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GROUNDWATER FLUCTUATION IN SELECTED ALBERTA AQUIFERS AND POSSIBLE CLIMATIC LINKAGES

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled, "Groundwater Fluctuation in Selected Alberta Aquifers and Possible Climatic Linkages" submitted by Timothy Allan Dahm in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

Data from the Alberta Groundwater Observation Well Network was available for this thesis. This network of wells monitors fluctuations in water table elevations at observation well sites across Alberta. It was desired to determine if fluctuations present in the climatic regime were responsible in some fashion for similar fluctuations at the water table. Through a better understanding of the climate / groundwater system, groundwater level predictions and management decisions are enhanced.

Well sites were selected according to two criteria : 1) the site had to have reasonably complete data twenty years in duration or longer, 2) the well site had to be situated nearby to a weather station which could provide quality precipitation and temperature data of the same record length. Eleven wells were selected which satisfied these criterion. The selected wells were variable in terms of geographic distribution across the province and aquifer lithology type (surficial and bedrock type aquifers are represented).

None of the well sites displayed a significant long term declining trend suggesting the present day climate regime is supplying adequate groundwater recharge.

Cross correlation revealed that a moderate relationship was present between well and climate data in the surficial

aquifer sites. Deeper bedrock aquifers displayed much weaker correlation. Factor analysis allowed the well sites to be grouped according to both geography and aquifer lithology. It was also suggested in the factor analysis that the grouping may be dependent upon the precipitation regime. Cycling within the data sets was examined through harmonic analysis. None of the cycles present within the observation well data were significant, however the unusual behaviour of certain cycles common to the well sites suggested that cycling may indicate a future direction of study.

In terms of forecasting groundwater levels, surficial aquifers respond more closely to climatic fluctuations than do deep wells, and greater success is expected with predictions when using recent climate data. Deeper aquifers appear influenced by longer term cycles, and would require longer sequences of climate data when predicting groundwater levels.

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Dedicated to Allan, Jackie, and Christopher

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CHAPTER 1

INTRODUCTION

This Thesis examines the fluctuation of groundwater in selected aquifers within the province of Alberta.

Groundwater fluctuation will be considered from two points of view; first, fluctuations will be examined as a stand alone variable and second, fluctuations will be examined in terms of available climatic data.

1.1 Historical Perspective

Since early historical times the importance of groundwater has been recognized in southern Alberta's predominantly arid climate. Groundwater availability has influenced the geographic location of townsites and the economic viability of certain types of industry. Recognizing the need for quality hydrogeological information, Federal and Provincial governments have been involved in the mapping and evaluation of Alberta's groundwater resources. Dowling (1918) produced geologic maps of the Southern Alberta Plains, and recognized a large artesian basin in which the Milk River Sandstone could be developed as an aquifer (Nielsen, 1971). This discovery lead to drilling programs and the development of a ranching economy in the area.

Further exploration of Alberta's groundwater resources did not occur until after the Second World War except in the form of specific geologic mapping of certain areas (Nielsen, 1971). A major well inventory of the Province was carried out by the Geological Survey from 1947 to 1953, and the results published. In 1953, the Provincial Government passed the "Groundwater Control Act", parts of which specified that all drillers hold a valid permit, that groundwater flow be controlled, and that the Province could gain access to wells, drilling equipment, and drilling records. (Nielsen, 1971). The Research Council of Alberta formally organized a Groundwater Division in 1955 (Farvolden et. al., 1963). At that time a general survey of water conditions in the Province was carried out.

A hydrogeological recognizance map series was produced from the late 1960's to the early 1980's by the Alberta Research Council. The project involved the synthesis of well reports, geological and hydrogeological data into a series providing probable groundwater yield and quality, and surficial and other geological characteristics of an area. Map detail is greatest for the southern portion of the province as more data was available, but the map series does cover the majority of the province.

The Alberta groundwater observation-well network was formed at the suggestion of a groundwater consultant at a provincial round-table conference on groundwater resources and development in Alberta held in Edmonton, 1955 (Alberta

Research Council, 1956). It was suggested that one of the responsibilities of the groundwater division should be to "establish a modest and effective water-level observation program to keep a long-term check or inventory on available water (within the province)". The Alberta observation well network was established on a temporary basis with three wells in 1955, and on a permanent basis in 1956 as part of the Alberta Research Council's Geology Division. In 1982 the network became the responsibility of the Earth Sciences Division of Alberta Environment, and wells presently number into the hundreds (Gabert, 1986). Other work done in the province of Alberta includes numerous specific projects designed to examine and evaluate certain areas in terms of groundwater availability and/or potential.

1.2 Literature Review

The recharge and discharge of groundwater reservoirs (aquifers) is very much a function of the local geology and topography as it is of climate. Much work was done in North America during the 1960's and early 1970's in identifying and describing these areas of discharge and recharge. Toth (1963) and others developed theoretical models that accounted for the effects of topography on water table configuration. Flownets may be constructed using water table and hydraulic head measurements to obtain a 3 dimensional representation of groundwater movement. Freeze and Witherspoon (1967) further treat the topic of flownet construction for hydrogeologic systems.

Data adequate for scientific analysis has been collected from observation wells only recently relative to the collection of data from other hydrologic parameters such as stream flow. As such, observation well data from Albertan or other networks has not been worked with to any great extent. Gabert (1965), examined the fluctuation of Groundwater levels in response to the Prince William Sound Alaskan earthquake of March 1964, and was able to note the seismic event in the observation well hydrographs. In doing so he was able to demonstrate that certain tectonic events may be recorded in the record of groundwater level fluctuations.

A rigorous groundwater monitoring project was performed for the town of Olds, Alberta (Toth, 1973). This study was conducted on a confined bedrock aquifer the town and examined the response of water levels to pumpage. Through weekly monitoring of a network of 17 observation wells, it was possible to characterize aquifer response to pumpage. It was discovered that groundwater levels were able to recover to their former unpumped state within approximately 4 years after pumping stopped (Gabert, 1986).

The statistical or mathematical treatment of data derived from observation well level fluctuations as a time series is scarcely found in the literature. The relationship between precipitation and shallow groundwater in Illinois was examined by Changnon et. al. (1988). Using data from an observation well network similar to that in place in Alberta, an ARIMA (autoregressive-integrated moving average) model was used with reasonable success to examine data from the time series and determine regional relationships for drought assessment.

The thesis also explores the role of cycling within the time series. The investigation of cycles within natural phenomena is common; Charles Darwin attempted to map an 18.6 year lunar nodal tide in the oceans over 100 years ago (Currie, 1984). Sunspots have been reported on the sun for at least 2000 years, and more than a century ago a German amateur astronomer, Henrich Schwabe discovered during 17 years of observations that sunspots come and go in a sunspot cycle of approximately 11 years (Berman, 1983).

The examination of spectra derived from natural and climatological time series is usually performed in order to identify cycle frequencies of sufficient strength for predictive and research purposes. Currie (1974, 1976, 1979, 1980, 1981a, b, c, d, 1982) reports evidence for a periodic 18.6 year, and cyclic 11 year term in parameters such as the length of the day, air temperature, air pressure, and height of sea level for some regions such as North America, Europe, and Japan. Currie (1984c) analyzed the long term world air temperature and pressure records and obtained evidence for the 18.6 and 11 year terms worldwide. Such global occurrence of certain cycles within natural parameters makes the search for cycle similarity within groundwater and climate data as performed in this thesis imperative.

CHAPTER 2

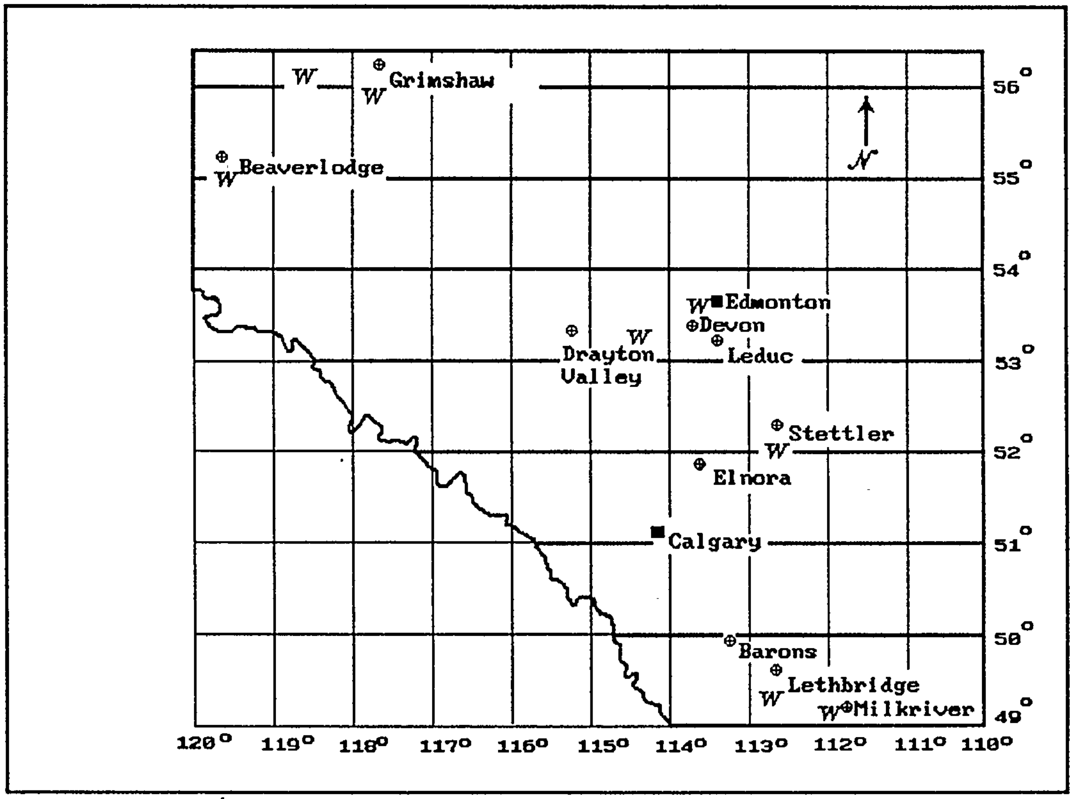
STUDY AREA EXTENT AND GENERAL CHARACTERISTICS

2.1 Study Area - General Description

Observation wells used in this thesis are located within the province of Alberta. General characteristics of the observation wells used in the study are presented in Table 1. All wells are located south of the 57th parallel. The study area is described in some detail in a report by Nielsen, (1971). Observation wells used in this thesis, and weather stations from which climate data originate are presented in Figure 1. These aquifers were selected due to their long length of data record (exceeding 20 years), and their proximity to weather station data.

Southern Alberta, Canada

Well and Weather Station Sites



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⊕	Observation Well Site
W	Weather Station
■	Municipality

FIGURE 1

STUDY AREA - SOUTHERN ALBERTA

TABLE 1

GENERAL OBSERVATION WELL DATA

Well Site	Depth Meters	Rechg./Disch. Type		Aquifer Lithology	Data Srt.	Pump Y/N
Milk River	7.6	D	Surficial	Sand	56	N
Lethbridge	21.0	R	Surficial	Sand	62	Y
Barons	19.8	D	Horseshoe	Sandstone	71	Y
Elnora	5.2	D	Surficial	Sand	62	N
Stettler #6	40.2	D	Horseshoe	SS / Shale	57	N
Stettler 137	65.5	D	Horseshoe	SS / Shale	61	Y
Leduc	22.1	D	Horseshoe	SS / Coal	56	Y
Devon #2	7.6	D	Surficial	Sand	65	Y
Drayton Vly.	61.0	RD	Paskapoo	Sandstone	56	Y
Grimshaw	36.9	D	Grimshaw	Gravel	75	Y
Beaverlodge	35.3	D	Wapiti	SS / Shale	59	Y

2.2 General Observation Well and Well Site Characteristics

General observation well and well site characteristics are described on a per site basis :

Milk River (Well 103)

Milk River observation well is located approximately 15 km. east of the town of Milk River, and 15 km. north of the Canada / US border. Well depth is 7.6 meters within surficial sand. Local topography suggests the observation well is located in a discharge zone. Estimated groundwater yield in this area is 25 - 100 litres / min., in keeping with discharge area characteristics. The observation well likely lies above the Milk River sandstone aquifer. This site is not forested.

Lethbridge Airport (Well 109)

This observation well is located at the Lethbridge airport approximately 4 km south of the city. The depth of the well is 21.03 meters, and is drilled in what is described as a surficial sand aquifer. The topography of the area is that of a gently sloping till covered plain through which the Oldman River has cut, leaving a steep scarp face. The plains area is likely acting as a recharge area to the Oldman. Estimated groundwater yield for this area is under 5 litres / min. and is consistent with the idea the area behaves as a recharge zone. The observation well is located within 1 km of a pumping station and is therefore likely to be affected by any pumpage occurring at the station. Forest is absent at this site.

Barons 615 E. (Well 117)

Barons is located approximately 33 km N.W. of Lethbridge, Alberta. The observation well at this site is 19.8 meters deep within the Horseshoe Canyon Sandstone. Climate data used in conjunction with this well has been obtained from the Lethbridge weather station. The observation well is situated upslope of a small lake and marshy land, and is therefore likely to be monitoring an active discharge area. Estimated groundwater yields for the immediate observation well area are between 25-100 litres per minute. Just downslope of the observation well estimated groundwater yields are up to 500 litres / min. within alluvial gravels likely deposited by the Little Bow River early in the Holocene. The site is unforested.

Elnora #2 (Well 131)

Elnora is located approximately 45 km S.E. of Red Deer, Alberta. The depth of this observation well is 5.18 meters, and is located within a surficial deposit of sand. Topography of the area can be described as "rolling", and is likely to be of mixed hydrological characteristics. The observation well is located in a valley which is occupied by 2 small lakes, and it is safe therefore to assume the area is behaving as a discharge zone. Less than a kilometer north of the well is Ghostpine Creek, an intermittent stream. The southern most part of Pine Lake lies three kilometers N.W. of the well. The area suggests a complex hydrologic makeup, Pine Lake being the discharge zone of a regional groundwater flow system, while the area in which the observation well is located is likely part of a intermediate flow system, acting as the discharge area. The probable yield of the area is estimated to be up to 500 litres / min. while 1000 meters upslope of the well position yields are estimated to be 5-25 litres / min. which further suggests the area is in fact a discharge area for groundwater. Forest is absent at this site.

Stettler #6 (Well 136)

Stettler is located approximately 70 km. east of Red Deer, Alberta. The observation well is completed to a depth of 40.2 meters within the Horseshoe Canyon sandstone / shale formation. This observation well is located within the townsite limits and is likely affected by groundwater pumpage by a water well across the town (1000 meters). The topography of the area is a gently sloping plain. The observation well is located downslope of the plain. Numerous small lakes and ephemeral lakes dot the area, and there are no streams of major significance in the nearby area. Cold Lake is located just 400 meters east of the well site. The presence of nearby intermittent lakes and the topography suggest the area acts as a discharge zone. The estimated groundwater yield of the area is up to 500 litres / min. for a small area south of Stettler. It is likely that this higher yield portion represents the discharge zone for the immediate area. Forest is absent at this site.

