the water balance of the Varsity Village area. Initially, discussion will focus on the physical methods used in this study, with emphasis on the field and laboratory techniques applied. The remainder of this section will emphasize the calculation techniques derived and implemented to carry out the urban water balance of this region.

4.2 Field Work

Field work in this study consisted of borehole drilling and water well installation, soil sampling, well and lake level monitoring, and infiltration experimentation. Each of the field methods applied will be discussed in detail below.

4.2.1 Borehole Drilling and Water Well Installation

Between May 1994 and June 1996, 37 boreholes and water wells were installed throughout the study region. The location of water wells appears in Figure 4.1. All boreholes were drilled with an auger drill stem, at 5 and 15 centimetre diameters.

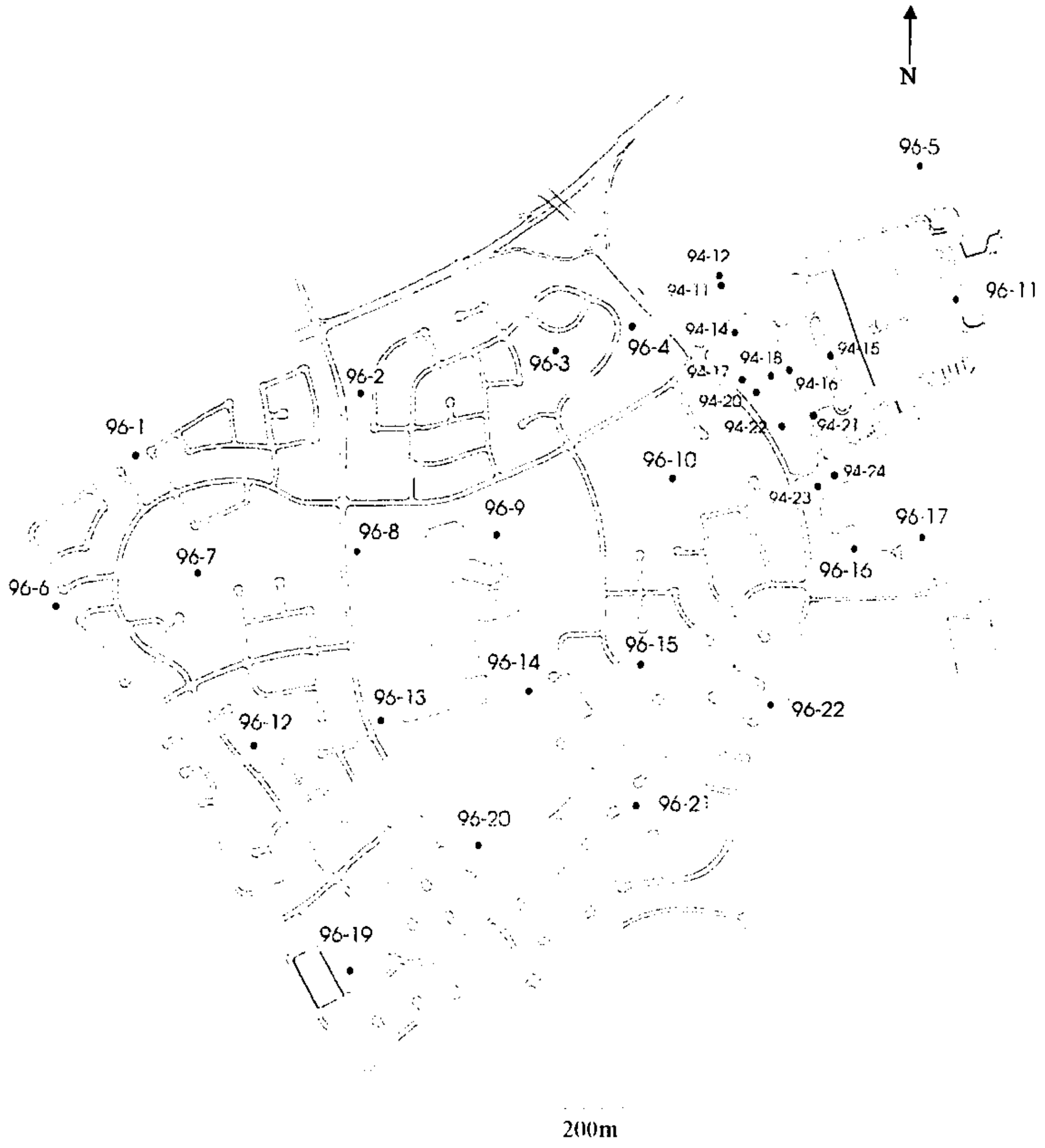


Figure 4.1 Water Wells Installed in the Varsity Village and University of Lethbridge Areas.

Scale: 1:17000

The boreholes drilled at a five centimeter diameter were drilled using a motorized post hole drill fitted with steel extension rods. Wells drilled by this method typically had a maximum depth of 3.2 metres. No soil samples or well logs were obtained from these boreholes. Wells completed by this method include 94-11, 94-13, 94-16, 94-19, 94-21 and 94-23.

The remainder of boreholes drilled within the study region were completed by the use of a drill truck using a 15 centimetre auger stem. Soil samples and well logs were obtained. Well logs including soil moisture, texture, well depth, and installation date have been included as Appendix A.

Slotted PVC pipe was inserted into each of the boreholes. The wells installed in June 1996 have 2.5 cm PVC tubing, with slotting cut every 30 centimetres, beginning one metre from the surface. Pea grade gravel fill was inserted around the PVC tubing to within thirty centimeters of the surface. The remaining 30 cm was filled with a bentonite seal to prevent surface runoff from infiltrating into the well.

Wells installed in June of 1994, are composed of 3.8 cm tubing with regular 30 cm slotting below 1 metre from the surface. Fill around the PVC tubing consisted of backfill. The top 30 centimetres of each well was sealed with concrete.

Borehole locations were selected to provide uniform coverage over the study area.

Wells were also installed in certain areas to assess water movement from observed surface water features. Water well location, and elevation was determined by surveying from known bench marks.

4.2.2 Soil Sampling

Soil samples were obtained from a number of locations within the study area. Samples were obtained during drilling at depths of 30 cm and then at one metre increments to the bottom of the hole. The remainder of soil samples brought in were obtained through the use of an Oakfield probe having a diameter of 20mm. Each sample was taken off the drill stem or from the Oakfield probe and then sealed in a zip-lock bag. The sample was then placed into a ice filled cooler, until it could be transferred to a freezer. Many of the samples obtained were analysed to determine water content, and texture. The analysis techniques used are described in section 4.3.

4.2.3 Well Monitoring

In the study area a number of monitoring wells had been installed prior to the wells drilled in May and June 1994. All wells monitored as a part of this study have been included as Figures 4.2 and 4.3. Wells monitored in Varsity Village are illustrated in Figure 4.2, and wells monitored on the University of Lethbridge campus are illustrated in Figure 4.3. Frequent and detailed records of water table elevations for the University of Lethbridge are available primarily after May of 1994. Records of water table elevations in the Varsity Village area are available in geotechnical reports held by local engineering companies. Details of water levels prior to construction are

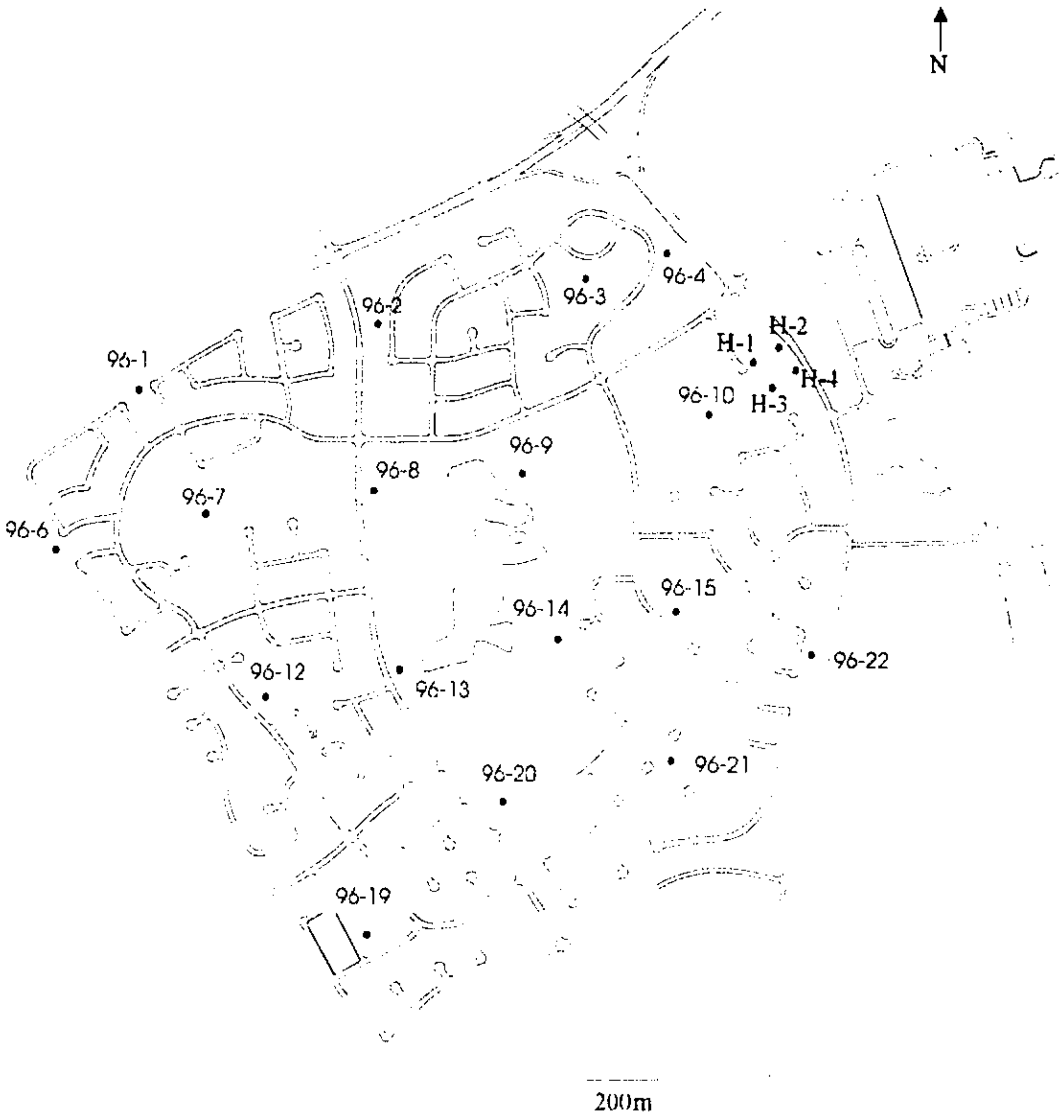


Figure 4.2 Water Wells Monitored in the Varsity Village Area.

Scale: 1: 17000

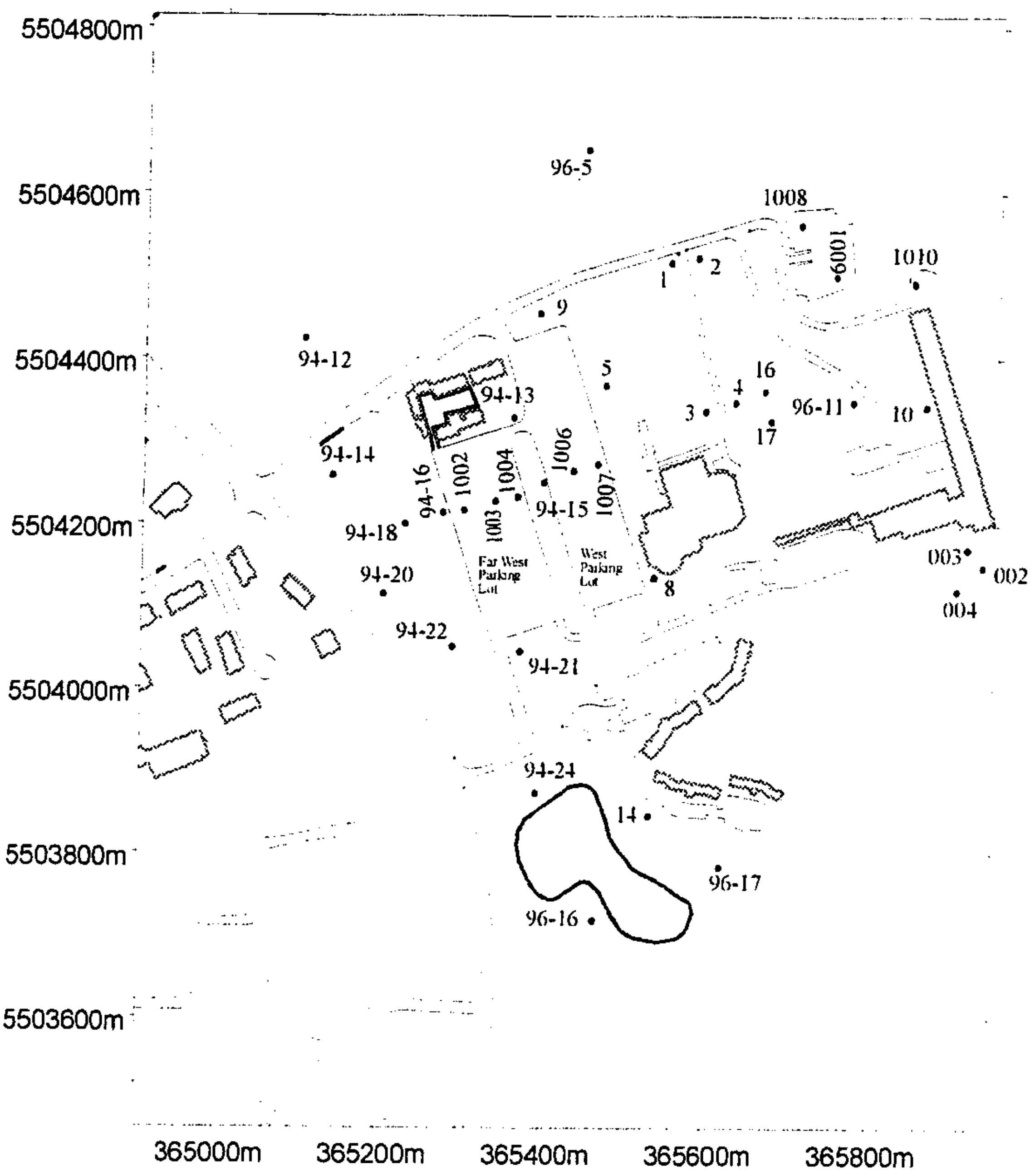


Figure 4.3 Water Wells Monitored on the University of Lethbridge Campus

Scale 1:7500
Projection: UTM

infrequent as previous bylaw requirements did not always state that such testing be completed for the construction of new subdivisions.

Water levels at each of the wells was determined through the use of a Water Level Indicator (Slope Indicator Co. model 51453). Depth to water level was determined by lowering an electrode down the well casing. Contact with the water allows an electrical current to pass through the battery operated device thus signaling the operator. The level at which a sound or light was observed was then noted by measuring to the nearest marked increment on the lowered electrical wire. During the months of peak irrigation the wells were monitored two to three times per week.

4.2.4 Lake Level Monitoring

Lake levels were monitored daily at Nicholas Sheran lake between October 15, and December 15, 1996. Lake levels were not measured during the summer period due to frequent fluctuations of water elevation caused by continual withdrawals for irrigation.

Water elevations were obtained from a stilling well constructed from two PVC pipes. The stilling well consisted of a 4.5 cm outer tube approximately 1.2 metres in length. This outer tube was slotted at 1 cm intervals and inserted into approximately 50 centimetres of water. The pipe was driven approximately 30 centimetres into the lake bottom. Pea grade gravel was then inserted into the lower 40 centimetres of the pipe. A diagram of the constructed stilling well has been included as Figure 4.4.

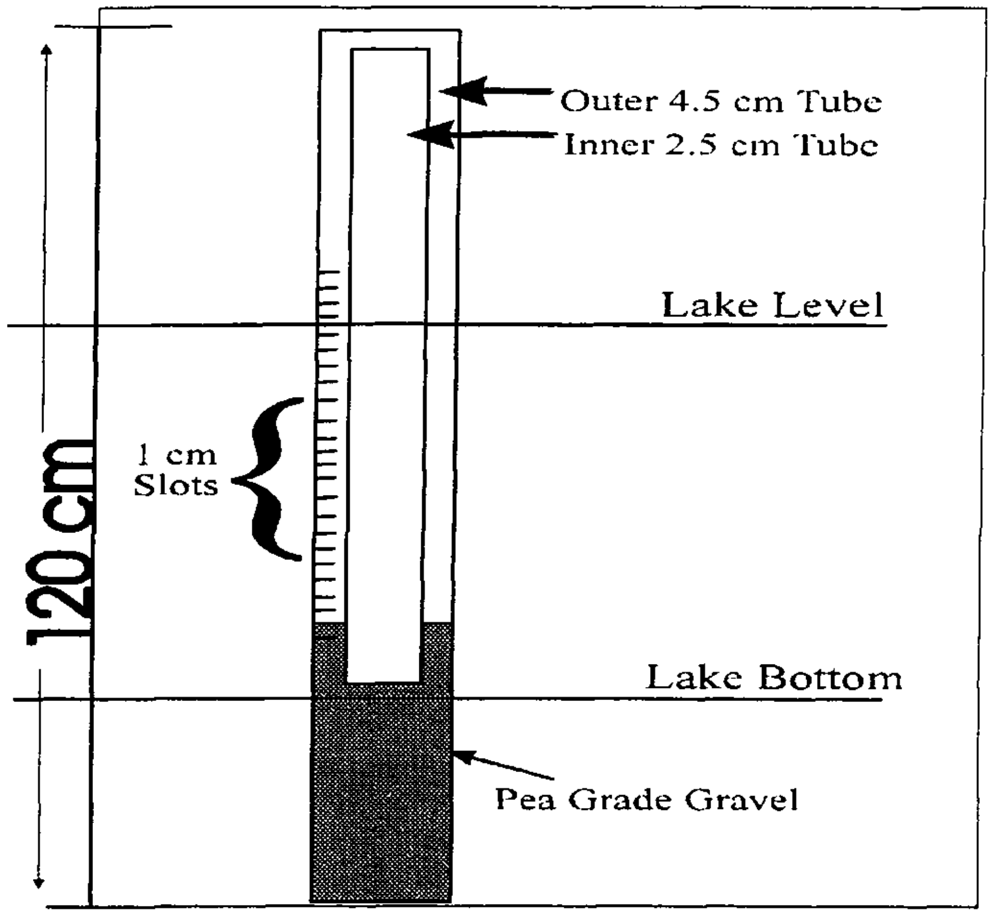


Figure 4.4: Stilling Well Constructed for Lake Level Monitoring

A second unslotted pipe approximately 90cm in length and 2.5cm in diameter was then inserted inside of the first tube. This pipe was pushed no more than 10cm into the pea gravel. The outer pipe was held in place by a nail driven through the pipe into a wooden beam supporting a bridge.

Measurements of lake level were taken from within the inside pipe, to the nearest millimetre. Measurements were taken using a length of cardboard which was inserted flush with the outer tube. The elevation of the outer tube was determined through surveying from known bench marks.

4.2.5 Infiltration Experimentation

To estimate turf grass infiltration rates, a one metre diameter iron ring approximately 40cm in height was created. Two lengths of 20 gauge steel were rolled and then welded to form the infiltration ring. The end of the ring used to penetrate the soil surface was beveled to ease insertion into the soil. A large diameter ring was used for infiltration experimentation in order that the ratio between the water entry value, h_{cr}, and diameter is essentially zero (Bower, 1986). Rings of smaller diameters (less than one metre) are less accurate due to divergence of flow. A ring of larger size was not created due to practical considerations, including transport and handling.

Once a site for experimentation was located, the area was saturated with a garden hose for approximately ten minutes. This initial saturation aided in the insertion of the infiltrating ring. Then the constructed ring was pounded approximately 5cm into turf (Bouwer, 1986; Taylor, 1991). Pounding was done as carefully as possible to prevent disturbance of the soil.. Then approximately 25 centimetres of water was added to the ring. This water was allowed to infiltrate for a period of at least one hour, refilling the ring if necessary (Hamilton, 1990; Taylor, 1991). Complete saturation of the area inside of the ring is necessary to measure minimum infiltration rates.

After the one hour period, measurements of infiltration rates were obtained from a ruler placed inside the ring. When the level of water in the ring reached approximately 5-7cm above the ground surface a stopwatch was started (Taylor, 1991). The depth of water from which infiltration measurements were obtained was kept as low as possible to prevent the effects water depth can have on infiltration rates (Bouwer, 1986). Time required for the water level to drop 5 mm increments was recorded. Once the water level reached approximately 3 cm above the ground surface, the ring was again refilled to approximately 7-10 cm above the ground, and a second set of readings recorded (Taylor, 1991). The infiltration rate was determined by calculating the average amount of time per 5 mm level drop recorded over the two trials.

4.3 Laboratory Testing

From the wells drilled, and soil samples obtained within the study area, the laboratory methods used in sample analysis will be discussed below.

4.3.1 Gravimetric Soil Water Content Test

Soil samples which were obtained from various depths were removed from the freezer and were allowed to thaw for a period of two hours. The thawed sample was weighed and then placed in an oven for a period of 24 hours. After this period the samples were removed and weighed once again. The gravimetric water content was determined by:

$$\theta_g = 100(W_w/W_s) \tag{4.1}$$

where

θ_g is the gravimetric water content (percentage)
W_w is the mass of water in the soil (g)
W_s is the mass of soil particles (g) (Fetter, 1994).

Soil moisture data for each of the wells is included in Appendix A.

4.3.2 Soil Texture Analysis: the Hydrometer Method

Soil texture of the obtained samples was determined through the hydrometer method as outlined in Bouyoucos (1962) and Day (1965). The method of Bouyoucos (1962) was chosen as the time requirements necessary to complete particle size analysis suggested by Day (1965) were prohibitive given the large number of samples obtained. Unfortunately after all testing was completed it was discovered that the values of clay contents obtained using this method may be overestimated as discussed in Sur and Kukal (1992). For this reason, the results of soil testing completed must be interpreted with some caution.

The oven dried soil sample was broken up and then passed through a 2 mm sieve to remove particles over this size. Materials less than 2 mm were weighed and then mixed with hydrogen peroxide (H_2O_2) to oxidise all the organic matter in the sample. 40mL of a dispersing solution and approximately 500mL of distilled water were added to the sample. The dispersing solution was 40 mL of a Calgon solution, prepared by dissolving 38 grams of Calgon and 8 grams of Sodium Carbonate (Na_2CO_3) in one litre of distilled water.

The resulting sample was mixed vigorously for approximately 10 minutes. The mixed sample was then passed through a 63 micron (0.063mm) sieve in order to partially remove the sand fraction of the sample. The removed sand was oven dried for four hours and then weighed to determine its percentage of the total weight of the sample. The remaining soil in solution and dispersing agent was added to a one litre cylinder. The cylinder was then filled to exactly one litre with distilled water.

A second cylinder containing one litre of 40 mL of Calgon solution and distilled water was also set up as a control cylinder to calibrate the hydrometer. The hydrometer was released in this control cylinder and the hydrometer reading was recorded. This reading is referred to as HD.

The cylinder containing the mixture of soil, Calgon solution, and distilled water was mixed thoroughly. After mixing, the contents were allowed to settle for a period of 40 seconds, at which time a hydrometer reading was obtained. The corrected hydrometer reading taken at 40 seconds is divided by the amount of dry soil taken subtracted by the amount of sand sieved from the soil itself, and then multiplied by 100. This is the percentage of material still in suspension at the end of 40 seconds (Bouyoucos, 1962) The percentage of soil particles in suspension at a given time period was calculated by the equation:

$$W\% = 100\,\frac{(Hx - HD)V}{WS} \qquad (4.2)$$

where:

Hx	Hydrometer reading at time x, gram/litre
HD	Hydrometer reading for Calgon solution
Ws	Weight of soil solids, grams
V	Volume of suspension, litres.

Once this calculation was completed for both 40 seconds and two hours, the amount of clay could be determined. The percentage of silt is obtained by the difference between the two values (Bouyoucos, 1962). Once the respective percentages are known, soil texture can be determined through use of the soil texture triangle. An example of the soil texture triangle is illustrated in Figure 5.1.

4.3.3 Determination of Field Capacity, Wilting Point, and Hydraulic Conductivity

The approximate value of field capacity and wilting point of the soil was determined through the equations developed by Oosterveld and Chang (1980). The moisture content of the soil at field capacity (θ_{fc}) can be estimated by the equation:

$$\theta_{fc} = (25.713 + 0.469C - 0.184S - 0.0329D)C^{-0.080} \qquad (4.3)$$

where:

C= clay portion in percent by weight
S= sand portion in percent by weight
D= depth of the sample in cm (Oosterveld and Chang, 1980).

Wilting point (θ_{wp}) or soil moisture at 1500 kPa as suggested by Oosterveld and Chang (1980) was estimated by the equation:

$$\theta_{wp} = 4.035 + 0.299C - 0.034S - 0.016D \qquad (4.4)$$

The average percent of clay and sand taken at a 30cm depth from all of the samples collected and analysed throughout the study area was used in calculation of field capacity and wilting point. In the study area, particle size analysis was completed on 32 samples taken at a 30 cm depth. The sampling sites has been included as Figure 4.5. The mean value of sand and clay percent obtained from all samples was used to account for spatial heterogeneity observed throughout the study area. Variation in soil texture type was found to occur at different scales across the area.

Saxton *et al* (1986) developed an equation from non linear multiple regression techniques to estimate hydraulic conductivity of a soil based on texture. The equation has been found to provide reasonable estimates of hydraulic conductivity through the soil textural ranges where $5\% \leq \%$ sand $\leq 30\%$ with $8\% \leq \%$ clay $\leq 58\%$ and $30\% \leq \%$ sand $\leq 95\%$ with $5\% \leq \%$ clay $\leq 60\%$ (Saxton, *et al*, 1986). All of the samples obtained for this study fell within this range. Hydraulic conductivity (K) for a soil

based on the soil texture was determined through the equation by Saxton, *et al* (1986):

$$K = 2.778 \times 10^{-6} \{\exp[12.012 - 0.0755 (\%\ \text{sand}) + [-3.8950 + 0.03671 (\%\ \text{sand}) - 0.1103 (\%\ \text{clay}) + 8.7546 \times 10^{-4} (\%\ \text{clay})^2] (1/\theta)]\} \qquad (4.5)$$

4.4 Determining Household Flow to City Wastewater Treatment Facility

At the outset of the study it was suggested by city officials that household weeping tile connected to city sanitary sewers was contributing to high flows observed during

Figure 4.5 Soil Sampling Locations in the Varsity Village Area.

Scale: 1: 17000

precipitation events. Daily wastewater flow data (F_d) from the City of Lethbridge wastewater treatment facility was obtained from March 29, 1991 to September 16, 1996. The Flow data considered waste from all city users: commercial, industrial, and residential. Since flow from weeping tile from households was the objective of this component of the study, flow from households had to be subtracted from overall waste flow to the wastewater treatment facility.

Flow from households was determined by obtaining the average flow from Sundays (F_s) in each month. The day Sunday was chosen as it is expected that flow from industry (an expected major user of water) would be lowest on this day, and therefor household flow (F_h) would predominate.

To determine household flow on a daily basis the monthly average week-day flow (F_w), or flow to the wastewater treatment plant occurring Monday to Friday, was determined. This value was then subtracted by the total amount of expected household flow (F_w - F_s), resulting in an estimate of the total amount of industry flow (F_i). The daily flow occurring on weekdays (Monday to Friday) as measured at the wastewater treatment (F_d) plant could then be subtracted by the estimate of industry flow (F_i), to provide an estimate of household flow (F_h).

In order to attempt to remove practically all sources of flow other than flow originating from households, the average amount of daily flow, [as measured on

Sundays, or as calculated above (F_d -F_i)] expected from households for each month was subtracted by the average flow measured on December 25, 1992-1995. It is expected that December 25th represents the one day in the year where daily flow (F_d) is roughly equal to household flow (F_h).

The average difference between monthly average daily flow and December 25th flow was calculated for the months of October through April. The average difference was then subtracted from the monthly average daily flow for each month, resulting in an estimate of total monthly household flow not due to weeping tile. The average difference between monthly average flow and December 25th flow was only obtained from the months October through April as flow from weeping tile is expected to be lowest during this period, due to an observed lowering of water tables (see discussion in section 5.3 below).

In order to determine the amount of flow due to weeping tile during the irrigation season (May through September) the average monthly flow October through April was then subtracted from the corrected monthly average daily flow for each month in the irrigation period, May through September. The total amount of flow above average daily flow October through April was expected to be due to flow from household weeping tile connected to the city sanitary system. These results are reported in section 5.4.2.

To determine the total amount of monthly flow from individual households, the average monthly daily flow recorded in $m^3 \times 10^3$ was divided by the total number of households in the city of Lethbridge and then multiplied by the number of days in that month. For the irrigation season the total amount of monthly flow expected from households was determined by calculating the amount that average daily flow May through September exceeds the average daily flow October through April. The amount by which average daily flow May through September exceeds average daily flow October through April, was divided by the number of single detached dwellings in the City of Lethbridge, and then multiplied by the number of days in that month. The total number of single detached dwellings was used rather than the total number of households because the total number of households includes apartment dwellers. Apartments generally have much lower turfgrass areas than individual households, so irrigation flow to weeping tile from households in apartments or row housing is expected to be very low.

Total volumes of water discharged to the city during as a direct result of precipitation events was calculated by determining the average monthly discharge to the wastewater treatment plant for weekdays and for weekends. Monthly average flow was subtracted from flow on days receiving 10 or more millimetres of rainfall on that day or the previous day. Ten millimetres of precipitation was chosen as the critical value as precipitation values below this did not significantly affect observed flow, unless high amounts of precipitation had been received in days prior to this precipitation event.

Precipitation from the previous day was considered to account for lag time in receiving flow from entire city, or to account for precipitation occurring during the evening, but affecting flow observed in the following day. Lag times in excess of one day were observed for larger precipitation events, possibly due to backups in the system due to the abundant flow.

4.5 Calculation of Park Irrigation and Contribution to Water Tables

The total amount of irrigation applied in excess to park areas was evaluated using a water balance equation derived from the equations used by Kincaid *et al* (1979) and Morton *et al* (1988):

$$SM_i = PPT_i + IRR_i - PET_i - R_o + SM_{i-1} \qquad (4.6)$$

where:

SM_i = change in soil moisture storage on a given day,
PPT_i = total amount of precipitation on a given day,
IRR_i = total amount of irrigation to park on a given day,
PET_i = calculated amount of potential evapotranspiration as computed by the modified Jensen-Haise equation on a given day,
R_o = total amount of runoff
SM_{i-1} =soil moisture storage on the previous day.

Using the approach of Kincaid *et al* (1979) and Morton *et al* (1988) percolation through the root zone was expected to occur anytime SM_i exceeded θ_{fc} (determination of field capacity was discussed above in section 4.3.3). The depth of the root zone used for the calculation of soil moisture was 61 cm, as recommended by Beard (1973). The total amount of percolation for each day was added to the monthly estimate of percolation through the root zone. The methods used to evaluate each of the variables defined in equation 4.6 will be discussed below.

The water balance could only be evaluated for Varsity Village parks on scheduled irrigation programs. These parks included: Rutgers, Sheridan, Trinity, Laval, Columbia, and Lafayette. Nicholas Sheran Park, although irrigated, is currently not on a scheduled irrigation program, therefore average values of irrigation calculated from the other parks were used to calculate a water balance. Location of parks examined in this study are illustrated in Figure 3.8.

4.5.1 Precipitation

Meterological data used for the computation of PPT_i and PET_i for this study was recorded at the Canadian Agricultural Research Station at Lethbridge, approximately 15 km away from the study area. Location of the Canadian Agricultural Research Station in relation to the study area is illustrated in Figure 3.1.

4.5.2 Irrigation

The total amount of irrigation (IRR_i) for each day was determined by estimating the amount of water applied (m^3) divided by total irrigated area (m^2), resulting in a total depth of water applied (m).

The estimated quantity of water applied to the park was determined by obtaining the number of sprinkler heads in each park. Each park has several different types of sprinklers, set up to best water the given area. Once the number of sprinklers and the type of each sprinkler was obtained, the projected output of each sprinkler in gal/min was multiplied by the number of minutes each sprinkler was left on, as determined through irrigation schedules provided by city staff. The total area of the park was determined through the GIS package PAMAP.

Currently the irrigation schedules of Varsity Village parks account for precipitation events. Following precipitation events in excess of 25 mm, irrigation is discontinued for the remainder of the week (Peterson, pers. Com., 1996). To account for this practice in the water balance model, no irrigation is assumed for five days following a precipitation event of this magnitude.

A portion of the water applied never reaches the intended area under irrigation. This water is lost due to wind drift and evaportation (Cuenca, 1989). High winds can carry water droplets away from the irrigated area. Losses due to wind drift will increase the higher the water is directed into the air as wind velocities increase logarithmically with height (Wilson, 1990). Evaporation of the irrigated water will also occur, especially to small droplets formed under high irrigation system operating pressures (Cuenca, 1989). To account for the amount of wind drift and evaporation the total depth of irrigation was multiplied by the percentage of wind drift and evaporation calculated. The total amount of wind drift and evaporation was calculated by Cuenca, (1989):

$$L_s=[1.98(ND)^{-0.72} + 0.22(D)^{0.63} + 3.6 \text{ X } 10^{-4}(h)^{1.16} + 0.14(U)^{0.7}]^{4.2} \quad (4.7)$$

where:

L_s is evaporation and wind drift, as a percent,

ND is nozzle diameter, in millimetres,
h is the nozzle operating pressure, kPa,
D is the vapour pressure defcit, kPa,
U is the wind velocity, in m/s at 2 metres.