Stettler 1960-4 (Well 137)

Well 137 is located approximately 2.5 kilometers northwest of Stettler. This well is completed to a depth of

65.53 meters within the same aquifer as well 136. The topography and hydrologic characteristics of this area are very similar to those already described for well 136 except that 137 is located beside a small manmade reservoir and intermittent stream. The area is behaving as a discharge area. Groundwater suggested yield is 25 - 100 litres / min. Groundwater expected yield at this site is lower possibly due to the site being at a slightly higher elevation (6.6 meters).

Leduc (Well 153)

Leduc is located approximately 15 km. south of Edmonton, Alberta. The observation well is completed to a depth of 22.1 meters within Horseshoe Canyon sandstone & coal formations. The well is located within the townsite proper, and the general topography of the area is that of till covered plain. Telford Lake is located within a kilometer of the well site, and a small creek 1/2 kilometer east of the townsite feeds into the Whitemud Creek. Marshy areas exist to the east and northeast of the townsite area suggesting this area is a discharge zone for groundwater. Estimated groundwater yields for this area are 25-100 litres / min. An area approximated by a 10 km. radius from Leduc has lower estimated groundwater yields, and further suggests the observation well area is a discharge zone. Forest is absent at this site.

Devon #2 North (Well 159)

The town of Devon is located on the south side of the North Saskatchewan River, approximately 16 km. southwest of Edmonton, Alberta. The observation well is located on the north side of the river, approximately 2 km. northeast of the town. This well is completed to a depth of 7.62 meters within a surficial sand deposit likely of fluvial origin. The topography may be described as gently rolling. The hydrology of the area suggests it to be a discharge area in association with the North Saskatchewan River. The observation well is in close proximity to a tributary supplying North Saskatchewan River and is therefore very likely to be located within a discharge zone. Marsh land is located less than a kilometer north of the well. Estimated groundwater yield for this site is up to 500 litres / min. This site is forested.

Drayton Valley (Well 321)

Drayton valley is located approximately 90 km. west of Edmonton, Alberta. The observation well is located 30 km. further west of the townsite. Well completion is to a depth of 61 meters within Paskapoo sandstones and shales. The area is part of the Pembina oil field, and natural gas and oil wells are scattered throughout the entire area in a dense network. The majority of the area around the well site is forested rolling terrain. The Pembina River is located approximately 4 km northwest of the well site. Large marshy areas exist within 2.5 km. north and south of the well site, and within 5 km. east. The well is located at a mid slope position of a rise from the Pembina River elevation of 850 meters to 950 meters at the top of the rise. Being at midslope position, and with the absence of any clues of immediate hydrologic behaviour, it is difficult to classify the nature of the well in terms of recharge / discharge area. It likely behaves as both, depending on the moisture regime of a given time period. Estimated groundwater yield at this site is 25-100 litres / min. Downslope of the well site in the likely discharge area, the estimated yield is up to 500 litres / min. The well site is not forested.

Grimshaw Kerndale (Well 339)

Grimshaw is located approximately 27 km. west of the town of Peace River. The observation well is located 12 km. further west of the town of Grimshaw. Well completion is to a depth of 36.9 meters within a deposit known as "Grimshaw Gravels". The topography of the area is that of a very gently sloping plain. The observation well lies in the lower portion of the plain. Cardinal lake is located 3 km. northeast of the well site, and numerous small ephemeral lakes dot the area. The Peace River is located 18 km to the south of the well. The topographic position and proximity of the well to Cardinal lake suggest the well monitors a large discharge area. Estimated groundwater yields for this site up to 500 litres /

min. and would seem to verify the idea the area is acting as a discharge zone for groundwater. The site is unforested.

Beaverlodge (Well 341)

Beaverlodge is located 40 km east of the Alberta - British Columbia provincial border and 35 km west of Grande Prairie. The observation well is located 2 km. S.E. of the town. Well completion is to a depth of 35.3 meters within the Wapiti sandstone and shale formation. Topography of the area is gently undulating. The townsite is located at a higher elevation than the observation well, which is situated in a local topographic low point. Several ephemeral lakes exist in the area and the areas immediate to the observation well site are marshy in character. Tributaries start in the Beaverlodge area gathering water to eventually join with the Wapiti River located 20 km. south of the observation well. The observation well site may be characterized as a local discharge area, but in fact the entire Beaverlodge area acts as a recharge zone to the Wapiti River area. Estimated groundwater yield of the area is 25-100 litres / min. and is consistent with discharge zone yields in the province.

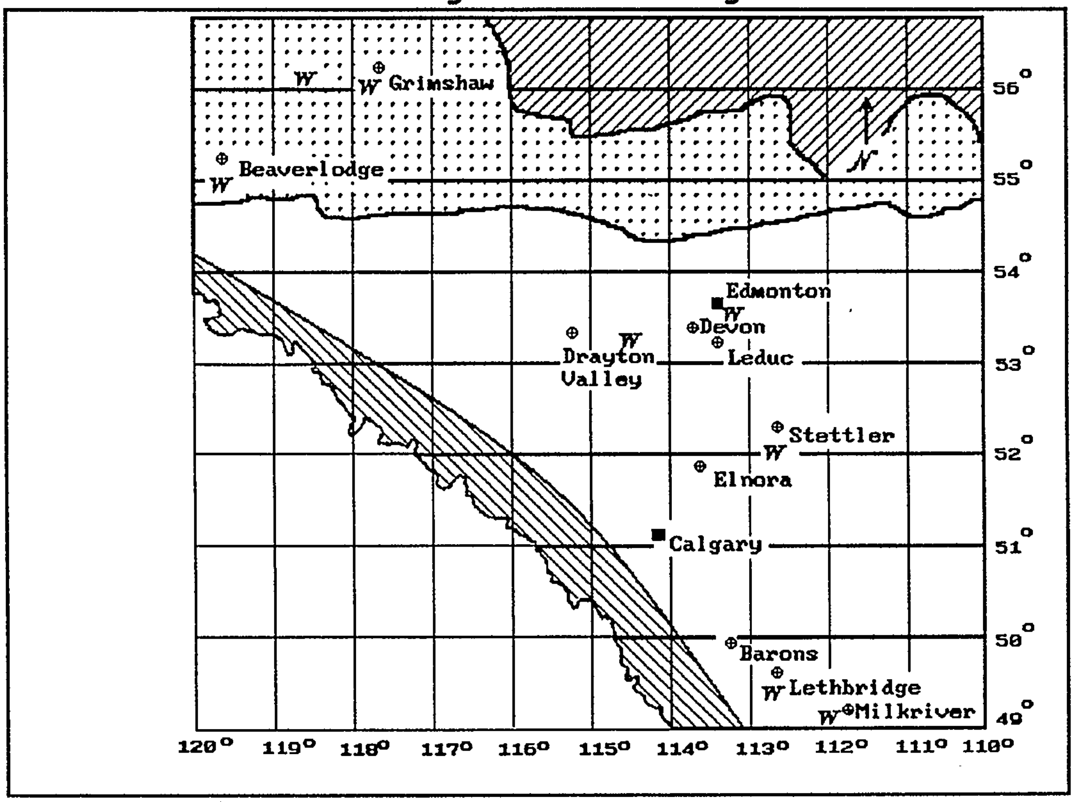
2.3 Geologic Setting

The Canadian Shield is a hard crystalline granite / granite gneiss dome which in fact forms the core of the North American continent. On all sides except that facing the Atlantic Ocean, it dips beneath younger, generally flat lying sedimentary rocks laid down during the Proterozoic eon in shallow seas at the inner margin of geosynclines and in continental waters (Bird, 1980). In Manitoba, the dip of the shield is to the southwest at a rate of approximately 5 cm/km until in Alberta, the Shield is approximately 3 kilometers beneath sedimentary rock (Bird, 1980). The Interior Plains region has formed on top of these sedimentary rocks, and presents a variety of unusual topographic features formed under the influence of Laurentide glaciation, and the effect of water and wind.

The wells are all within the Interior Plains Region, Peace-Slave Lowland (see Figure 2). This area is also part of what is known as the Western Canada Sedimentary Basin. This region may be subdivided into Tertiary and Cretaceous sub-regions. Both formations consist of flat to gently dipping sedimentary strata, thinnest in the east, increasing to over 4900 meters thick adjacent to the Cordilleran Region. Although the sedimentary basin includes strata as old as Cambrian (500 - 570 x 10 6 bp) only the Upper Cretaceous (100 - 65 mybp) and Tertiary (36 - 65 mybp) strata are involved in active groundwater movement (Nielsen, 1971). Due to the several glaciation episodes which have occurred over western Canada, most of the province is covered by a mantle of glacial till, varying in thickness from centimeters to hundreds of meters. The presence or absence of till can have a profound effect on the hydrology of an area, as glacial till is usually

Southern Alberta, Canada

Geological Setting



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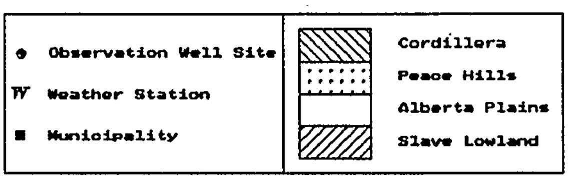


FIGURE 2

GEOLOGICAL SETTING OF THE STUDY AREA

characterized as having low permeabilities, and retards water infiltration increasingly with deposit thickness.

Relief is greater in the area underlain by Tertiary strata, and precipitation is greater generally due to the orographic effect of the mountains, and the general direction of travel of the storm track from west to east. The greater amounts of precipitation received, and the higher permeability of the sediments in this area (generally) result in groundwater yields usually being higher in this area than other areas of the Province (Nielsen, 1971).

2.4 Climatic Characteristics

The majority of southern Alberta excluding the montane region is best described as a continental type of climate. Continental climates are characterized as having bitterly cold winters, short warm summers, and a light precipitation regime. (Hare & Thomas, 1974). The Rocky Mountains form an effective barrier from the potentially moderating effects of the Pacific Ocean. Predominant airflow direction is from west to east, and passage of air over the mountain range often results in an adiabatic warming of the air as it descends on the eastward side of the mountains, and can provide significant climate modification in regions along the foothills.

The absence of any topographic barrier across the northern portion of the prairies region results in the free passage of arctic air masses into the Alberta region during the winter time and contributes to the cold winters. Winter in the prairie region (including most of southern Alberta) starts in October or early November as the daily temperature curve crosses the threshold at most stations. (Hare & Thomas, 1975). Mean January temperature is approximately 0° C. February usually records the lowest amount of precipitation for the year, and average precipitation during the winter months is approximately 25 mm.

Spring usually occurs after the first week of April throughout the Prairies as the mean temperatures are above the freezing mark (Hare & Thomas, 1975). As May arrives, precipitation over the Prairie regions usually increase to around 50 mm.

Summer mean daily temperatures on the Prairies rise above 16° C in early June, and can drop below 16° C as early as mid August. The prairie region has the greatest daily range of temperature because of altitude and continentality (Hare & Thomas, 1975). The hottest month is July with an average temperature between 18° to 21° C. The majority of precipitation occurs during the summer months. June precipitation totals range from 75-130 mm. July and August totals are normally less than 50 mm.

Fall temperature approximates 16° C on September 1 and dropping to 9° C by October 1, and the freezing point by November 1. September precipitation averages less than 50 mm, October precipitation averages less than 25 mm.

CHAPTER 3

GROUNDWATER OCCURRENCE

3.1 Groundwater Occurrence in General

Groundwater occurrence depends upon a variety of factors including topography, climate, and geologic characteristics of the water bearing strata. In general terms, wells, observation or otherwise, are usually understood to be located within an "aquifer". A typical definition of an "aquifer" is provided by Linsley et. al. (1982) : "A geologic formation which contains water and transmits it from one point to another in quantities sufficient to permit economic development is called an aquifer." According to this definition, some of the observation wells are likely not monitoring aquifer formations, but rather "aquicludes". An aquiclude is defined by Linsley et. al. (1982) as "a formation which contains water but cannot transmit it rapidly enough to furnish a significant supply to a well or spring". Observation wells monitoring aquicludes can still yield important information about the behaviour of groundwater in the region.

Many of the observation wells used in this study monitor aquifers of variable lithology. An aquifer described as "surficial sand and gravel" can include a wide spectrum of grain sizes, porosities and permeabilities comprising the "aquifer" as a unit.

Almost all groundwater is meteoric water derived from precipitation (Linsley et. al., 1982). The phenomenon that the long-term average contour of the water table (top of the saturated zone), on a large scale, is a subdued replica of the topography indicates that precipitation is the main source of water for recharge (Gabert, 1986). Other sources of groundwater include connate water, which is water that was present in the material at the time of its formation. Juvenile water occurs in small quantities and is that water which is formed chemically within the earth and brought to the surface in intrusive rocks (Linsley et. al., 1986).

At this point it would be prudent to review the classification scheme of sub-surface water.

Meinzer (1923) defines all water that exists below the earth's surface as "subsurface water" thus distinguishing it from surface and atmospheric water. Water is able to exist beneath the surface if the subsurface material contains interstitial spaces.

The earth's crust is generally composed of materials which have varying degrees of porosity and permeability. Primary or original porosity is defined as the porosity with which the material was originally endowed at its formation. Secondary porosity refers to fractures or cracks within the material enhancing porosity which have occurred after formation of the material. Porosity is a material characteristic which can allow fluids to occupy the pore spaces. Water is a common fluid which may occupy pore spaces of terrain crustal materials below the surface. Increasing crustal depth corresponds to an increase in pressure due to the gravity weight of the material above. As pressure increases around porous crustal materials, pore space is reduced to the point where fluids may no longer be held. Reduction in porosity with depth depends largely upon the rock material characteristics, and the reduction value may be spatially varied over an aquifer body.

Hitchon (1968) has shown the average porosities within strata of the western plains region of the western Canadian sedimentary basin decreases with age and depth of burial. He calculated average porosities of 26.3, 17.3, and 6.8 percent for Cenozoic, Mesozoic, and Paleozoic units respectively.

Two major subsurface porous zones are divided by a water table which is a subdued replica of the local topography. The water table is the locus of points in unconfined material where hydrostatic pressure equals atmospheric pressure (Linsley et. al., 1986). Above the water table the soil pores may contain water or air, and is thus termed the zone of aeration, or the vadose zone. The phreatic zone or zone of saturation lies below the water table surface and the pores are filled with water.

The unsaturated zone is divided from the land surface downward into three subzones : 1) a soil-water subzone, 2) an intermediate subzone, and 3) the capillary-fringe zone

(Gabert, 1986). The soil-water subzone represents that portion of the soil profile in which water is available to plants' roots. Water in the intermediate zone moves downward under the force of gravity to eventually become capillary or groundwater. Water in the capillary-fringe zone is water held by capillary force in the pore spaces of rock located just above the saturated surface (water table). Water in the lower part of the capillary-fringe subzone is continuous with water in the saturated zone, but strictly speaking, is at less than atmospheric pressure (Gabert, 1986).

The saturated zone is not subdivided. The lower limit of the saturated zone is theoretically accepted by hydrogeologists as that depth below the surface where the pressure exerted from overlying geologic structures is sufficient to close interstitial voids which may be present in the rock. Figure 3 provides a summary of the classification of sub-surface water.

FIGURE 3

CLASSIFICATION OF SUBSURFACE WATER *

Main Division	**Subdivision**	**Classification of Water**
	Soil-Water Subzone	Soil-Water
UNSATURATED ZONE	Intermediate Subzone	Intermediate Water
	Capillary-Fringe Subzone	Capillary Water
############### W A T E R	T A B L E ################	
SATURATED ZONE		Groundwater

* Source : Gabert, 1986

3.2 Geologic Formations Serving as Aquifers

Following is a discussion relating the types of geologic formations or deposits typical to aquifers within the province of Alberta..

3.2.1 Bedrock Aquifers

Within the Interior Plains region of the province bedrock aquifers are typically sandstone and coal layers within less permeable shales and siltstones. Interstitial voids (pore space) results in some permeability, but the highly permeable aquifers result mostly from secondary porosity, or fracturing (Nielsen, 1971).

The Milk River Sandstone is a major artesian aquifer south of the South Saskatchewan River and east of Lethbridge.

The aquifer consists of up to 30 meters of fine grained sandstone increasing in depth northward from its outcrop area along Milk River to about 275 meters deep. The aquifer is overlain by an impervious aquifuge marine shale known as the Pakowki formation (Nielsen, 1971).

The Oldman and Foremost formations are collectively known as the Belly River Group, and consist of siltstone, shale, coal and minor sandstone. They are characterized as having a low permeability with typical yields less than 25 lpm for individual wells in the Lethbridge area; slightly higher yields are obtained in east east-central Alberta.

The marine Bearpaw Shale contains one water bearing unit, the Bulwark Sandstone which is reported to yield up to 75 lpm in the Oyen area (Kunkle, 1962).

The Bearpaw Formation in Southern Alberta is overlain by the Blood Reserve Sandstone, which Nielsen (1971) states as "having considerable groundwater potential." This unit thins northward and becomes part of the Edmonton Formation, consisting of shale, sandstone, and coal seams. Estimates are that possible yields may be as high as 135 lpm for individual wells in this formation (Nielsen, 1971).

The Tertiary Paskapoo Formation in the west is characterized by some very high yield wells, some in excess of 500 lpm. The exceptionally high yields may be attributed to a very high degree of fracturing, and to the leaching out (removal) of calcareous cementing agents.

The Tertiary Porcupine Hills Formation many be found south of Calgary. It is underlain by Tertiary age freshwater sandstone and shale beds. Permeability is characteristically lower than that found in the Paskapoo Formation, but natural springs are common which are able to provide water for domestic uses (Nielsen, 1971). Below the Porcupine Hills Formation lies the Willow Creek Formation. The composition of this formation is shale and soft siltstones. Yields from this formation are poor and are typically less than adequate for domestic uses.

Outside of the study area, Cretaceous sandstones in the Cordillera characteristically yield sufficient water for domestic purposes.

3.2.2 Buried Valley Aquifers

Subsequent to Palaeocene time (Tertiary Era), uplift occurred in the Cordilleran, terminating deltaic deposition of the Paskapoo Formation and its equivalents (Nielsen, 1971). This meant that the deltaic sedimentary deposition which was occurring in the western prairie area and Cordillera was halted as uplift began and the area was raised above sea level. The uplift meaning the end of deltaic deposition also marked the beginning of erosion in the area. River action carved valleys through the mountains, and also laid down deposits of sand and gravel. Subsequent glaciations in these areas covered some of the deposits with till, and had the effect of burying the alluvial deposits. Post glacial periods would see the re-establishment of drainage patterns in roughly the same pattern in the mountain and foothills areas where valleys had been deeply incised, but on the prairies, the subsequent drainage patterns which were established may not have had any relationship to previous drainage patterns.

Where buried valley gravels are below the present base-level of erosion they are saturated, and constitute some of the highest yielding aquifers of the province (Nielsen, 1971).

3.2.3 Surficial Deposits

Surficial deposits are usually understood to be those deposits overlying geologic structure, and having been deposited in more or less recent (Holocene) times.

Most of Alberta is covered by surficial deposits of some description. The Wisconsin glaciation covered most of the study area, and indeed most of the province with the exception of the upper Cypress Hills, an area near Del Bonita, and parts of the Porcupine Hills.

A result of the Wisconsin (and prior) glaciations was the deposition of a till mantle over much of the province. Glacial till is an unsorted, unstratified mixture of random clast sizes from clay to boulder size. It is best conceptualized as "boulder clay". Till is usually characterized as having a low permeability, but the actual value depends on the exact nature of the till, whether the deposit has been leeched, reworked etc.

Other glacial deposits include kames / eskers and outwash plains, which are sorted gravel and mixed sand & gravel features formed by runoff from the glacier. The permeability of such features is generally high, but the limited extent of the deposits restricts their size as aquifers.

Formations deposited by water are also surficial deposits. Surficial deposits by water include alluvial sands and gravels left behind by rivers and streams, deltaic deposits by rivers and streams and lacustrine silts and clays deposited in lakes and ponds. For any number of reasons including climatic changes, land use or vegetation changes, the water sources may dry up and leave behind these surficial deposits.

Alluvial sands, gravels, and deltaic fans have been formed in post glacial times, and typically have high permeabilities. Lacustrine deposits may be hundreds of meters thick, and are finer grained richer in clay sized particles. As such, the permeability is much less in these types of deposits, but they are able to hold substantial quantities of water.

CHAPTER 4

PROVINCIAL GROUNDWATER USE

4.1 Groundwater Usage in Alberta

A report published by Nielsen (1971) contains an accounting of groundwater use in southern Alberta in 1970. The information contained in the report provides a conceptual framework for understanding present day (1990) water usage in the province.

As of 1971, annual Provincial groundwater consumption was estimated to be 55.9 million cubic meters for the Saskatchewan Nelson Basin (Nielsen, 1971). Hess (1984) estimated groundwater use at 137.2 million cubic meters annually, thus representing an increase 41 % in 13 years. Since the writing of the Nielsen report in 1971, Alberta's population has tended to increase mainly in the major centers of Calgary, Edmonton, Lethbridge, Olds, etc. Within the Saskatchewan-Nelson Basin, 141 communities were using groundwater, 84 were using surface water. Per capita consumption was .2 cubic meters per day of groundwater, and .15 cubic meters per day of surface water in 1971.

Secondary recovery of oil in southern Alberta oilfields was the largest consumer of groundwater at 11 million cubic meters. In 1971, half that consumption was by the Pembina oil field (Nielsen, 1971).

Nielsen (1971) using 1966 census records estimated that annual groundwater use by farms was 10 million cubic meters per annum by assuming that of 212,000 people on 52,000 farms in the Alberta part of the Saskatchewan-Nelson Basin, 50 % used .26 cubic meters of water per day from a groundwater source. Table 2 breaks down an annual 5.7 billion cubic meter provincial groundwater usage by sector as of 1971. Nielsen (1971) concluded that development potential of the resource still remained, little depletion of groundwater was occurring, and that groundwater supplies were satisfactory in most areas.

TABLE 2

TOTAL GROUNDWATER USE (1971)
SASKATCHEWAN-NELSON BASIN, ALBERTA*

USE	AMOUNT USED M^3
Municipal†	7,230,065
Agricultural	10,435,146
Secondary recovery (Oilfield)	10,956,903
Gas Processing Plants	2,236,103
Other Industrial	25,044,350
Total	55,902,567

* Source : Nielsen, 1971

† Municipal refers to communities with populations >1000 Rural refers to communities with populations <1000 and farm populations.

In a publication by Gabert (1986), estimated groundwater usage for Alberta in 1984 is presented :

TABLE 3

1984 WATER USAGE IN ALBERTA*
(VOLUMES IN M^3)

Use	Total	Groundwater	Groundwater % of Total
Municipal	402,460,000	8,049,000	2
Rural	34,803,000	30,235,000	87
Industry	686,279,000	17,898,000	3
AGRICULTURE‡			4
Livestock	90,061,000	81,055,000	
Irrigation	1,867,413,000	0	
Totals	3,081,016,000	137,237,000	4

* Source : Gabert, 1986

‡ Agricultural use is sub-divided into livestock and irrigation uses.

Table 4 compares 1971 groundwater usage figures with 1984 groundwater use estimates :

TABLE 4

CHANGE IN GROUNDWATER USAGE IN ALBERTA FROM 1971- 1984
(VOLUMES IN 1000 M^3)

Use	1971	1984	% Increase
Municipal	7,230	8,049	8.9
Agriculture	10,435	90,061	88.0
Rural	?	30,235	?

Although data is somewhat incomplete to accurately trace changing groundwater use in detail, it is clear from these figures that groundwater use is increasing in the province of

Alberta, and there is no reason to expect a reversal in that trend in the future.

4.2 Provincial Perceptions of Groundwater Concerns

In February 1981 a survey of concerns regarding groundwater resources in Alberta was carried out by M.E. Gordon for the Environment Council of Alberta. This survey was "conducted to determine the extent of groundwater use and current and anticipated problems" (Gordon, 1981).

The conclusions of the Environment Council were as follows :

> 1) At the municipal level, the surveyed urban and rural municipalities failed to reflect much concern regarding groundwater management. Most concerns about local groundwater supplies relate to natural chemical and flow characteristics, problems considered as natural constraints to be lived with.
>
> 2) At the regional and provincial levels, problems related to overproduction and pollution of groundwater are recognized as specific aspects of larger environmental and land/water management issue. Most regional planning commissions expressed concerns that upper limits of groundwater use are being reached.
>
> 3) The strongest concerns expressed in the survey came from the agricultural representatives. They questioned current groundwater management practices, particularly those related to rural residential development, increasing competition, seismic activities, and certain agricultural practices. Many industry-related concerns were also raised.

The Environment Council of Alberta (ECA) came to the collective conclusion that groundwater management was "not an issue of sufficient concern to warrant public hearings" at that time. The ECA also concluded that the survey pointed to a need for "more a comprehensive research program oriented towards groundwater management, and was best assumed at that time by the appropriate provincial departments".

The final recommendations of the ECA downplay somewhat the concerns outlined in the report. Half of the municipal respondents in the survey anticipated an increase in the use of groundwater, especially in the central portion of the province. Over half of the responding municipalities considered poor quality or inadequate supply of groundwater as a problem. Although the survey showed southern Alberta municipalities were showing little tendency for the growth of rural establishments, the central and northern Alberta municipalities are experiencing growth which is carrying over to the rural communities, which tend to be large consumers of groundwater.

4.3 Water Usage Patterns by Provincial Geographic Region

The dry climate in three southern Regional Planning Commissions is a primary factor determining the settlement patterns (Gordon, 1981). Low annual precipitation and high evapotranspiration slow groundwater recharge rates rendering aquifers less productive. The lack of plentiful and quality water has dictated the geographic distribution of town settlement in the southern Alberta region to a certain extent. Larger centers tend to be located near to plentiful surface water sources, while communities using groundwater for local supply are limited in size.

Groundwater quality in the southern provincial region tends to be marginal, having a high dissolved mineral content, and its use as domestic supply usually requires treatment. The Energy Conservation Board (ECB) report states that pressure for increased acreage development could be a potentially serious threat to groundwater supplies.

Groundwater resources of central Alberta tend to be plentiful and of good quality. A large proportion of central Albertan communities excepting the major centers depend on groundwater at least in part for their municipal supply. The larger consumers of groundwater are approaching the upper limit of their capacity to provide water to meet their growing needs; limited supplies in the Calgary area resulted in the building of an 80 km pipeline to link Olds, Didsbury, Carstairs, and Crossfield to water supplied from the Red Deer River (Gordon, 1981).

Gordon (1981) points out that almost all rural residential water demand is supplied by groundwater. Groundwater also meets a large portion of the demand for agricultural and industrial waters in this region, the largest industrial users being the oilfield sector. The agriculture and oilfield industries are expected to increase their demand on groundwater supplies in the future. Presently groundwater supply in the central Alberta region is generally adequate, but there are suggestions that it is already being stressed. Residential acreages west of Calgary have reported incidents of lower residential well levels, and of a growing inadequacy.

Groundwater is used extensively for municipal, domestic, industrial (especially oil and gas operations), and general agricultural purposes throughout the Peace River region and northern Alberta (Gordon, 1981) Large scale industrial projects as the oil sands project demand highly on groundwater resources. Groundwater supply in the northern Alberta region is not as good as in central Alberta, and high demand for groundwater is believed to have caused lowering of well levels near Beaverlodge, and has limited municipal growth in the communities of Wembley, Clairmont, and Sexsmith. Better management of groundwater in the northern Alberta region seems to be required in view of declining well levels and aquifer storage.

Groundwater usage will likely become an issue of increasing public awareness in the years and decades to come in light of increasing usage by growing population centers. The concerns outlined by the provincial survey underline the need for the continual accumulation of data pertaining to the groundwater resource.

CHAPTER 5

THE GROUNDWATER BALANCE

5.1 Groundwater Movement

Fluctuations in groundwater storage are accomplished by the movement of water through the soil.

Water in the form of rainfall or snowmelt enters the soil surface through a process known as infiltration. Gravity water travels through the larger interstitial voids, while water fills the smaller voids via capillary action. As the pore spaces closer to the surface are filled with water, the infiltration rate decreases. Thus the infiltration rate is governed by antecedent moisture conditions, the rate and intensity of the rainfall event, and of the soil structure itself. Additionally, soil texture changes quickly with depth. The decrease of porosity and permeability of soil with depth can be rapid. Due to these factors, infiltration is usually limited to the shallow upper layers of the soil profile, and moisture introduced into the soil column rarely is able to penetrate much beyond a couple of feet in depth. Unless the aquifer is extremely close to the land surface, infiltration rarely accounts for any significant portion of recharge to the groundwater reserve.

Percolation refers to the movement of water through the soil profile (gravity water) and is distinguished from infiltration which describes the entry of water into the surface soil layers. Movement of moisture in soil is governed by the moisture potential following the equation :

$$q = - K \frac{\partial \Lambda}{\partial x}$$

(1.1)

(Linsley, et. al., 1982)

Where :

q is flow per unit time through unit area normal to the direction of flow.

x is the distance along the line of flow.

K is conductivity.

Λ is potential.

After gravity water has left the soil, the principal component of total potential is the capillary potential. Conductivity increases with moisture content and decreases with pore size (Linsley et. al., 1982).

Water vapour movement becomes an important mechanism of water transport as the soil dries to the point where capillary movement may no longer take place. The direction of movement of water vapour is always from high temperature (high vapour pressure) to low temperature (low vapour pressure) The actual amounts of moisture moved by this mechanism are small.

5.2 The Groundwater Balance

Groundwater movement occurs within the hydrologic cycle in response to forces of hydrologic equilibrium.

Natural groundwater levels are either rising, falling or remaining constant in response to the net effect of hydrologic processes active in the atmosphere, at the surface of the earth, in the unsaturated zone and in the saturated zone itself (Gabert, 1986). The hydrologic processes involved are a complex interaction of components belonging to the hydrologic cycle, and include the mechanisms of precipitation, infiltration, percolation, evaporation, evapotranspiration, and condensation. Barring pumpage, hydrographs of most observation wells reveal that the hydrologic processes are in a state of dynamic equilibrium, as groundwater fluctuation is restricted to relatively narrow boundaries. The equilibrium achieved within the saturated zone is referred to as the groundwater balance, and can be expressed in very simple form by the general hydraulic equation from Gabert (1986) :

$$Ws = \text{Inflow} - \text{Outflow} \qquad (1.2)$$

Where :

Ws is the change in groundwater storage.