Physical measurement of the nozzle diameter (ND) was very difficult without removal of sprinkler, therefore ND was determined by obtaining the wetted diameter of each sprinkler, and the operating pressure of the system (h). These variables were recorded on the irrigation system design blueprints.

A regression analysis was performed for the nozzle diameter recorded in Table 4.1, and the predicted wetted diameter, at the system operation pressure (h) recorded on the design blueprints. At 240 kPa (typical operation pressure) r^2 was equal to 0.99.

Table 4.1 Wetted Diameter from Sprinkler Nozzel*

Pressure kPa	Wetted Diameter in metres Nozzle Diameter (mm)							
	2.381	**3.175**	**3.572**	**3.969**	**4.366**	**4.763**	**5.159**	**5.556**
240	21.3	22.9	25.0	26.2	24.4	28.7	29.6	30.5
275	21.3	23.2	25.3	26.8	28.0	29.3	30.2	31.1
310	21.6	23.5	25.3	27.1	28.3	29.9	30.8	31.7
345	21.6	23.5	25.9	27.4	29.0	30.5	31.4	32.3

*Source: After Cuenca (1989).

The nozzle diameter (ND) could then be calculated by:

$$ND = WD(0.32498) - 4.4781 \qquad (4.8)$$

where:
WD= wetted diameter in metres.

The vapour pressure deficit **D** was determined by the equation:

$$\mathbf{D} = 0.61 \exp[17.27\, T / (T+237.3)]\,(1\text{-}RH) \qquad (4.9)$$

where:

T is air temperature, in °C, taken as T_{mean},
RH is the relative humidity, fraction.

Wind velocity for this study was recorded at the Canadian Agricualtural Research Station at Lethbridge, at an elevation of 10m off the ground. This value had to be corrected for an elevation of 2m. Wind velocity was corrected by the equation, reported in Wilson (1990):

$$u/u_o = (z/z_o)^{0.15} \qquad (4.10)$$

where:

u_o = wind speed at anemometer at height z_o ,
u = wind speed at some higher level.

4.5.3 Evapotranspiration

The total amount of potential evapotranspiration (PET_i) was determined with a modified version of the Jensen - Haise equation (Foroud et al. 1989). The modified Jensen - Haise equation is locally calibrated and includes a wind parameter. An unmodified Jensen - Haise equation will underestimate potential evapotranspiration in windy southern Alberta (Grace and Quick, 1988). Potential evapotranspiration as discussed in chapter 2.4.1 was determined by the equation:

$$PET_i = 0.00824\,(RS)\,(TA+7.1)\,0.00304(W) \qquad (2.3)$$

where:

PE	Potential Evapotranspiration as computed by the modified Jensen Haise method in millimetres per day

RS	Total solar radiation in megajoules per square metre per day
TA	Daily average temperature in degrees Celsius
W	Total wind in (Km/day)

The values 0.00824, 7.1 and 0.00304 are locally calibrated constants (Foroud et al, 1989).

Potential evapotranspiration was converted into the expected amount of evapotranspiration through the use of a crop coefficient (K). The crop considered for this study is turf grass. Turf was identified as the dominant vegetation type observed within the region of study. The K value has been calculated with a third degree polynomial for a number of common southern Alberta crops (Hobbs and Krogman, 1983) The actual value of K was determined through the equation:

$$K= -1.003+(-2.547E\text{-}03xJD)+(1.722E\text{-}04xJD^2)+(-5.494E\text{-}07xJD^3) \qquad (4.11)$$

where:

JD is the Julian Day.

Figure 4.6 illustrates the turfgrass consumptive curve calculated in equation 4.11.

PET_i has been limited when soil moisture drops below 0.5 of θ_{fc} and θ_{wp}, defined as θ_d. Section 2.4.1 discussed the drop in plant transpiration rates which will occur with a decrease in soil moisture. To reflect this drop in transpiration rates the use of a evapotranspiration limiting function is incorporated. An evapotranspiration limiting function of the type depicted in Figure 4.7 is in close agreement with studies completed by: Feddes *et al*, (1978); Gardner and Ehlig, (1963); Gardner and Hillel, (1962); Homes, (1961); Peschke *et al*, (1986) listed in Shuttleworth (1993). Similar

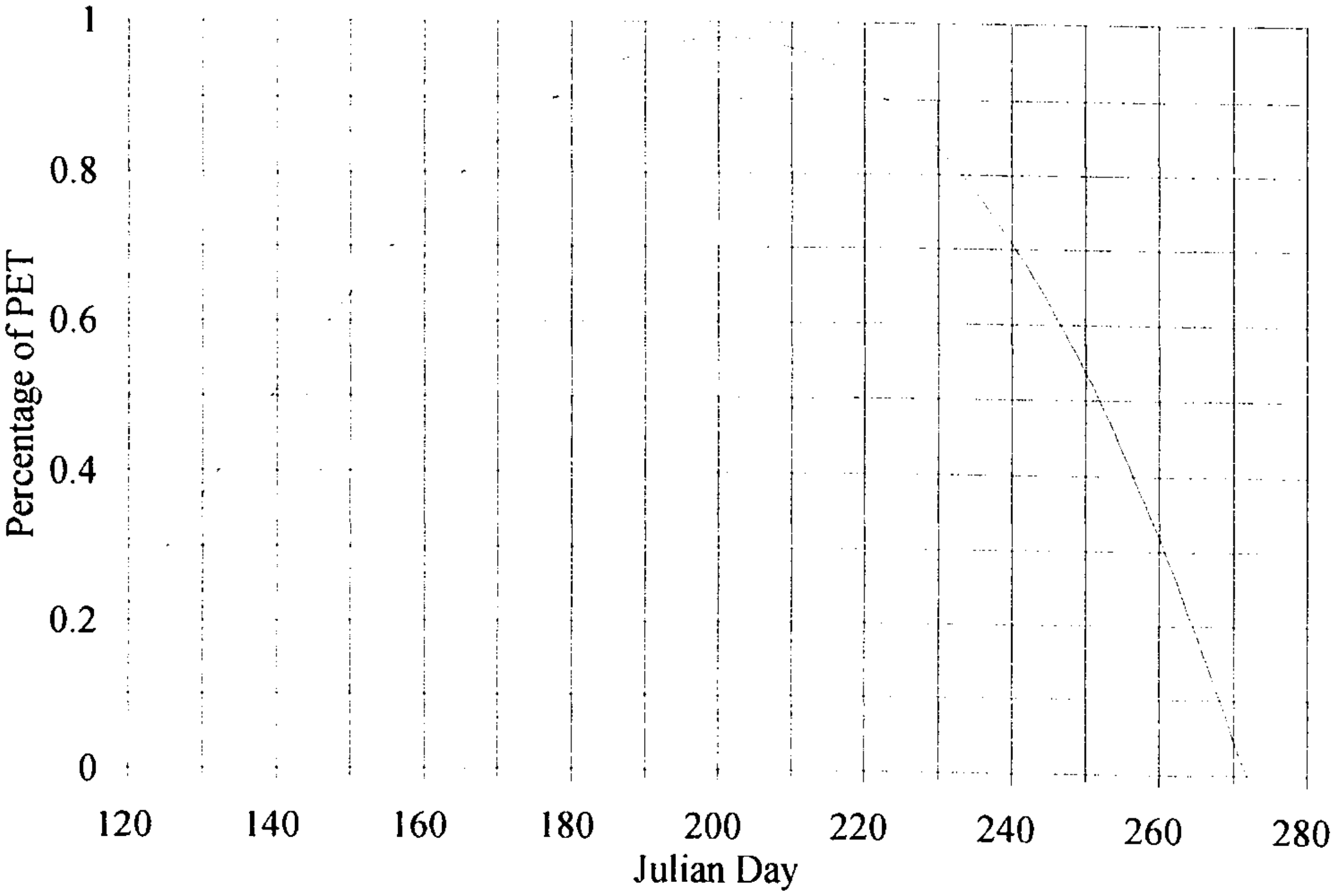


Figure 4.6 Crop Coefficent Curve (K) for Grass

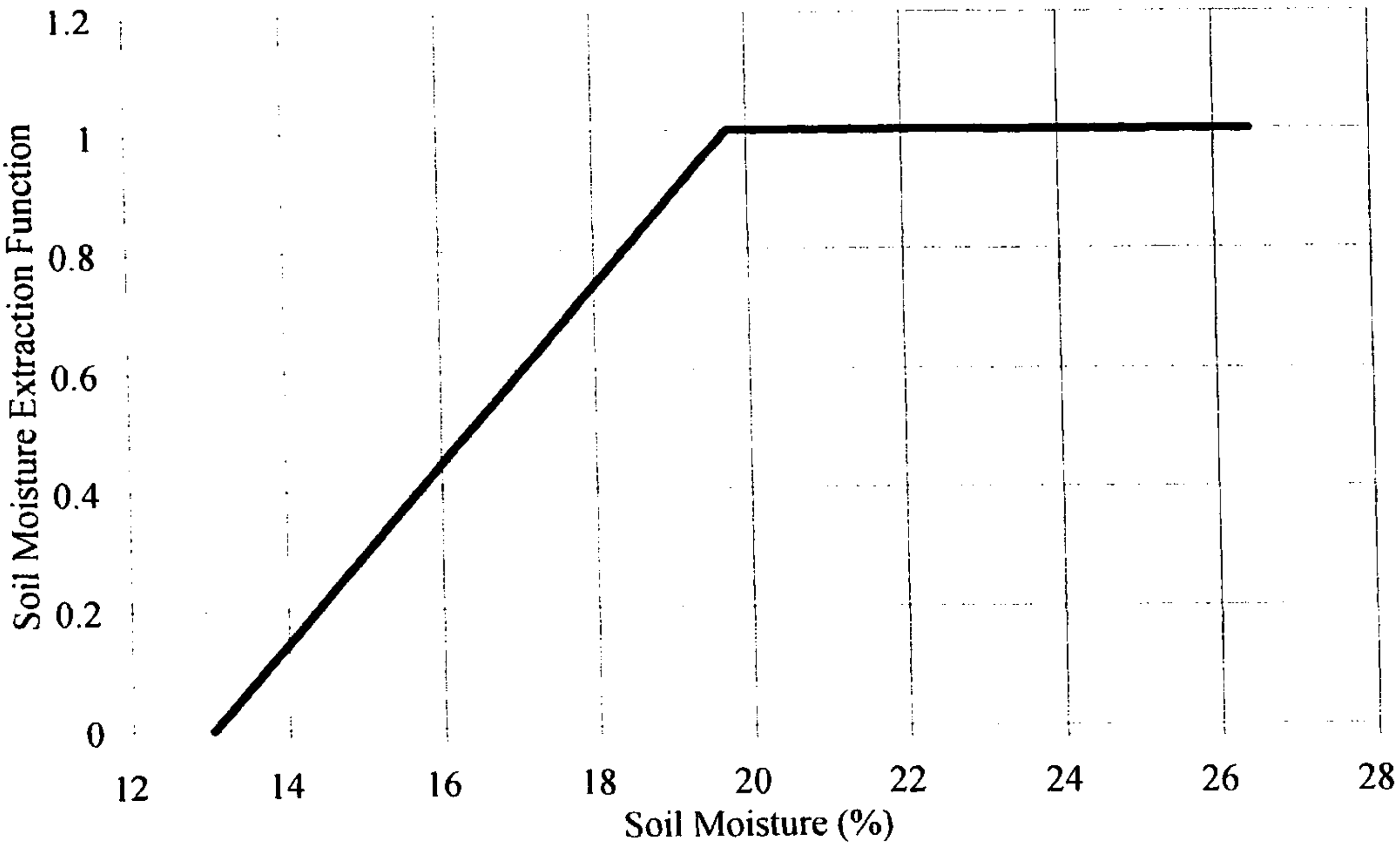


Figure 4.7 Slope of the Soil Moisture Extraction Function During a Drying Cycle. Assuming Field Capacity = 26.5% and Wilting Point = 13%. This function is applied to limit PET when soil moisture drops below 0.5 between field capacity and wilting point.

soil moisture stress equations have also been adopted by: Belmans et al (1983), and de Jong and Kabat (1990). Based on Figure 4.7, the soil moisture extraction function ($f(\theta)$) to limit PET_i can be determined by the equation:

$$f(\theta)=2(\theta_A{}^{*}-\theta_{wp})/(\theta_{fc}-\theta_{wp}) \quad (4.12)$$

where:

θ_A is the actual water content of the soil

*when $\theta_A < \theta_d$.

The soil moisture extraction function was then multiplied by the PET_i.

Since temperature data for the study area were collected outside of the city, PET_i was corrected for urban heat island effects (Chandler, 1976; Grimmond *et al.*, 1986; Landsberg, 1981; Oke, 1979). Chandler (1976) reports that T_{max} and T_{min} can be corrected for heat island effects by adding 0.5 and 0.9 respectively for suburb areas in medium to large towns in mid-latitudes. The adjusted values of T_{max} and T_{min} were used to compute PET_i.

Under high wind conditions, common in the Lethbridge region, heat island effects are assumed to be minimal. The critical wind speed necessary to minimize effects of the urban heat island have been evaluated by Oke and Hannell (1970). The critical wind speed necessary to minimize urban heat island effects can be found by the equation as reported in Chandler (1976):

$$U = -11.6 + 3.4P \qquad (4.13)$$

where:

U= the critical wind speed necessary,
P= is the logarithm of the population.

The critical windspeed necessary for the Lethbridge region (population ≅ 65000) is 4.76 m/s at 2 metres. Days where wind speed exceeded this critical value the actual measured values of T_{max} and T_{min} were used in computation of PET_i.

4.5.4 Runoff

Runoff (R_o) from a turfgrassed park area was estimated using the Soil Conservation Service (SCS) Runoff Curve Number (CN) method. This method attempts to estimate the amount of water lost due to initial abstraction, which is all the water losses prior to runoff. The amount of water lost due to initial abstraction has been found to be related to the hydrologic soil group, the cover type, treatment, and antecedent runoff conditon (SCS, 1986). The hydrologic soil group for this study area was found to relate to soil class C in the SCS method. Soil characteristics for class C are described as: slowly infiltrating, fine texture soils such as clay loam, or shallow sandy loam (Pilgrim and Cordery, 1994). The remaining soil classes A, B, and D are for deep sandy soils, moderately fine soils such as sandy loam, and for plastic clays or claypan respectively.

The cover type used for determining the correct curve number was open lawn space, in good hydrologic condition, (grass cover over 75% of total area). The hydrologic condition refers to whether the vegetation is thick, and the amount of organic matter present in the soil. Soils in good hydrologic condition will have a high infiltration rate potential for their specific hydrologic soil group. Once the soil and hydrologic conditions were determined a curve number could be selected from a series of tables provided in SCS (1986), partially listed below in Table 4.2. The curve number (CN) is used to determine the potential maximum retention before runoff begins (S) in the equation:

$$S = \frac{1000}{CN} - 10 \tag{4.14}$$

The values in Table 4.2, refer to the CN derived for watersheds with an antecedent moisture condition defined as average. Curve numbers are also available for wet and dry moisture conditions. CN values for antecedent moisture conditions defined as average were used.

Table 4.2 Runoff Curve Numbers for an Urban Area

Cover Type and Condition	Curve Numbers for Individual Hydrologic Soil Groups			
Open Space (lawns or parks)	**A**	**B**	**C**	**D**
Poor Condition <50% turf cover	68	79	86	89
Fair Condition >50<75% turf cover	49	69	79	84
Good Condition >75% turf cover	39	61	74	80

Source: U.S. Soil Conservation Service, 1986. *Urban Hydrology for Samll Watersheds,* Technical Release no. 55, Washington, D.C.

For any rainfall event the expected amount of runoff (Q) in inches could be estimated by the equation:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{4.15}$$

where:

P is precipitation in inches.

4.5.5 Soil Moisture

For the purposes of this study soil moisture (SM_{i-1}) budget was started assuming 25, 50, and 75 percent available water in the soil root zone starting on April 30th. The three values of initial soil moisture status were included to illustrate groundwater contributions at different levels of intial moisture condition.

4.6 Calculation of Household Lawn Irrigation and Contribution to Water Tables

Household irrigation and contributions to local groundwater were also determined by the water balance equation reported above.

$$SM_i = PPT_i + IRR_i - PET_i - R_o + SM_{i-1} \qquad (4.16)$$

where:

SM_i = change in soil moisture storage for a given month,
PPT_i = total amount of precipitation in a given month,
IRR_i = total amount of irrigation calculated for each month,
PET_i = calculated amount of potential evapotranspiration as computed by the modified Jensen-Haise equation for a given month,
R_o = total amount of runoff,
SM_{i-1} =soil moisture storage on the last day of the previous month.

For households this water balance equation had to be used on a monthly basis rather than a daily basis due to period of data collected. Precipitation and other weather variables were collected at Canadian Agricultural Research Station at Lethbridge.

Change in soil moisture storage and percolation beyond the root zone were calculated as defined above for each of the irrigation zones for the five year period 1990 - 1994.

4.6.1 Household Irrigation

Household irrigation was determined by household water meter readings. The City of Lethbridge obtains meter readings from households every second month, measured in cubic metres. Between readings the city bases individual household water use (for billing purposes) on the amount used during the previous month. Over- or under-estimations of water usage are added or subtracted to the next obtained reading. These readings were obtained for the years 1990 through 1994 from 400 households in the Varsity Village area of West Lethbridge. From these readings the average water usage was obtained for each month through the time period. Based on these readings the amount of irrigation applied to lawns and gardens in the urban area was determined by subtracting the average water consumption from January - April and October - December for all five years, by the average water consumption for each month May - September, 1990 to 1994. The water consumption for each month (recorded in cubic metres) was divided by the irrigated area (lawn and garden) of an average sized lot. Since the total amount of irrigation is determined by subtracting monthly use in summer from average monthly use in winter, activities such as car washing, or filling a swimming pool are recorded as irrigation. For this reason the actual amount of irrigation may be slightly overestimated. However, very few swimming pools were observed in the study area (less than 10 outdoor pools for over 1800 households) therefore over estimations of irrigation by this source were minimal.

The total amount of irrigation for each month was multiplied by the average monthly amount of evaporation and wind drift calculated for each park, and then this amount was subtracted from the total amount of irrigation applied.

The irrigated area of the study region was determined by use of a geographic information system (GIS). The study area was digitized from orthophotos taken in 1988 at a scale of 1:2000, and from quarter-section map sheets. From these maps information concerning land use in Varsity Village, average lot size, and average lot land usage was determined.

To obtain additional information concerning irrigation practices of Varsity Village residents, irrigating households were broken up into four groups based on the average amount of irrigation over a five year period: high, moderately high, moderately low, and low irrigation water users. Average irrigation for households in each irrigation zone was determined by subtracting total average monthly irrigation season consumption May - September 1990-1994 in m^3, by the total average household use during the non-irrigation season October - April 1990-1994 also in m^3. Irrigation zones were determined by street name (e.g. households on street named Lafayette Blvd.). Each of the irrigation zones (streets) were then ranked and divided into quartiles forming the four water use groups. Irrigation of each of the four water use groups was determined by calculating the average amount of irrigation in each of the water use groups for each month and then dividing by the average irrigated area of a lot in each of the four water use groups. Individual irrigation zones (streets) were not used because for some streets the sample size (total number of household water meter readings received) was too small. The bimonthly collection of data would also cause problems, as typically water meter reading data is collected on a street basis, therefore water use data on a particular street would not be available for six months of the year.

For low water users the average monthly irrigation water applied was below 11.1 m^3 for the years 1990-1994. The next group of moderately low water users was defined as irrigation zones applying more than 11.1 m^3 but less than 14.9 m^3. Moderately high irrigation zones were found in areas irrigating more than 15.0 m^3 but less than 21.1 m^3. The final irrigation group, the high water users were found to irrigate above 21.1 m^3 for each month of the irrigation season.

4.6.2 Household Roof Runoff

Equation 4.16 was modified to include inputs due to runoff from household roofs. During a survey of the study region it was determined that majority of households in the Varsity Village discharge runoff from roofs onto lawns. Inputs due to discharge from roofs onto irrigated lawns was determined by:

$$I_{roof} = ((P_{roof} \times A_{roof})/IA) \times 0.85 \qquad (4.17)$$

where:

I_{roof} is the total input from runoff from residential roofs
P_{roof} is precipitation recorded over the study region subtracted by 1 mm to account for an estimated amount of precipitation stored on residential roofs
A_{roof} is the total area of roofs in Varsity Village
IA is the total irrigated area of residential lawns in Varsity Village

Precipitation storage on a household roof was determined by a rainfall simulation experiment. The flow rate of a sprinkler device, providing a wetted diameter of two metres was determined. This sprinkler was then placed on a household roof for a period of 5 minutes. The total volume of water not stored on the roof was measured. The volume of water applied during the 5 minute period was compared to the volume of water collected to derive the amount of water lost due to storage and evaporation. To minimize loses of water due to evaporation and wind drift, the experiment was completed during the early morning on calm days.

The total daily amount of roof runoff was multiplied by 0.85. This index is included to account for households discharging runoff onto an impermeable surface such as sidewalks or driveways, as identified during a survey of discharge characteristics of the region.

4.6.3 Evapotranspiration

PET_{grass} was calculated as described above in section 4.5.3. The total amount calculated for each day was added for each month and then applied to equation 4.16. If soil moisture for given month fell below the critical value defined above, the soil moisture stress equation defined as equation 4.12 was used to calculate monthly potential evapotranspiration.

4.6.4 Runoff

R_o from household lawns was calculated using equations 4.14 and 4.15, using soil group C, in good hydrologic condition. R_o estimated from households lawns included water applied as a result of drainage from rooves. The total volume of precipitation and roof runoff was divided by the total lawn area to estimate total runoff that would occur. Total lawn area was used estimate potential lawn runoff to account for the observation that typically home owners discharge roof runoff close to their homes. Roof runoff then spreads across the lawn area surrounding the home.

4.7 Calculation of Water Losses from Surface Water Bodies

Water balance equations were derived for the campus wetland, and Nicholas Sheran Lake. Destruction of monitoring equipment at the University of Lethbridge irrigation reservoir prevented any analysis at this location. For each of the water bodies analysed, water loss due to groundwater flow was estimated. This estimate assumed water loss, or gain not due to evaporation or precipitation was due groundwater flow. This assumption was legitimate in the case of the wetland as it a relatively isolated system. Water input occurs as precipitation and recharge from the University irrigation reservoir, connected to the wetland by a pipe. Water level changes were monitored using a staff gauge driven into the bottom of the wetland.

Nicholas Sheran Lake unlike the wetland, cannot be considered a isolated system, as frequent withdrawals from this reservoir for irrigation, and flow to the University irrigation reservoir occur. Only after October 15, 1996, when water withdrawals were discontinued for the fall and winter period, could water loss be attributed to evaporation, and groundwater flow. Water input during this time period could be attributed only to precipitation. Water level change was monitored using the stilling well described in section 4.2.5.

The form of the water balance equation used to estimate water loss due to recharge of groundwater from the two water features, in millimetres per day was:

$$GWF = +/- \Delta S - (ET + PPT) \qquad (4.18)$$

where:

GWF are losses or gains attributed to groundwater flow,
ΔS is the observed change in storage in millimetres,
ET are losses due to evapotranspiration in millimeters,
PPT are gains due to precipitation, in millimetres.

ΔS was evaluated through monitoring of installed stilling wells or staff gauges.

ET for water features was estimated with the equation recommended by Shuttleworth (1994):

$$ET = F^1 A + F^2 \mathbf{D} \qquad (4.19)$$

where:

F^1 is a function of temperature and elevation of the site,
A is defined as the energy available for evaporation,

F^2 is a function of temperature, wind speed and elevation of the site,
D is the average vapour pressure deficit.

The function for temperature and elevation of the site, F^1 is determined through the equation:

$$F^1 = \frac{\Delta}{\Delta + \gamma} \tag{4.20}$$

where:

Δ is the slope of the saturated vapour pressure curve, kPa/°C and,
γ is the psychromatic constant., kPa/°C (Shuttleworth, 1994).

The slope of the saturated vapour pressure curve is determined by:

$$\Delta = 4098\ e_s / (237.3 + T)^2 \text{ kPa/°C} \tag{4.21}$$

where:

e_s is the saturated vapor pressure, kPa, and
T is temperature, °C (Shuttleworth, 1994).

The saturated vapour pressure e_s is calculated by the equation:

$$e_s = 0.6108 \exp [\ 17.27\ T / (237.3 + T)] \text{ kPa/ °C.} \tag{4.22}$$

The psychromatic constant can be evaluated through the equation:

$$\gamma = 0.0016286\ P/\lambda \quad \text{kPa/°C} \tag{4.23}$$

where:

P is the atmospheric pressure in kPa,
λ is the latent heat of vaporization of water in MJ/kg (Shuttleworth, 1994).

Atmospheric pressure can be determined through the equation:

$$P = 101.3\ [\ (293 - 0.0065Z)/\ 293]^{5.256} \tag{4.24}$$

where:

Z is equal to the elevation of the site in metres (Shuttleworth, 1994).

The latent heat of vaporization of water was determined by the equation:

$$\lambda = 2.501 - 0.002361\ T_s \qquad \text{MJ/kg} \qquad (4.25)$$

where:

T_s is the surface temperature of the water in degrees Celsius.

Unfortunately surface water temperature was not obtained for this experiment, so water temperature was estimated based on weekly air temperature data. The effects of estimating water temperature by this method would result in an overestimation of water temperature thereby slightly overestimating of the amount of evaporation. However, the effects of estimating water temperature are not expected to have a great impact on the calculated latent heat of vaporization because the amount of energy required decreases only slightly with an increase in temperature as evident in equation 4.25.

The parameter A was defined as the energy available for evaporation. This was determined by dividing the total amount of net radiation recorded for that day in MJ m^{-2} day^{-1}, by equation 4.26 resulting in the net radiation in mm day^{-1} (Shuttleworth, 1994).

The function F^2 was calculated by the equation:

$$F^2 = [\Delta / (\Delta + \gamma)]\ 6.43\ (1 + 0.536\ u_2)\ /\ \lambda \qquad (4.26)$$

where:

u_2 is wind speed measured at 2 metres, defined above in equation 4.10.

For the purposes of equation 4.19 the vapour pressure deficit **D**, was calculated differently than in equation 4.9. **D** was calculated by Shuttleworth (1994):

$$D = [e_s(T_{max}) + e_s(T_{min}) / 2] (1 - RH) / 100 \quad kPa. \qquad (4.27)$$

4.8 Mapping Methods

From the outset of this study it was determined that the use of Geographic Information System (GIS) was essential to the completion of this project. As indicated above, various computations involved in this study required accurate measurements of area, reporting land use of different areas, and recording the water use of specific zones. GIS is a excellent tool for this type of analysis as areas and relevant data are stored and easily retrieved in an associated database. The GIS chosen for use in this study was PAMAP. PAMAP was chosen based on the availability of the software, and the software's vector and raster data handling capabilities.

The initial stage of this project was the creation of a spatially referenced database of the study area. This database was created by manually digitizing landuse and orthophoto maps. Landuse maps consisted of a number of quarter-section map sheets designating specific parcel landuse for a particular area as outlined in the City of Lethbridge Land Use By-law 4100. The quarter section map sheets were provided by the City of Lethbridge. From these maps parcel landuse was digitized.

The second maps digitized were orthophoto maps at a scale of 1:2000. The orthophoto of the study area was taken in November, 1988. Since this time only three new developments have occurred in the Varsity Village area. Each of the developments was updated in the database using the quarter-section map sheets. Information manually digitized from the orthophotographs included: roads, alleys, parking lots, large building footprints, water features, and surface relief.

After digitizing, surface area calculations could be obtained. Area calculation involves the construction of polygons from the spatially registered vector data which was manually digitized from the respective map sheets. During polygon formation a grid is created over the database level of interest. From the created grid, areas can be determined due to linkages between the number of grid squares in a defined polygon. For each polygon up to 100 attributes can be stored in the GIS. Attributes stored for each polygon included: X and Y coordinates of the centre point of each polygon (taken to be the location of the polygon tag identifier), landuse associated with that polygon, and the calculated amount of percolation through the root zone available for different years throughout the study period. For this study the grid size chosen for calculation of polygon areas was 2.5 metres, or less than one third the width of the narrowest features digitized on the map (back alleys). A smaller grid size was not chosen due to the computation time involved. A smaller grid size may also exaggerate the positional errors which are introduced into a manually digitized database.

4.8.1 Gridding Methods

The spatial occurrence of high groundwater conditions observed and predicted in Varsity Village and the University of Lethbridge campus was displayed with the contouring and 3D surface mapping software package SURFER. SURFER was chosen for the geostatistical technique of kriging utilized by this software. Several studies listed in Mulugeta (1996) stated that kriging provides optimal results for most data sets.

Kriging is a geostatistical technique for interpolation of values at point locations. The basic kriging model used in SURFER defines a boundary from which a point value is estimated from the spatial dependence of the data. This boundary is also defined by the spatial dependence of the data. Only points within the defined boundary are used in point value estimation (Mulugenta, 1996). The equation for kriging is:

$$Z^* (x) = \sum_{i=1}^{N} \lambda_i Z(x_i) \qquad (4.28)$$

Where: $Z^*(x)$ is the estimated value
$Z(x_i)$ is a neighboring data value
N is the number of neighboring data points
λ_i is a weight applied to each $Z(x_i)$.

The kriging model selected for this study assumed stationarity or the absence of a trend in the data. In the SURFER model "ordinary or punctual kriging" (assuming stationarity) is used when no drift is selected (Keckler, 1994). The use of linear or quadratic drift options implements "universal kriging" which implies an underlying trend in the data (Keckler, 1994). However, studies listed in Mulugenta (1996) suggest that universal kriging provides little improvement over ordinary kriging even in data exhibiting strong trends.

The variogram model selected in SURFER is linear with a zero nugget effect. The variogram model determines the weight of neighborhood observations used in calculating a node Z value. The use of a linear estimator assumes data is isotropic where datum points closer to a grid node have a greater weight than points further away. The use of a linear variogram is recommended in the absence of extensive variogram information (Keckler, 1994).

Selection of a nugget effect in the SURFER program implies that there is random error in the data. With this option selected SURFER will act as smoothing interpolator giving less confidence to the individual data points (Keckler, 1994).

Three data series were gridded by the program SURFER producing maps of water table elevation, depth to water table, and predicted depth to water table based on a water table development model. The easting and northing coordinates of each of the water table well locations were exported from PAMAP to SURFER as an ASCII file. The elevation or depth to water table was entered as the Z value for each of the exported well locations illustrated on Figure 4.2. A 25 metre grid was produced across the area of study. Interpolation between grid lines in SURFER is determined by z values at each node. Straight lines are drawn between adjacent grid lines where determined by interpolation between Z values at adjacent nodes (Keckler, 1994).

The final image produced in the program SURFER was based on a derived model of water table depth as predicted by amounts of percolation below the root zone available. The regression equation:

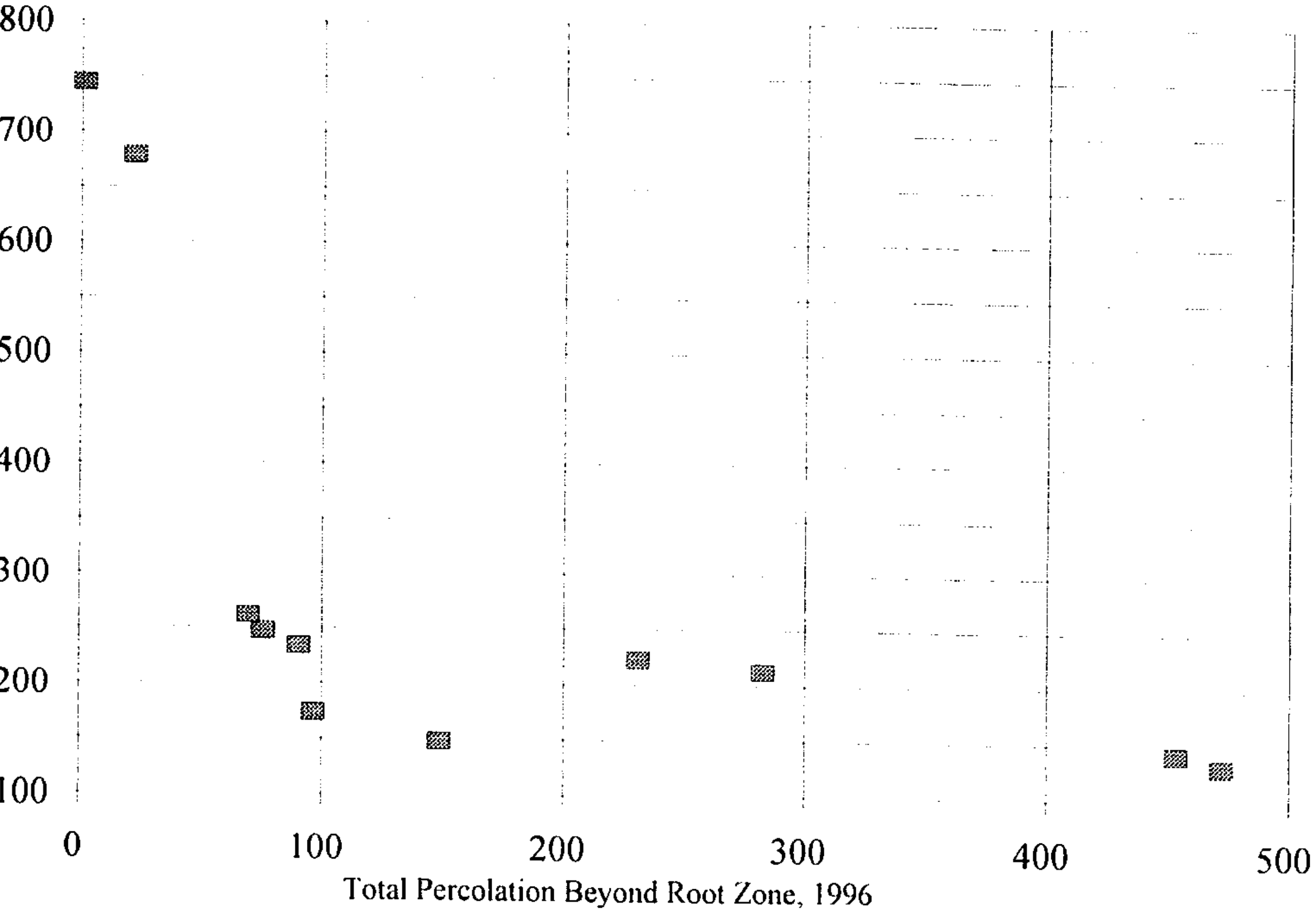
$$WTD = P(-253.3558) + 781.8962 \tag{4.29}$$

where:

P is the logarithm of the expected amount of peculation through the root zone in millimetres and,
WTD is the calculated water table depth in centimetres,

resulted in a statistically significant (0.95) r^2 value of 0.80 (n=11). The expected amount of percolation beyond the root zone for each irrigation area (as calculated in section 4.5), and average water table depth for each well in the study area as recorded between June 14 and September 26, 1996 was used in the calculation of equation 4.29. Only water table wells drilled in areas with accurate measurements of irrigation water applied were included in the calculation of equation 4.29.