Inflow refers to water entering the groundwater reservoir, and corresponds to groundwater recharge.

Outflow refers to water leaving the groundwater reservoir, and corresponds to groundwater discharge.

Inflow or groundwater recharge represents the addition of water to the saturated zone, and usually a rise in water table level. Such a rise in water table level may be recorded by a stage recorder at an observation well. Outflow, or groundwater discharge represents the removal of water from the saturated zone, and is usually manifest by a drop in the water table, which may also be recorded by an observation well. Understanding the equivalence of inflow / outflow to recharge / discharge, the groundwater balance equation may be rewritten as follows :

$$Ws = Qr - Qd \tag{1.3}$$

Where :

Ws = Change in storage - Change of water table elevation x specific yield -or- Change of piezometric head x storage coefficient.

Qr = Groundwater recharge - Deep percolation of rainwater and snowmelt + Seepage from streams + Artificial recharge.

Qd = Groundwater discharge - Evapotranspiration from plants drawing on the saturated zone + Seepage to streams, lakes, and marshes + Pumpage.

5.3 Recharge and Discharge of Groundwater Reservoirs

In general, areas of higher relief are characterized as being recharge areas, areas of lower relief, discharge areas. The change of groundwater levels and their relationship to groundwater flow systems in Alberta can be more easily comprehended if one considers that the ground surface is frozen during most of the winter months in Alberta and recharge through infiltration and percolation is not occurring. Fluctuations that are occurring in the groundwater reservoirs are therefore the result of water movement from recharge to discharge areas. In the winter months therefore, it would be expected that recharge areas would exhibit a decline in water table elevation, with water movement toward the discharge areas, which would display an increase in water table elevation. Gabert (1986) points out that a decrease in water table elevation is evident at both recharge and discharge sites as discharge is able to occur at discharge sites beneath ice covered lakes and rivers.

While precipitation constitutes the majority of water available for recharge to a groundwater aquifer, the form of the water can vary. Recharge to the groundwater reservoir can occur from rainfall or snowmelt through the mechanisms of infiltration and percolation to the water table. These mechanisms have already been discussed. Other sources of recharge include seepage from streambeds and lakebeds, and in some instances, artificial recharge. Where received amounts of precipitation are quite low, streams and lakebeds become important and often the main source for groundwater reservoirs. Streams which contribute to the recharge of groundwater are known as influent. Under some climatic conditions, the stream may dry up completely during certain periods of the year, as percolation depletes all flow. Streams which flow only part of the year in this fashion are called ephemeral streams. Most streams are influent over a portion or portions of their length (Linsley et. al., 1982). Percolation is greatest in association with coarse grained materials.

Discharge of groundwater may occur in several fashions. As a stream intersects the water table, it may begin to receive water from the groundwater reservoir, thus becoming an effluent stream. Perennial streams are generally effluent through at least a portion of their length (Linsley et. al., 1982). Springs occur where the water table intersects the surface, and may provide for small discharges of groundwater. Vegetation provides for the evapotranspiration of large amounts of groundwater, phreatophytes (plants deriving their moisture requirement mainly from groundwater) may transpire 10×10^6 m^3/km^2 at a rate of 1m/year of evapotranspiration (Linsley et. al., 1982). Direct evaporation may occur from the capillary fringe where the water table is close to the land surface. Pumpage by man is another way in which discharge occurs from a groundwater reservoir. Obviously, the effect of pumpage varies depending on the amount of water removed from the reservoir, the size of the reservoir, and the rate of natural recharge to the reservoir.

The addition of water to the saturated zone has the effect of steepening the profile of the water table. In order to maintain a state of equilibrium the steepened condition of the water table has the effect of increasing discharge from the aquifer. It is this action which introduces fluctuations in water table elevation to the groundwater reservoir. Observation wells monitoring the reservoir may record these fluctuations.

5.4 Water-Table Fluctuations Viewed as the Net Result of Recharge and Discharge Occurring to the Groundwater Reservoir

Todd (1959) states that the main factor governing groundwater-level changes is recharge, and that the magnitude of the fluctuations is dependant upon the amounts of water being discharged and recharged. According to Freeze (1969a, 1969b), fluctuations in water table elevation occur when the recharge or discharge rate of groundwater is not balanced by the same rate of infiltration or evaporation in the unsaturated zone. Water table fluctuations are interpreted by Freeze (1969a, 1969b) in terms of recharge and discharge as follows :

a) The water table level will rise when the rate of recharge is less than that infiltration rate which is supplying water to the top of the saturated zone (water table).

b) When the recharge rate exceeds the rate of infiltration to the saturated zone, the water table elevation will decline.

c) The water table level will decline when the rate of discharge is less than the rate of evaporation to the saturated zone.

d) When the discharge rate exceeds the rate of evaporation at the saturated zone, the water table level will rise.

Gabert (1986) points out the importance of recognizing the direction of water flow in the saturated zone with respect to the water table, but also points out that recharge may occur at discharge areas due to local mounding of the water table.

Other factors which may induce fluctuations in water table elevation include changes in atmospheric pressure, which can have the greatest potential effect on confined groundwater reservoirs, but little on open unconfined water table reservoirs. Aquifer compression and dilation can occur from seismic activity such as earthquakes, or activities of man. The gravitational attraction between the earth, moon, and sun, and the centrifugal force due to the earth's rotation cause rhythmic deformations of the earth which not only cause oceanic tides to occur, but earth tides as well (Gabert, 1986).

Earth tides have the effect of dilating and compressing the pore volume of terrain materials, which results in fluctuations of the water table level. Groundwater level fluctuations due to an earthquake in Alaska, March 1964, were recorded in 5 Alberta observation well hydrographs (Gabert, 1964).

CHAPTER 6

METHODOLOGY

6.1 The Water Balance

Examination of the water balance enables a better understanding of the fluctuations occurring at the water table.

The groundwater balance is a calculated subset of the total hydrologic balance, which encompasses surface, subsurface, and atmospheric hydrologic mechanisms.

Dunne & Leopold (1978) provide an equation describing the water balance of a small drainage basin underlain by impervious rock :

$$P = I + AET + OF + \Delta SM + \Delta GWS + GWR \tag{2.1}$$

Where :

P = Precipitation.

I = Interception (by vegetation and other obstacles).

AET = Actual Evapotranspiration.

OF = Overland Flow (Moisture not infiltrating into the surface soil).

ΔSM = Change in Soil Moisture.

ΔGWS = Change in Groundwater Storage.

GWR = Groundwater Runoff.

The precipitation term is most often obtained from weather station records, or is evaluated through the use of a raingauge network, depending on the resolution of data that is required. Interception is moisture which is "intercepted" and held by vegetation or other obstacles and evaporated back to the atmosphere during and after the precipitation event. Interception is estimated using rain gauge measurements above and below the vegetation canopy and making observations of changes in moisture content of litter beneath the canopy. Tables of estimated interception by vegetation type are often used instead of taking field measurements of this variable. Overland flow can be measured directly (as water depth), and change in soil moisture may be monitored through the use of lysimeters. The change in groundwater storage is reflected by fluctuations in water table elevation, and may be recorded by observation wells equipped with stage recording devices. Groundwater runoff may be computed through the use of Darcy's equation, or by the separation of baseflow from a stream hydrograph with which the groundwater reservoir is known to be in association.

6.2 Potential Evapotranspiration

Potential evapotranspiration is usually computed through a mathematical model, usually Penman or Thornthwaite. Actual evapotranspiration may be calculated using PE as in the following equation from Mather (1974) :

$$AE = PE \frac{SM_a}{SM_{fc}}$$

(2.2)

Where :

SM_a = the actual soil moisture content.

SM_{fc} = the soil moisture content at field capacity.

PE = the potential evapotranspiration, which may be computed with the Thornthwaite equation.

The Thornthwaite method of computing the potential evapotranspiration uses air temperature as an index of the energy available for evapotranspiration, assuming that air temperature is correlated with the integrated effects of net radiation and other controls of evapotranspiration, and that the available energy is shared in fixed proportion between heating the atmosphere and evapotranspiration (Dunne & Leopold, 1978). The Thornthwaite equation is as follows :

$$E_t = 1.6 \left[\frac{10T_a}{I} \right]$$

(2.3)

Where :

E_t = the potential evapotranspiration in cm/month.

T_a = mean monthly air temperature (Celcius).

I = the annual heat index; computed from the formula :

$$\sum_{i=1}^{12} \left[\frac{T_{ai}}{5} \right] \tag{2.4}$$

The value of **a** is computed using the formula :

$$a = 0.49 + 0.0179I - 0.000077I^2 + 0.000000675I^3 \tag{2.5}$$

Table 5 is an excerpt of 1 years duration from a water balance computed for the Lethbridge area. In the computation of the water balance, the Thornthwaite model is used to estimate the potential evaporation occurring in the area. For this model, the change in groundwater storage required the initialization of the soil moisture variable to field capacity prior to the computational run. The data sequences were examined to ensure that indeed a wet year was chosen as that to be initialized to field capacity. Values for interception and overland flow have been removed from the calculation for computational simplicity.

TABLE 5

WATER BALANCE FOR THE LETHBRIDGE AREA, 1985
(ALL VALUES ARE IN mm)

Month	Precip.	A. E.	Soil Moisture	Change in SM Storage	Deficit -	Surplus
Jan	0.0	6.3	150.0	0.0	0.0	0.0
Feb	0.0	16.5	150.0	0.0	0.0	0.0
Mar	8.7	16.8	150.0	8.7	0.0	8.1
Apr	45.7	38.7	140.6	45.7	0.0	0.0
May	89.4	30.7	95.2	76.0	13.4	0.0
Jun	103.0	3.2	49.1	49.3	53.7	0.0
Jul	140.4	6.6	20.2	35.5	104.9	0.0
Aug	105.1	88.4	18.1	90.5	14.6	0.0
Sep	51.4	116.6	83.3	51.4	0.0	0.0
Oct	30.4	23.8	140.9	30.4	0.0	0.0
Nov	0.0	33.5	150.0	0.0	0.0	0.0
Dec	0.0	13.7	150.0	0.0	0.0	0.0

A deficit in soil moisture exists for the months of May through August, while only the month of March shows a small surplus of soil moisture in this fairly typical annual representation of the water balance at the Lethbridge site. The water balance reveals that no (or very little) surplus water is available to the aquifer system for recharge. The water balance for Lethbridge is representative of the general behaviour of the water balance for all the well sites.

6.3 Well Data - Gathering and Numerical Treatment

Data is collected from the observation wells by means of Stevens type "F" mechanical drum level recorders on paper charts and may later be digitized in order to produce a digital record of well level behaviour suitable for computer analysis. Data is accurate excepting occasions of extreme weather such as intense cold where the ink used to record fluctuations may freeze resulting in data loss. During those times, a gap is introduced into the well level record.

Missing data is also introduced from human error at the digitizing stage. Errors introduced at the digitizing stage can result in too many or two few data points being recorded per year. Mechanical and Human errors result in different numbers of observations per year being collected for each year of record. In each case, the total number of data points recorded during a twelve month period is taken to represent one year's worth of data. In order to prepare the data for time series analysis (which requires continuous equidistant in time observations), the data was made continuous with equal numbers of observations per time interval, i.e. 12 segments constitute monthly divisions. In this fashion, gaps and excesses of data are averaged out. For those wells in which entire years' worth of data are missing, the existing data is treated as though it were continuous; i.e., a missing year of well data would result in the removal of the same year's worth of climate data from the sequence. In this fashion, unjustified assumptions as to the behaviour of well levels over the course of an entire year are not made.

6.4 Climate Data - Gathering and Numerical Treatment

The two parameters which would impact most directly on the fluctuation of groundwater are precipitation and evaporation. Precipitation because it is the main input to the groundwater system, and evaporation because it controls the soil moisture reservoir and thus the size of the gravity drainage because it could lower stream levels at discharge areas and steepen the hydraulic gradient resulting in a change in discharge. Where water tables are shallow, evaporation could lead to direct discharge from the water table through evapotranspiration by vegetation tapping into the reservoir.

The response of the groundwater table to changes in precipitation may not be immediate. A time lag may be involved in the stimulus-response schedule of the water table. The length of the lag is not known before hand and must be determined through numerical experimentation. The use of lag and cross correlation techniques provides one tool in the experimental process.

Precipitation and temperature data were obtained for each well from a weather station as near as possible to each well site still within the same climate region. In some instances, where a station was a few tens of kilometers further from a well but had higher quality or more complete data, this was substituted. Care was also taken in ensuring selected weather stations were located within topography as similar to the observation wells as possible.

Missing data encountered within weather records was substituted as appropriate from nearby weather stations located within the same drainage basin. In the case of data missing from a remote (in terms of relative basin location) station, an average value from all weather stations located in the basin was used in the calculation of missing values.

Weather data was obtained from two distinct data bases currently maintained by the Atmospheric Environment Service of Environment Canada : the Daily Climate Database (DCD), and the Monthly Climate Database (MCD). Data contained in the DCD data base records data at a resolution of one day, the MCD data base a resolution of one month. Well data resolution was adjusted as required to synchronize with data extracted from the climate bases. This was accomplished by averaging time sectors of the desired length. The length of data used from the climate bases corresponds with the length of record of well level fluctuations at the well site.

Calculations show computational correlation coefficient and lagged coefficients derived between measurements of water table elevation and actual evapotranspiration, and levels and temperature are very similar in size and occurrence in time. A correlation coefficient of .92 is computed between the time series of AE and temperature at the Lethbridge site, and is typical of the relationship between AE and temperature at all sites. Taking this similarity into consideration, it was decided to omit the computation of actual evapotranspirations at the well sites and use temperature data as a surrogate for that variable. Computational time is saved and generalized assumptions required to compute AE are thus avoided.

6.5 Analytical Strategy

The first step in the analysis was to examine the fluctuations in an isolated fashion.

6.5.1 Cross Correlation Techniques

Cross-correlation (or lagged correlation) was used to explore the data. Cross correlation uses a process whereby a series of correlation coefficients is computed; each at a successive lag between the two data sets. i.e. :

If two series being compared are Y_{1i} and Y_{2i}, and n^* is defined as the number of overlapped positions between the two sets, the cross-correlation for the match position **m** is defined by the formula :

$$r_m = \frac{n^*\Sigma Y_1 Y^2 - \Sigma Y_1 \Sigma Y_2}{\sqrt{[n^*\Sigma Y^2_1 - (\Sigma Y_1)^2)]\ [n^*\Sigma Y^2_2 - (\Sigma Y_2)^2]}}$$

(2.6)

(Davis, 1986)

The significance test for the cross correlation coefficient is the "t" test, and is computed as follows :

$$t = r_m \sqrt{\frac{n^* - 2}{1 - r_m^2}} \tag{2.7}$$

The test has $(n^* - 2)$ degrees of freedom (Davis, 1986). The **t** test is based on a comparison of the correlation coefficient which would result from correlating two normal populations. The null hypothesis is that correlation at the specified match position will be zero.

Cross correlation is used as an exploratory technique as it will reveal the effect that time has on the aquifer / climate system. A time lag considers that time period which passes as moisture falling on the soil surface must first infiltrate, then percolate to the water table before any fluctuation in water table elevation may be recorded by an observation well. In theory, when the appropriate lagging of the data sets is introduced into the correlation computation, the actual response of the groundwater reservoir to recharge moisture can be evaluated. i.e., if the average time required for moisture to infiltrate and percolate to the groundwater reservoir approximates 4 months, a lag of 4 would produce the highest correlation coefficient between data sequences of groundwater level and precipitation data of monthly interval. If weekly interval data was used, the lag period required for maximum correlation would likely approximate 16 (4 months x 4 weeks / month). In using cross correlation to investigate the relationship between groundwater level fluctuations and precipitation as the climatic parameter, the strongest correlation coefficient occurring after lag zero will approximate the time period represented by the processes of infiltration and percolation to the water table, and the time taken for water input to specific time to travel from the recharge zone to the observation well position, although a "spectrum" of response will likely be observed where correlation strength increases steadily to a maximum point.

Important information regarding the time period required for moisture to reach the water table is gained from cross-correlation analysis. The cross correlation series is also able to yield important information regarding relationships of the two data sets in longer term cycles. This is accomplished by examining the correlation coefficients computed at longer lag periods. A typical line of enquiry might be to examine correlation strengths at lags corresponding to decade length cycles commonly associated with sunspot activity. High correlation strengths at this lag may suggest a possible linkage of the phenomena being examined with sunspot activity.

The strength of the strongest correlation coefficient computed immediately after lag zero hints at the sensitivity of the groundwater-climate system. I.e., a perfect correlation at lag 4 using monthly data would indicate the pattern of precipitation received at the surface soil layer is exactly duplicated in water table recharge / discharge fluctuation.

Perfect or strong correlations suggest that processes impeding, altering or preventing moisture from recharging the reservoir are minimized. These factors may include : overland flow, interception by vegetation, and physical factors in soil preventing or slowing recharge moisture. This does not preclude the possibility that near perfect correlations are possible when a consistent percentage (perhaps 50 %) of water falling upon the surface is able to enter the water table as recharge. In this case, the same peaks and valleys present in the precipitation data would be preserved. Recalling the climate descriptions typical of Alberta, the province often experiences periods of light rain. Such precipitation events are seldom able to provide moisture to the saturated zone (depending also on the antecedent moisture conditions), and therefore will not reflect changes in water table elevation. Such precipitation data may have the overall effect of reducing the correlation strength between the two data sequences.

Cross correlation of observation well data with temperature is accomplished in the same fashion as with the precipitation data described above. In this situation, a high correlation coefficient computed at lag zero would suggest that evapotranspiration and subsequent discharge from the saturated zone occurs in concert with fluctuation in temperature. The highest correlation strength obtained after lag zero will represent the period of time taken up with such processes as uptake of moisture by vegetation roots, vapour transport, or direct evaporation from effluent streams.

Correlation analysis will therefore answer some fundamental questions regarding the relationship which exists between fluctuations occurring in the saturated zone, and the climatic parameters of precipitation and temperature i.e. :

1) If there is any relationship between observation well level fluctuations, and the climatic parameters of temperature and precipitation.

2) If a relationship is present, the lag periods at which maxima in correlation strength are computed will :

a) Hint at the infiltration and percolation time periods, and travel time and permeability of the aquifer in terms of the shorter lag maxima.

b) Correlation maxima occurring at longer lag periods (on the order of years) will yield information about the possible existence of long term cycles within the water balance.

c) Hint at the overall sensitivity of the aquifer / climate system when the correlation strength is examined.

6.5.2 Time Series Analysis Techniques

Following simple regression and correlation analysis, time series analytical techniques were used in analyzing the data. This was done in recognition of distinct cycling activity noted to be present within the power spectra of most wells' data.

In general, techniques collectively known as "time series analysis" constitute a means of extracting and measuring the strength of cycles and trends present within a data set. Some of the techniques falling into the category of time series are Fourier analysis, cross correlation, and autoregression. Although many texts present a thorough discussion of these topics, Davis (1986) on Fourier analysis and cross-correlation, Box & Jenkins (1976) on autoregressive time series techniques), a very brief introduction to these techniques is presented here in order to acquaint the reader with the nature of the analysis performed.

6.5.2.1 Fourier Analysis

Fourier analysis is known also as spectral analysis, harmonic analysis and frequency analysis, and is characterized by mathematical examination of vibratory motion. Jean Baptiste Fourier (1768-1830) proved that any continuous, single valued function could be represented by a series of sinusoids, and it is this concept that is the essence of Fourier analysis (Davis, 1986).

As applied in terms applicable to the objective at hand, Fourier analysis provides for a means whereby cycles present within the data sequences may be analyzed in terms of their strength and significance. As an example, Fourier analysis applied to temperature data will frequently reveal a very strong annual cycle. In addition to an annual cycle however, cycles of longer time duration may be revealed. It is not unusual that a cycle approximating 10-11 years be present in a temperature data sequence. Cycles of this length are often attributed to similar cycles which are known to occur within sunspot activity on the sun (Currie, 1979). The same approach may be taken with observation well level data and climatic data. Fourier analysis of well level data will reveal the presence and significance of cycles within the record of data. As cycles are detected within fluctuations occurring at the saturated zone, the same cycles may be sought within the remaining components of the water balance. Using this approach, the terms of the water balance having an influence on water table fluctuations are looked at for the existence of similar behaviour as that recorded in the observation wells. This approach works towards establishing the similarity and relationship which exists between water table level fluctuations and climatic parameters. In summary, Fourier analysis of the well level and climatic data will :

1) Reveal cycles that are present within the data sets.

2) Establish similarity of cyclical behaviour among the data sets, thereby indicating a possible causal link between groundwater fluctuations at the saturated zone and climate, based upon the similarity of cycles.

The Fourier Series for a simple sequence is given by Davis (1986) :

$$Y_1 = \sum_{n=1}^{\infty} \left(\alpha_n \cos \frac{2n\pi Xi}{\lambda} + \beta_n \sin \frac{2n\pi Xi}{\lambda} \right) \tag{2.8}$$

This states that the amplitude, Yi , at a point Xi is determined by the sum of the amplitudes of the component sine and cosine waves at a distance Xi from the origin of the series. The subscript i is the harmonic number. The Fourier equation may be simplified by designating :

$$C_n = \cos \frac{2n\pi Xi}{\lambda} \quad \text{and} \quad S_n = \sin \frac{2n\pi Xi}{\lambda} \tag{2.9}$$

The equation may then be rewritten in a simplified form as :

$$Y_i = \sum_{n=1}^{\infty} (\alpha_n C_n + \beta_n S_n) \tag{2.10}$$

(Davis, 1973)

In a finite series containing **N** equally spaced observations; we can compute **N/2** harmonics (the Nyquist frequency). The equations for the coefficients are the terms from the Fourier series given by Davis, (1973) :

$$\alpha_n = 2/N \sum_{n=1}^{N} Y_i \cos \frac{2n\pi X_i}{\lambda} \tag{2.11}$$

and

$$\beta_n = 2/N \sum_{n=1}^{N} Y_i \sin \frac{2n\pi X_i}{\lambda} \tag{2.12}$$

A power spectrum (periodogram) may be obtained by plotting successive values of power against the harmonic number **n**.

A better impression of the periodic structure of a time series may be obtained through smoothing the power spectrum with a moving average of some sort. Smoothing algorithms are used for this purpose; the Hanning filter is a triangular function commonly used for this purpose :

$$\hat{s}_n = \frac{s^2_{n-1}}{4} + \frac{s^2_n}{2} + \frac{s^2_{n+1}}{4} \tag{2.13}$$

(Davis, 1973)

Where :

$\hat{s}^2_n$ is the variance of the **n**th harmonic.

The presence of dominant harmonics may be testes for by a modified Fisher's test. The test involves the calculation of the ratio :

$$\hat{g} = \frac{s^2_{max}}{2s^2}$$

(2.14)

(Davis, 1973)

Where :

$\hat{g}$ is the test statistic.

s^2_{max} is the largest peak in the periodogram.

s is the variance of the entire time series.

The calculated value of **g** is compared to a critical value of **g**. If the test statistic **g** exceeds the critical value of **g**, the cycle is presumed significant. If the test value does not exceed the critical value, the cycle could have arisen by chance.

The critical value of **g** is calculated using the following equation :

$$g_{crit} \approx 1 - e^{\frac{\ln p - \ln m}{m-1}}$$

(2.15)

(Davis, 1973)

Where :

g_{crit} is the critical value of **g**.

e is the numerical value of 2.71.

ln*p* is the natural log of the desired probability for the test.

m is equal to **n/2** if the time series contains an even number of observations, or **(n-1)/2** if it contains an odd number.

Once the periodograms have been generated for the individual time series, a comparison can be made to see if similar cycles are occurring among all 3 data sets. While this may be done visually and qualitative conclusions drawn, it is desirable to be able to make quantitative statements regarding the similarity of cycles. Quantitative statements may be made by cross correlating periodograms computed for the individual time series. In doing this, the similarity of cycles and cycle pattern may be directly computed between the data sets. The technique of cross correlation was selected as it allows for the effect of time lagging to be detected, and may therefore identify out of phase cycle relationships.

Cycles of interest or higher significance may be isolated from the data set as frequency gains in a statistical process known as (complex) demodulation. In this fashion, the status of the cycle frequency may be traced through time. To use a common example, it is possible to compute the log gain of an 11 year cycle from sunspot data in examining the periodicity of sunspot cycles. Higher spectral density may be associated with greater activity in sunspot occurrence. In similar fashion with well and climate data, certain spectral frequencies of significance or interest may be further examined. High spectral densities occurring at certain cycles may be found to have a controlling influence on the expression of water table levels. Higher spectral density within cycles common to well levels and climatic data may yield clues for approaches to be taken in predicting water table levels from climate data. Cross correlation again will be used to make a quantitative statement of similarity of spectral density occurring within the selected cycles. This approach is taken because it should identify the effect of a cycle's spectral density presence in time has upon the expression of water table levels. Two approaches are used, first, cross correlation is carried out using the gain variable data from both data sets, and second, the gain variable derived from climate only is cross correlated with the raw water table fluctuation data.

6.5.3 Cluster Analysis

Factor analysis is used to study the correlations of a large number of variables by collapsing the variables into factors. The variables contained within each factor are highly correlated, and this allows an interpretation of each factor based on the variables belonging to it. Many variables are therefore summed by a few factors. The factor analysis model expresses each variable as a function of factors common to several variables and a factor unique to the variable :

$$z_j = a_{j1}f_1 + a_{j2}f_2 + \ldots a_{jm}f_m + U_j \tag{2.16}$$

Where :

z_j is the **j**th standardized variable.

m is the number of factors common to all the variables.

U_j is the factor unique to variable z_j.

a_{ji} are the factor loadings.

f_i are common factors.

Ideally, the number of factors, **m** should be small, and the contributions of the unique factors should also be small. The individual factor loadings $\mathbf{a_{ji}}$ for each variable should be either very large or very small so each variable is associated with a minimum number of factors (BMDP, 1983).

Cluster analysis has also been used to group variables. K-means cluster analysis was employed as it generated clusters easily interpreted. The computational procedure carried out by BMDP in performing a K-means cluster analysis is presented in the appendix.

CHAPTER 7

RESULTS

7.1 Water Table Fluctuations in Terms of the Hydrologic Balance

All observation wells with the exception of Lethbridge and Drayton Valley are monitoring discharge areas as suggested by topographic and hydrologic characteristics. Well level hydrographs and associated precipitation and temperature time series are presented in Figures 4 - 14. Simple correlation and recharge / discharge attributes are presented in Table 6. In terms of the interpretation of fluctuations recorded in observation wells, the distinction being made between recharge and discharge areas can have considerable impact.