The logarithm of calculated percolation beyond the root zone was used to reflect the relationship observed in Figure 4.8. This Figure is a scatter plot of water table elevation verses calculated percolation beyond the root zone. Figure 4.8 illustrates



.8 Average 1996 water table depth (cm) vs. 1996 calculated percolation beyond the Root Zone (mm).

the declining impact of input on measured depth to water table.

In Figure 4.9 water table elevation is plotted against the logarithm of calculated percolation through the root zone. This equation was used to calculate water table depth or Z values across the region of study.

The regression illustrated in Figure 4.9 appears to be very dependent upon a single datum point (0, 750). This datum point is very important to the regression as it is representative of deep water tables observed at several monitoring wells throughout the study region not receiving irrigation.

Unfortunately household consumption values for the 1996 irrigation season could not be obtained. Therefore the expected amount of irrigation for 1996 was derived through a multiple linear regression. The equations derived were:

$$IRR_{L} = PET_{grass}(-1.27739) + PPT(-1.38388) + 1045.10 \tag{4.30}$$

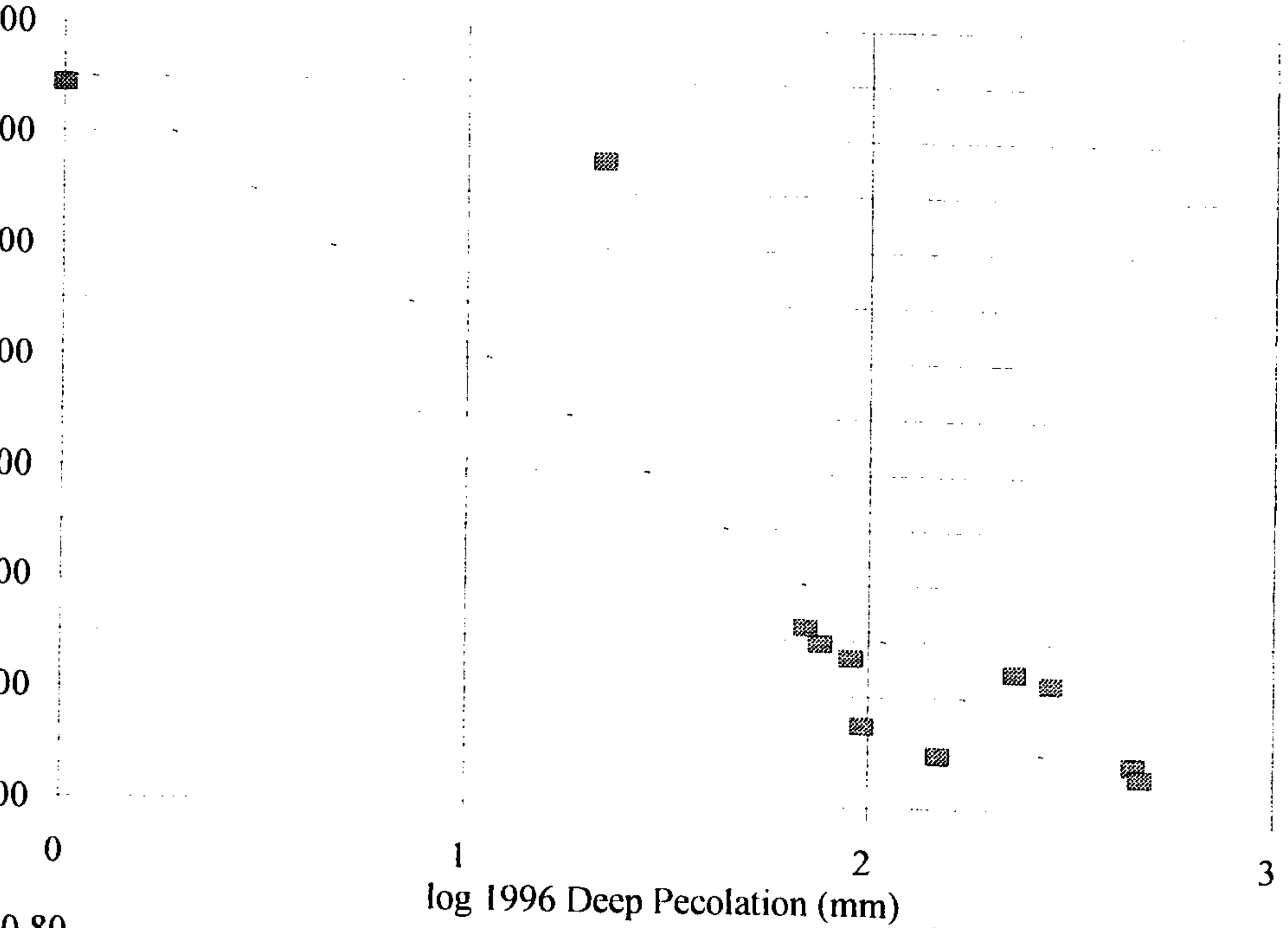
$$IRR_{ML} = PET_{grass}(-0.2985) + PPT(-1.3756) + 812.148 \tag{4.31}$$

$$IRR_{MH} = PET_{grass}(-0.39126) + PPT(-1.40173) + 883.812 \tag{4.32}$$

$$IRR_{H} = PET_{grass}(-0.09812) + PPT(-1.62957) + 866.633 \tag{4.33}$$

where:

IRR_{L}, IRR_{ML}, IRR_{MH}, and IRR_{H} is irrigation water applied to low, moderately low, moderately high, and high water use areas respectively, in millimetres ($n = 5$ yrs, $r^2 = 0.97, 0.88, 0.83, 0.83$ respectively).



0.80

STD Err of Y Est= 100cm

4.9 Average 1996 water table depth (cm) vs. 1996 calculated percolation through root zone(mm).

Percolation through the root zone for 1996 was estimated with multiple linear regression equations produced for each of the water use groups defined as high, moderately high, moderately low and low water users. The equations used were (n=5 yrs, $r^2 = 1.0, 0.92, 0.95, 0.99$ respectively):

$$P_L = PET_{grass}(-2.13160) + PPT(0.23263) + IRR(0.32885) + 862.298 \tag{4.37}$$

$$P_{ML} = PET_{grass}(-1.33671) + PPT(1.02547) + IRR(0.76331) + 275.646 \tag{4.36}$$

$$P_{MH} = PET_{grass}(-1.18642) + PPT(0.99366) + IRR(0.69936) + 267.235 \tag{4.35}$$

$$P_H = PET_{grass}(-0.73644) + PPT(1.14683) + IRR(0.73270) + 70.4277 \tag{4.34}$$

where:

P_L is expected percolation from low water users,
P_{ML} is expected percolation from moderately low water users,
P_{MH} is expected percolation from moderately high water users,
P_H is expected percolation through the root zone from high water users,

The logarithm of $P_{\bullet}$ was then determined and applied to equation 4.29 to determine the expected water table depth for areas under irrigation in each of the four irrigation zones.

Kriging in SURFER requires X, Y, and Z values for a series of points before gridding can be completed. As indicated above the Z value for each point was calculated with equation 4.29. During polygon formation in PAMAP from the manually digitized vector data, each polygon was tagged with a identifier. This tag was placed at the centre of each polygon or zone. The values of X,Y, and Z for each zone were then exported from PAMAP as an ASCII file for gridding in SURFER. However, it was determined that some polygons or zones could not be represented adequately by a single central point. These polygons, generally large in size, and or irregular in shape, were represented by nodes having the same Z value triangularly spaced approximately 50 metres apart across the polygon in question.

4.9 Summary

This chapter has detailed the methods used to evaluate water balances for Varsity Village parks, household lawns, and surface water features. The water balance model which considers inputs from irrigation, precipitation and roof runoff; and outputs from evapotranspiration and runoff will be used to evaluate amounts of deep percolation occurring within the study area.

Detail into methods used to evaluate the soils, and geology of the region were also provided, as was the methodology used to combine the study of hydrologic properties of the region with the urban water balance to form a technique to evaluate water table depths throughout the area of study. The following chapter will examine the results obtained.

Chapter 5

RESULTS AND DISCUSSION

5.1 Introduction

This chapter will provide an overview of the findings of this study. Results reported below have been summarized in the form of tables and figures when appropriate. This chapter examines current groundwater conditions observed in the Varsity Village and University of Lethbridge areas, and potential factors influencing the water elevation observed. This chapter also includes water balance assessments performed for turfgrass areas, and surface water bodies within the study region, to investigate volumes of water available for groundwater recharge. Relationships between inputs received and water table elevation is investigated, and an attempt at modeling this relationship is presented.

5.2 Hydrogeology of the Varsity Village Area

Generally the surficial geology of the area is of a clay till, a heterogeneous mixture of silts to gravels, predominately silty, and sandy. For the majority of wells, logged the till material was brown and damp to moist. Throughout the area pockets of silt or sand lenses were observed. The thickness of these lenses was between 1mm and 15cm. Most sand lenses were quite damp, especially those observed under areas of irrigation. Fully saturated sand lenses were observed at borehole locations 96-3, 96-7, 96-9, 96-13, and 96-19 (see Figure 4.2). Based on a particle size analysis the overall textural class a saturated sand lens was sandy clay loam.

In the Varsity Village and University of Lethbridge areas, particle size analysis was conducted for 97 soil samples obtained from depths between 30 cm and 9 metres. The average percent sand and clay found at 30 cm, 1-2 metres, 3-4 metres, 5-6 metres, and below seven metres has been included as Figure 5.1. As illustrated in Figure 5.1, there appears to be slight trend for increasing percentage of sand, and decreasing percentage of clay with depth. This trend is may be explained by an overall increase in the number of sand lenses observed with depth. Very few sand lenses, were observed within 1.5 metres of the surface.

Water table depth at boreholes where fully saturated sand lenses were observed, did not appear to be controlled by the sand lens itself. At each well location water table depth was found to be above the saturated lens. This observation is demonstrated in Table 5.1. Observation of water table elevations at similar depths in wells not affected by sand lenses, suggests that water elevation observed is due to factors other than the presence of saturated sand lenses.

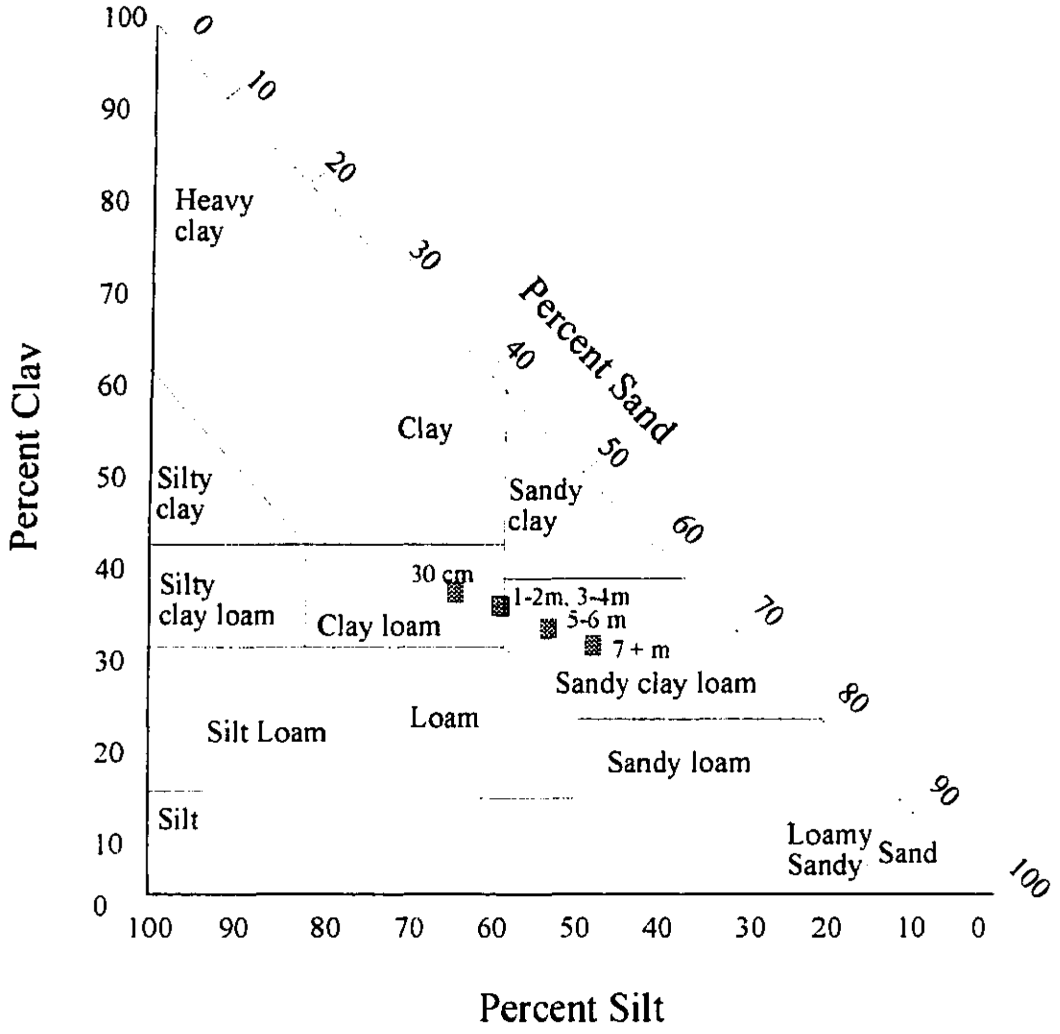


Figure 5.1 Average Percent of Sand and Clay for Samples Obtained Between Depths of 30cm and 9 metres in the Varsity Village and University of Lethbridge Areas

Table 5.1: Depth to Sand Lens as Observed June 11th and 12th, 1996, Compared to the Recorded Depth to Water Table on June 19, 1996.

Water Table Well Number	Observed Depth to Fully Saturated Sand Lens, June 11th and 12th	Observed Depth to Water Table, June 19th
96-3	4.0 metres	2.44 metres
96-7	4.5 metres	2.01 metres
96-9	6.5 metres	1.55 metres
96-13	4.5 metres	1.94 metres
96-19	2.0 metres	1.33 meters

As demonstrated in Table 5.1, sand lenses may not have a significant impact on the overall depth to water table observed in the Varsity Village area, as water table depth is often observed far above these deposits. Sand lenses may however have a significant impact on the movement of water in the study area as higher permeabilities would allow for the faster transport of water than through the low permeability till. However, this aspect of sand lenses and water transport through the till was not the focus of this study, and accumulated data are insufficient to test such a hypothesis.

The till was moist at most locations at all depths sampled. High moisture values were observed in areas under irrigation, typically in samples obtained between one and three metres below the surface. Below three metres the till was noticeably drier. The moisture profiles of all boreholes drilled on June 11 and June 12 have been included as Figures 5.2 through 5.8. These figures illustrate soil moisture content as a percentage at various depths, as calculated by equation 4.1. As illustrated in these figures high moisture

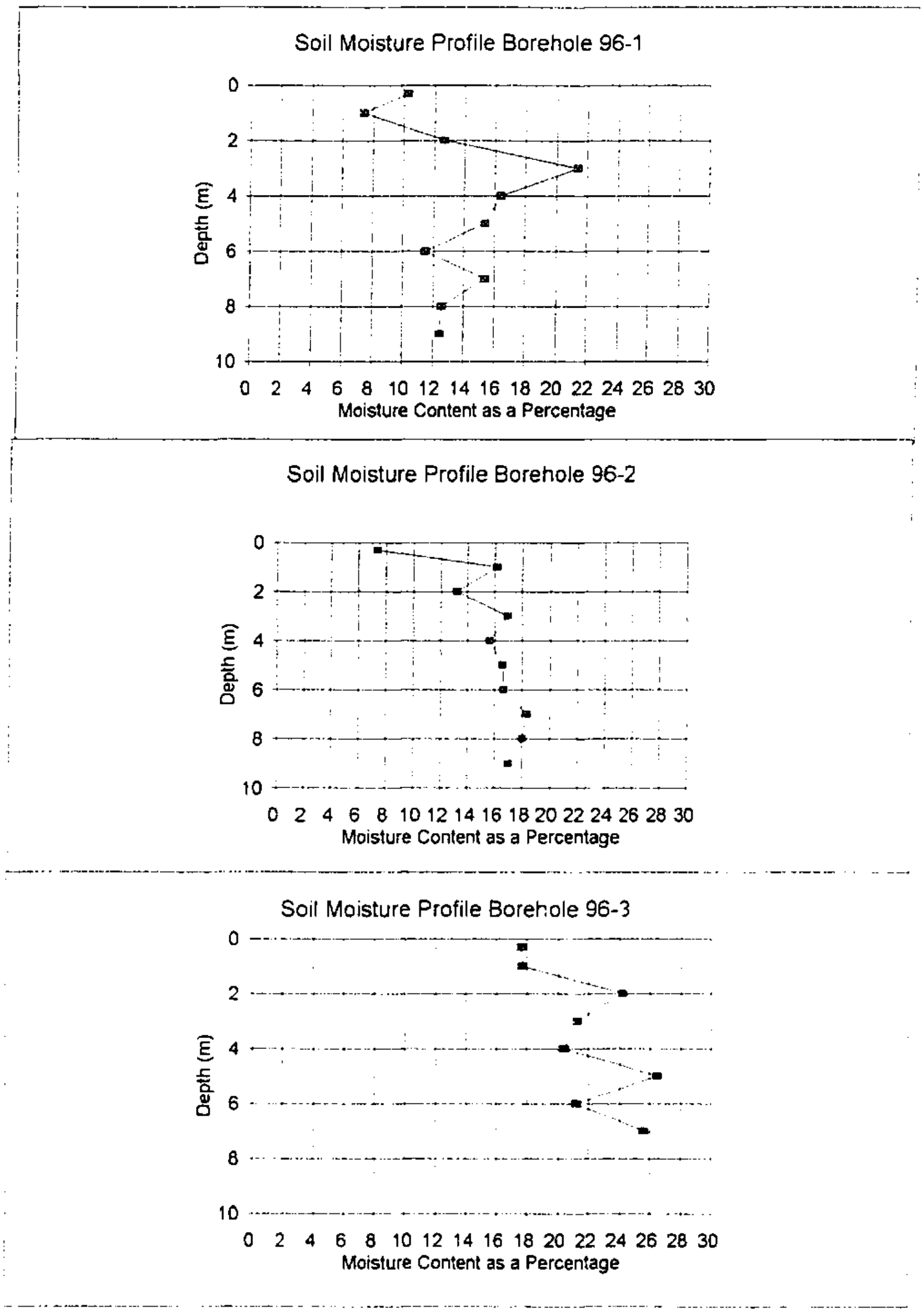


Figure 5.2: Soil Gravimetric Water Contents at Sampled Depths for Boreholes 9 96-2, 96-3

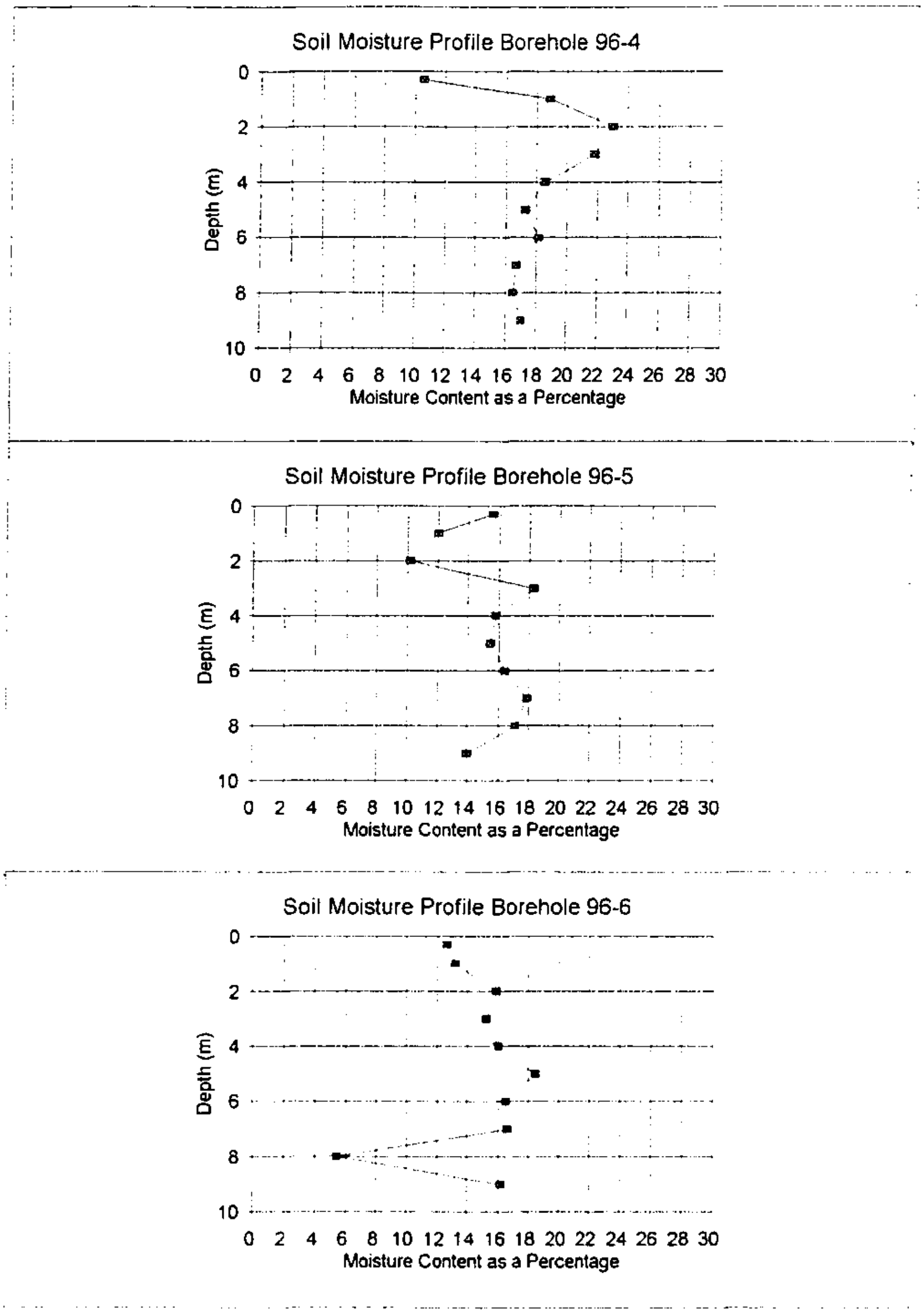


Figure 5.3: Soil Gravimetric Water Contents at Sampled Depths for Boreholes 96-4, 96-5, 96-6

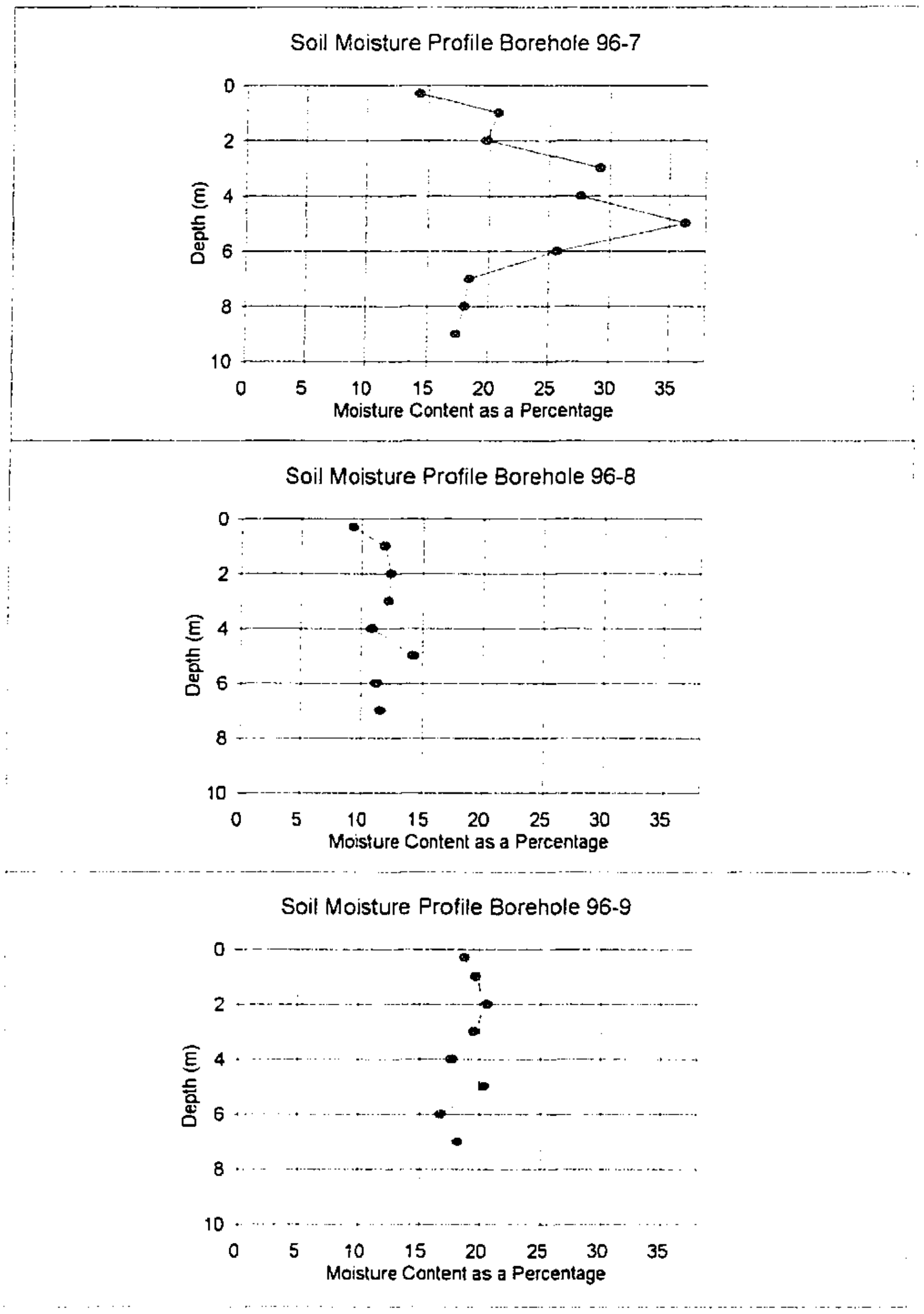


Figure 5.4: Soil Gravimetric Water Contents at Sampled Depths for Boreholes 96-7, 96-8, 96-9

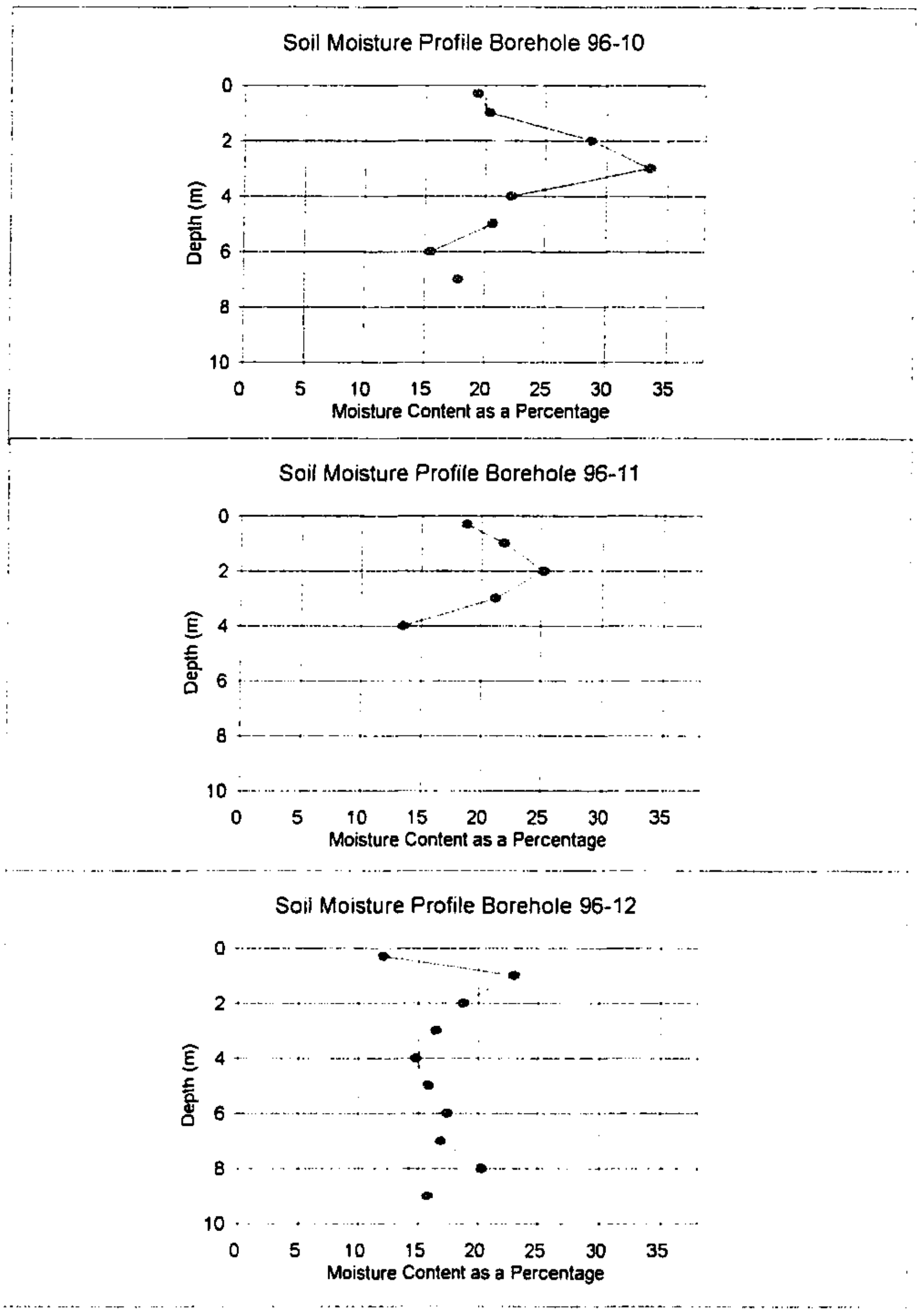


Figure 5.5: Soil Gravimetric Water Contents at Sampled Depths for Boreholes 96-10, 96-11, 96-12

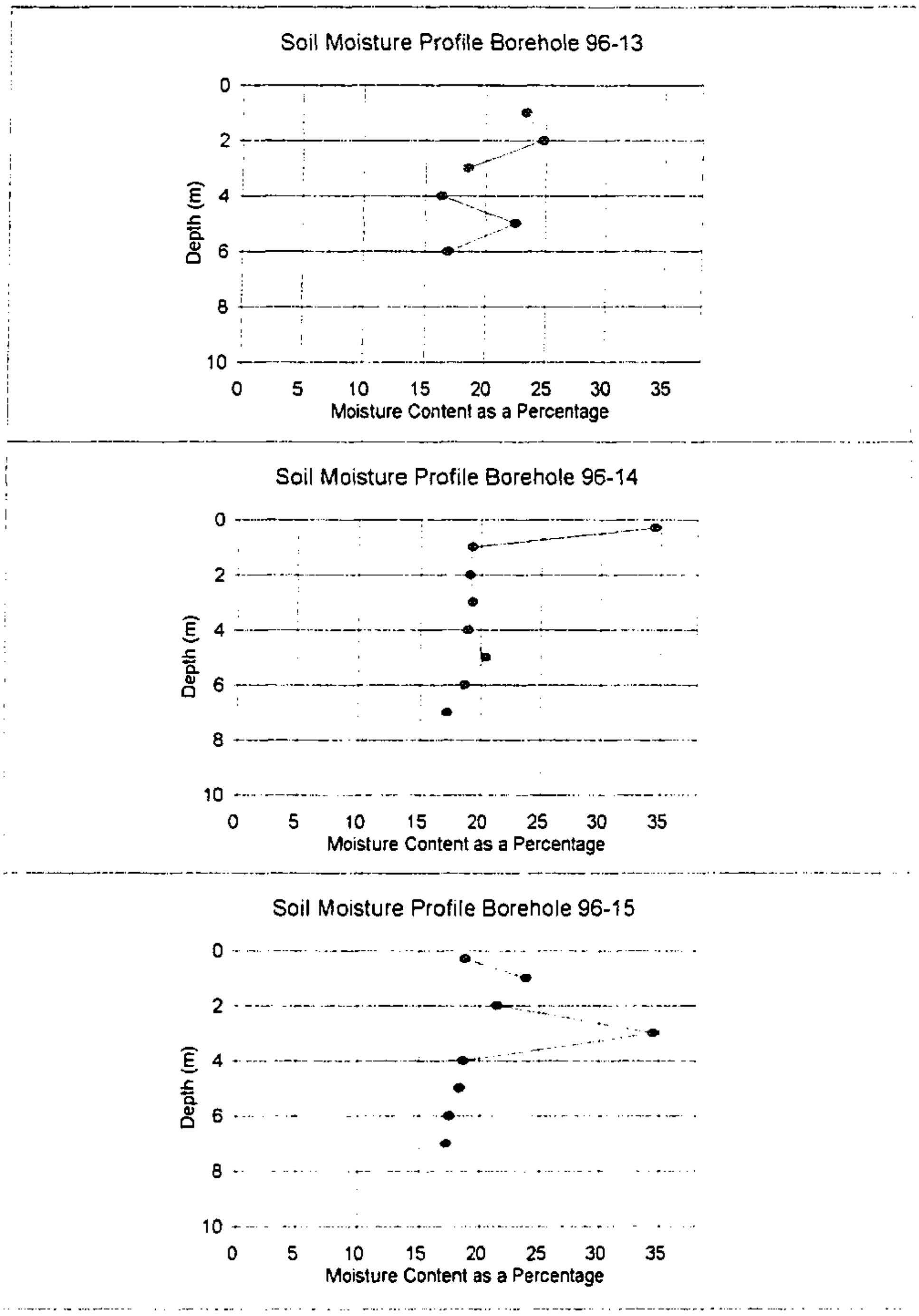


Figure 5.6: Soil Gravimetric Water Contents at Sampled Depths for Boreholes 96-13, 96-14, 96-15

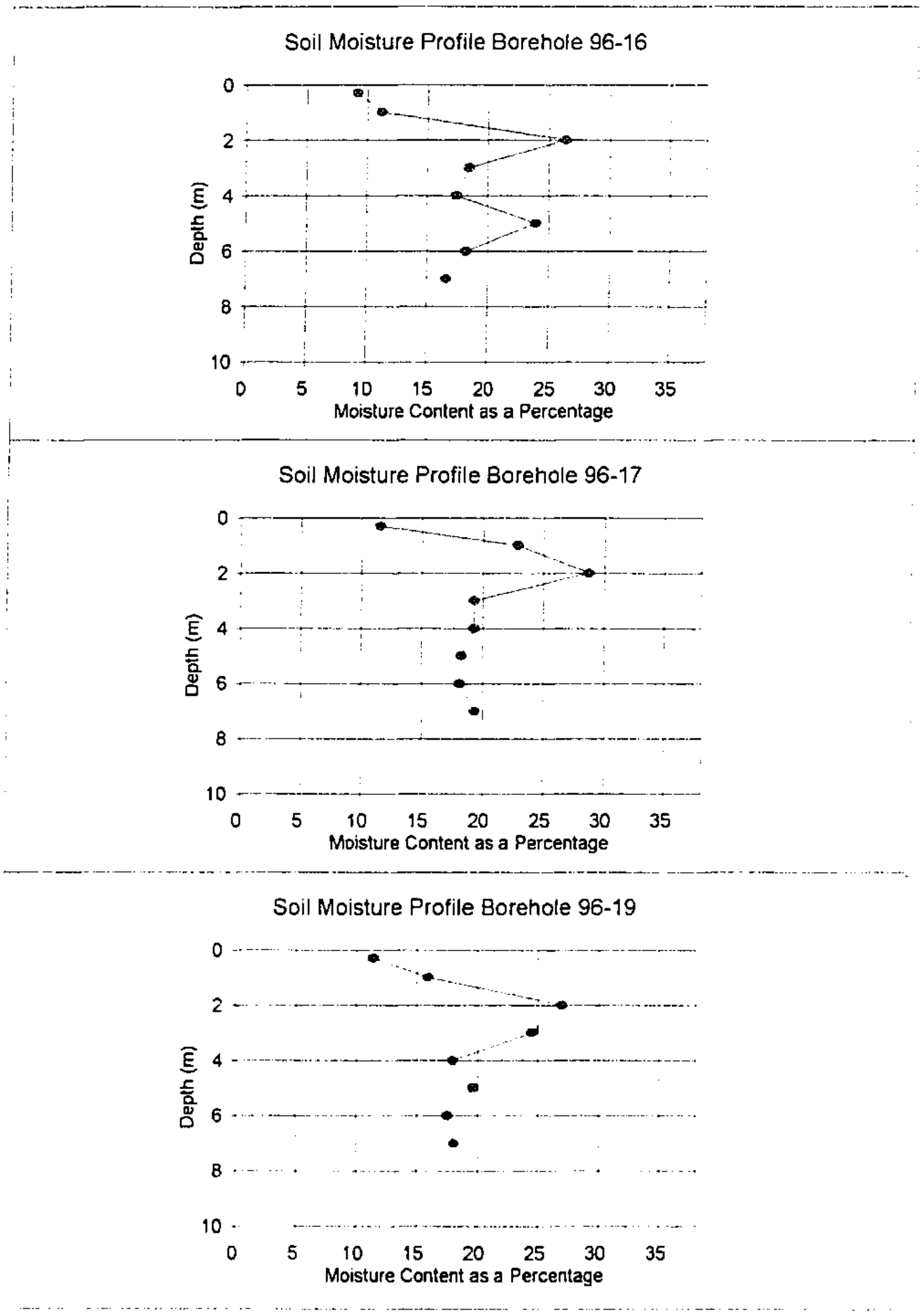


Figure 5.7: Soil Gravimetric Water Contents at Sampled Depths for Boreholes 96-16, 96-17, 96-19

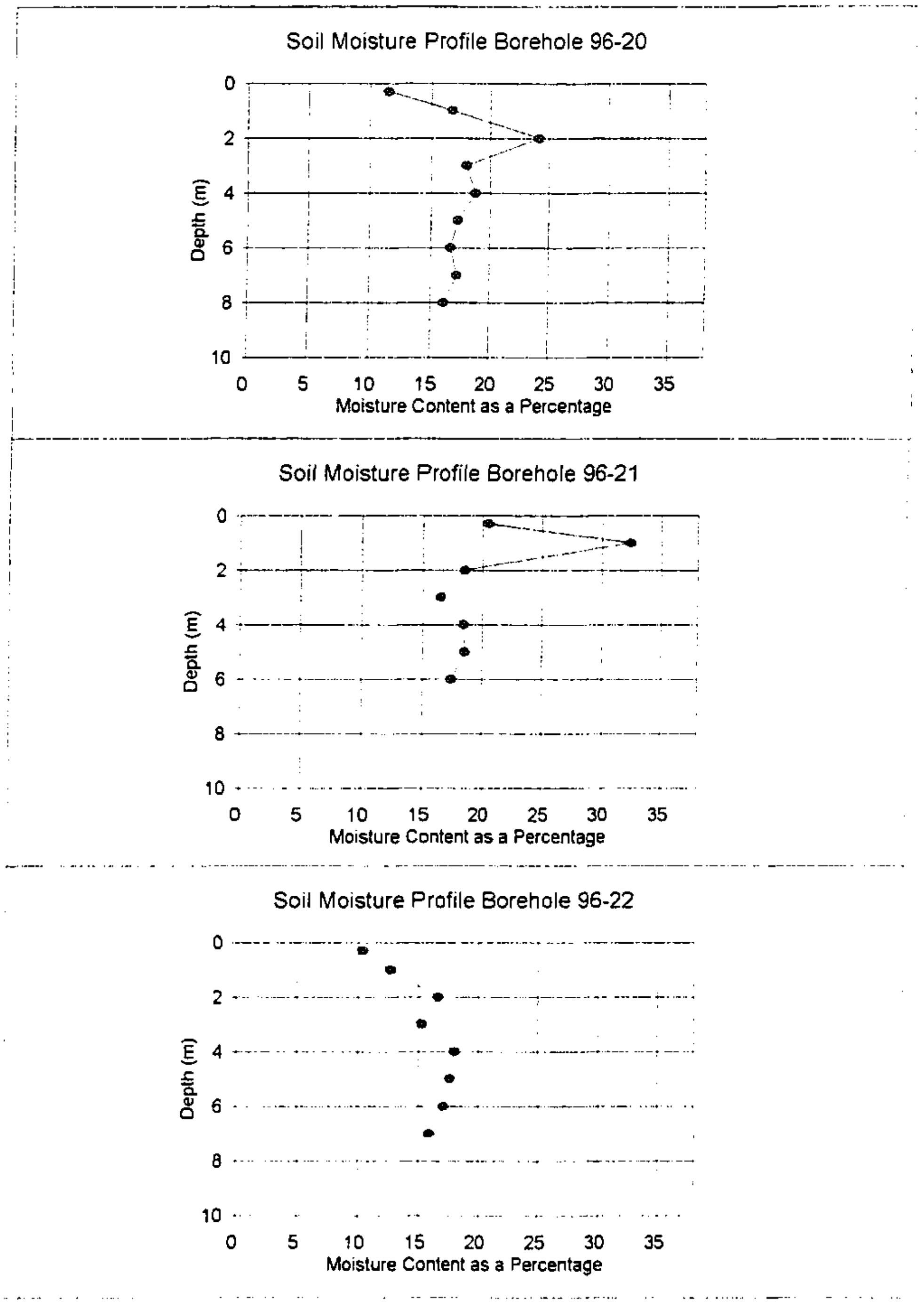


Figure 5.8: Soil Gravimetric Water Contents at Sampled Depths for Boreholes 96-20, 96-21, 96-22

contents are observed between one and three metres, typically below this depth moisture values decline. This trend is particularly evident at boreholes 96-4, 96-10, 96-11, 96-12, 96-13, 96-15, 96-19, 96-20, and 96-21, each of these borehole locations are located in areas associated with irrigation.

Approximately six of the installed wells, 96-1, 96-2, 96-6, 96-16, 96-17, and 96-22 were placed in areas where they would not receive any irrigation. The remaining wells were placed in locations where irrigation would be expected. During the summer the average water levels of the wells receiving regular irrigation was approximately 2.5 metres below the surface, wells not receiving irrigation had an average water table near 6 metres below the surface. Two of the wells placed in non-irrigated areas did not record a water table at any time during the summer. It is expected that no water table is observed due to the lack of irrigation water which may cause the appearance of perched water tables observed in other areas across the study area. Areas currently not under irrigation often did not exhibit the moisture trend described above. These areas currently not under irrigation do not appear to be affected by the formation of perched water tables. Higher water tables observed at wells 96-16, and 96-17 may be the result of water movement from the University of Lethbridge irrigation reservoir. A contour map of water table elevations throughout the study area for August 24, 1996 has been included as Figure 5.9.

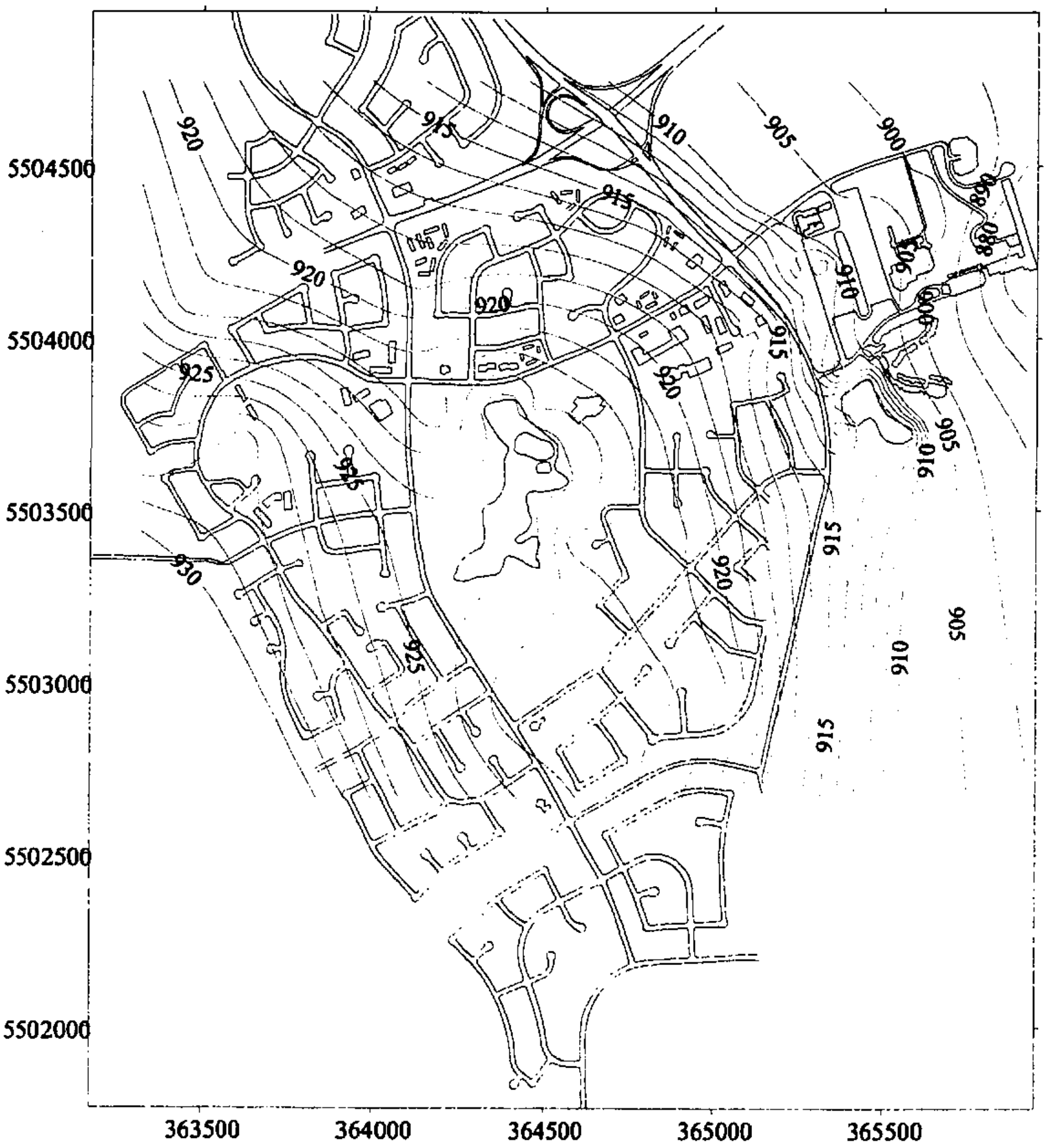


Figure 5.9: Contour Map of Water Table Elevations Throughout the Varsity Village Area, August 24, 1996

Scale: 1:20000
Projection: UTM

Figure 5.9 illustrates the water table surface observed throughout Varsity Village. Generally the observed water table in this area slopes towards the north-east in the direction of the coulees. The slope of the water table in this direction is expected as it roughly follows the natural surface relief of the area. The change in slope of the contour surface immediately east of the University of Lethbridge irrigation reservoir illustrates potential water flow. The slope of the water table surface becomes much more pronounced in the eastern part of the map due to the increase in slope near to the coulee edge.

Water tables throughout the region are described as perched systems as the regional aquifer lies in deposits of higher permeability far below the till. The perched water table system was closely linked with the presence of irrigation. A statistical relationship ($r^2 = 0.80$, $n=11$) was discovered between the logarithm of the 1996 depth of percolation through the root zone added as a result of irrigation and precipitation, and water table depth. The depth to water table can be estimated by the equation, as defined in section 4.8.1:

$$WTD = P(-253.3558) + 781.8962 \tag{4.29}$$

where:

P is the logarithm of the expected amount of deep peculation in millimetres,
WTD is the calculated water table depth in centimetres,

The consistent development of perched water table conditions in irrigated areas at the 1.5 to 2.5 metre level may be explained by high recharge (as discussed below) in an area of relatively high permeability at the surface (discussed below), overlying till of lower permeability. Similar conditions discussed in Schwartz *et al*, (1982) also resulted in the formation of perched water tables. Hendry (1982) discussed the decline of hydraulic conductivity with depth. Water infiltrating into material of lower hydraulic conductivity with depth, is eventually impeded, allowing for the build up of a perched groundwater system.

5.3 Soil and Turf Grass Properties of the Varsity Village Area Potentially Influencing the Development of Perched Water Tables

Several researchers have found that the hydraulic conductivities of the rooting zone (Beard and Green, 1994; Hamilton, 1990; Hino *et al*, 1987; Partsch *et al*, 1993; Taylor *et al*, 1991) in the upper topsoil are much higher than conductivities of the till below (Hendry 1982; Hendry 1988; Schwartz *et al*, 1987). Infiltration rates of turfed grassed areas was tested throughout the Varsity Village area to compare infiltration rates of the planted surface to rates of water movement observed by other researchers in the till below.

The average infiltration rate observed from 17 flooding ring infiltration experiments on household turf grasses in the Varsity Village area was 4.38 x 10^{-5} m•s^{-1} with a standard deviation of 4.78 x 10^{-5} m•s^{-1}. Large spatial variation of infiltration rates was observed. Similar amounts of spatial variation in lawn infiltration rates were obtained by Hamilton (1990) and Partsch (1992). The highest infiltration rate observed was 2.19 x 10^{-4} m•s^{-1}, while the slowest rate was 1.34×10^{-5} m•s^{-1}. Two tests on the same lawn approximately 15 metres apart varied by 1.86×10^{-5} m•s^{-1}.

The Bouyoucos (1963) particle size analysis was carried out for soil samples obtained from each infiltration experimentation site. For each site the observed infiltration rate was compared to an estimated value of hydraulic conductivity (Saxton, *et al*, 1986) to determine if observed texture had an effect on the infiltration rates at the site. A low correlation value of 0.40 (n=14) was calculated between the estimated unsaturated hydraulic conductivity based on textural properties of the soil, and infiltration rates measured in the field. This supports an argument that water infiltration rates into a turfed grassed soil are not highly influenced by the soil texture. Other factors such as the influence of turf grass roots, as suggested by Hamilton (1990), Hino (1987), and Partsch (1992), may have a dramatic affect on the infiltration rate observed.

It is expected that the development of a perched water table system is the result of fairly large quantities of water infiltrating through the upper topsoil at rates of approximately 4.38×10^{-5} m•s^{-1}. This flow of water is eventually impeded by tills with hydraulic conductivities between 2.5×10^{-9} m•s^{-1} to 7.0×10^{-7} m•s^{-1} (Hendry, 1982) resulting in the development of a perched water table system. When a threshold hydraulic conductivity is exceeded by a critical volume of infiltrating water, a temporary perched water table develops. The depth at which this threshold exists may be observed as the depth of water table recorded at that site, this threshold is likely affected by the total amount of water available, and the local hydraulic conductivity. This is supported by seasonal fluctuations in water table elevation in relation to the amount of input received. Seasonal fluctuations in water table elevations for a number of wells monitored on the University of Lethbridge Campus, are plotted with monthly precipitation in Figure 5.10. Figure 5.10 demonstrates an overall decline in water table depth associated with the reduction in the amount of input due to precipitation. The wells used to demonstrate this trend were chosen based on the period of time for which detailed records of water table elevation were available.

It is expected that perched water table development is the result of conductivity differences with depth as reported in Hendry (1982). Currently, the critical hydraulic conductivity rate that will impede the flow of water, thereby allowing for the build up of the perched water tables, is not known. Schwartz *et al* (1987) reported that perched water table development due to this effect has not been observed within the Southern Alberta region, however, given the high water tables observed within the study region, and overall lack of abrupt geologic discontinuities, the mechanism by which water table development occurs must be due to an overall decline in hydraulic conductivity with depth.

Throughout the Varsity Village and University of Lethbridge area this critical conductivity value is being exceeded allowing for the perched water tables systems observed. It is expected that observed variations in the depth to water table are due to

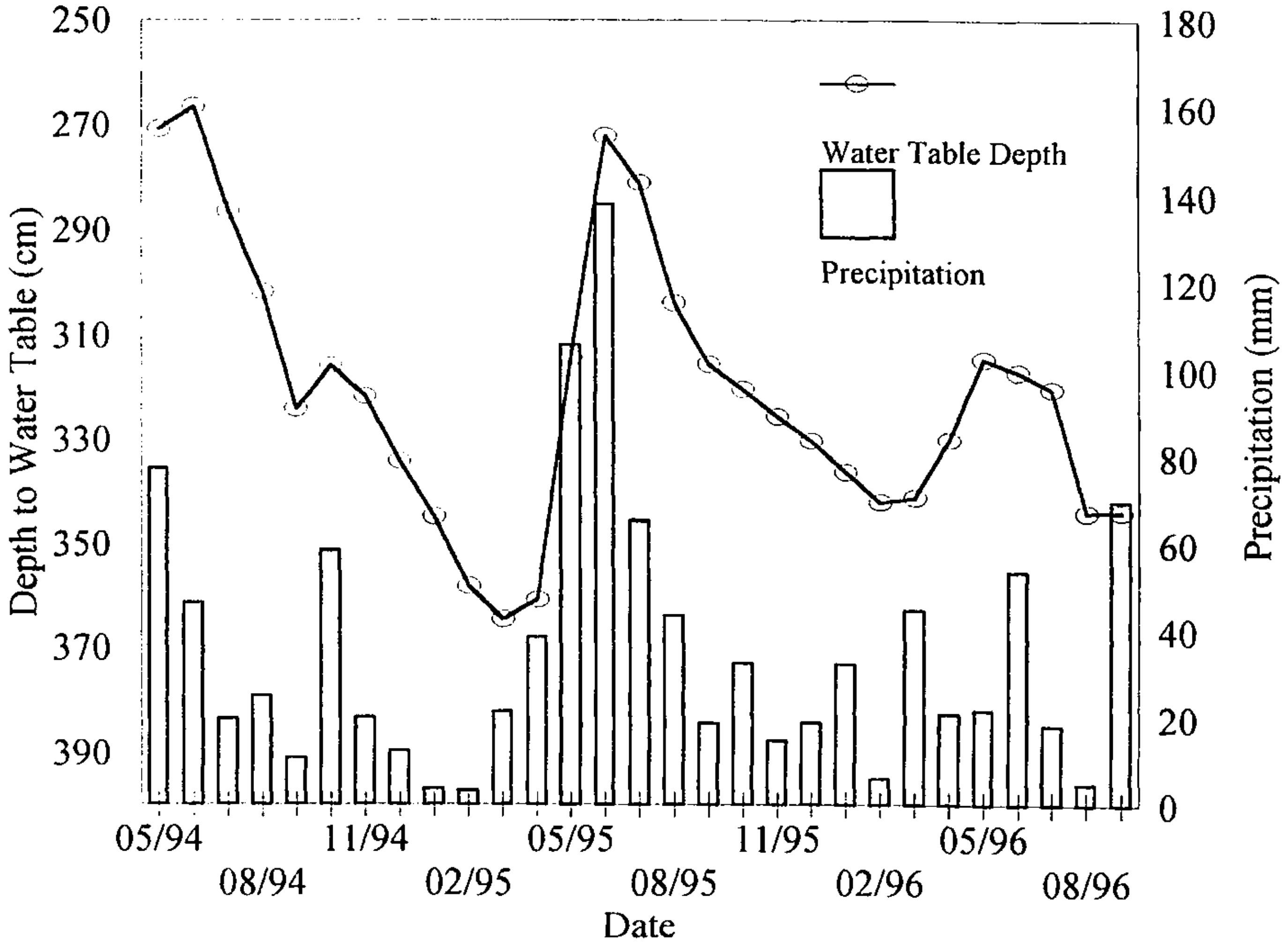


Figure 5.10 Average Water Table Depth and Precipitation for Water Wells 1-5, 8-10,14, 16 and 17, May 1994 - September 1996.

variations in permeability controlled by the local geologic material. Complicating the definition of this boundary is the change of hydraulic conductivity in a non-linear fashion with moisture content (Domenico and Schwartz, 1990).

5.4 Results of the Urban Water Balance Assessment for Varsity Village

Recognising the importance of water in the development of perched water table conditions, discussion below will attempt to evaluate the quantities of water available for groundwater. The results of the urban water balance assessment for the Varsity Village area has been broken down into the following sections: Varsity Village parks, individual homes, and water storage areas. For each of the sub-water balances, total inflow to the system, through precipitation, and irrigation is examined. Investigated outflows from the system include evapotranspiration, runoff, and flow to sanitary systems. Evapotranspiration, and runoff was modeled for turf grass, the dominant vegetation within the study area. For each of the sub-water balances, a total depth of water available for percolation through the rooting zone was calculated for the study periods, with an annual average expected amount of percolation reported. This total depth of water available for deep percolation is calculated based on initial soil moisture (SM) conditions as outlined in section 4.5.5.

5.4.1 City of Lethbridge Parks: Varsity Village

As outlined in section 4.5, a water balance was conducted for six Varsity Village parks on regular irrigation schedules. Parks currently not on irrigation schedules could not be analysed, because irrigation could not be accounted for. Inputs due to precipitation and irrigation, and outputs due to evapotranspiration and runoff are reported below. The expected amount of percolation resulting from irrigation practices followed in Varsity Village parks is also examined.

5.4.1.1 Precipitation and Irrigation

Two sources of water inputs were identified for Varsity Village park areas: precipitation and irrigation. The total depth of irrigation and precipitation applied to each of the examined parks is included in the second and third columns of Tables 5.2 through 5.7.

5.4.1.2 Evapotranspiration

Evapotranspiration losses from irrigated turf grass in the Varsity Village area are summarized in Table 5.8 below. Potential evapotranspiration from irrigated surfaces in urban enivronments is higher than from rural areas due to advected energy from dry surfaces. To account for this temperatures recorded at the Canadian Agricultural Research Station at Lethbridge were corrected as defined in section 4.5.3 according to Chandler (1976).

Table 5.8: Calculated Potential Evapotranspiration at Agriculture Canada Research Station at Lethbridge and Potential Evapotranspiration at Varsity Village Lethbridge, in millimetres

Year	Potential ET at Research Station (mm)	Potential ET at Varsity Village (mm)
1990	521.7	532.9
1991	479.0	490.6
1992	450.9	462.3
1993	410.4	420.7
1994	464.4	474.9
1995	397.0	407.5
1996	501.2	511.3

Table 5.2 Water Balance and Percolation Calculated for Columbia Park*

Year	Irrigation	Precipitation	Calculated ET	I+P-ET	Amount of Deep Percolation	
					SM=50%	SM=75%
1990						
May	92.6	71.0	35.4	128.1	87.2	107.7
June	90.1	42.1	112.7	19.5	30.9	30.9
July	101.8	29.8	108.1	23.5	16.0	16.0
August	102.6	14.6	78.3	38.9	34.6	34.6
Sept	101.2	6.0	36.2	71.1	68.7	68.7
TOTALS	**488.3**	**163.5**	**370.8**	**281.0**	**237.4**	**257.9**
1991						
May	77.4	53.4	37.9	92.9	52.0	72.4
June	76.5	119.2	97.8	97.9	98.7	98.7
July	106.8	26.7	126.4	7.1	27.1	27.1
August	87.1	36.5	75.6	48.0	48.2	48.2
Sept	92.9	29.8	21.0	101.7	99.3	99.3
TOTALS	**440.8**	**265.6**	**358.8**	**347.6**	**325.3**	**345.7**
1992						
May	91.4	14.8	48.6	57.6	19.7	39.8
June	82.3	87.6	74.7	95.2	92.6	92.6
July	83.3	89.8	81.0	92.1	92.1	92.1
August	82.6	36.3	71.2	47.7	47.7	47.7
Sept	106.5	23.9	25.3	105.1	105.1	105.1
TOTALS	**446.1**	**252.4**	**300.7**	**397.8**	**357.2**	**377.3**
1993						
May	92.5	44.2	44.1	92.6	51.8	72.1
June	81.8	111.2	88.3	104.7	104.7	104.7
July	44.2	133.0	79.1	98.2	118.9	118.9
August	78.3	62.6	55.9	85.0	64.6	64.6
Sept	93.2	72.0	19.1	146.1	146.1	146.1
TOTALS	**390.0**	**423.0**	**286.4**	**526.6**	**486.2**	**506.5**
1994						
May	67.6	77.4	41.1	103.9	66.7	87.0
June	106.6	46.4	83.3	69.7	66.2	66.2
July	102.2	19.7	114.4	7.5	10.5	10.5
August	97.1	25.0	66.9	55.2	55.2	55.2
Sept	106.4	10.8	25.8	91.3	91.3	91.3
TOTALS	**479.9**	**179.3**	**331.6**	**327.6**	**290.0**	**310.3**
1995						
May	73.4	105.8	31.7	147.6	106.6	127.1
June	83.0	137.8	70.9	150.0	150.0	150.0
July	87.7	65.5	103.3	49.9	62.7	62.7
August	97.3	28.3	76.6	49.0	49.0	49.0
Sept	103.1	18.8	17.9	103.9	103.9	103.9
TOTALS	**444.5**	**356.2**	**300.4**	**500.4**	**472.2**	**492.7**
1996						
May	97.6	21.7	36.2	83.2	42.2	62.7
June	76.1	53.5	118.4	11.2	33.5	33.5
July	111.1	18.1	127.3	1.9	0.0	0.0
August	96.1	4.8	75.9	25.0	9.6	9.6
Sept	83.5	70.0	23.0	130.5	125.1	125.1
TOTALS	**464.5**	**168.1**	**380.8**	**251.8**	**210.5**	**230.9**

*in Millimetres

Table 5.3 Water Balance and Percolation Calculated for Lafayette Park*

Year	Irrigation	Precipitation	Calculated ET	I+P-ET	Amount of Deep Percolation	
					SM=50%	SM=75%
1990						
May	59.5	71.0	35.4	95.0	55.4	75.8
June	58.0	42.1	112.7	-12.6	14.7	14.7
July	65.4	29.8	108.1	-12.9	0.0	0.0
August	61.7	14.6	78.3	-2.0	0.0	0.0
Sept	65.1	6.0	36.2	34.9	23.8	23.8
TOTALS	**309.7**	**163.5**	**370.8**	**102.5**	**93.9**	**114.4**
1991						
May	49.7	53.4	37.9	65.3	24.4	44.8
June	49.2	119.2	97.8	70.6	71.4	71.4
July	68.7	26.7	126.4	-31.1	11.6	11.6
August	56.0	36.5	75.6	16.9	2.8	2.8
Sept	59.7	29.8	21.0	68.5	56.6	56.6
TOTALS	**283.3**	**265.6**	**358.8**	**190.2**	**166.8**	**187.3**
1992						
May	58.8	14.8	48.6	25.0	0.0	7.1
June	52.9	87.6	74.7	65.8	50.4	63.2
July	53.5	89.8	81.0	62.3	62.3	62.3
August	53.1	36.3	71.2	18.2	18.3	18.3
Sept	68.4	23.9	25.3	67.1	66.9	66.9
TOTALS	**286.7**	**252.4**	**300.7**	**238.4**	**197.9**	**217.9**
1993						
May	59.4	44.2	44.1	59.5	20.4	40.7
June	52.6	111.2	88.3	75.5	77.2	77.2
July	28.4	133.0	79.1	82.3	99.9	99.9
August	50.3	62.6	55.9	57.0	33.0	33.0
Sept	59.8	72.0	19.1	112.7	112.7	112.7
TOTALS	**250.5**	**423.0**	**286.4**	**387.1**	**343.2**	**363.5**
1994						
May	43.5	77.4	41.1	79.7	45.9	66.2
June	68.5	46.4	83.3	31.6	26.5	26.5
July	65.7	19.7	114.4	-29.1	0.0	0.0
August	62.4	25.0	66.9	20.5	0.0	0.0
Sept	68.4	10.8	25.8	53.3	43.7	43.7
TOTALS	**308.4**	**179.3**	**331.6**	**156.1**	**116.1**	**136.4**
1995						
May	47.2	105.8	31.7	121.3	83.6	104.1
June	53.3	137.8	70.9	120.2	117.0	117.0
July	56.3	65.5	103.3	18.5	39.8	39.8
August	62.5	28.3	76.6	14.2	8.6	8.6
Sept	66.2	18.8	17.9	67.0	67.0	67.0
TOTALS	**285.5**	**356.2**	**300.4**	**341.3**	**316.0**	**336.5**
1996						
May	62.7	21.7	36.2	48.2	7.3	27.8
June	49.0	53.5	118.4	-15.9	8.0	8.0
July	71.5	18.1	127.3	-37.8	0.0	0.0
August	61.8	4.8	75.9	-9.3	0.0	0.0
Sept	53.6	70.0	23.0	100.6	54.8	54.8
TOTALS	**298.6**	**168.1**	**380.8**	**85.9**	**70.0**	**90.5**