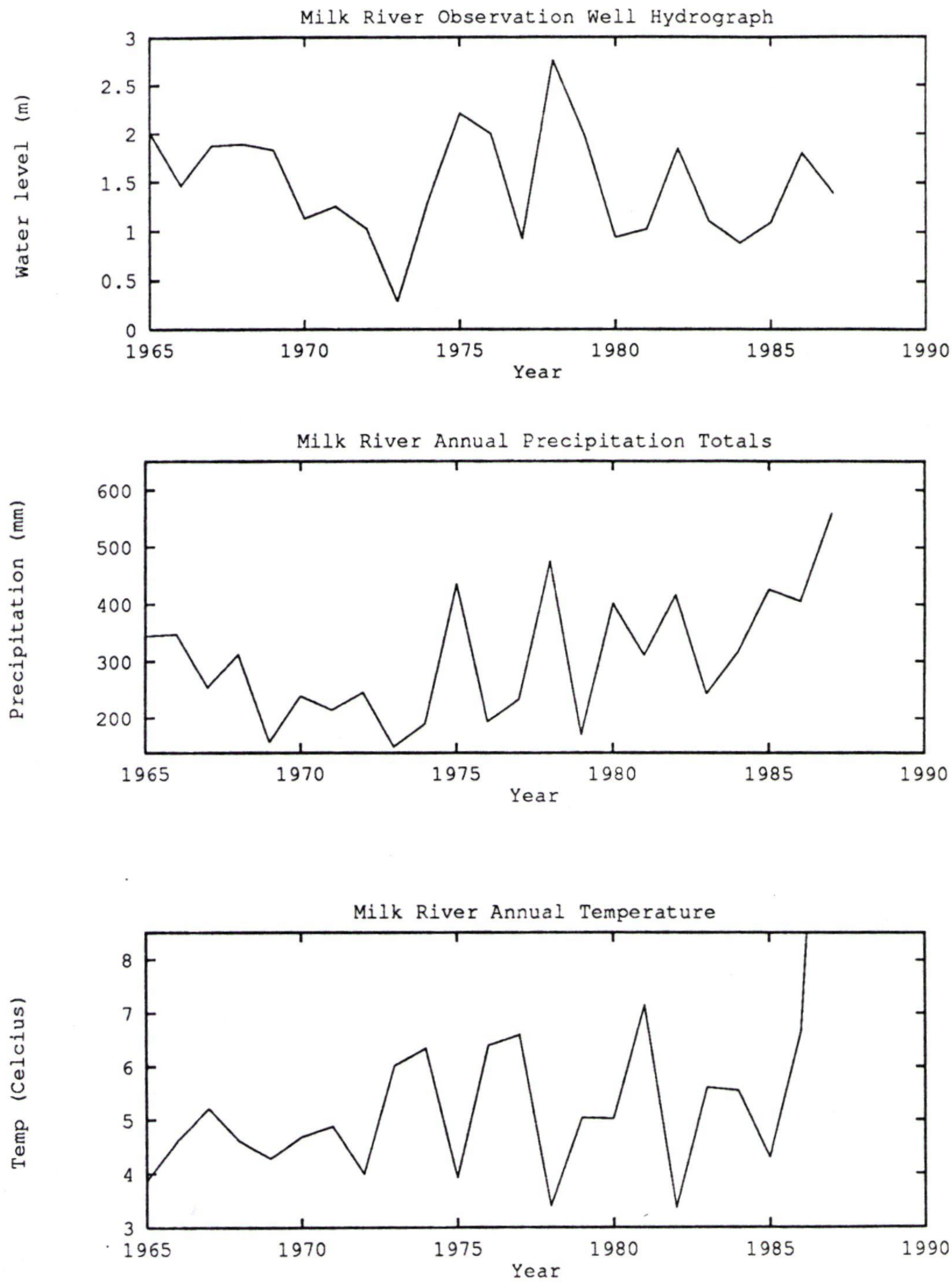


FIGURE 4

MILK RIVER SITE DATA PLOTS

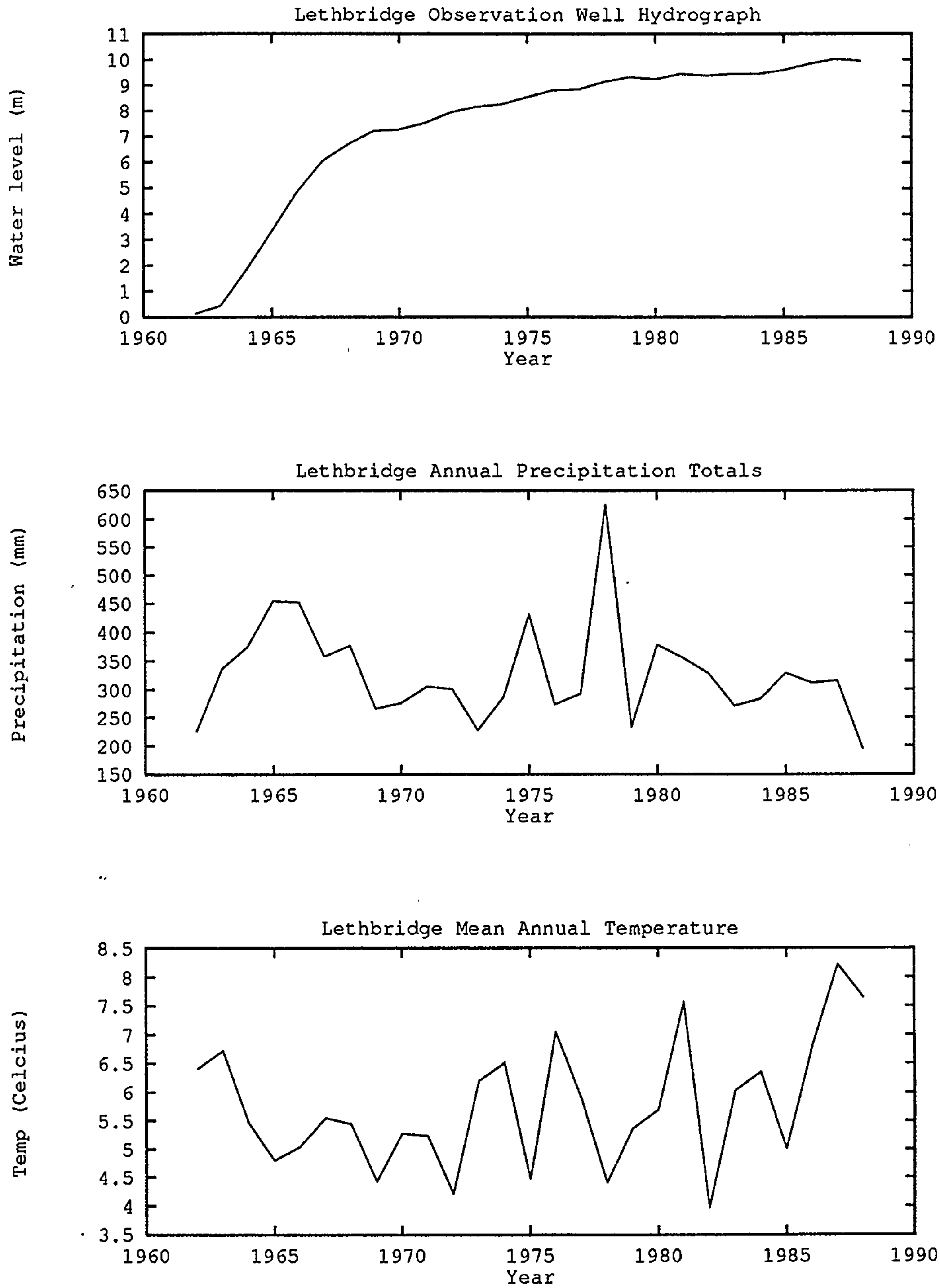
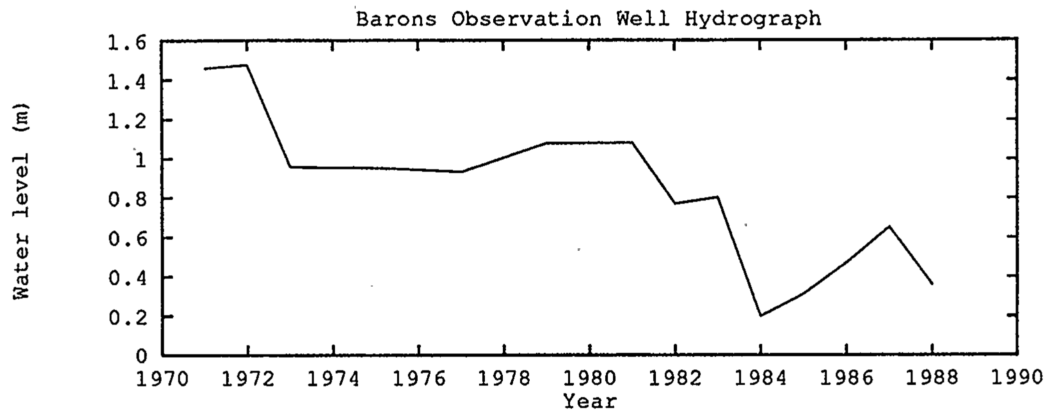
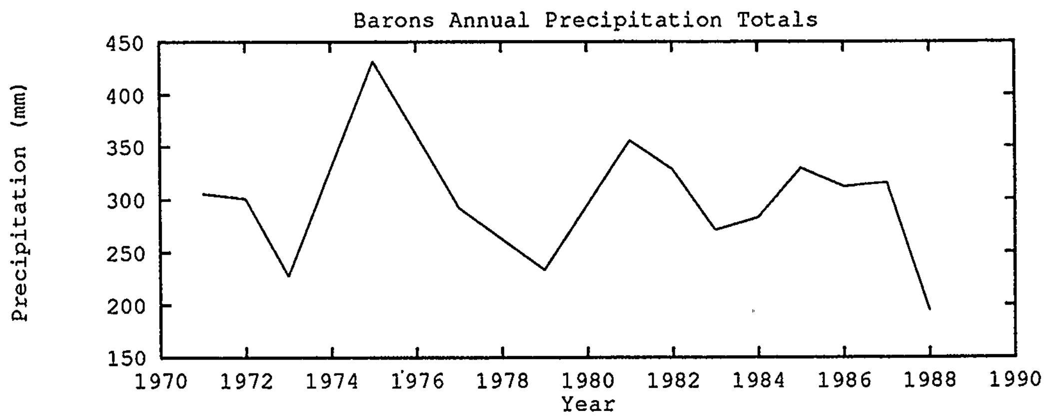