*in Millimetres

Table 5.4 Water Balance and Percolation Calculated for Laval Park*

Year	Irrigation	Precipitation	Calculated ET	I+P-ET	Amount of Deep Percolation	
					SM=50%	SM=75%
1990						
May	75.1	71.0	35.4	110.7	70.2	90.7
June	73.0	42.1	112.7	2.4	22.4	22.4
July	82.6	29.8	108.1	4.3	0.0	0.0
August	77.8	14.6	78.3	14.1	17.4	17.4
Sept	82.1	6.0	36.2	52.0	48.7	48.7
TOTALS	**390.7**	**163.5**	**370.8**	**183.4**	**158.8**	**179.2**
1991						
May	62.8	53.4	37.9	78.3	37.4	57.8
June	62.1	119.2	97.8	83.4	84.2	84.2
July	86.7	26.7	126.4	-13.1	18.8	18.8
August	70.7	36.5	75.6	31.6	21.2	21.2
Sept	75.4	29.8	21.0	84.2	80.4	80.4
TOTALS	**357.6**	**265.6**	**358.8**	**264.5**	**242.0**	**262.5**
1992						
May	74.1	14.8	48.6	40.3	2.4	22.5
June	66.8	87.6	74.7	79.7	77.1	77.1
July	67.6	89.8	81.0	76.4	76.4	76.4
August	67.1	36.3	71.2	32.1	32.1	32.1
Sept	86.4	23.9	25.3	85.0	85.0	85.0
TOTALS	**362.0**	**252.4**	**300.7**	**313.6**	**273.1**	**293.2**
1993						
May	75.0	44.2	44.1	75.2	35.2	55.5
June	66.4	111.2	88.3	89.3	88.5	88.5
July	35.9	133.0	79.1	89.8	110.6	110.6
August	63.6	62.6	55.9	70.3	48.0	48.0
Sept	75.6	72.0	19.1	128.6	128.6	128.6
TOTALS	**316.5**	**423.0**	**286.4**	**453.1**	**410.8**	**431.2**
1994						
May	54.8	77.4	41.1	91.1	55.7	76.0
June	86.5	46.4	83.3	49.6	45.2	45.2
July	83.0	19.7	114.4	-11.8	0.7	0.7
August	78.8	25.0	66.9	36.9	26.6	26.6
Sept	86.3	10.8	25.8	71.2	71.2	71.2
TOTALS	**389.4**	**179.3**	**331.6**	**237.1**	**199.5**	**219.8**
1995						
May	59.6	105.8	31.7	133.7	93.7	114.1
June	67.4	137.8	70.9	134.3	133.4	133.4
July	71.2	65.5	103.3	33.4	50.7	50.7
August	79.0	28.3	76.6	30.7	30.7	30.7
Sept	83.7	18.8	17.9	84.5	84.5	84.5
TOTALS	**360.8**	**356.2**	**300.4**	**416.6**	**393.0**	**413.5**
1996						
May	79.2	21.7	36.2	64.8	23.8	44.3
June	61.7	53.5	118.4	-3.2	20.0	20.0
July	90.2	18.1	127.3	-19.1	0.0	0.0
August	77.9	4.8	75.9	6.8	0.0	0.0
Sept	67.8	70.0	23.0	114.8	84.5	84.5
TOTALS	**376.8**	**168.1**	**380.8**	**164.2**	**128.3**	**148.8**

*in Millimetres

Table 5.5 Water Balance and Percolation Calculated for Rutgers Park*

Year	Irrigation	Precipitation	Calculated ET	I+P-ET	Amount of Deep Percolation	
					SM=50%	SM=75%
1990						
May	97.3	71.0	35.4	132.9	91.9	112.4
June	100.3	42.1	112.7	29.7	35.7	35.7
July	113.1	29.8	108.1	34.8	32.1	32.1
August	106.7	14.6	78.3	43.0	44.9	44.9
Sept	112.5	6.0	36.2	82.4	80.5	80.5
TOTALS	**529.9**	**163.5**	**370.8**	**322.7**	**285.2**	**305.6**
1991						
May	86.0	53.4	37.9	101.5	60.6	81.0
June	85.1	119.2	97.8	106.5	107.3	107.3
July	118.7	26.7	126.4	18.9	31.9	31.9
August	96.8	36.5	75.6	57.7	57.9	57.9
Sept	103.1	29.8	21.0	111.9	109.5	109.5
TOTALS	**489.7**	**265.6**	**358.8**	**396.5**	**367.2**	**387.7**
1992						
May	101.6	14.8	48.6	67.8	29.9	50.0
June	91.4	87.6	74.7	104.3	101.8	101.8
July	92.4	89.8	81.0	101.3	101.3	101.3
August	91.8	36.3	71.2	56.8	56.8	56.8
Sept	118.3	23.9	25.3	116.9	116.9	116.9
TOTALS	**495.5**	**252.4**	**300.7**	**447.2**	**406.7**	**426.7**
1993						
May	102.7	44.2	44.1	102.8	62.0	82.4
June	91.0	111.2	88.3	113.9	113.9	113.9
July	49.1	133.0	79.1	103.0	123.8	123.8
August	86.9	62.6	55.9	93.6	74.3	74.3
Sept	103.4	72.0	19.1	156.3	156.3	156.3
TOTALS	**433.0**	**423.0**	**286.4**	**569.6**	**530.2**	**550.5**
1994						
May	75.1	77.4	41.1	111.4	73.2	93.4
June	118.5	46.4	83.3	81.5	79.0	79.0
July	113.5	19.7	114.4	18.8	21.9	21.9
August	107.8	25.0	66.9	66.0	66.0	66.0
Sept	118.2	10.8	25.8	103.1	103.1	103.1
TOTALS	**533.1**	**179.3**	**331.6**	**380.8**	**343.2**	**363.5**
1995						
May	81.5	105.8	31.7	155.6	114.7	135.1
June	92.2	137.8	70.9	159.1	159.1	159.1
July	97.4	65.5	103.3	59.6	69.7	69.7
August	108.1	28.3	76.6	59.8	59.8	59.8
Sept	114.3	18.8	17.9	115.2	115.2	115.2
TOTALS	**493.4**	**356.2**	**300.4**	**549.2**	**518.4**	**538.9**
1996						
May	108.4	21.7	36.2	93.9	53.0	73.4
June	84.7	53.5	118.4	19.8	41.6	41.6
July	123.5	18.1	127.3	14.3	0.0	0.0
August	106.8	4.8	75.9	35.7	33.3	33.3
Sept	92.6	70.0	23.0	139.6	134.2	134.2
TOTALS	**516.1**	**168.1**	**380.8**	**303.4**	**262.1**	**282.6**

*in Millimetres

Table 5.6 Water Balance and Percolation Calculated for Sheridan Park*

Year	Irrigation	Precipitation	Calculated ET	I+P-ET	Amount of Deep Percolati	
					SM=50%	SM=75%
1990						
May	133.6	71.0	35.4	169.1	128.2	148.7
June	137.2	42.1	112.7	66.5	66.5	66.5
July	155.2	29.8	108.1	76.8	78.2	78.2
August	146.2	14.6	78.3	82.5	82.6	82.6
Sept	154.2	6.0	36.2	124.1	124.0	124.0
TOTALS	**726.3**	**163.5**	**370.8**	**519.1**	**479.5**	**500.0**
1991						
May	117.9	53.4	37.9	133.4	92.5	113.0
June	116.6	119.2	97.8	137.9	138.8	138.8
July	162.8	26.7	126.4	63.1	66.5	66.5
August	132.8	36.5	75.6	93.7	93.8	93.8
Sept	141.7	29.8	21.0	150.4	148.0	148.0
TOTALS	**671.7**	**265.6**	**358.8**	**578.6**	**539.6**	**560.1**
1992						
May	139.3	14.8	48.6	105.5	67.5	87.6
June	125.4	87.6	74.7	138.3	135.7	135.7
July	127.0	89.8	81.0	135.8	135.8	135.8
August	126.0	36.3	71.2	91.0	91.0	91.0
Sept	162.2	23.9	25.3	160.9	160.9	160.9
TOTALS	**679.8**	**252.4**	**300.7**	**631.5**	**590.9**	**611.0**
1993						
May	140.9	44.2	44.1	141.1	100.3	120.6
June	124.7	111.2	88.3	147.6	147.6	147.6
July	67.5	133.0	79.1	121.4	142.2	142.2
August	119.4	62.6	55.9	126.1	110.8	110.8
Sept	142.1	72.0	19.1	195.0	195.0	195.0
TOTALS	**594.5**	**423.0**	**286.4**	**731.1**	**695.8**	**716.1**
1994						
May	103.0	77.4	41.1	139.3	98.5	118.8
June	162.5	46.4	83.3	125.6	125.6	125.6
July	155.8	19.7	114.4	61.1	64.2	64.2
August	148.0	25.0	66.9	106.1	106.1	106.1
Sept	162.1	10.8	25.8	147.0	147.0	147.0
TOTALS	**731.4**	**179.3**	**331.6**	**579.0**	**541.4**	**561.7**
1995						
May	112.0	105.8	31.7	186.1	145.2	165.6
June	126.6	137.8	70.9	193.5	193.5	193.5
July	133.7	65.5	103.3	95.9	101.8	101.8
August	148.3	28.3	76.6	100.0	100.0	100.0
Sept	157.1	18.8	17.9	158.0	158.0	158.0
TOTALS	**677.6**	**356.2**	**300.4**	**733.4**	**698.4**	**718.9**
1996						
May	148.8	21.7	36.2	134.3	93.4	113.9
June	116.0	53.5	118.4	51.0	71.0	71.0
July	169.4	18.1	127.3	60.1	40.2	40.2
August	146.4	4.8	75.9	75.3	78.1	78.1
Sept	127.3	70.0	23.0	174.3	168.9	168.9
TOTALS	**707.8**	**168.1**	**380.8**	**495.1**	**451.6**	**472.1**

*in Millimetres

Table 5.7 Water Balance and Percolation Calculated for Trinity Park*

Year	Irrigation	Precipitation	Calculated ET	I+P-ET	Amount of Deep Percolation	
					SM=50%	SM=75%
1990						
May	137.5	71.0	35.4	173.0	132.1	152.6
June	133.4	42.1	112.7	62.8	62.8	62.8
July	151.1	29.8	108.1	72.8	74.4	74.4
August	142.3	14.6	78.3	78.6	78.9	78.9
Sept	150.1	6.0	36.2	120.0	119.7	119.7
TOTALS	**714.4**	**163.5**	**370.8**	**507.1**	**467.8**	**488.2**
1991						
May	114.8	53.4	37.9	130.3	89.4	109.9
June	113.4	119.2	97.8	134.8	135.6	135.6
July	158.6	26.7	126.4	58.8	62.8	62.8
August	129.3	36.5	75.6	90.2	90.4	90.4
Sept	138.0	29.8	21.0	146.8	144.4	144.4
TOTALS	**654.1**	**265.6**	**358.8**	**560.9**	**522.6**	**543.0**
1992						
May	135.5	14.8	48.6	101.8	63.8	83.9
June	122.1	87.6	74.7	135.0	132.4	132.4
July	123.7	89.8	81.0	132.6	132.6	132.6
August	122.7	36.3	71.2	87.7	87.7	87.7
Sept	158.0	23.9	25.3	156.6	156.6	156.6
TOTALS	**662.1**	**252.4**	**300.7**	**613.7**	**573.2**	**593.3**
1993						
May	137.3	44.2	44.1	137.4	96.6	117.0
June	121.3	111.2	88.3	144.3	144.3	144.3
July	65.8	133.0	79.1	119.7	140.5	140.5
August	116.3	62.6	55.9	123.0	107.4	107.4
Sept	138.4	72.0	19.1	191.4	191.4	191.4
TOTALS	**579.1**	**423.0**	**286.4**	**715.7**	**680.1**	**700.4**
1994						
May	100.3	77.4	41.1	136.5	95.8	116.1
June	158.3	46.4	83.3	121.3	121.3	121.3
July	151.8	19.7	114.4	57.0	60.2	60.2
August	144.1	25.0	66.9	102.2	102.2	102.2
Sept	157.8	10.8	25.8	142.8	142.8	142.8
TOTALS	**712.2**	**179.3**	**331.6**	**559.9**	**522.3**	**542.6**
1995						
May	109.1	105.8	31.7	183.2	142.3	162.7
June	123.3	137.8	70.9	190.2	190.2	190.2
July	130.2	65.5	103.3	92.4	98.5	98.5
August	144.4	28.3	76.6	96.2	96.2	96.2
Sept	153.1	18.8	17.9	154.0	154.0	154.0
TOTALS	**660.2**	**356.2**	**300.4**	**716.0**	**681.2**	**701.7**
1996						
May	145.0	21.7	36.2	130.5	89.6	110.0
June	112.8	53.5	118.4	47.9	68.0	68.0
July	164.9	18.1	127.3	55.7	35.5	35.5
August	142.5	4.8	75.9	71.4	74.2	74.2
Sept	124.1	70.0	23.0	171.1	165.7	165.7
TOTALS	**689.2**	**168.1**	**380.8**	**476.5**	**433.0**	**453.5**

*in Millimetres

The total amount of evapotranspiration calculated for each of the parks analysed in Varsity Village is included in column four of Tables 5.2 through 5.7.

5.4.1.3 Runoff

During large precipitation events, runoff from turfgrassed areas is expected. Very little or no runoff is expected during irrigation events, since during the study period the estimated depth applied never exceeded the initial abstraction value (estimated in section 4.5.4). Runoff from turf grass areas is expected to be low due the exceptional water infiltration rates, and water holding capabilities both observed and as described in Hino *et al* (1987) and Gross *et al* (1990). As demonstrated in Table 5.9 the total depth of water due to lawn runoff is expected to be very low for the time period of May - September 1990-1996.

Table 5.9: Total Precipitation Received May-September and the Total Depth of Runoff Calculated for a Turfgrass Area, 1990 - 1996, in millimetres.

Year	Precipitation	Runoff
1990	163.5	3.3
1991	265.6	15.5
1992	252.4	2.3
1993	423.0	9.5
1994	179.3	0.7
1995	356.2	9.3
1996	168.1	2.7

5.4.1.4 Percolation

Columns six and seven of Tables 5.2 through 5.7 report the expected amount of percolation beyond the root zone under different levels of initial soil water storage (SM) beginning May 1st of each year. From Tables 5.2 through 5.7 it is evident that in each year more water was applied than was evaporated or stored in the soil profile. The result of surpassing the field capacity of the soil and the evapotranspiration rate are contributions to local perched water tables through percolation. Percolation occurred at all park locations during the study period regardless of initial soil moisture conditions.

The effects of calculated percolation on water table elevation at the six Varsity Village parks examined has been included as Figure 5.11. Figure 5.11 compares average water table depth of Varsity Village Parks with the average percolation calculated. As illustrated, increases or decreases in water table depth appears to lag behind estimated amounts of percolation. This is demonstrated very clearly in September 1996. Large amounts of percolation calculated for this month do not appear to affect water table elevation until October.

Large amounts of water available for percolation through the root zone were calculated for each of the park areas in the months of May, June, and September as demonstrated in Tables 5.2-5.7. The large estimates of percolation recorded in the months of May and September is due to the amount of irrigation applied despite the low amounts of evapotranspiration. For example, in May and September, 1990 in Columbia Park, the amount of irrigation applied during May was 162 percent higher than the amount of evapotranspiration calculated; for the month of September, irrigation exceeded evapotranspiration by 180 percent. At the present time, irrigation schedules do not lower irrigation rates in response to the lower rate of evapotranspiration. On the basis of

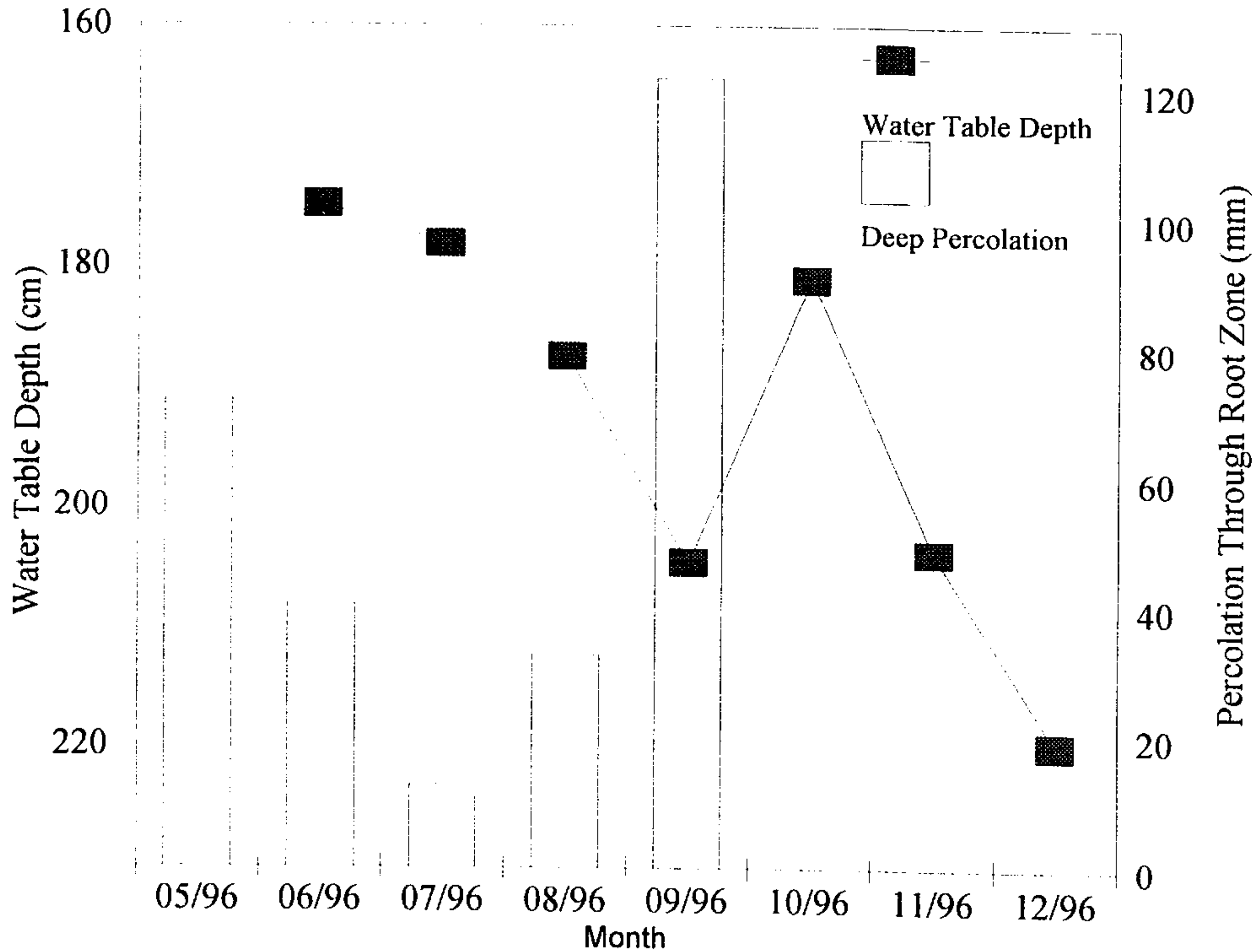


Figure 5.11 Average Estimated Percolation Through Root Zone and Water Table Elevation for Varsity Village Parks May - December, 1996

routine Over-watering in these months it is likely that irrigation schedules have been formulated to account for peak evaporative demands.

High percolation in June is possibly due to high amounts of rainfall typically received (demonstrated in Figure 3.2). During the study period, June precipitation was on average, 54% greater than the next wettest month (May). Despite efforts to schedule irrigation around precipitation events (as described in section 4.5.2), the amount of irrigation and precipitation is typically above the calculated evapotranspiration demands of the turf grass, resulting in a large amount of percolation. Irrigating grass below field capacity conditions, as suggested by Trooien and Reichman (1993), would prevent the high amount of percolation recorded in this month, by allowing for room in the soil profile for the storage of precipitation water. Irrigation water could be saved if crops were watered based on evapotranspiration rather than precipitation received.

As reported in Tables 5.2-5.7, the analysis has indicated routine overwatering of Varsity Village parks, especially during the Months of May, June and September. Overwatering is probably due to irrigation schedules operating at peak evaporative demands rather than the demands of the lawn at that particular time period. The calculated volumes of water applied in excess of evapotranspiration rates, and soil moisture storage available for deep percolation in each of the analysed Varsity Village parks is reported in Table 5.10.

Table 5.10: Potential Inputs of Water Due to Over-irrigation of Varsity Village Parks, in Cubic Metres

Year	Columbia	Lafayette	Laval	Rutgers	Sheridan	Trinity
1990	6171.6	2629.0	5029.2	19382.4	7355.0	3671.6
1991	8273.4	4303.6	7365.7	24584.9	8238.8	4083.7
1992	9028.8	5007.2	8226.0	27064.0	8988.5	4461.3
1993	12120.5	8352.9	12098.4	34915.7	10534.3	5267.1
1994	7424.6	3133.5	6167.3	23051.3	8262.9	4080.1
1995	11790.1	7732.5	11601.8	34176.5	10574.6	5276.4
1996	5526.2	2079.9	4174.2	17919.3	6944.6	3410.2
Total	**60335.3**	**33238.7**	**54662.6**	**181094.0**	**60898.6**	**30250.4**

5.4.2 Household Lawns and Gardens

A water balance was conducted for household lawns in the Varsity Village area between 1990 and 1994. Calculated inputs were: irrigation, precipitation, and roof runoff. Analysed outputs were: evapotranspiration, runoff, and flow to the waste water treatment plant through household weeping tile conected to city sanitary sewers. The expected amount of percolation available for groundwater recharge contributed as result of current irrigation practices will also be examined. Each of the components analysed in the calculation of the water balance will be discussed separately below.

5.4.2.1 Household Irrigation

As discussed in section 4.6.1 irrigating households in the Varsity Village area were broken up into four groups, high, moderately high, moderately low, and low water irrigation water users, based on the average amount of irrigation over a five year period. The amount of irrigation applied over the study period by each of the four groups has been summarized in Tables 5.11 through 5.14.

Table 5.11 Water Balance and Percolation Calculated for High Water Users in Millimetres

Year	Irrigation	Precipitation	Roof Runoff	Calculated ET	Percolation through Root Zone		
					SM=25%	SM=50%	SM=75%
1990							
May	3.1	71.0	37.2	35.4	19.5	22.2	42.7
June	47.4	42.1	22.4	112.7	0.0	0.0	0.0
July	183.1	29.8	12.9	108.1	116.8	116.8	116.8
August	207.6	14.6	19.8	78.3	149.8	149.8	149.8
Sept	189.7	6.0	3.1	36.2	162.7	162.7	162.7
TOTALS	**630.9**	**163.5**	**95.5**	**370.8**	**448.8**	**451.5**	**472.0**
1991							
May	0.0	53.4	26.6	37.9	0.0	0.0	18.5
June	51.5	119.2	64.1	97.8	94.2	94.4	94.4
July	17.9	26.7	12.0	126.4	0.0	0.0	0.0
August	175.8	36.5	27.4	75.6	138.3	138.3	138.3
Sept	68.1	29.8	15.7	21.0	92.4	92.4	92.4
TOTALS	**313.4**	**265.6**	**145.9**	**358.8**	**324.9**	**325.1**	**343.6**
1992							
May	11.5	14.8	5.0	48.6	0.0	0.0	0.0
June	161.1	87.6	47.2	74.7	178.4	181.6	170.5
July	85.6	89.8	47.5	81.0	139.4	139.4	139.4
August	49.5	36.3	28.4	71.2	33.7	33.7	33.7
Sept	71.1	23.9	9.6	25.3	79.4	79.4	79.4
TOTALS	**378.9**	**252.4**	**137.7**	**300.7**	**430.9**	**434.0**	**422.9**
1993							
May	0.0	44.2	21.8	44.1	0.0	0.0	1.4
June	52.8	111.2	61.0	88.3	103.7	102.2	121.1
July	26.2	133.0	72.4	79.1	143.6	143.6	143.6
August	39.8	62.6	34.7	55.9	63.1	63.1	63.1
Sept	85.4	72.0	38.7	19.1	174.2	174.2	174.2
TOTALS	**204.2**	**423.0**	**228.5**	**286.4**	**484.6**	**483.0**	**503.5**
1994							
May	0.0	77.4	42.8	41.1	30.8	30.7	51.1
June	82.3	46.4	25.3	83.3	70.0	70.0	70.0
July	38.7	19.7	9.7	114.4	0.0	0.0	0.0
August	155.6	25.0	12.1	66.9	88.3	88.3	88.3
Sept	249.2	10.8	5.5	25.8	239.6	239.6	239.6
TOTALS	**525.8**	**179.3**	**95.3**	**331.6**	**428.8**	**428.7**	**449.1**

Table 5.12 Water Balance and Percolation Calculated for Moderately High Water Users in Millimetres

Year	Irrigation	Precipitation	Roof Runoff	Calculated ET	Percolation through Root Zone		
					SM=25%	SM=50%	SM=75%
1990							
May	8.1	71.0	37.2	35.4	24.5	27.3	47.7
June	36.2	42.1	22.4	112.7	0.0	0.0	0.0
July	139.3	29.8	12.9	108.1	61.8	61.8	61.8
August	182.0	14.6	19.8	78.3	124.3	124.3	124.3
Sept	187.7	6.0	3.1	36.2	160.6	160.6	160.6
TOTALS	**553.3**	**163.5**	**95.5**	**370.8**	**371.2**	**374.0**	**394.4**
1991							
May	0.0	53.4	26.6	37.9	0.0	0.0	18.5
June	66.2	119.2	64.1	97.8	108.8	109.1	109.1
July	24.0	26.7	12.0	126.4	0.0	0.0	0.0
August	138.1	36.5	27.4	75.6	95.5	95.5	95.5
Sept	60.7	29.8	15.7	21.0	84.9	84.9	84.9
TOTALS	**288.9**	**265.6**	**145.9**	**358.8**	**289.2**	**289.5**	**307.9**
1992							
May	22.6	14.8	5.0	48.6	0.0	0.0	0.0
June	152.4	87.6	47.2	74.7	160.7	163.8	172.9
July	88.0	89.8	47.5	81.0	141.8	141.8	141.8
August	34.6	36.3	28.4	71.2	18.8	18.8	18.8
Sept	72.3	23.9	9.6	25.3	80.6	80.6	80.6
TOTALS	**370.0**	**252.4**	**137.7**	**300.7**	**401.9**	**405.0**	**414.1**
1993							
May	0.5	44.2	21.8	44.1	0.0	0.0	1.9
June	59.3	111.2	61.0	88.3	110.8	109.2	127.7
July	31.5	133.0	72.4	79.1	148.8	148.8	148.8
August	43.5	62.6	34.7	55.9	66.8	66.8	66.8
Sept	70.6	72.0	38.7	19.1	159.4	159.4	159.4
TOTALS	**205.4**	**423.0**	**228.5**	**286.4**	**485.8**	**484.2**	**504.7**
1994							
May	0.0	77.4	42.8	41.1	30.8	30.7	51.1
June	81.0	46.4	25.3	83.3	68.7	68.7	68.7
July	19.6	19.7	9.7	114.4	0.0	0.0	0.0
August	164.0	25.0	12.1	66.9	108.9	108.9	108.9
Sept	196.9	10.8	5.5	25.8	187.3	187.3	187.3
TOTALS	**461.5**	**179.3**	**95.3**	**331.6**	**395.6**	**395.5**	**416.0**

Table 5.13 Water Balance and Percolation Calculated for Moderately Low Water Users in Millimetres

Year	Irrigation	Precipitation	Roof Runoff	Calculated ET	Percolation through Root Zone		
					SM=25%	SM=50%	SM=75%
1990							
May	10.6	71.0	37.2	35.4	27.0	29.7	50.2
June	19.5	42.1	22.4	112.7	0.0	0.0	0.0
July	152.8	29.8	12.9	108.1	58.7	58.7	58.7
August	150.9	14.6	19.8	78.3	93.1	93.1	93.1
Sept	172.9	6.0	3.1	36.2	145.8	145.8	145.8
TOTALS	**506.7**	**163.5**	**95.5**	**370.8**	**324.6**	**327.3**	**347.8**
1991							
May	1.3	53.4	26.6	37.9	0.0	0.0	19.8
June	67.1	119.2	64.1	97.8	110.0	110.0	110.0
July	30.8	26.7	12.0	126.4	0.0	0.0	0.0
August	114.9	36.5	27.4	75.6	66.6	66.6	66.6
Sept	57.9	29.8	15.7	21.0	82.2	82.2	82.2
TOTALS	**272.1**	**265.6**	**145.9**	**358.8**	**258.8**	**258.8**	**278.6**
1992							
May	11.4	14.8	5.0	48.6	0.0	0.0	0.0
June	124.8	87.6	47.2	74.7	142.2	145.4	134.0
July	72.0	89.8	47.5	81.0	125.8	125.8	125.8
August	58.7	36.3	28.4	71.2	42.9	42.9	42.9
Sept	65.9	23.9	9.6	25.3	74.2	74.2	74.2
TOTALS	**332.8**	**252.4**	**137.7**	**300.7**	**385.1**	**388.3**	**376.9**
1993							
May	0.8	44.2	21.8	44.1	0.0	0.0	2.3
June	39.8	111.2	61.0	88.3	91.6	90.0	108.1
July	34.4	133.0	72.4	79.1	151.8	151.8	151.8
August	34.5	62.6	34.7	55.9	57.8	57.8	57.8
Sept	58.9	72.0	38.7	19.1	147.7	147.7	147.7
TOTALS	**168.4**	**423.0**	**228.5**	**286.4**	**448.8**	**447.3**	**467.7**
1994							
May	0.0	77.4	42.8	41.1	30.8	30.7	51.1
June	75.5	46.4	25.3	83.3	63.2	63.2	63.2
July	16.3	19.7	9.7	114.4	0.0	0.0	0.0
August	154.2	25.0	12.1	66.9	101.2	101.2	101.2
Sept	190.7	10.8	5.5	25.8	181.1	181.1	181.1
TOTALS	**436.7**	**179.3**	**95.3**	**331.6**	**376.3**	**376.2**	**396.7**

Table 5.14 Water Balance and Percolation Calculated for Low Water Users in Millimetres

Year	Irrigation	Precipitation	Roof Runoff	Calculated ET	Percolation through Root Zone		
					SM=25%	SM=50%	SM=75%
1990							
May	12.7	71.0	37.2	35.4	29.1	31.9	52.3
June	13.5	42.1	22.4	112.7	0.0	0.0	0.0
July	27.5	29.8	12.9	108.1	0.0	0.0	0.0
August	122.4	14.6	19.8	78.3	52.6	52.6	52.6
Sept	148.6	6.0	3.1	36.2	121.6	121.6	121.6
TOTALS	**324.7**	**163.5**	**95.5**	**370.8**	**203.3**	**206.0**	**226.5**
1991							
May	0.0	53.4	26.6	37.9	0.0	0.0	18.5
June	56.2	119.2	64.1	97.8	99.1	99.1	99.1
July	28.4	26.7	12.0	126.4	0.0	0.0	0.0
August	92.8	36.5	27.4	75.6	41.2	41.2	41.2
Sept	51.0	29.8	15.7	21.0	75.3	75.3	75.3
TOTALS	**228.5**	**265.6**	**145.9**	**358.8**	**215.7**	**215.7**	**234.1**
1992							
May	22.1	14.8	5.0	48.6	0.0	0.0	0.0
June	118.4	87.6	47.2	74.7	164.2	160.4	165.6
July	71.8	89.8	47.5	81.0	125.6	125.6	125.6
August	49.1	36.3	28.4	71.2	33.2	33.2	33.2
Sept	58.1	23.9	9.6	25.3	66.3	66.3	66.3
TOTALS	**319.4**	**252.4**	**137.7**	**300.7**	**389.4**	**385.5**	**390.7**
1993							
May	2.3	44.2	21.8	44.1	0.0	0.0	3.8
June	25.5	111.2	61.0	88.3	91.7	90.2	93.9
July	21.5	133.0	72.4	79.1	138.8	138.8	138.8
August	7.0	62.6	34.7	55.9	30.3	30.3	30.3
Sept	23.1	72.0	38.7	19.1	111.8	111.8	111.8
TOTALS	**79.4**	**423.0**	**228.5**	**286.4**	**372.6**	**371.1**	**378.6**
1994							
May	0.0	77.4	42.8	41.1	30.8	30.7	51.1
June	65.3	46.4	25.3	83.3	53.0	53.0	53.0
July	7.4	19.7	9.7	114.4	0.0	0.0	0.0
August	133.4	25.0	12.1	66.9	92.2	92.2	92.2
Sept	123.8	10.8	5.5	25.8	114.2	114.2	114.2
TOTALS	**329.9**	**179.3**	**95.3**	**331.6**	**290.2**	**290.1**	**310.5**

Typically, during the irrigation season in Lethbridge, approximately 46% of all water put into distribution for Varsity Village homes is used for irrigation. Average monthly household water consumption throughout the study period is summarized in Figure 5.12.

High consumption values observed in October, a time when very little irrigation would be expected, may be the result of estimation errors in data collection. Since household water consumption is measured bi-monthly, estimations of water use in October may be greater than actual usage. Low average water consumptions observed in May, could be the result of underestimations based on meter readings taken from the month of April.

For the five year study period it was found that household irrigation for any irrigation season can be estimated by the equation:

$$IRR = -0.56420(PET_{grass}) + -1.43338(PPT) + 923.091 \qquad (5.1)$$

where:

IRR is irrigation in millimetres,
PET_{grass} is calculated evapotranspiration from turf grass in millimetres,
PPT is precipitation in millimetres.