FIGURE 5

LETHBRIDGE SITE DATA PLOTS





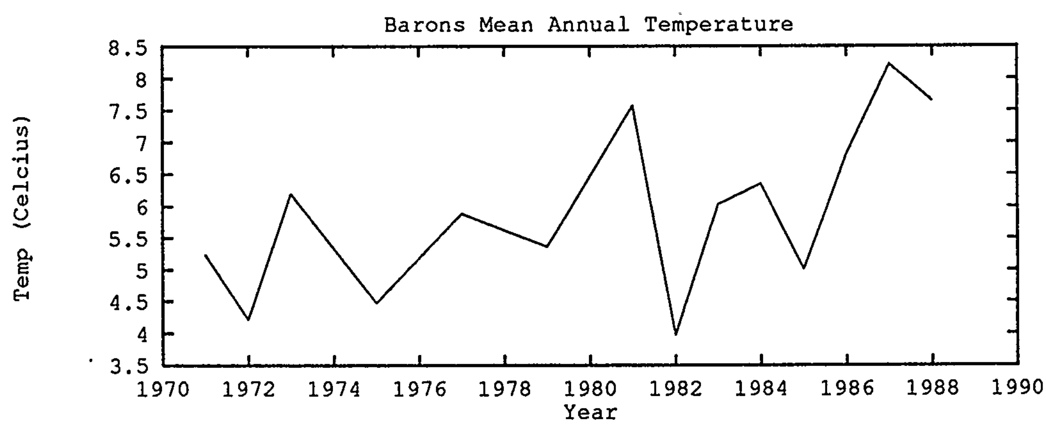


FIGURE 6

BARONS SITE DATA PLOTS

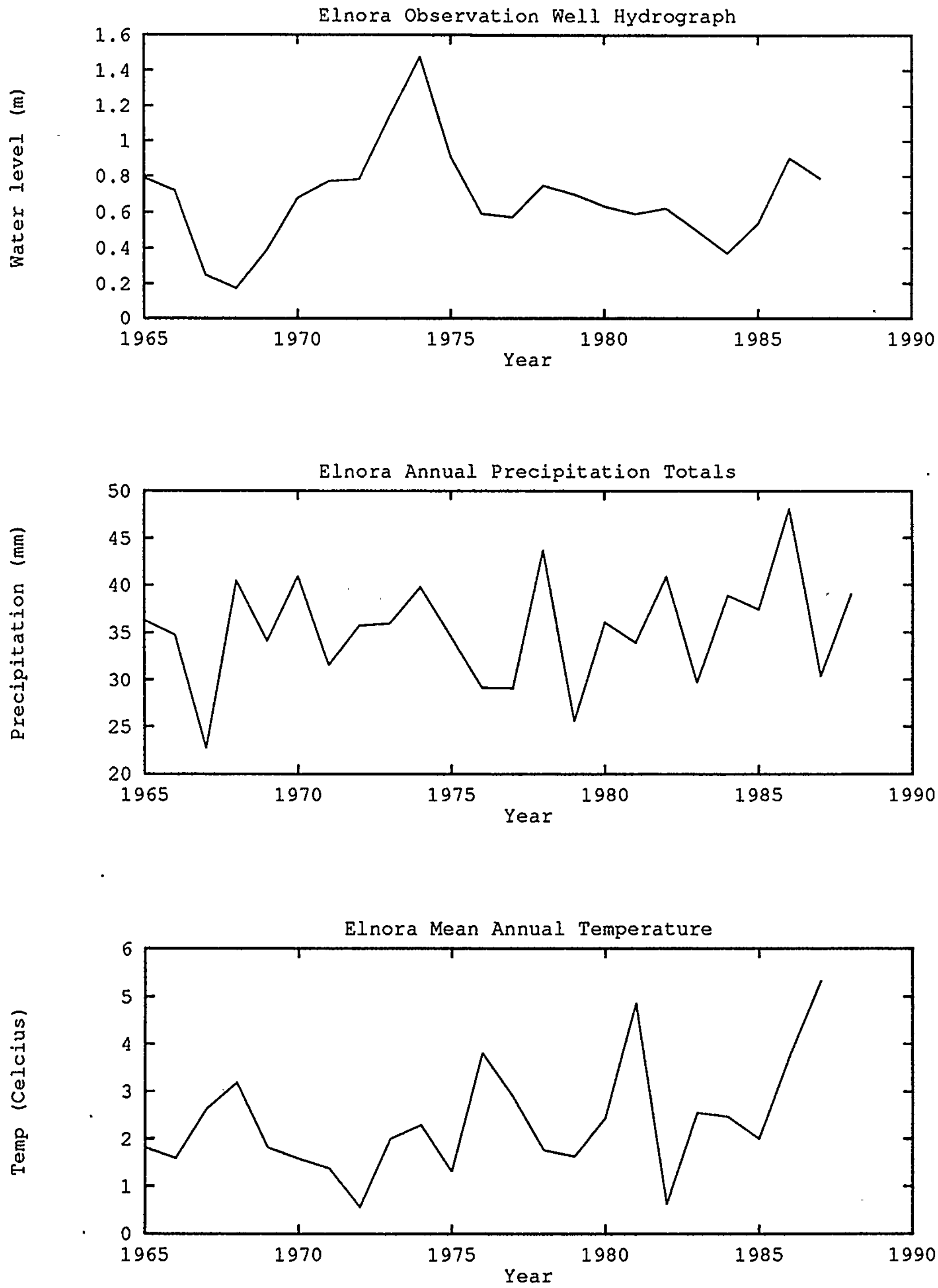


FIGURE 7

ELNORA SITE DATA PLOTS

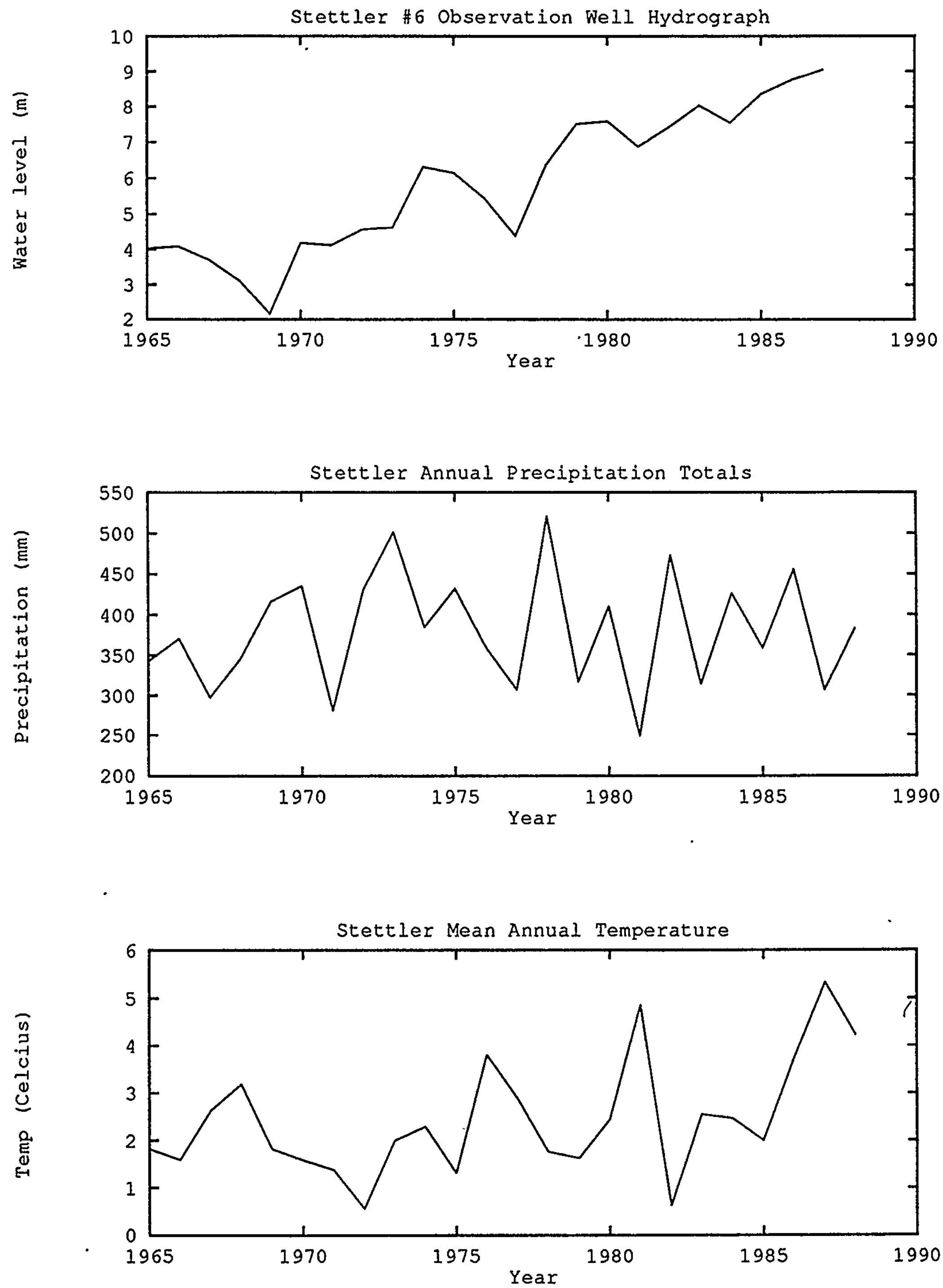


FIGURE 8

STETTLER #6 SITE DATA PLOTS

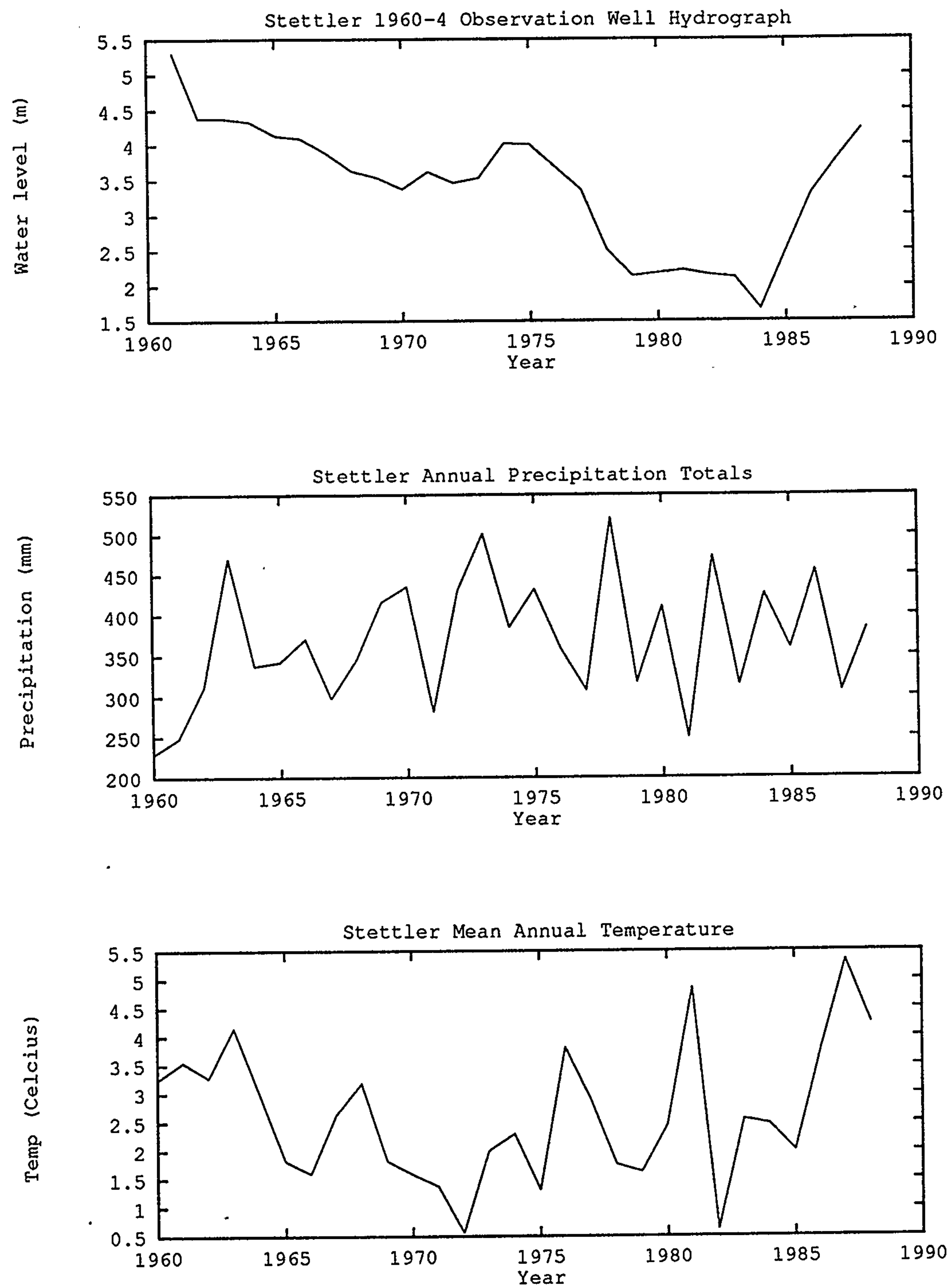


FIGURE 9

STETTLER 1960-4 SITE DATA PLOTS

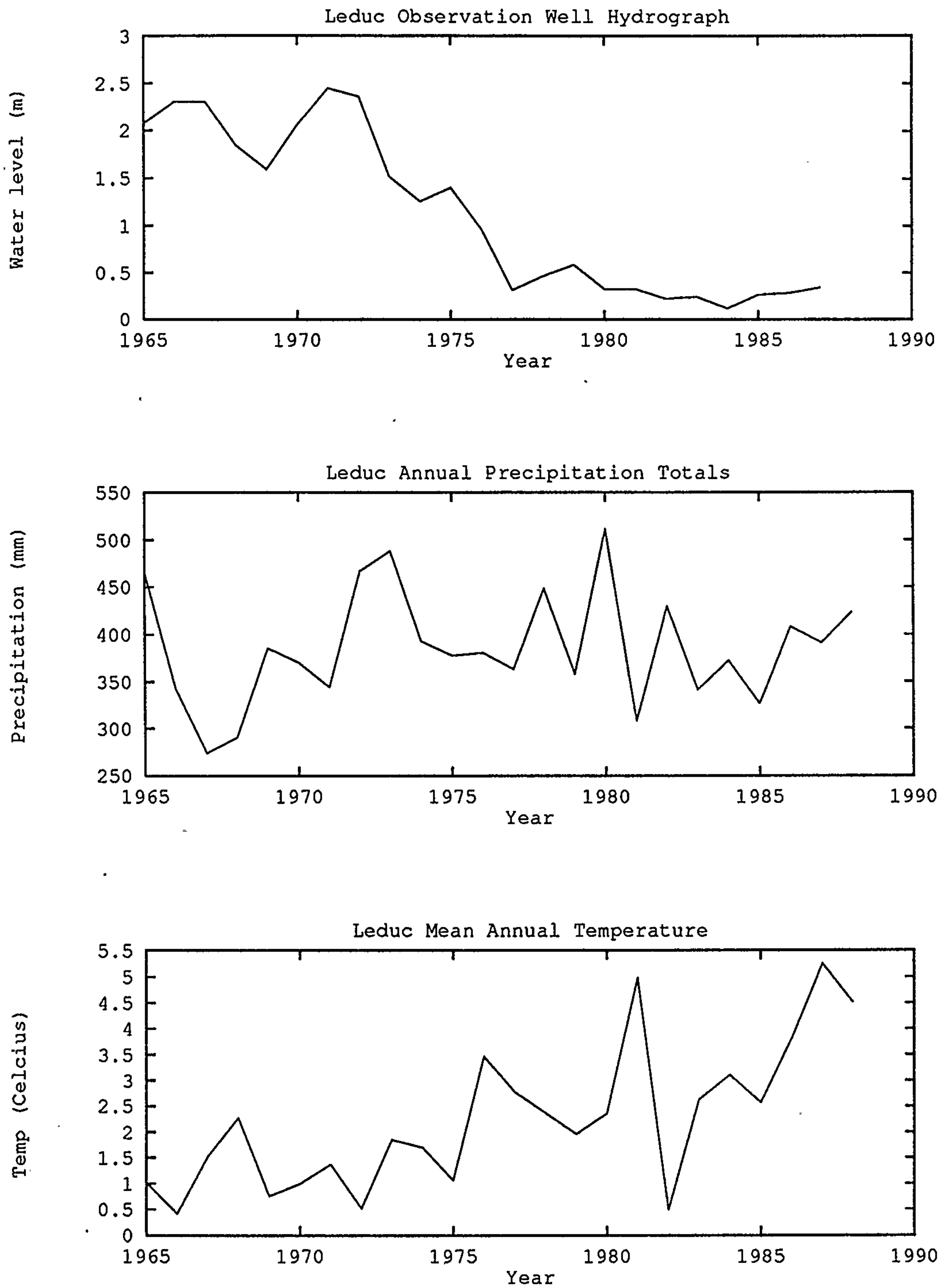
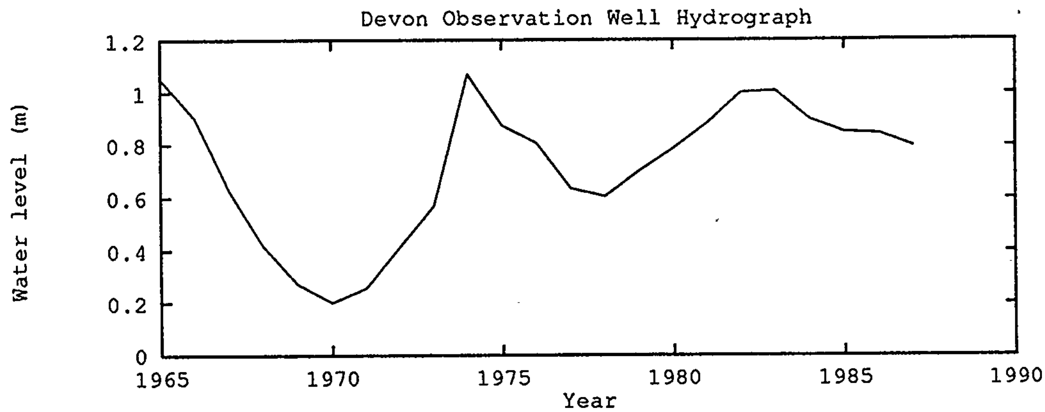
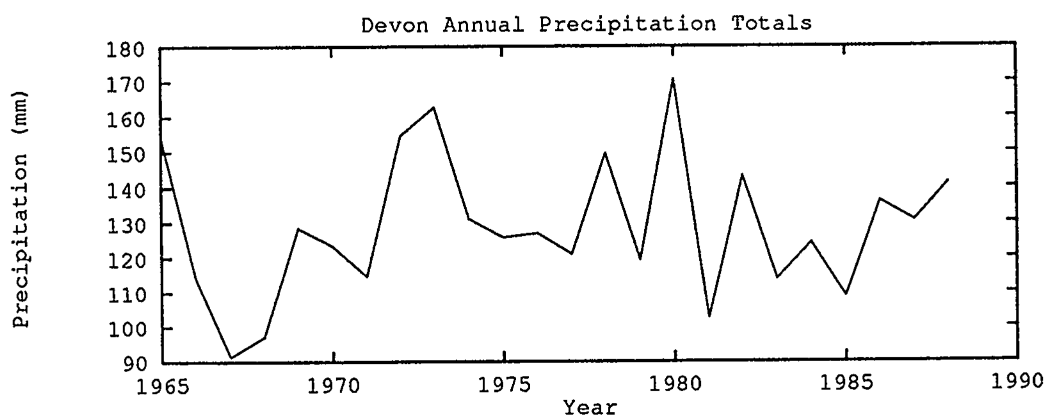