This formula was derived using a multiple regression using the collected data. The r^2 value of equation 5.1 was found to be 0.90 (n=5 yrs.).

Correlations (Pearson) were performed between the annual amount of irrigation water applied and the calculated amount of evapotranspiration and precipitation. Results are reported in Table 5.15 below.

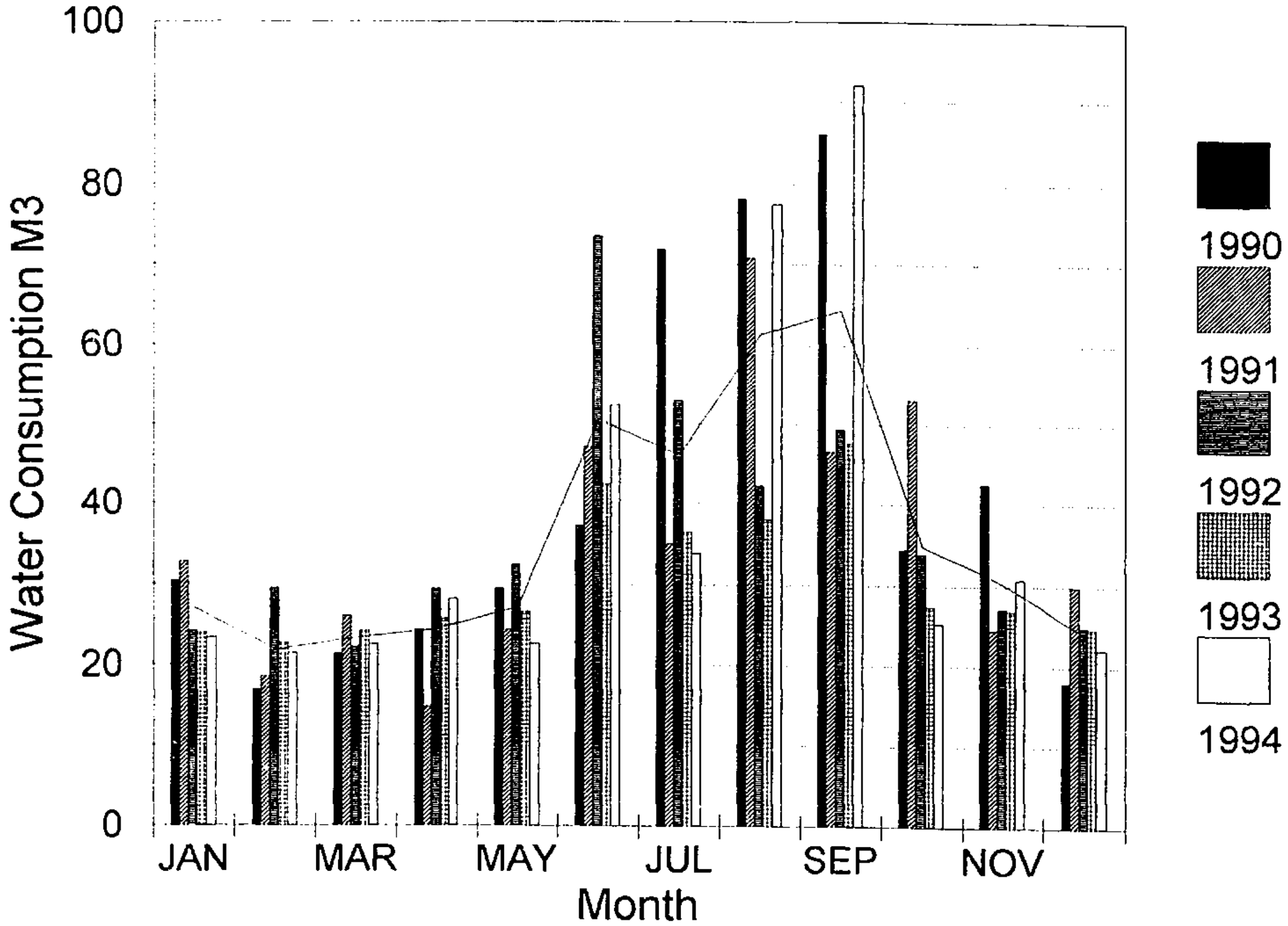


Figure 5.12: Varsity Village Monthly Water Consumption January 1990 to December 1994

Table 5.15 Correlations Between Irrigation Water Applied and Calculated amount of Precipitation and Evapotranspiration (n=5 years)

	Irrigation
Precipitation	-0.9429
Evapotranspiration	0.6333

The high correlation between irrigation water applied throughout the summer period and precipitation would indicate that the strongest factor influencing a home owners decision to irrigate is precipitation received. The calculated amount of evapotranspiration, which to the average homeowner would be perceived as the amount of heat, and the amount of irrigaiton recieved, is not as strongly correlated. In the Varsity Village area, home owners perceive precipitation as the strongest factor controling soil moisture, as precipitation unlike evapotranspiration is both visible and tangible. Similar results were obtained by Grimmond and Oke (1986). In this study, home irrigation response to precipitation was immediate.

The strength of the relationship between weather variables and irrigation (in millimetres), varies according to the amount of water applied each year as irrigation. As discussed previously households in the study area were broken up into four equal sized groups based on irrigation season average water use. As water use increased, the relationship between irrigation water applied and precipitation, and evapotranspiration declined. This relationship is illustrated in Table 5.16.

Table 5.16: Strength of Relationship Between Water Applied and Weather Variables Precipitation and Evapotranspiration, Expressed in Terms of R-Squared Values Obtained in a Multi-Linear Regression Analysis (n=5 years)

Water Use Group	R-Squared Value
L	0.9726
ML	0.8817
MH	0.8334
H	0.8315

Despite increased lot size for the higher water users, the strength of relationship between water applied and the variables precipitation and evapotranspiration declined. This result suggests that higher water users are irrigating without regard to the amount of water necessary to meet evaporative demands.

It was determined that for each water use group the total amount of irrigation for a given year could be estimated through the following equations previously defined in section 4.8.1:

$$IRR_L = PET_{grass}(-1.27739) + PPT(-1.38388) + 1045.10 \quad (4.30)$$

$$IRR_{ML} = PET_{grass}(-0.2985) + PPT(-1.3756) + 812.148 \quad (4.31)$$

$$IRR_{MH} = PET_{grass}(-0.39126) + PPT(-1.40173) + 883.812 \quad (4.32)$$

$$IRR_H = PET_{grass}(-0.09812) + PPT(-1.62957) + 866.633 \quad (4.33)$$

where:

IRR_L, IRR_{ML}, IRR_{MH}, and IRR_H are irrigation water applied to low, moderately low, moderately high, and high water use areas respectively, in millimetres.

5.4.2.2 Precipitation and Roof Runoff

The total amount of precipitation reaching lawns and gardens in the study area has been included in Tables 5.11 - 5.14. The amount of water reaching household lawns is enhanced due to the practice of many Varsity Village residents of diverting rain water collected on roofs to the grassed areas around their home. As discussed in section 4.6.2, approximately 1 mm of precipitation is lost as storage on building roofs. However, additional rainfall is available for runoff through downspouts and onto residential lawns.

Houses, garages, or other structures occupy approximately 38% of an average lot in the Varsity Village area. A survey of drainage characteristics from homes found that approximately 85% of homeowners discharged roof runoff onto the turf, the remaining 15% of downspouts were discharged onto an impermeable surface. The total volume of water discharded from roofs and applied to turf surfaces is reported in Table 5.17.

Table 5.17: Potential Volume of Roof Runoff Water From Residential Homes, and Garages in the Varsity Village During the Irrigation Season, May - September

Year	Potential Input in m^3
1990	32877.3
1991	55445.5
1992	52117.2
1993	92747.5
1994	38682.0

5.4.2.3 Evapotranspiration

The total amount of evapotranspiration from a turfed grass surface has been examined above in section 5.4.1.3 as determined in section 4.5.3. The total amount of evapotranspiration from household turfgrass is in Tables 5.11 - 5.14.

5.4.2.4 Runoff

Runoff from household lawns is expected to be higher than runoff estimated from park areas due to the practice of many Varsity Village residents of discharging roof runoff onto surrounding turf areas. Calculated depths of water available for runoff and the amount of precipiation plus roof runoff received May - September 1990-1994 is included as Table 5.18. Runoff available from irrigation events could not be calculated for this study because amount of daily household irrigation could not be calculated due to data collection periods used.

Table 5.18: Total Precipitation and Roof Runoff Recieved May-September and the Total Depth of Runoff Calculated for a Turfgrass Area, 1990 - 1994, in millimetres.

Year	Precipitation and Roof Runoff	Runoff
1990	245.2	14.7
1991	402.2	46.2
1992	380.8	15.5
1993	651.5	45.4
1994	274.6	8.1

5.4.2.5 Weeping Tile Flow to Sanitary Sewers

As discussed in section 4.4, in Varsity Village and the majority of the city of Lethbridge, household weeping tile is connected to the sanitary system. During high precipitation events (especially events over 10mm), flow to the waste water treatment plant is enhanced. Extensive flow through sanitary sewers has caused several problems in the Lethbridge area, including discharge into basements. This excess flow, likely due to connections of household weeping tile to the sanitary system, is analysed below.

Figure 5.13 illustrates that flow to the wastewater treatment plant for the years 1991 through 1996 is highest during June, July, August, and September, the main months of the irrigation season. During the non-irrigation season flows are much lower.

The construction of buildings causes several changes to the hydraulic conductivity of the soil. Excavation of basements results in the formation of a high hydraulic conductivity zone surrounding the building. The areas undisturbed by excavation may have much lower hydraulic conductivities than prior to construction due to compaction from machinery. Abrupt changes in hydraulic conductivity are also formed as topsoil, which is often removed prior to construction, is replaced, forming an abrupt boundary significantly affecting the hydraulic conductivity. A study by Partsch *et al.* (1993) identified that compaction beneath a lawn had effects on infiltration rates after 12 years of continuous lawn coverage.

During a rainstorm or irrigation event, water is able to move relatively quickly through the soil disturbed by excavation during construction. The disruption of the soil potentially allows for the build up of a perched water table at or below the level of the weeping tile. The newly recharged perched water table around buildings is drained into the sanitary sewers, especially during the summer months when the soil is routinely saturated through

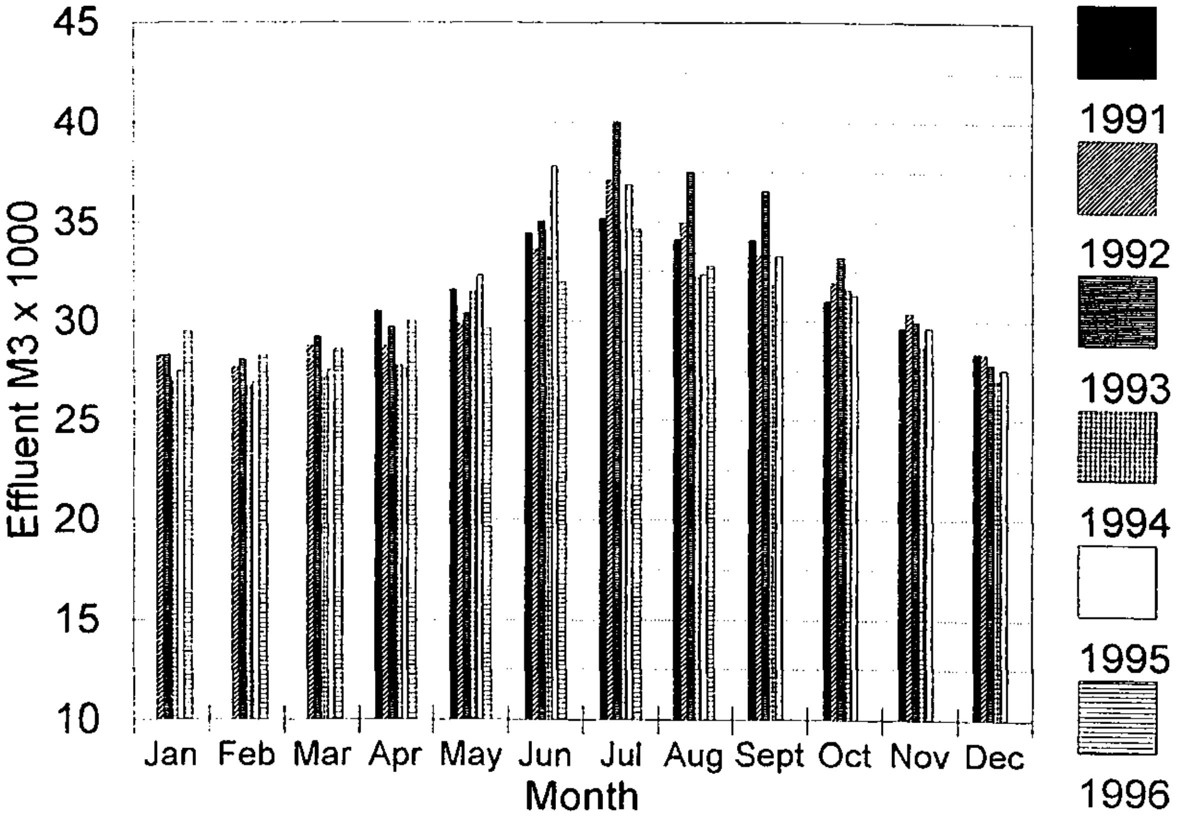


Figure 5.13: Estimated Household Return Flow to City of Lethbridge Wastewater Treatment Plant

irrigation events. Precipitation events cause problems to city sanitary lines because at these times all buildings connected to the sewer line are contributing water, unlike during irrigation when only buildings actually irrigating are contributing. Total volume of flow occurring during, or one day after, a large precipitation event (defined as days with more than 10mm of precipitation) in excess of average monthly flow, are in Figure 5.14. During precipitation events, flow attributed to weeping tile can account for up to 40 percent of total daily flow. Approximately 552183 m^3 of water was treated as a result of city of Lethbridge household and other building hookups to sanitary between April 1991 through August 1996. Based on this value, the annual cost for treatment of water derived from irrigation and precipitation events is approximately $17000 per year, assuming an average treatment cost of 18.5¢/m^3 (Viergutz personal communication, 1996).

As demonstrated in Figure 5.13, flow to the sanitary system is enhanced during the irrigation period. However the data in Figure 5.13 includes flow from industry and commercial enterprises, therefore it is of very little use for determining actual flow from City of Lethbridge households. City of Lethbridge homes had to be used for this study rather than homes located in Varsity Village as data concerning sanitary flows have only been collected on a city-wide basis. Actual flow expected from an irrigating household in the City of Lethbridge has been estimated by methods described in section 4.4, and included as Figure 5.15. Flow above yearly average flow of October through April is expected to be due to weeping tile connected to city sanitary sewers. Table 5.19 lists flow expected from household weeping tile.

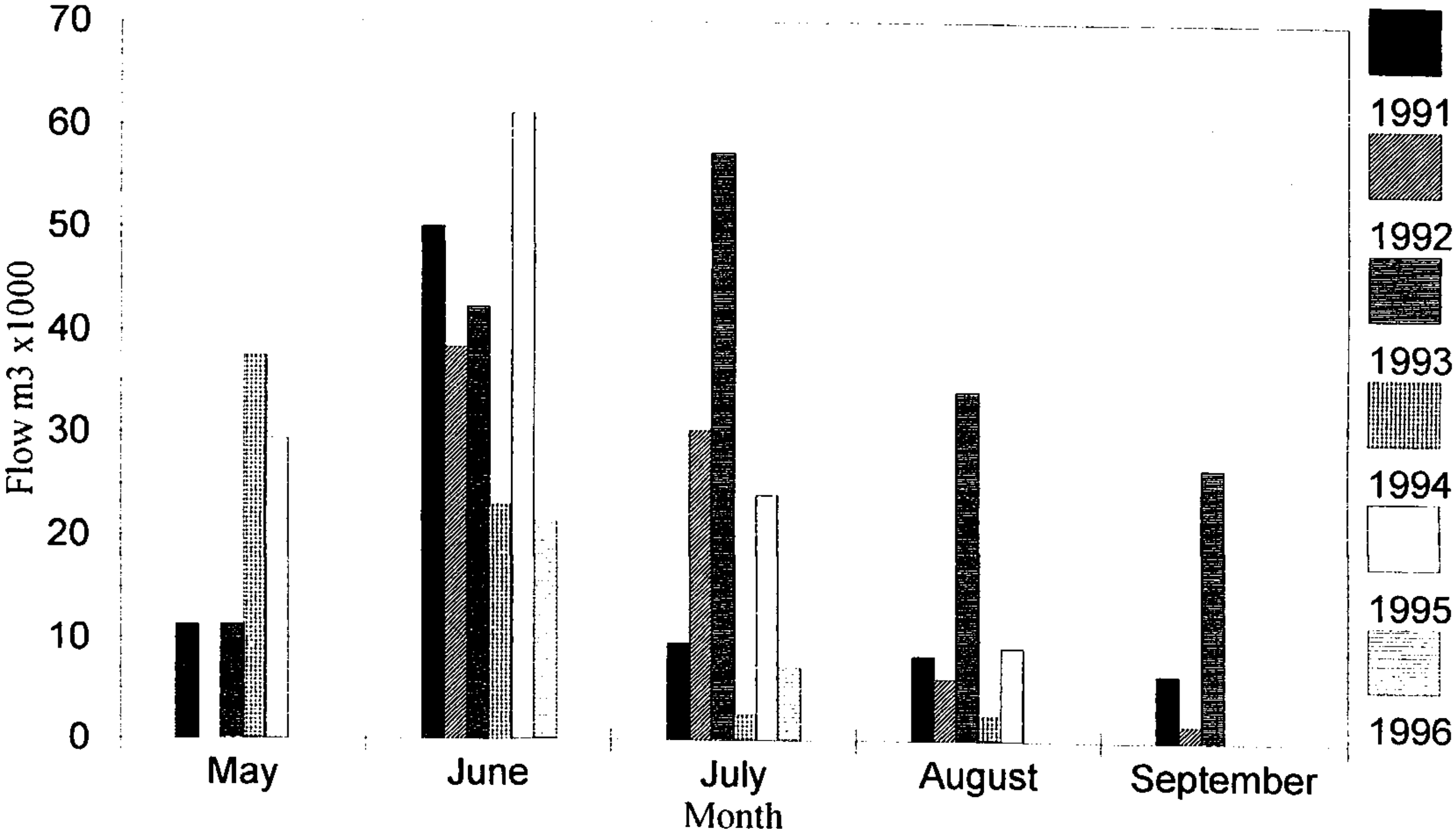
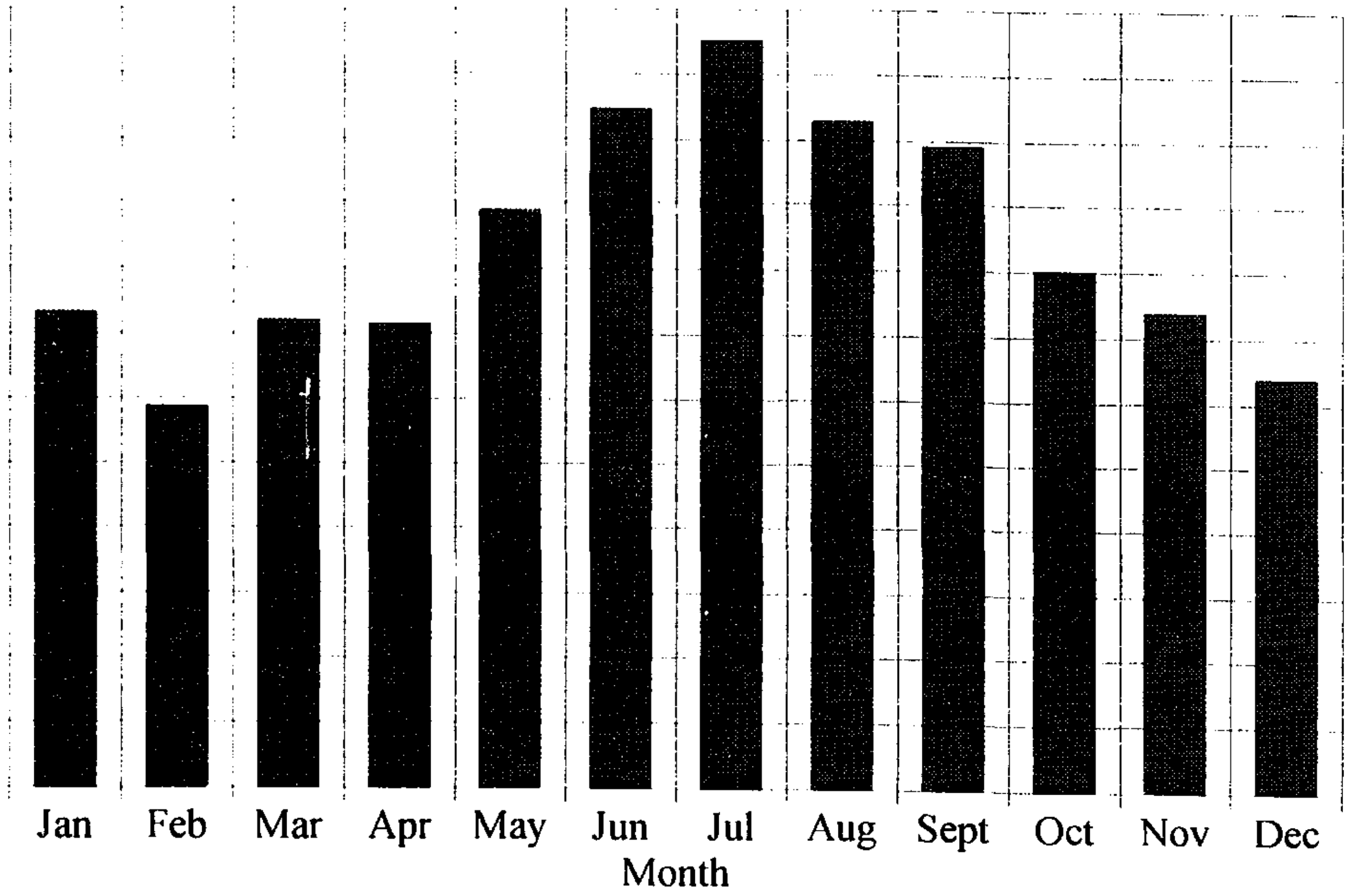


Figure 5.14 Flow to Sewage Treatment Plant Above Monthly Average Flow as a Result of Precipitation Events



.15. Average Predicted Household Flow to Sanitary Sewer for the City of Lethbridge

Table 5.19. Average Flow expected from Weeping Tile to Sanitary Sewer for an Average Irrigating Household in the City of Lethbridge for the Years 1991-1996

Month	Discharge From Weeping Tile m^3
May	4.6
June	8.6
July	11.2
August	8.1
September	7.1
Total	39.6

5.4.2.6 Household Contributions to Percolation Beyond Root Zone

Over the study period, lawn and garden irrigation exceeded evapotranspiration rates for each year, in each subgroup, as reported in Tables 5.11, 5.12, 5.13 and 5.14. These tables report the expected depths of water in millimeters available for deep percolation assuming initial soil moisture (SM) conditions of 25%, 50%, and 75% between wilting point and field capacity.

In three months, June 1990, July 1991, and July 1994 large moisture deficits were recorded. These moisture deficits may be explained by timing of precipitation events in the preceding month. In May 1990, a total of 55.8 mm of rain fell between May 25 and May 31, in June 1991 a total of 34.4 mm of rain fell between June 26 and June 30, with a 63.0 mm rainfall on June 21 1991. These data may help to explain large moisture deficits observed in June 1990, and July 1991. The large moisture deficit observed in July 1994 is difficult to account for. Precipitation in late June 1994 only amounted to 15 mm, and monthly precipitation for the month of July was only 19.7 mm.

The analysis here indicate that overwatering of lawns and gardens by households results in large quantities of water being available for increasing surface soil and groundwater supply. The calculated amounts of water available annually due to over irrigation are reported in Table 5.20.

Table 5.20 Potential Inputs of Water Due to Lawn Over Irrigation in Varsity Village

Year	Potential Input in m^3
1990	79012.8
1991	35230.2
1992	100456.5
1993	112006.6
1994	73263.6

In order to determine the estimated volume of water available for percolation beyond the root zone from the four water use groups, the following multiple linear regression equations were developed. For high, moderately high, moderately low and low water users respectively, the equations derived were:

$$PH = PET_{grass}(-0.73644) + PPT(1.14683) + IRR(0.73270) + 70.4277 \qquad (4.34)$$

$$PMH = PET_{grass}(-1.18642) + PPT(0.99366) + IRR(0.69936) + 267.235 \qquad (4.35)$$

$$PML = PET_{grass}(-1.33671) + PPT(1.02547) + IRR(0.76331) + 275.646 \qquad (4.36)$$

$$PL = PET_{grass}(-2.13160) + PPT(0.23263) + IRR(0.32885) + 862.298 \qquad (4.37)$$

where:

PH is expected percolation from high water users,
PMH is expected percolation from moderately high water users,
PML is expected percolation from moderately low water users,
PL is expected percolation from low water users.

Values of r^2 for the water use groups were 0.99, 0.95, 0.92, and 1.00 respectively, based on five years of measured and calculated data.

The volumes of water applied in excess throughout Varsity Village indicate that residents are not irrigating with regard to the amount of water required. Relatively low prices of water, lack of knowledge of proper irrigation practices, and irrigation based on aesthetic values contribute to this problem. If residents are not aware of the costs (perched water table development) associated with maintaining a lush green lawn, mismanagement of irrigation water will occur. Prevention of over irrigation requires that residents be informed of costs associated with over-irrigation, followed by training in proper irrigation techniques, which may lead to a change in values concerning turfgrass appearance.

5.4.3 Water Loss from Surface Water Features

It is expected that surface water bodies impact water table levels adjacent to the water body itself. To account for water lost due to leakage from surface water features, water level measurements were obtained for two surface water features in the study area. Water loss from the lake or pond was then compared with water loss due to evaporation, in order to determine rate of water flow out of the surface water body. The two water features examined included the campus wetland, and Nicholas Sheran Lake.

5.4.3.1 University of Lethbridge Campus Wetland

In order to investigate water loss from the campus wetland, the area was filled to a surface water elevation of 915.0 metres on July 7, 1994, and a staff gauge was installed. The amount of water loss was determined by a second reading, taken 14 days later, at the same time of day. During the course of the 14 days water level had declined approximately 260 millimetres. Lake evaporation as calculated in section 4.7; amounted to 101.9 mm, with approximately 19 mm of precipitation added during the time period. Total water lost due to change in storage was approximately 177 mm. During the 14 day period, water leaked from the pond area at a rate of 1.5×10^{-7} m • $\sec^{-1}$.

Water loss from the pond not due to evaporation is available for recharge to groundwater. Losses to groundwater will be higher during initial filling of the reservoir as areas previously not inundated with water will infiltrate relatively quickly due to lower moisture in the soil. Areas routinely covered in water will lose water at a much lower rate due to settling of fine particles in cracks and fractures over time as discussed in section 2.4.1. To prevent high amounts of water loss from this pond, care should be taken in the amount of water applied. Decreasing the wetted surface area of the pond, will lower the amount of water available, especially to areas where infiltration rates would be highest. Naturally, to prevent all anthropogenic contributions to groundwater from this source, removal of the water source would be required.

5.4.3.2 Nicholas Sheran Lake

Water loss from Nicholas Sheran lake was determined through daily measurement taken between October 15, and November 14, 1996. Water measurement obtained from the stilling well as discussed in section 4.3.4 were highly variable. The variation in water elevation recorded is expected to be related in part to wind speed.

Wind movement over a water surface result in a phenomenon referred to as wind tide or wind setup or setup (Smith, 1978). As wind blows over the surface of the water, force or drag is exerted in the windward direction. This results in the piling up of water on the downwind side of the water body (Smith, 1978).

Due to the high variation in water level potentially due to wind action, the observation period starting date and finishing date were chosen on days where very low wind speed was recorded. Water level measurements and wind speed recorded throughout the observation period are included as Figure 5.16.

During the 30 day observation period lake level declined approximately 43 mm. Total lake evaporation calculated for the time period was 34.5 mm with 5.6 mm of precipitation. Total water loss from Nicholas Sheran lake not due to evaporation was 13.3 mm over the 29 day observation period. This translates to approximately 29.0 m^3 of water lost to groundwater per day. Overall groundwater flow from Nicholas Sheran Lake is expected to occur at 5.3×10^{-9} m • sec^{-1}. It is expected that unless water movement through sand lenses is occurring, overall water movement from the lake is slow.

5.5 Predictions of Water Table Development and Occurrence

Figure 5.17 illustrates the impacts of urbanization on the development of water tables in

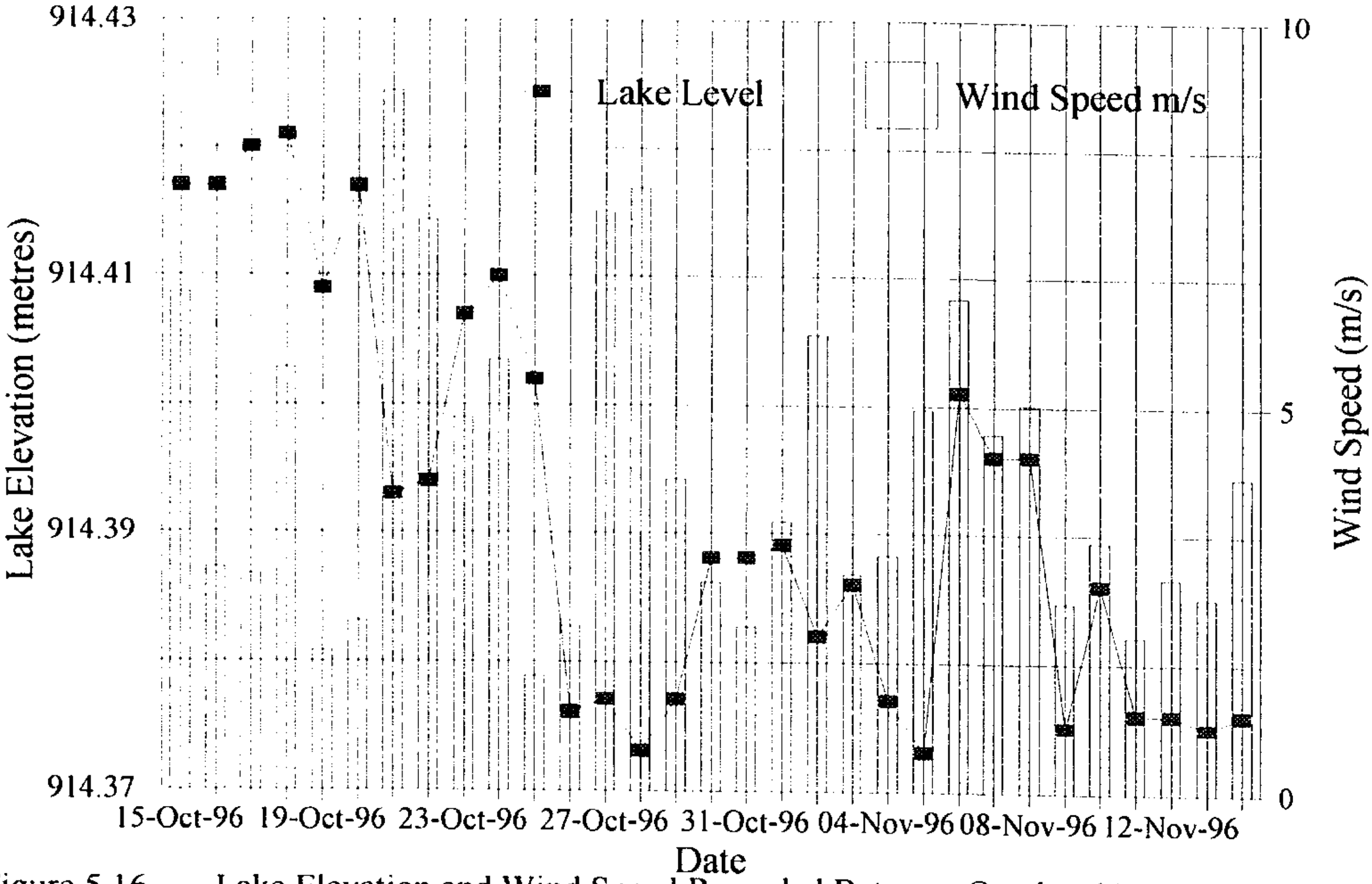


Figure 5.16. Lake Elevation and Wind Speed Recorded Between October 15 and November 14, 1996.

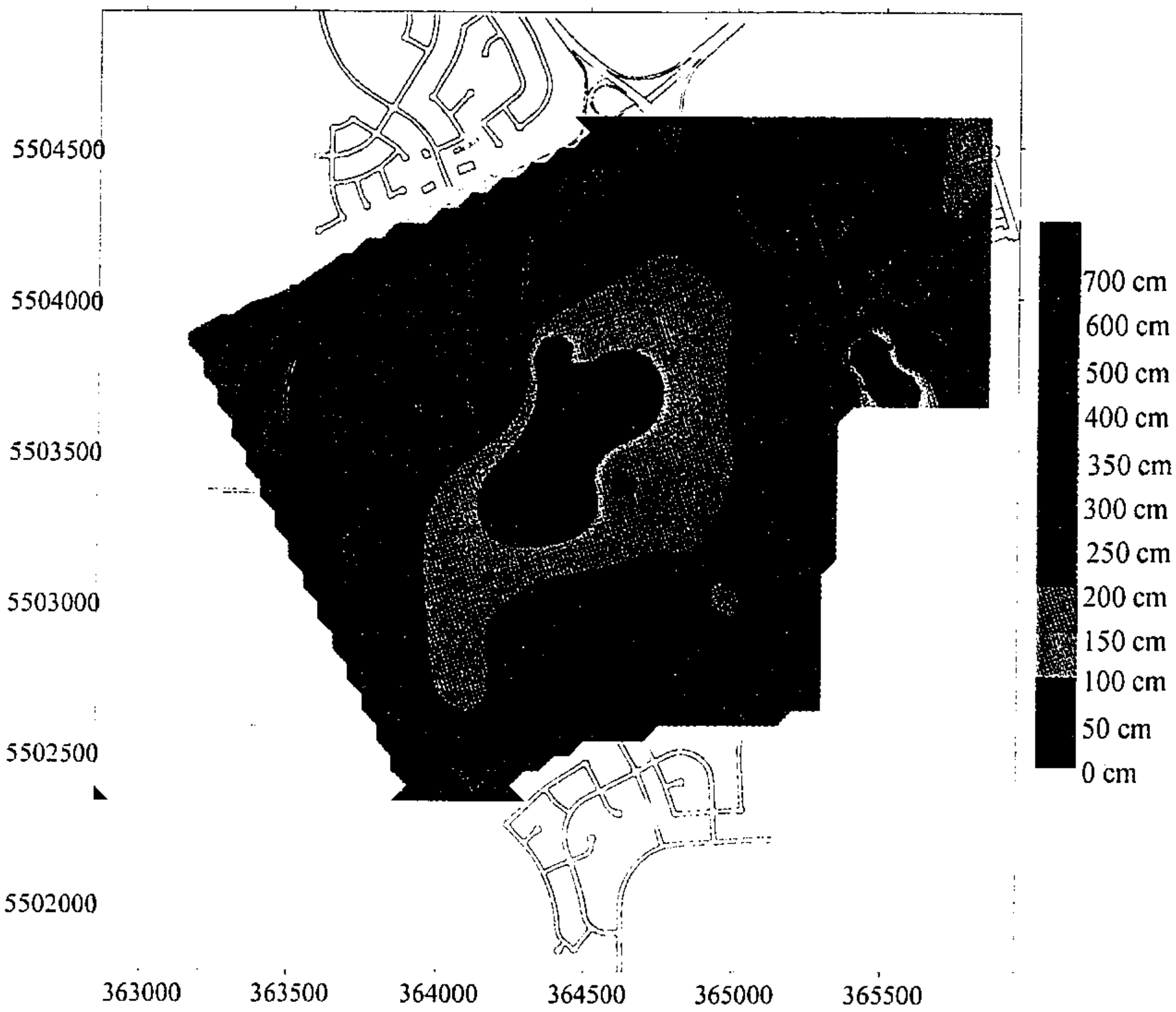
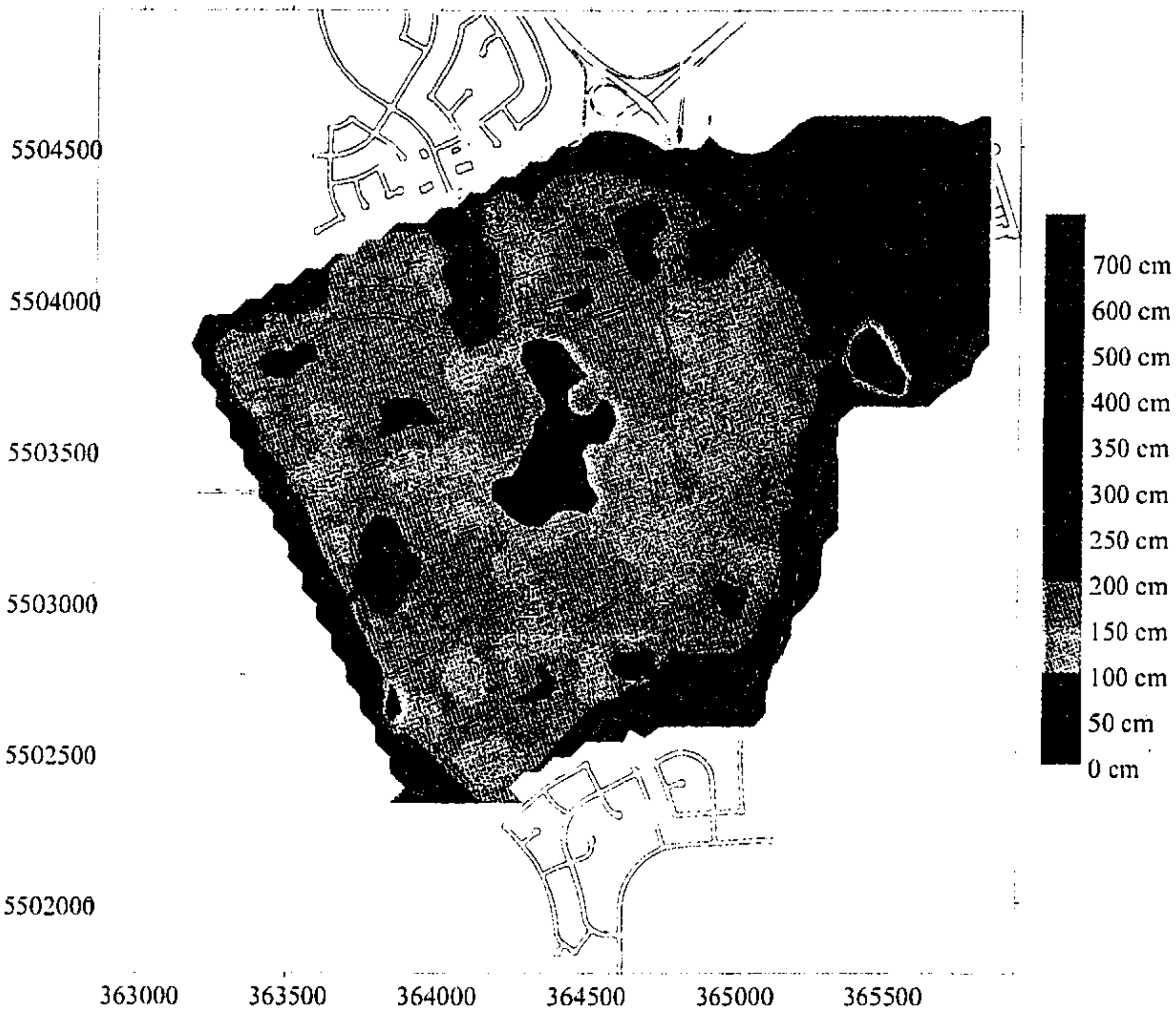


Figure 5.17: Contour Map Illustrating Average Depth to Water Table During the 1996 Irrigation Season

the Lethbridge area. It is a contour map illustrating predicted depth to water table based on average water table elevation observed during the 1996 irrigation season. As illustrated, the highest water table depths are in irrigated urban areas, or areas adjacent to large surface water features. Water well 96-8 located west of Nicholas Sheran lake was under regular irrigation but did not record a water table (Figure 4.1). The lack of a water table in this area is confusing amid high water tables observed in irrigated areas elsewhere. However local features such as the presence of nearby trees, and the impact of subsurface infrastructure such as the LNID canal which connects to Nicholas Sheran Lake, must be considered. The potential effects of subsurface infrastructure may have on the development of water tables is examined below.

Equation 4.29 was used to develop Figure 5.18, a predicted depth to water table surface based on the logarithm of inputs received in each area. The use of yearly total inputs as a means of estimating perched water table elevation in the Varsity Village area has been demonstrated statistically, see discussion in sections 4.8.1 and 5.2. The use of this equation in the construction of Figure 5.18 is expected to result in a fairly realistic prediction of perched groundwater levels, during the irrigation season in the Varsity Village area. Since the model only accounts for input, incongruities between what the model assumes and actual conditions, can occur.

Figure 5.19 identifies areas where large variations occur between water table elevations predicted by equation 4.29 and water tables elevations estimated by contouring between



.Figure 5.18: Contour Map Illustrating Depth to Water Table as Calculated by Equation 4.29

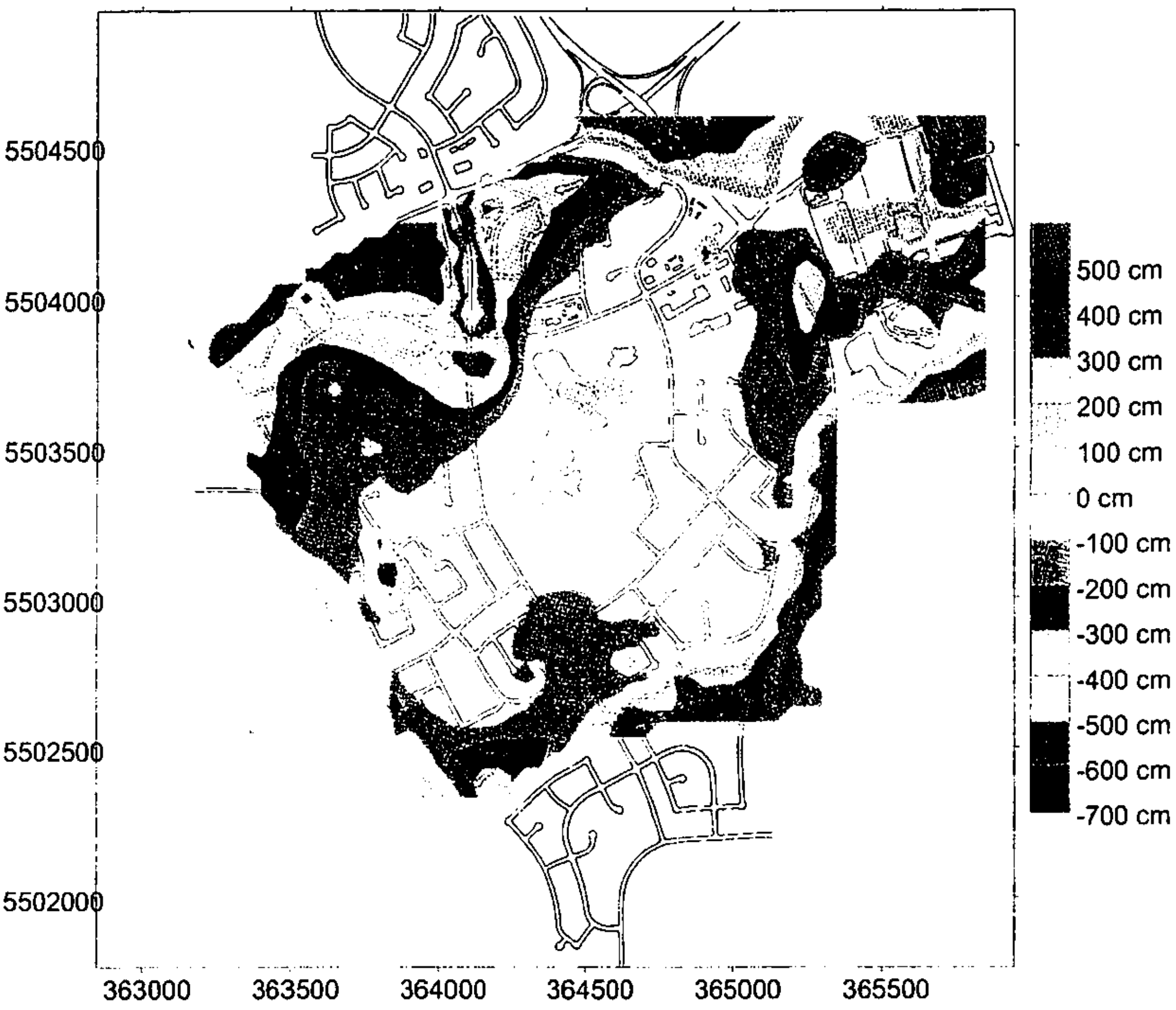


Figure 5.19: Contour Map Illustrating Differences Between Predicted Water Table Depth as Calculated by Equation 4.29, and Contoured Average Water Table Depth as Measured During the 1996 Irrigation Season.

well locations. Overall, perched water table elevations estimated by both methods varied by less than one metre across 46% of the region of study. As illustrated in Figure 5.19, areas where water tables predicted by equation 4.29 are greater than one metre above, or below, the water table estimated by simply contouring between individual wells, are represented by varying shades of green, or red respectively.

Figure 5.18 appears to overestimate water tables as compared to the levels estimated in Figure 5.17, in the north west of the study area (shaded various colors of green in Figure 5.19). The large discrepancy between the two images in this area is likely due to a low number of data points in the vicinity. Four wells installed in this area, wells 96-1, 96-2, 96-6 and 96-8, greatly affect the results obtained in Figure 5.17. These wells have very deep water tables, or were dry throughout the observation period. Of the installed wells, 96-l, 96-2 and 96-6, were placed in areas of no irrigation, thus the low water table is expected. However, the lack of data points in between these wells, in irrigated developed areas, where a higher water table should be observed, effects the reliability of water table depths estimated in Figure 5.17.

The lack of a water table at well 96-8 is not anticipated using equation 4.29, since the area is under irrigation. Although equation 4.29 has been shown to predict the occurrence of perched water table elevations as a function of input, the impacts of other factors such as zones of higher hydraulic conductivity could not be considered due to the lack of data in this area.

Poor agreement between Figures 5.17 and 5.18 reflected by orange and red areas on Figure 5.19 are observed on the University of Lethbridge campus, and along the south east of the study area. Incongruity between Figures 5.17 and 5.18 on campus is due primarily to the inability of equation 4.29 to function in areas controlled by factors not related to irrigation for example: under asphalt or areas influenced by subsurface infrastructure. Observed impacts of each of these factors is examined more fully below.

Poor agreement in the south east area of the study region is expected to be influenced by the low number of sampling points used to produce Figure 5.17. In this area no sampling points were placed outside of the developed area, the lack of data points in the region will not allow for an accurate portrayal of the conditions observed.

A relationship between surface water features and water table elevation, could not be isolated in this study. Two wells located in areas adjacent to Nicholas Sheran Lake, and the University of Lethbridge irrigation reservoir routinely recorded high water table conditions, often less than 2 metres from the surface. However, the observation of frequent irrigation at both locations hinders speculation as to the role these water features have on water table elevations observed.

Two features examined which had considerable effect over the water table observed were subsurface infrastructure and asphalt. The effects of each of these features will be examined separately below.

5.5.1 The Effect of Subsurface Infrastructure on Water Table Elevations Observed

The installation of subsurface infrastructure may have an enormous affect on water table elevations. When subsurface infrastructure such as storm, or sanitary sewers are installed the pipes are generally placed on top of a gravel bed before the hole is refilled. This bed of gravel would allow for the relatively quick movement of water as opposed to the low permeably till. The refilling process above the pipe itself would also have a considerable effect on the hydraulic conductivity of the till itself, potentially making it much more permeable. Where subsurface infrastructure is observed, flow is expected along this channel as hydraulic conductivities are much higher due to excavation, and placement of gravel.

At one location on the University of Lethbridge campus a water table drop of three metres was observed between two wells spaced approximately 20 metres apart. These two wells are separated by a sanitary sewer, and an electrical conduit. Flooding into these structures had been problematic in the past, prompting the need for subsurface drains. Levels of irrigation were similar on both sides of the subsurface infrastructure, therefore the observed drop in water elevations is due at least in part to the affect subsurface infrastructure has on the hydraulic conductivity of till.

Figure 5.17 appears to illustrate the affect of a deep sanitary sewer (below 8 metres) roughly running northwest along University Drive, on the University property. This sanitary line roughly follows University Drive approximately 10 metres east of the road on campus land. The sanitary line crosses the north access road to the University Campus, and then is directed north east towards the river bottom. As observed on Figure 5.17, a large drop in water tables is observed in this area on the campus side of University Drive. Water wells on the west side of University drive 60 metres from the wells located on University Campus, record water elevations 4 metres higher than those observed on campus. When the drop in water table elevation across University Drive is mapped as illustrated in Figure 5.17, the drop of water table in this area appears to mirror the observed location of the deep sanitary line. The role subsurface infrastructure has on the water tables levels observed in this area is complicated by the low volumes of irrigation.

5.5.2 The Effect of Asphalt on Water Table Elevations Observed

Studies at the University of Lethbridge found that high water levels are not limited to irrigated areas. High water tables have also been observed beneath campus parking lots. High water levels beneath the west and far west parking lots were observed in 1991 during an early attempt to repave the parking lot surface (for location see Figure 4.3). Saturation of sub-base gravels and underlying till prevented the use of heavy equipment on asphalt surfaces as a reduction in pavement strength was apparent. A 1992 study by Stanley and Associates Engineering Ltd. concluded that perched water levels are much higher beneath asphalt surfaces than non asphalt surfaces on campus. The report explained that the asphalt was preventing evaporative losses (Stanley As.ociates Engineering Ltd., 1993). Similar problems have been observed on other paved areas in Varsity Village.

In August of 1994 the west lot on the University campus was repaved and subsurface drains were installed at a depth of 90 cm. It was expected that resurfacing the parking lots would cause an overall drop in water levels because the cracks that were allowing for inflow of surface water would be sealed, and any water in the sub-base gravels would be drained.

Overall, water table elevations recorded in the west parking lot during the summers of 1995, and 1996 did not show a great decline, as illustrated in Figure 5.20. This may be explained by the affects of construction on soil hydraulic conductivities. The construction of parking lots requires extensive earth moving, leveling, and compaction with the use of heavy machinery, thereby lowering the permeability of the soil. Compaction of underlying till is still occurring due to weight of the asphalt and daily traffic. Water which enters cracks in the pavement flows easily through the subgrade gravel, however, further movement into the underlying clay till is very slow. The layer of asphalt prevents any evaporative losses from occurring thus perpetuating the high water levels observed. This condition is observed when the difference in water levels beneath the asphalt surface is compared with water levels recorded at a well located on a grassed area adjacent to far west parking lot on the University Campus. Treatment at both sites is expected to be similar (same amounts of compaction due to earth moving and leveling). Water levels beneath the grassed surface are much lower throughout the year than wells beneath the asphalt surface. This is expected due to the impact turf grass has on increasing the permeability of soil (Hino, 1987), and depending on water table depth,

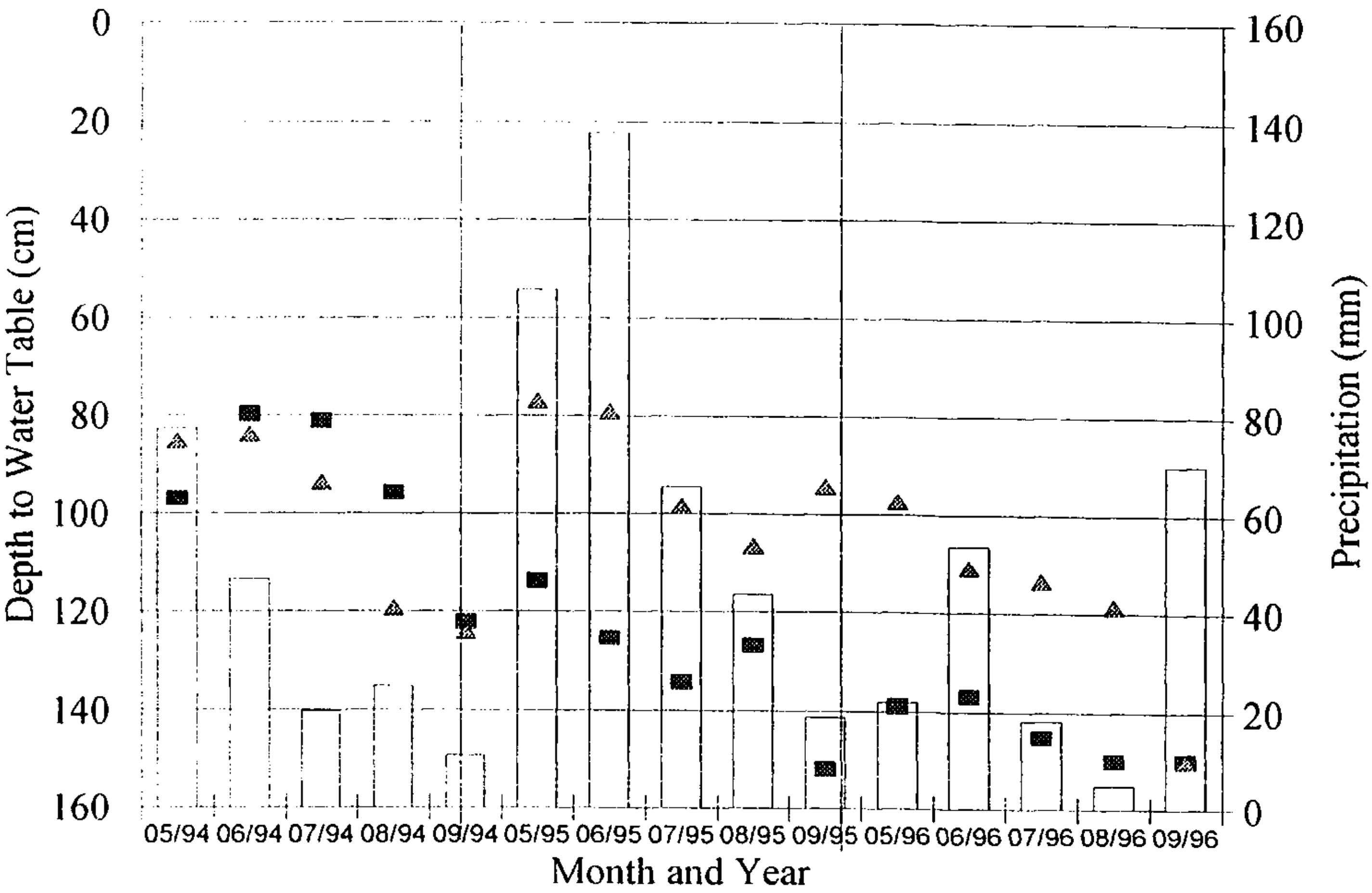


Figure 5.20: Average Monthly Water Table Depth and Monthly Precipitation Observed In the West Parking Lot at Water Wells 1006 and 1007.

water loss through evapotranspiration. Neither of these conditions can occur beneath the asphalt surface. Due to the considerable compaction, the abrupt change in lithologic materials, and lack of evapotranspiration losses, any water which seeps into the asphalt will be available for the development of a perched water table. Resurfacing the lot, thereby eliminating cracks in the asphalt and thus the potential source of water, does not appear to have a dramatic effect on water table decline. Potentially low volumes of water penetrating the asphalt surface are responsible for the perched water systems observed. The impact of precipitation on water table depths recorded at water wells located in University of Lethbridge parking lots can be examined in Figures 5.20.

Chapter 6

SUMMARY, CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

6.1 Summary of Findings

In subhumid to semi arid climates throughout the world recharge to groundwater in urban areas has often been found to be higher than pre-urbanization rates, despite the growing percentage of surfaces impermeable to precipitation (Lerner, 1990). Groundwater recharge in the city of Lethbridge is substantially higher than recharge rates prior to urbanization, resulting in the formation of perched water table conditions. High perched water table conditions, typically at depths between one and 2.5 metres, have created problems for the city and the University of Lethbridge maintenance engineers. Problems such as road and parking lot instability, basement flooding, inundation of buried utility corridors, and coulee slope failure are created by excess water applied to the low permeability soils characteristic of the region. This study estimated the volumes of excess water made available for groundwater recharge. Interactions between the surficial geology of low hydraulic conductivity, and water received are examined and an attempt at modeling water development is made. Results of this study are summarized below.

- Turf grass irrigation was calculated for a seven year period, from May through September, 1990 through 1996, in the Varsity Village area of West Lethbridge, Alberta for area parks, and for a five year period 1990-1994 for households. The calculated amount of irrigation and observed precipitation was compared to the calculated amount of evapotranspiration and soil moisture storage. This comparison revealed that the majority of parks and households in Varsity Village area overwatered turf grass during the study period.
    - In the Varsity Village area water was applied to parks far above evapotranspiration demands for turf grass. Water applied in excess of evapotranspiration demand for parks averaged 403 mm per year, for all the parks analysed in the Varsity Village area. Over-irrigation is most evident during May, June, and September. Irrigation systems have been calibrated to operate at peak evaporative demands, thus over-irrigating in the late spring and early fall.
    - For households, an average of 381.8 mm of water is applied above turf grass requirements. Over the five years data was collected for households in the Varsity Village area (1990-1994), an estimated 399969.7 cubic metres of water was contributed to groundwater.

- Surficial geology observed in the region is dominated by till fairly high in clay. Soil and till moisture values obtained at 30cm, and one metre intervals revealed high water contents in irrigated areas at depths of one to three metres. Moisture levels generally decline thereafter with depth. Irrigation was found to have an effect on water table elevations observed throughout the study area. During the summer monitoring period (June through September 1996) the average water level of the wells receiving regular irrigation was approximately 2.5 metres. Wells not receiving irrigation had an average water table near 6 metres. Many of the areas currently not under irrigation appear to be unaffected by the formation of perched water tables impacting many of the irrigated areas of Varsity Village, nor do they exhibit the moisture trend described above.
- The consistent development of water tables in irrigated areas throughout the Varsity Village area is related to differences in hydraulic conductivity with depth. Infiltration experimentation throughout Varsity Village revealed that the average infiltration rate for household lawns was 4.38×10^{-5} m•s^{-1}. Whereas, hydraulic conductivities in the upper weathered units of southern Alberta tills have been estimated to be between 2.5×10^{-9} m•s^{-1} to 7.0×10^{-7} m•s^{-1} (Hendry, 1982), water infiltrating past this upper root zone will ultimately reach the till of lower hydraulic conductivity. The low hydraulic conductivity of the till slows further downward movement enhancing the development of the perched systems observed.
- The amount of water applied in excess of turf grass demands, and water table depth were found to be related. A statistical relationship ($r^2 = 0.80$) between the logarithm of the 1996 depth of percolation beyond the root zone added as a result of irrigation

and precipitation, and water table depth was derived. The depth to water table was estimated by the equation:

$$WTD = P(-253.3558) + 781.8962 \qquad (4.29)$$

where:

P is the logarithm of the expected amount of peculation in millimetres,
WTD is the calculated water table depth in centimetres,

- The formation of perched water tables in the region may have dramatic affects on city structures, most notably to ashphalt surfaces, sanitary system, and buildings located adjacent to coulee slopes.
    - High water conditions can affect the stability of ashphalt by saturating subgrade gravels, thereby reducing the allowable maximum loads, and leaving the ashphalt more susceptable to frost action.
    - Perched water tables may impact the sanitary system by affecting the amount of flow occuring in weeping tile, connected to the city sanitary lines. Higher flows to the city wastewater treatment plant are observed during the irrigation season. These higher flows could be attributed to over-irrigation throughout the irrigation season. An estimated 39.6 cubic metres of water drained from each irrigating household over a typical irrigation season (May - September). During a rainstorm or irrigation event, water is able to move relatively quickly through the soil disturbed by excavation during construction allowing for the build up of a perched water table at or below the level of the weeping tile. Large amounts of flow originating from building weeping tile especially during

large precipitation events could potentially occur at rates above system capacity.

- The development of high water table elevation in areas adjacent to coulee slopes causes subtantial problems with slope stability (Ruban and Thomson, 1983).

6.2 Conclusions

Irrigation has been shown to have a great impact on the development of perched water tables within the Varsity Village area of the city of Lethbridge. The amounts of water routinely input into soils as a result of irrigation have been shown to be far above the water requirements of turf grasses. The relationship between the amount of water applied and the development of perched water table systems was strong enough that equations between inputs and water table depth could be derived. Without high volumes of irrigation input, the development of perched water table systems will not occur to the degree observed in the Varsity Village area.

Prevention of perched water table development can only be realized through strict management of water applied to the soil. Irrigation should never be applied above evapotranspiration rate of the turfgrass itself. This requires careful monitoring of the amount of water applied in order to ensure no excess water is being administered. A turfgrass model to determine consumptive use could be implemented to determine the amount of water required. Irrigation of a site should never be completed to field capacity, as water may be free to drain below rooting depth, enhancing water tables. Ideally, water should be applied well below field capacity, thereby leaving room in the soil profile for precipitation (Trooien and Reichman, 1993).

6.3 Directions for Future Research

During the course of this study a number of possiblities for future research were identifed. Three main directions for future research are proposed. These propoals include the construction of an urban irrigation schedualing model, the continuation of urban water balance studies within in the city of Lethbridge, and a further evaluation of the hydrogeologic properties involved in water table development within the area.

6.3.1 Urban Irrigation Scheduling Model

The present study has identified both the extent and the importance of over-irrigation on the development of perched water tables throughout the Varsity Village area. The only means of reducing the extent of over-watering oberserved, and the damages that can be caused, is through the reduction of the amount water that is applied. Reduction of the amount of water applied in irrigation could be obtained through education of city irrigators and adoption of an irrigation scheduleing model.

Low prices of water, lack of knowledge of proper irrigation practices, and irrigation based on aesthetic values contribute to the over irrigation that is currently observed.

Problems associated with excess irrigation could reduced by educating residents about the potential difficulties associated over-irrigation and development of an urban irrigation scheduleing model which would detail the amount of water required by turf vegetation. The irrigation scheduleing model which could be constructed based on models used in this study could be made available city use. Daily or weekly reports documenting water requirements of turf grassed areas could be made available to the public via local papers, radio, and the internet.

6.3.2 Continuation of Urban Water Balance Studies Within the City of Lethbridge

The present study has documented the effectivness of a modification of the urban water balance model to examine over irrigation of turf. This model or a refined model of this type could be used to examine a number of other problem areas noted throughout the city of Lethbridge. Specific examples are:

- A Water balance model could be derived to examine inputs in neighboorhoods adjacent to coulee slopes in order to assess the potential for coulee slope failure due to an over abundance of water from household sources.
- Water balance modeling could be done on city mains and sewers to assess leakage throughout the city.
- The current study has initially quantified possible household weeping tile flow to city sanitary sewers. Continued study of this problem including focusing on an individual neighboorhood rather than the entire city, as was done in the present study, would allow for more accurate measurements of the problems extent.

6.3.3 Continued Study of Hydrogeologic Properties and Water Table Development

Research into the hydrogeology of the Varsity Village area of the city of Lethbridge is not complete. The present study has identified a number of problems that require better knowlege of the regions hydrogeology to better understand water table development, and water flow in the study area.

- Sand lenses were observed throughout the region. The role of these sand lenses on lateral and verticle water movement throughout the study area has not been examined.
- Although water loss from two surface water features observed within the study area was estimated, the effects of this water loss on local groundwater conditions could not be examined.
- No measurements of till hydraulic conductivities were made in the course of this study. Detailed analysis of of till hydrogeology, including drop of hydraulic conductivity with depth as discussed in Hendry (1982) could allow for a physically based model of percolation to be constructed. Detailed knowledge of till hydraulic conductivity could identify safe limits of percolation for developed regions.

REFERENCES

Agra Earth & Environmental Engineering. 1995. *Uplands Subdivision Phases 7 to 9 Groundwater Monitoring Program.* Report issued to the City of Lethbridge, Environmental Utilities Department.

Allen, R.G., M.E. Jensen, J.L. Wright, and R.D. Burman, 1989. Operational Estimates of Evapotranspiration, *Agronomy Journal,* **81** pp. 650-662

American Water Works Association, Commitee on Water Use, 1973. "Trends in Water Use". *Journal of the American Water Works Association,* **65**, pp. 285-300.

Aston, A., 1977. "Water Resources and Consumption in Hong Kong". *Urban Ecology,* **2**, pp. 327-353

Baier, W. And G.W. Robertson. 1965. "Estimation of Latent Evapotration from Simple Weather Observations". *Canadian Journal of Plant Science,* **45**, pp. 276-284.

Baier W. And G.W. Robertson, 1966. "A New Versatile Soil Moisture Budget". *Canadian Journal of Plant Science,* **46** pp. 299-315

Barendregt, R.W. 1997. "The Geology of the Lethbridge Area". in *Alberta Beneath our Feet: A Guide to Geology of Alberta.* ed. J.B. Godfrey. Edmonton Geological Society. Edmonton, Alberta.

Beard, J.B., 1973. *Turfgrass: Science and Culture,* Prentice-Hall, Inc. Englewood Cliffs, New Jersey.

Beard, J.B., and R.L. Green, 1994. "The Role of Turfgrasses in Environmental Protection and Their Benefits to Humans". *J. Environmental Quality.* **23**: 452-460

Beaty, C.B. 1975. "Coulee Alignment and the Wind in Southern Alberta, Canada". *Geological Society of America Bulletin.* **86**: 119-128.

Beaty, C.B. 1972. "Geographical Distribution of Post-Glacial Slumping in Southern Alberta". *Canadian Geotechnical Journal.* **9**: 219-224.

Bell, F.C., 1972. "The Acquisition, Consumption and Elimination of Water by Sydney Urban System". *Proceedings of the Ecological Society of Australia.* no. 7 160-176.

Belmans,C., J.G. Wesseling, and R.A. Feddes. 1983. "Simulation Model of the Water Balance of a Cropped Soil: SWATRE". *Journal of Hydrology.* **63**:271-286

Berg, A.A., Byrne, J.M., and Rogerson, R., 1996. "An Urban Water Balance Study, Lethbridge, Alberta: Estimation of Urban Lawn and Garden Overwatering and the Potential Effects on Local Water Tables". *Canadian Water Resources Journal.* **21(4)** 17-27.

Bouwer, H., 1986. Intake Rate: Cyclinder Infiltrometer. In A. Klute (ed) *Methods of Soil Analysis. Part 1. 2nd Ed.* pp. 825-844. Agron. Monograph. ASA, Madison, WI.

Bouyoucos, G.J. 1962. "Hydrometer Method Improved for Making Particle Size Analysis of Soils". *Agronmy Journal* **54**: 464-465

Bosman, H. 1995. General Manager of Environmental Utilities, City of Lethbridge. Personal Communication.

Brady, N.C. 1990. *The Nature and Properties of Soils tenth edition.* Macmillan Publishing Co. New York.

Calder, I.R. 1979. "Do Trees Use More Water than Grass?" *Water Services,* **83** pp. 11-14.

Calder, I.R. 1978. "Transpiration Observations from a Spruce Forest and Comparisons with Predictions from an Evaporation Model". *Journal of Hydrology,* **38** pp. 33-47

Calder, I.R. 1977. "A Model of Transpiration and Interception Loss from a Spruce Forest in Plynlimon, Central Wales". *Journal of Hydrology,* **33** pp. 247-265.

Calder I.R., R.J. Harding, and P.T.W. Rosier, 1983. "An Objective Assessment of Soil-Moisture Deficit Models". *Journal of Hydrology,* **60** pp 329-355

Campbell, T., 1982. "La Ciudad de Mexico Como Ecosistema". *Ciencias Urbanas,* **1**, pp. 28-35.

Canadian Climate Normals 1961-1990: Prairie Provinces. Environment Canada.

Chandler, T.J., 1976. *World Meteorological Organization Technical Note No. 149 Urban Climatology and its Relevance to Urban Design.* Published by the World Meteorological Organization. 61 pgs.

Chang, C., T.G. Sommerfeldt, T. Entz, and D.R. Stalker. 1990. "Long-Term Soil Moisture Status in Southern Alberta". *Canadian Journal of Soil Science.* **70**: 125-136.

Christie, H.W., D.N. Graveland, and C.J. Palmer. 1985. "Soil and Subsoil Moisture Accumulation Due to Dryland Agriculture in Southern Alberta". *Canadian Journal of Soil Science.* **65**: 805-810.

Cuenca, R.H., 1989. *Irrigation System Design: An Engineering Approach, First Ed.* Prentice Hall. New Jersey, pp 552.

Dagan, G. 1986. "Statistical Theory of Groundwater Flow and Transport: Pore to Laboratory, Laboratory to Formation, and formation to Regional Scale". *Water Resources Research.* **22(9)**: 120-134.

Dagan, G. 1982. "Stochastic Modeling of Groundwater Flow by Unconditional and Conditional Probabilities 1. Conditional Simulation and the Direct Problem". *Water Resources Research,* **18(4)**:813-833.

Day, P.R. 1965. "Particle Fractionation and Particle Size Analysis". in *Methods of Soil Analysis-Part 1.* C.A. Black (ed) American Society of Agronomy Inc. Madison WI. pp. 545-567.

de Jong, R., and P. Kabat. 1990. "Modeling Water Balance and Grass Production". *Soil Science Society of America Journal.* **54**:1725-1732.

Doorenbos, J., and W.O. Pruitt. 1977. "Crop Water Requirements". *Irrigation and Drainage Paper,* 24, UN Food and Agriculture Organization, Rome, Italy.

Domenico, P.A. and F.W. Schwartz. 1990. *Physical and Chemical Hydrogeology.* John Wiley & Sons. Toronto.

Douglas, I. 1983. *The Urban Environment.* Edward Arnold, London.

Dzikowski, P., R.T. Heywood. 1990. *Agroclimatic Atlas of Alberta.* Alberta Agriculture, Conservation and Development Branch.

EBA Engineering Consultants Ltd. 1996a. *Slope Stability Measures, Stafford Coulee Zone 4, Lethbridge, Alberta.* Report submitted to the City of Lethbridge, Environmental Utilities Department

EBA Engineering Consultants Ltd. 1996b. *Seepage Investigation Heritage Close West Lethbridge, Alberta.* Report submitted to the City of Lethbridge, Environmental Utilities Department.

EBA Engineering Consultants Ltd. 1995. *Groundwater Study Willow Ridge Subdivision Lethbridge, Alberta.* Report submitted to the City of Lethbridge, Environmental Utilities Department

EBA Engineering Consultants Ltd. 1991. *Geotechinal Evaluation for Proposed Elementary School, Lethbridge, Alberta.* Report submitted to the City of Lethbridge.

EBA Engineering Consultants Ltd. 1990. *Geotechnical Evaluation of a Proposed Roman Catholic Parish Church of St. Martha's, Lethbridge, Alberta.*

EBA Engineering Consultants Ltd. 1986. *Proposed West-Side Elementary School, Catholic Separate School District no. 9, Lethbridge, Alberta.*

Environmental Utilities Department, City of Lethbridge. 1994. *Detailed Engineering Standards and Design Guidelines: Lot Grading and Drainage.*

Feddes, R.A., P.J. Kowalik, and H. Zaradny,. 1978. "Simulation of Field Water Use and Crop Yield". *PUDOC,* Wageningen.

Fetter, C.W. 1994. *Applied Hydrogeology.* Macmillan Publishing. Toronto.

Foroud, N., C. Chang, and T. Entz. 1989. "Potential Evapotranspiration in the Southern Alberta Chinook Region." *Canadian Water Resources Journal.* **14(3)**: 30-42.

Foster, S.S.D, 1990. Impact of Urbanization of Groundwater. *Hydrological Processes and Water Management in Urban Areas* (Proceedings of the Duisberg Symposium, April 1988). IAHS publication no. 198

Foster, S.S.D., B.L. Morris, and A.R. Lawrence. 1994. "Effects of Urbanization of Groundwater Recharge." *Groundwater Problems in Urban Areas Proceedings of the International Conference Organized by the Institution of Civil Engineers.* ed. W.B. Wilkinson. Thomas Telford. London.

Gardner, W.R. and C.F. Ehlig,. 1963. "The Influence of Soil Water on Transpiration of Plants", *Journal of Geophysical Research.* **68**: 5719-5724.

Gardner, W.R., and D.I. Hillel, 1962. "The Relation of External Evaporative Conditions to the Drying of Soils". *Journal of Geophysical Research.* 67: 4319-4325.

Geiger, K.W., 1965. "Bedrock Topography of Southwestern Alberta". *Research Council of Alberta Prel. Report.* 14pp.

Geiger, K.W. 1962. Report Concerning High Water Table Conditions in South Lethbridge. Research Council of Alberta, Groundwater Division, Edmonton, Alberta.

Grace, B. and B. Quick. 1988. "A Comparison of Methods for the Calculation of Potential Evapotranspiration under the Windy Semi-arid Conditions of Southern Alberta." *Can Water Resources J.* 13(1): 9-19

Greswell R.B., J.W. Lloyd, and D.N. Lerner. 1994. Rising Groundwater in the Birmingham Area. *Groundwater Problems in Urban Areas Proceedings of the International Conference Organized by the Institution of Civil Engineers.* ed. W.B. Wilkinson. Thomas Telford. London.

Grimmond, C.S.B., T.R. Oke, and D.G. Steyn. 1986 "Urban Water Balance 1. A Model for Daily Totals." *Water Resources Research*, **22(10)**: 1397-1403.

Grimmond, C.S.B., and T.R. Oke. 1986. "Urban Water Balance 2. Results from a Suburb of Vancouver, British Columbia." *Water Resources Research*, **22(10)**: 1404-1412.

Grisak, G.E., J.A. Cherry, J.A. Vonhof, and J.P. Blumele. 1976. "Hydrogeologic and Hydrochemical Properties of Fractured Till in the Interior Plains Region". In *Glacial Till: An Interdisciplinary Study.* Edited by R.F. Legget. Royal Society of Canada, Special Publication No. 12.

Gross, C.M., J.S. Angle, and M.S. Welterlen. 1990. "Nutrient and Sediment Losses from Turfgrass". *J. Environmental Quality.* **19**: 663-668

Hamilton, G.W. 1990. Infiltration Rates on Experimental and Residential Lawns. M.S. thesis, Agronomy Dept., Penn State University., University Park

Hendry, M.J. 1982. "Hydraulic Conductivity of a Glacial Till in Alberta". *Ground Water.* **20(2)**: 162-169.

Hendry, M.J. 1983. "Groundwater Recharge Through a Heavy-Textured Soil". *Journal of Hydrology.* **63**: 201-209.

Hendry, M.J. 1988. "Hydrogeology of Clay Till in a Prairie Region of Canada." *Ground Water*, **26(5)**: 607-614

Hendry, M.J., J.A. Cherry, and E.I. Wallick. 1986. "Origin and Distribution of Sulfate in a Fractured Till in Southern Alberta, Canada". *Water Resources Research.* **22(1)**: 45-61.

Hino, M., K. Fujita, and H. Shutto. 1987. "A Laboratory Experiment on the Role of Grass for Infiltration and Runoff Processes. *J. Hydrology*, **90**: 303-325

Hobbs, E.H. and K.K. Krogman. 1983. "Scheduling Irrigation to Meet Crop Demands." Agriculture Canada, Research Branch, Technical Bulletin 1983-10E.

Horton, R.E., 1940. 'An approach Toward a Physical Interpretation of Infiltration Capacity". *Soil Science Society of America Proceedings.* **4**: 399-417.

Homes, R.M., 1961. Discussion of a "Comparison of Computed and Measured Soil Moisture under Snap Beans", *Journal of Geopysical Research.* **66**: 3620-3622.

Irish, E.J.W., 1967. Geology, Lethbridge, Alberta; *Geologic Survey of Canada Prel. Series Map 20-1967-* with descriptive notes.

Istok, J.D. and L. Boersma., 1986. "Effect of Antecedent Rainfall on runoff during Low-intensity Rainfall". *Journal of Hydrology.* **88**: 329-342.

Jarvis, P.G., 1981. Stomatal Conductance, Gaseous Diffusion and Transpiration. *Plants and Their Atmospheric Environment.* Eds. J. Grace, E.D. Ford, and P.G. Jarvis. Blackwell Scientific Publications, Oxford, pp. 175-204.

Jensen, M.E. and H.R. Haise. 1963. "Estimating Evapotranspiration from Solar Radiation." *Journal of Irrigation and Drainage Division ASCE,* **89(IR4)** pp. 15-41.

Jensen, M.E., J.L. Wright, and B.J. Pratt. 1971. "Estimating Soil Moisture Depletion from Climate, Crop and Soil Data". *Transactions of the American Society of Agricultural Engineers.* **14(5)** pp. 954-959.

Johnson, S.T., 1994. "Rising Groundwater Levels: Engineering and Environmental Implications". *Groundwater Problems in Urban Areas Proceedings of the International Conference Organized by the Institution of Civil Engineers.* ed. W.B. Wilkinson. Thomas Telford. London.

Journel, A.G., 1974. "Geostatics for Conditional Simulations of Ore Bodies". *Economic Geology.* **69(5)**: 673-687.

Jury, W.A. and C.B. Tanner, 1975. "Advection Modification of the Priestly and Taylor Evapotranspiration Formula". *Agronomy Journal,* **67**: 840-842

Karieli, A., A. Issar, and M. Wolf. 1984. "Effect of Urbanization in an Arid Region: formation of a Perched Water Table that Causes Environmental Damages". *Environmental Geology and Water Science.* **6(1)**: 51-63

Keckler, D., 1994. *Surfer for Windows User's Guide, Contouring and 3D Surface Mapping.* Golden Software Inc. Golden Co.

Keller, C.K., G. van der Kamp, and J.A. Cherry. 1991. "Hydrogeochemistry of a Clayey Till 1. Spatial Variability". *Water Resources Research.* **27(10)** : 2543-2554

Keller, C.K., G. van der Kamp, and J.A. Cherry. 1989. "A Multiscale Study of the Permeability of a Thick Clayey Till". *Water Resources Research.* **25(11)**: 2299-2317.

Keller, C.K., G. van der Kamp, and J.A. Cherry. 1988. "Hydrogeology of Two Saskatchewan Tills, 1. Fractures, Bulk Permeability, and Spatial Variability of Downward Flow". *Journal of Hydrology.* **101**:. 97-121

Kincaid, D.C., E.G. Kruse, H.R. Duke, and D.F. Champion. 1979. "Evapotranspiration Computed to Estimate Leaching Fractions". *Transactions of the American Society of Agricultural Engineers.* **22**: 310-314, 319.

Kocaoglu, S.S. and W.W. Pettapiece, 1980. Soils of the Lethbridge Area (82 H NE). Alberta Institute of Pedology No. M-80-3.

Ku H.F.H, N.W. Hagelin, and H.T. Buxton. 1992. "Effects of Urban Storm-Runoff Control on Groundwater Recharge in Nassau County, New York". *Ground Water* **30(4)**: 507-514

Landsberg, H.E. 1981. *The Urban Climate.* Academic Press, Orlando, Fla.

Lerner, D.N. 1990. "Groundwater Recharge in Urban Areas". *Hydrological Processes and Water Management in Urban Areas* (Proceedings of the Duisberg Symposium, April 1988). IAHS publication no. 198, 59-65.

Lerner, D. N. 1986. Leaking Pipes recharge Ground Water. *Ground Water* **24**: 654-662

Lindh, G., 1978. "Urban Hydrological Modeling and Catchment Research in Sweden", in *Research on Urban Hydrology,* ed. B. McPherson, **2**: 229-265, UNESCO, Paris.

L'vovich, M.I., and G.M. Chernogayeva, 1977. "Transformation of the Water Balance within the City of Moscow". *Soviet Geography,* **18**, pp. 302-312.

Morton, T.G., A.J. Gold, and W.M. Sullivan. 1988. "Influence of Overwatering and Fertilization on Nitrogen Losses from Home Lawns". *Journal of Environmental Quality.* **17(1)**: 124-130.

Mulugeta, G. 1996. "Manual and Automated Interpolation of Climatic and Geomorphic Statistical Surfaces: An Evaluation". *Annals of the Association of American Geographers*. **86(2)** : 324-342

Nielsen, G.D. 1971. *Hydrogeology of the Irrigation Study Basin, Oldman River Drainage, Alberta, Canada*. Unpublished Ph.D. Dissertation, Brigham Young University, Provo, Utah.

Oke, T.R., 1979. "Advectively-assisted Evapotranspiration from Irrigated Urban Vegetation". *Boundary Layer Meteorology*, **16**: 167-174.

Oosterveld, M. and C. Chang. 1980. "Empirical Relations Between Laboratory Determinations of Soil Texture and Moisture Retention". *Canadian Agricultural Engineering*. **22 (2)**: 149-151.

Partsch, C.M. 1992. *Effects of Residential Lawn Establishment Methods on Hydrologic Responses*. Unpublished M.S. thesis, Penn. State Univ., University Park.

Partsch, C.M., A.R. Jarrett, and T.L. Watschke. 1993. "Infiltration Characteristics of Residential Lawns". *Transactions of the American Society of Agricultural Engineers*. **36(6)**: 1695-1701.

Pearce, A.J., J.H.C. Gash, and J.B. Stewart. 1980. " Rainfall Interception in a Forest Stand Estimated From Grassland Meteorological Data". *Journal of Hydrology*. **46**: 147-163.

Penman, H.L. 1948. "Natural Evaporation from Open Water, Bare Soil and Grass." *Proceeding fro the Royal Society*, **A93:** 120-145.

Peschke, g.l, V. Dunger, and J. Gurtz,. 1986. Changes in Soil Moisture by Infiltration and Evapotranspiration, *IAHS Publ. No. 156*.

Peters, R.S., 1994. *Cherry Creek Basin Lawn Irrigation Return Flow Study*, Engineering Report Case No. 89CW198, Water Division 1, Denver Water.

Peterson, R., 1996. Parks Manager, City of Lethbridge. Personal Communication.

Pruitt, W.O., and F.J. Lourence, 1985, Experience in Lysimetry for ET and Surface Drag Measurements. In *Advances in Evaporation* ASAE Publ. 14-85, American Society of Agricultural Engineers, St. Joseph Mich, pp. 51-69.

Pilgrim, D.H., and I. Cordery, 1994. "Flood Runoff". *Handbook of Hydrology* ed by D.R. Maidment, McGraw-Hill. Toronto. pp. 9.1- 9.42

Priestly, C.H.B. and R.J. Taylor. 1972. " On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters." *Monthly Weather Review*, **100**: 81-92.

Rapp, E. and J.C. van Shaik. 1972. "A Long Time Water Table Study of an Irrigation Project in Southern Alberta". *Canadian Agricultural Engineering*. **14(1)**: 29-32.

Rawls, W.J., L.R. Ahuja, D.L. Brakensiek, and A. Shirmohammadi. 1994. "Infiltration and Soil Water Movement". in *Handbook of Hydrology* ed. D.R. Maidment. McGraw-Hill. Toronto. pp. 4.1-4.53

Romeu, R.K., and B. Noetinger. 1995. "Calculation of Internodal Tansmissivities in Finite Difference Models of Flow in Heterogeneous Porous Media". *Water Resources Research*. **31(4)**: 943-959.

Ruban, A.F. and S. Thomson. 1983. *A Report on Slope Instability Along the Oldman River and Tributaries in the Vicinity of Lethbridge, Alberta*. Department of Civil Engineering, University of Alberta, Master of Engineering Report.

Rubin, Y. 1995. "Flow and Transport in Bimodal Heterogeneous Formations". *Water Resources Research*. **31(10)**: 2461-1468.

Rushton K.R., and A.A.R. Al-Othman. 1994. "Control of Rising Groundwater Levels in Riyadh, Saudi Arabia". in *Groundwater Problems in Urban Areas Proceedings of the International Conference Organized by the Institution of Civil Engineers*. ed. W.B. Wilkinson. Thomas Telford. London.

Saxton, K.E., W.J. Rawls, J.S. Romberger, and R.I. Papendick. 1986. "Estimating Generalized Soil-Water Characteristics from Texture. *Soil Science Society of America Journal*. **50**: 1031-1036.

Scracek, O. 1993. *Hydrogeology and Hydrogeochemistry of Buried Preglacial Valleys in the Lethbridge Area, Southern Alberta*. Unpublished Msc. Thesis, University of Waterloo, Waterloo Ontario.

Schwartz, F.W., A.S. Crowe, M.J. Hendry, and D.W. Chorley. 1987. "A Case Study to Assess the Potential for Saline Soil Development Due to Irrigation". *Journal of Hydrology*. **91**: 1-27.

Shuttleworth, W.J. 1994. "Evaporation". in *Handbook of Hydrology* ed. D.R. Maidment. McGraw-Hill. Toronto. pp. 4.1-4.53

Shuttleworth, W.J., and I.R. Calder, 1979. "Has the Priestley Taylor Equation any Relevance to Forest Evaporation?" *Journal of Applied Meteorology*. **18**: 639-646.

Sidle, R.C., A.J. Pearce, and ClL. O'Loughlin. 1985. *Hillslope Stability and Land Use*. Published by the American Geophysical Union, Washington, D.C.

Sladen, J.A. and R.C. Joshi, 1988. "Mining Subsidence in Lethbridge, Alberta". *Canadian Geotechnical Journal*. 25: 768-777.

Smith, C.D., 1978. *Hydraulic Structures*. University of Saskatchewan Printing Services.

Sommerfeldt, T.G. and D.C. MacKay, 1982. "Dryland Salinity in a Closed Drainage Basin at Nobleford, Alberta". *Journal of Hydrology*. **55**: 25-41.

Soil Conservation Service. 1986. *Urban Hydrology for Small Watersheds*. Technical Release 55.

Stalker, A.M. 1962. "Quaternary Stratigraphy in Southern Alberta". *Geological Survey of Canada Paper 62-34*

Stalker, A.M. 1968. "Identification of Saskatchewan Gravels and Sands". *Canadian Journal of Earth Sciences*. **5**: 155-163.

Stalker, A.M. 1975. "The Large Interdrift Bedrock Blocks of the Canadian Prairies". *Geological Survey of Canada, Paper* **75-1A**: 421-422.

Stalker, A.M. and R.W. Barendregt. 1993. "The Origin of the Valleys of Lethbridge". in *The Palliser Triangle: a Region in Space and Time*. eds. R.W Barendregt, M.C. Wilson, and F.J. Jankunis. Thomson Communications.

Stanley Associates Engineering Ltd. 1993. *University of Lethbridge Roadbed Groundwater Study*. Report submitted to the University of Lethbridge Physical Plant.

Sur, H.S. and S.S Kukal. 1992. "A Modified Hydrometer Procedure for Particle Size Analysis". *Soil Science* **153(1)**: 1-4

Tokarsky, O., 1974. *Hydrogeology of the Lethbridge-Fernie area*. Alberta Research Council of Alberta. Report 74-1.

Trooien, T.P., and G.A. Reichman. 1993. "Internal Drainage Under Irrigation of Two Slowly Permeable Subsoils of the Northern Great Plains". *Transactions of the American Society of Agricultural Engineers*. **36(3)**: 709-715.

Thomson S., and N.R. Morgenstern. 1977. "Factors Affecting Distribution of Landslides Along Rivers in Southern Alberta". *Canadian Geotechnical J.* **14**: 508-523.

Uunk, E.J.B., and F.H.M., van de Ven, 1984. "Water Budget for the Town of Lelystad". in *Proceeding of the 3rd International Conference on Urban Storm Drainage,* Gotoborg, 4-8 June, pp. 1221-1230.

van de Ven, F.H.M. 1994. "Houses with Wet Feet: Groundwater Nuisance and its Abatement in the Netherlands". *Water Sciences Technology* 29(1): 231-237

van de Ven, F.H.M. 1990. "Water Balances of Urban Areas". *Hydrological Processes and Water Management in Urban Areas* (Proceedings of the Duisberg Symposium, April 1988). IAHS publication no. 198, 21-32.

Viergutz, K., Senior Technologist, Environmental Utilties Engineering, City of Lethbridge. 1996. Personal Communication.

Ward, R.C. 1975. *Principles of Hydrology second edition.* McGraw-Hill Book Company. Toronto.

Wells, I. 1995. Assistant Superintendent of Grounds Maintence, University of Lethbridge. Personal Communication.

Wilson, E.M. 1990. *Engineering Hydrology.* 4th ed. Macmillan Pub. Hong Kong.

Zvi, A.G., 1977, Anticipated Effect of Future Urban Development on recharge into the Coastal Groundwater Aquifer of Israel, Proceedings, International Symposium on Urban Hydrology, Hydraulics and Sediment Control, July 18-21, pp. 171-179.

APPENDIX A

Well Logs, including moisture content and particle size analysis

Well # and Sample Depth	Water Content	Sample Description	Lab Texture Analysis (Percentage)			
			Sand	Silt	Clay	Classificatio
1-30	10.25	Loam	41.5	18.0	40.5	Clay
1-1	7.39	CL (till)	-	-	-	-
1-2	12.62	CL (till)	-	-	-	-
1-3	21.41	CL (till)	-	-	-	-
1-4	16.43	CL (till)	35.2	30.2	34.6	CL
1-5	15.40	CL (till)	-	-	-	-
1-6	11.46	CL (till)	-	-	-	-
1-7	15.38	Clay (till)	-	-	-	-
1-8	12.54	Clay (till)	-	-	-	-
1-9	12.43	Clay (till)	42.1	23.6	34.3	CL
2-30	7.36	SiL	-	-	-	-
2-1	16.16	SiCL	-	-	-	-
2-2	13.18	CL (till)	-	-	-	-
2-3	16.97	CL (till)	-	-	-	-
2-4	15.63	CL (till)	-	-	-	-
2-5	16.59	Clay (till)	26.6	25.7	47.7	Clay
2-6	16.68	Clay (till)	-	-	-	-
2-7	18.36	Clay (till)	-	-	-	-
2-8	18.04	Clay (till)	-	-	-	-
2-9	17.07	Clay (till)	34.6	27.4	38.0	CL
3-30	17.67	Loam	-	-	-	-
3-1	17.70	CL (till)	39.3	15.8	44.8	Clay
3-2	24.22	Clay	-	-	-	-
3-3	21.27	CL (till)	31.7	28.3	40.0	CL
3-4	20.43	CL (till)	38.2	49.0	12.8	Loam
3-4.5	26.48	CL (till)	-	-	-	-
3-5	21.22	CL (till)	37.5	25.9	36.7	CL
3-6	25.62	CL (till)	-	-	-	-
4-30	10.54	CL	-	-	-	-
4-1	18.88	CL (till)	-	-	-	-
4-2	23.02	CL (till)	-	-	-	-
4-3	21.87	CL (till)	41.5	26.0	32.5	CL
4-4	18.57	CL (till)	-	-	-	-
4-5	17.31	CL (till)	-	-	-	-
4-6	18.19	CL (till)	45.6	32.3	22.2	Loam
4-7	16.73	Clay (till)	-	-	-	-
4-8	16.52	Clay (till)	-	-	-	-
4-9	17.07	Clay (till)	-	-	-	-
5-30	15.57	CL	-	-	-	-
5-1	11.98	CL (till)	-	-	-	-
5-2	10.19	CL (till)	-	-	-	-
5-3	18.32	CL (till)	27.2	27.8	45.0	Clay
5-4	15.79	CL (till)	-	-	-	-
5-5	15.46	CL (till)	33.9	25.6	40.5	CL
5-6	16.42	CL (till)	-	-	-	-
5-7	17.93	Clay (till)	-	-	-	-
5-8	17.14	Clay (till)	-	-	-	-
5-9	13.98	Clay (till)	-	-	-	-

Well # and Sample Depth	Water Content	Sample Description	Lab Texture Analysis (Percentage)			
			Sand	Silt	Clay	Classification
6-30	12.6	Loam	-	-	-	-
6-1	13.2	CL (till)	-	-	-	-
6-2	15.9	CL (till)	42.4	27.7	29.9	CL
6-3	15.2	CL (till)	-	-	-	-
6-4	16.0	CL (till)	-	-	-	-
6-5	18.5	CL (till)	-	-	-	-
6-6	16.5	CL (till)	-	-	-	-
6-7	16.6	Clay (till)	-	-	-	-
6-8	5.4	Clay (till)	47.6	21.9	30.6	SCL
6-9	16.2	Clay (till)	-	-	-	-
7-30	14.2	Loam	-	-	-	-
7-1	20.7	CL (till)	32.5	23.9	43.5	Clay
7-2	19.8	CL (till)	38.1	20.6	41.2	Clay
7-3	29.2	CL (till)	-	-	-	-
7-4	27.6	CL (till)	9.6	37.8	52.5	Clay
7-5	36.3	SiCL (till)	-	-	-	-
7-6	25.7	Clay (till)	-	-	-	-
7-7	18.5	Clay (till)	-	-	-	-
7-8	18.1	Clay (till)	-	-	-	-
7-9	17.4	Clay (till)	-	-	-	-
8-30	9.3	Loam	-	-	-	-
8-1	11.9	CL (till)	24.6	26.4	49.0	Clay
8-2	12.4	CL (till)	-	-	-	-
8-3	12.2	CL (till)	33.8	25.6	40.6	Clay
8-4	10.9	CL (till)	-	-	-	-
8-5	14.3	CL (till)	-	-	-	-
8-6	11.3	CL (till)	-	-	-	-
8-7	11.6	Clay (till)	-	-	-	-
9-30	18.7	Loam	-	-	-	-
9-1	19.7	CL (till)	-	-	-	-
9-2	20.6	CL (till)	-	-	-	-
9-3	19.5	CL (till)	-	-	-	-
9-4	17.7	CL (till)	47.9	22.9	29.2	SCL
9-5	20.3	CL (till)	-	-	-	-
9-6	16.8	CL (till)	-	-	-	-
9-7	18.1	Clay (till)	60.8	17.6	21.6	SCL
10-30	19.4	Loam	-	-	-	-
10-1	20.4	CL (till)	-	-	-	-
10-2	28.7	SiC	2.2	47.6	50.1	SiC
10-3	33.5	SiC	24.0	32.3	43.8	Clay
10-4	22.2	SiC	-	-	-	-
10-5	20.7	CL (till)	-	-	-	-
10-6	15.5	Clay (till)	50.5	21.8	27.7	SCL
10-7	17.8	Clay (till)	-	-	-	-
11-30	18.8	Loam	-	-	-	-
11-1	21.9	CL (till)	-	-	-	-
11-2	25.2	CL (till)	23.4	27.6	48.9	Clay
11-3	21.2	CL (till)	-	-	-	-
11-4	13.5	CL (till)	321.3	29.6	38.1	CL

Well # and Sample Depth	Water Content	Sample Description	Lab Texture Analysis (Percentage)			
			Sand	Silt	Clay	Classification
12-30	12.08	Loam	-	-	-	-
12-1	22.97	CL (till)	-	-	-	-
12-2	18.75	CL (till)	-	-	-	-
12-3	16.46	CL (till)	42.4	13.7	43.9	Clay
12-4	14.81	CL (till)	47.8	30.1	22.1	Loam
12-5	15.84	CL (till)	-	-	-	-
12-6	17.40	CL (till)	-	-	-	-
12-7	16.85	Clay (till)	-	-	-	-
12-8	20.35	Clay (till)	-	-	-	-
12-9	15.78	Clay (till)	45.9	20.8	33.3	SCL
13-30		Loam	-	-	-	-
13-1	23.33	CL (till)	-	-	-	-
13-2	24.79	CL (till)	-	-	-	-
13-3	18.51	CL (till)	37.7	24.9	37.4	CL
13-4	16.35	CL (till)	38.5	21.9	39.5	CL
13-5	22.48	CL (till)	-	-	-	-
13-6	16.89	CL (till)	44.4	24.7	30.9	CL
14-30	34.47	Loam	-	-	-	-
14-1	19.27	CL (till)	-	-	-	-
14-2	19.05	CL (till)	30.4	28.7	41.0	Clay
14-3	19.29	CL (till)	43.9	27.1	29.0	CL
14-4	18.91	CL (till)	-	-	-	-
14-5	20.41	CL (till)	47.0	26.5	26.5	SCL
14-6	18.63	CL (till)	-	-	-	-
14-7	17.19	Clay (till)	-	-	-	-
15-30	18.80	Loam	38.6	21.9	39.5	CL
15-1	23.90	CL (till)	36.9	30.5	32.7	CL
15-2	21.48	CL (till)	-	-	-	-
15-3	34.49	CL (till)	11.4	33.9	54.7	Clay
15-4	18.66	CL (till)	-	-	-	-
15-5	18.35	CL (till)	-	-	-	-
15-6	17.52	CL (till)	-	-	-	-
15-7	17.26	CL (till)	48.4	19.8	31.7	SCL
16-30	9.20	Loam	-	-	-	-
16-1	11.21	CL (till)	20.6	14.4	65.0	Clay
16-2	26.41	CL (till)	-	-	-	-
16-3	18.45	CL (till)	-	-	-	-
16-4	17.45	CL (till)	-	-	-	-
16-5	23.94	CL (till)	-	-	-	-
16-6	18.21	CL (till)	31.4	27.0	41.6	Clay
16-7	16.60	Clay (till)	-	-	-	-
17-30	11.56	Loam	-	-	-	-
17-1	22.85	CL (till)	-	-	-	-
17-2	28.71	CL (till)	-	-	-	-
17-3	19.29	CL (till)	31.1	27.6	41.4	Clay
17-4	19.28	CL (till)	-	-	-	-
17-5	18.27	Clay (till)	31.9	25.5	41.6	Clay
17-6	18.16	Clay (till)	-	-	-	-
17-7	19.34	Clay (till)	23.6	18.0	58.4	Clay

Well # and Sample Depth	Water Content	Sample Description	Lab Texture Analysis (Percentage)			
			Sand	Silt	Clay	Classification
19-30	11.41	Loam	-	-	-	-
19-1	15.97	CL (till)	-	-	-	-
19-2	26.96	CL (till)	26.2	40.1	33.7	CL
19-3	24.50	CL (till)	32.2	24.2	43.6	Clay
19-4	17.97	CL (till)	-	-	-	-
19-5	19.68	Clay (till)	-	-	-	-
19-6	17.51	Clay (till)	43.7	23.8	32.5	CL
19-7	18.09	Clay (till)	-	-	-	-
20-30	11.56	Loam	-	-	-	-
20-1	16.81	CL (till)	-	-	-	-
20-2	24.16	Clay	15.9	40.9	43.2	SiC
20-3	18.03	CL (till)	-	-	-	-
20-4	18.80	CL (till)	38.2	27.5	34.3	CL
20-5	17.33	Clay (till)	-	-	-	-
20-6	16.71	Clay (till)	-	-	-	-
20-7	17.28	Clay (till)	-	-	-	-
20-8	16.18	Clay (till)	-	-	-	-
21-30	20.50	Loam	-	-	-	-
21-1	32.37	SiCL	12.8	47.7	39.4	SiCL
21-2	18.54	CL (till)	-	-	-	-
21-3	16.45	CL (till)	43.5	23.9	32.6	CL
21-4	18.45	CL (till)	-	-	-	-
21-5	18.54	CL (till)	-	-	-	-
21-6	17.40	CL (till)	42.9	15.0	42.1	Clay
22-30	10.36	Loam	-	-	-	-
22-1	12.70	CL (till)	-	-	-	-
22-2	16.55	CL (till)	-	-	-	-
22-3	15.25	CL (till)	40.6	21.2	38.2	CL
22-4	18.02	CL (till)	-	-	-	-
22-5	17.60	CL (till)	38.1	26.8	35.1	CL
22-6	17.04	CL (till)	-	-	-	-
22-7	15.85	CL (till)	-	-	-	-