FIGURE 10

LEDUC SITE DATA PLOTS





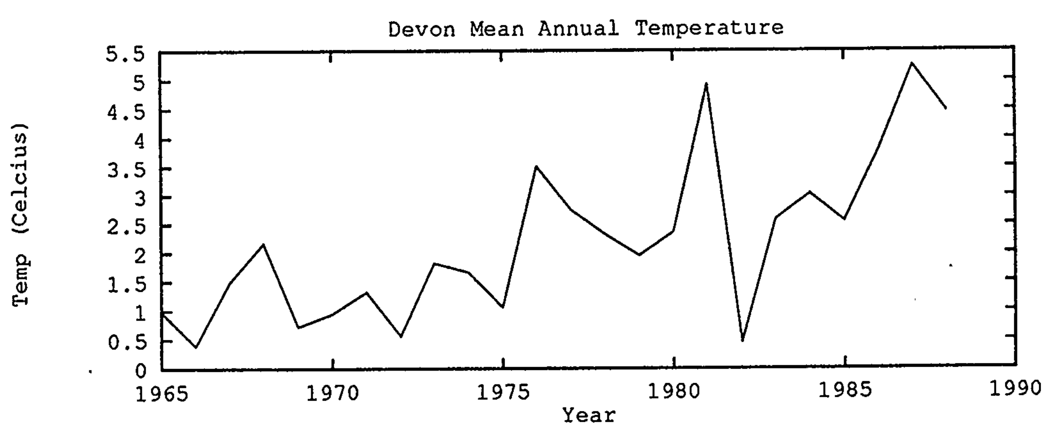


FIGURE 11

DEVON SIT DATA PLOTS

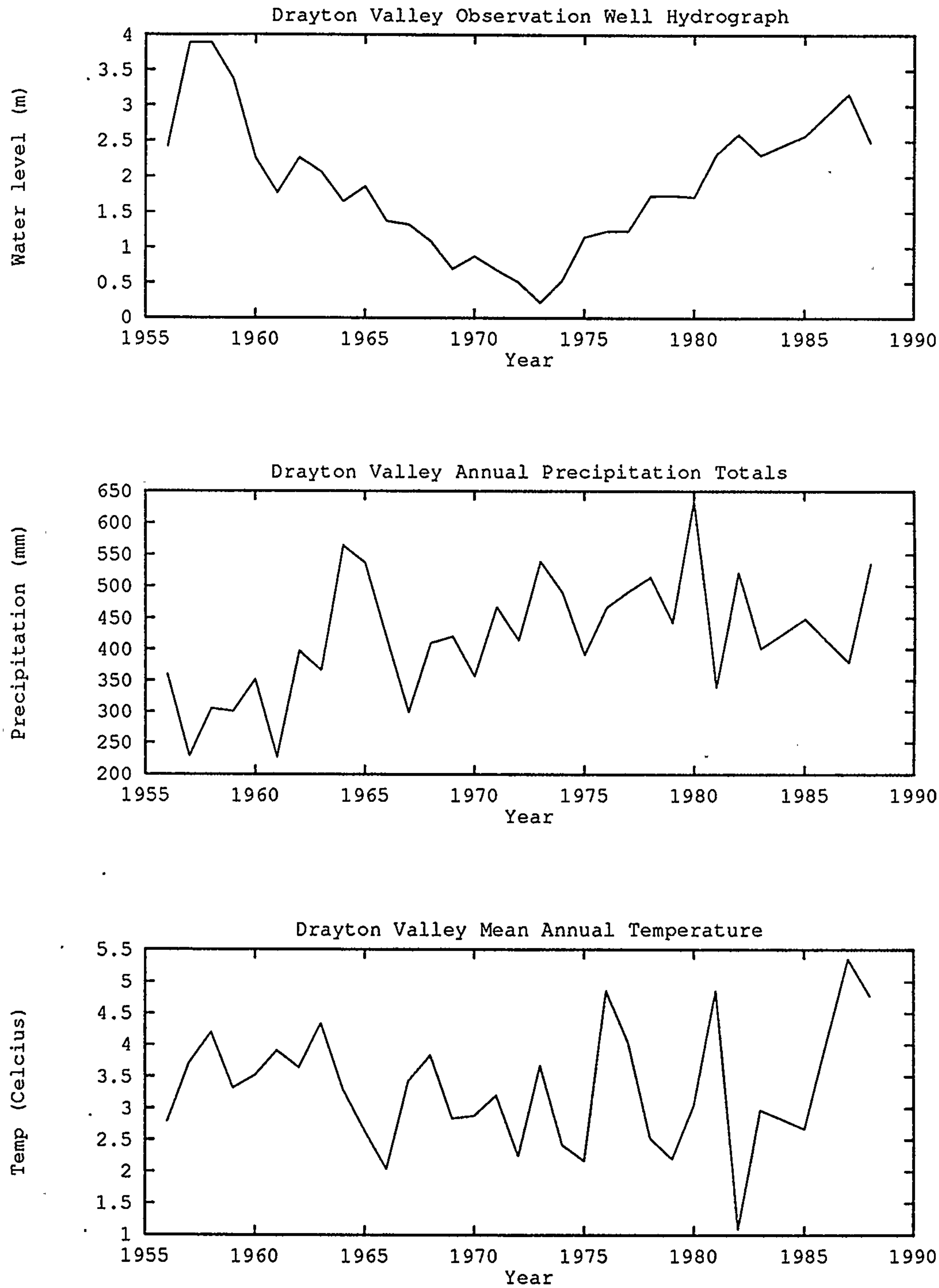
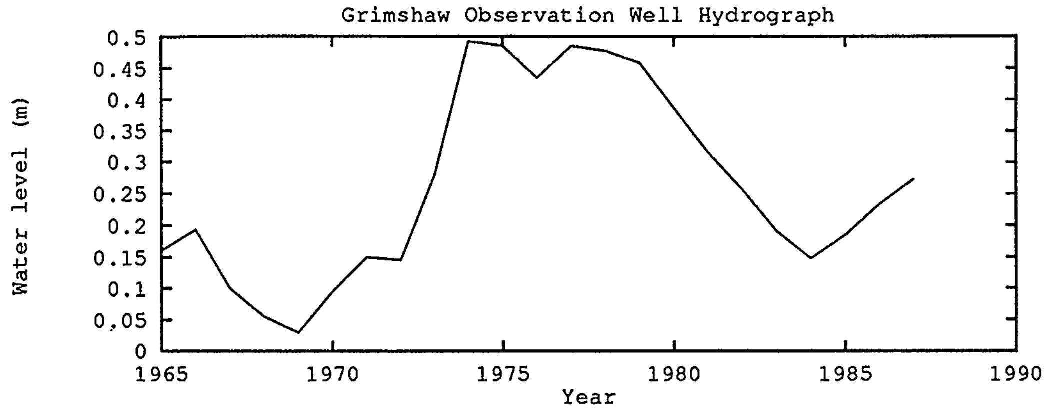
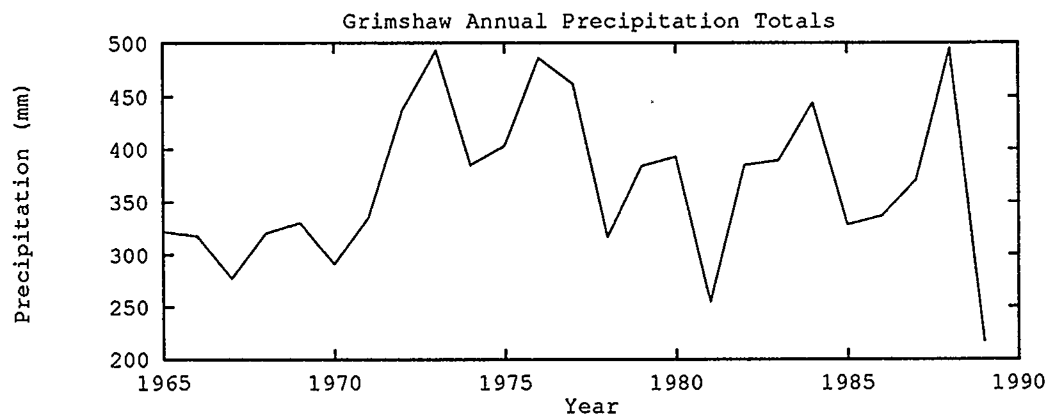


FIGURE 12

DRAYTON VALLEY SITE DATA PLOTS





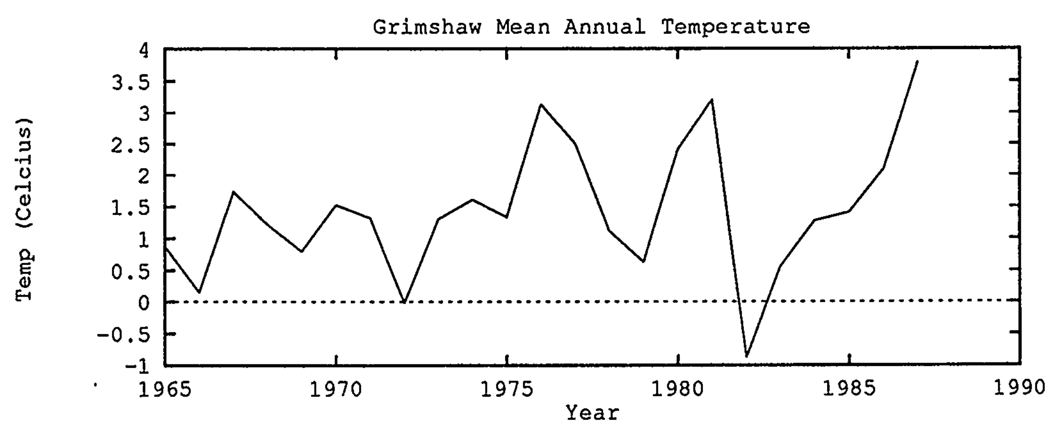


FIGURE 13

GRIMSHAW SITE DATA PLOTS

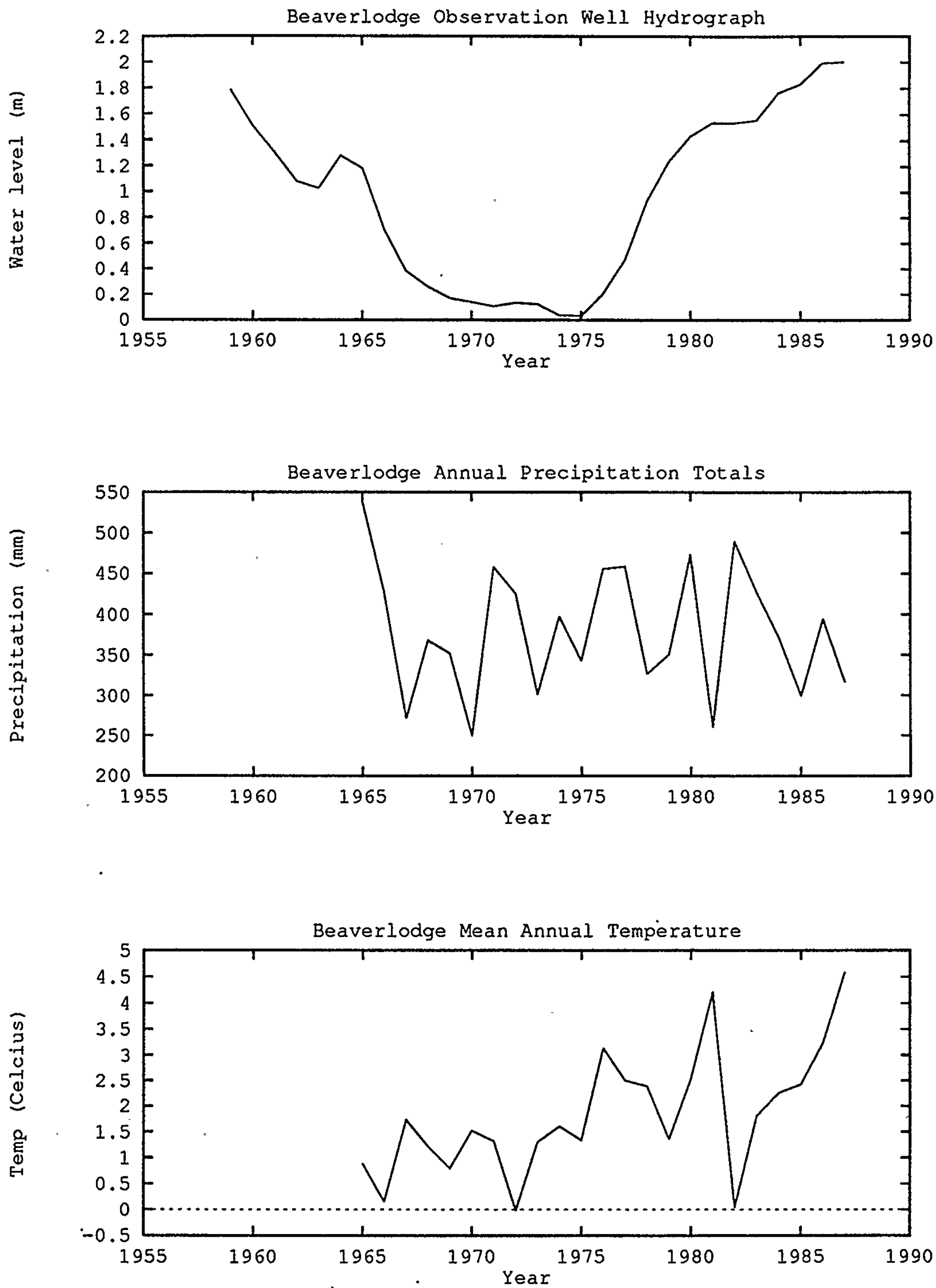


FIGURE 14

BEAVERLODGE SITE DATA PLOTS

TABLE 6

CORRELATION COEFFICIENTS OF WELL SITE DATA*

Well Site	PUMP Y N	LEVEL (r)	(sig)		PRECIP (r)	(sig)		TEMP (r)	(sig)	
Milk River	N	-.13	(.01)	S	.10	(.02)	S	.04	(.23)	S
Lethbridge	N	.87	(.00)	R	-.05	(.18)	F	.04	(.25)	S
Barons	Y	-.73	(.00)	S	-.03	(.33)	F	.08	(.17)	R
Elnora	N	.03	(.28)	S	.03	(.30)	S	.04	(.24)	S
Stettler (#6)	N	.91	(.00)	R	.07	(.07)	S	.01	(.41)	S
Stettler (137)	N	-.65	(.00)	S	See Above			See Above		
Leduc	Y	-.89	(.00)	S	.04	(.19)	S	.02	(.34)	R
Devon #2	Y	.34	(.00)	S	.02	(.37)	S	.09	(.07)	R
Drayton Valley	Y	-.15	(.00)	S	.30	(.00)	R	.01	(.45)	S
Grimshaw	Y	.33	(.00)	S	.00	(.49)	S	.04	(.27)	S
Beaverlodge	Y	.76	(.00)	S	-.02	(.37)	S	.08	(.10)	S

* Significance of correlation coefficient in parenthesis ()
Trend noted as (R)ising, (D)eclining, or (S)tationary

Long term well levels are steady or rising at the non pumped well sites. In the cases where well levels are rising, the long term trend in precipitation does not coincide, i.e., remains steady or is falling. This suggests that the present day climate regime is adequate to supply recharge to these groundwater systems. In the case of the large gains displayed at the Lethbridge site, irrigation waters may be contributing to a portion of the recharge.

Figures 15 and 16 show average monthly response of two wells to the annual precipitation cycle. The Milk River site (Figure 16) shows reasonable well level response to precipitation, with higher well levels recorded slightly prior to the seasonal peak in precipitation. The Beaverlodge site (Figure 17) is largely unresponsive to the annual precipitation cycle. These wells typify general aquifer response to the annual precipitation cycle; Milk River representing surficial type aquifers, Beaverlodge representing deep bedrock aquifers.

None of the well sites reported as being affected by nearby pumpage display a long term negative trend, nor do the corresponding precipitation regimes display rising trends. This might be interpreted as meaning longer term trends are responsible in greater part for controlling the shape of the well hydrograph, or that the recharge occurring to the groundwater system is sufficient to compensate for any pumpage taking place.

A positive correlation computed between water table elevation data and precipitation data indicates recharge is occurring to the saturated zone, or in terms of Freeze (1969), the discharge rate is exceeding the rate of evapotranspiration. Well response to climate fluctuations is revealed by lagged correlation analysis (Tables 7 and 8). In cases of quick well response to precipitation in a discharge zone as at Elnora and Devon, it is likely a local "mounding"

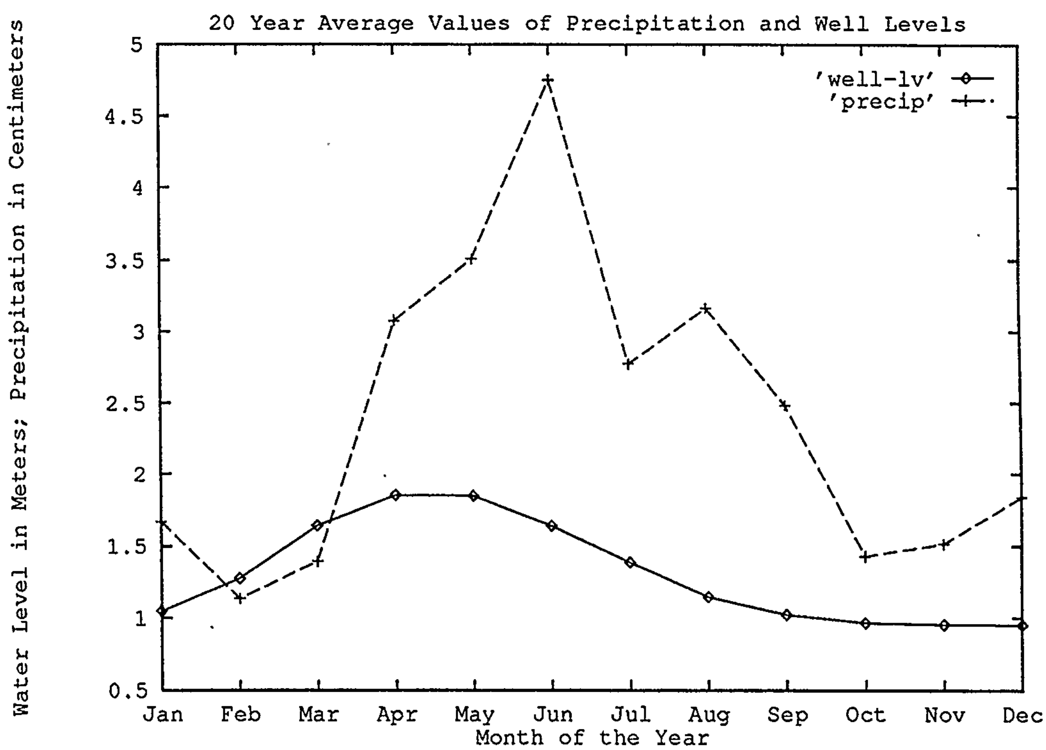


FIGURE 15

LONG TERM (20 YEAR) PLOT OF MONTHLY WELL AND PRECIPITATION DATA, MILK RIVER SITE

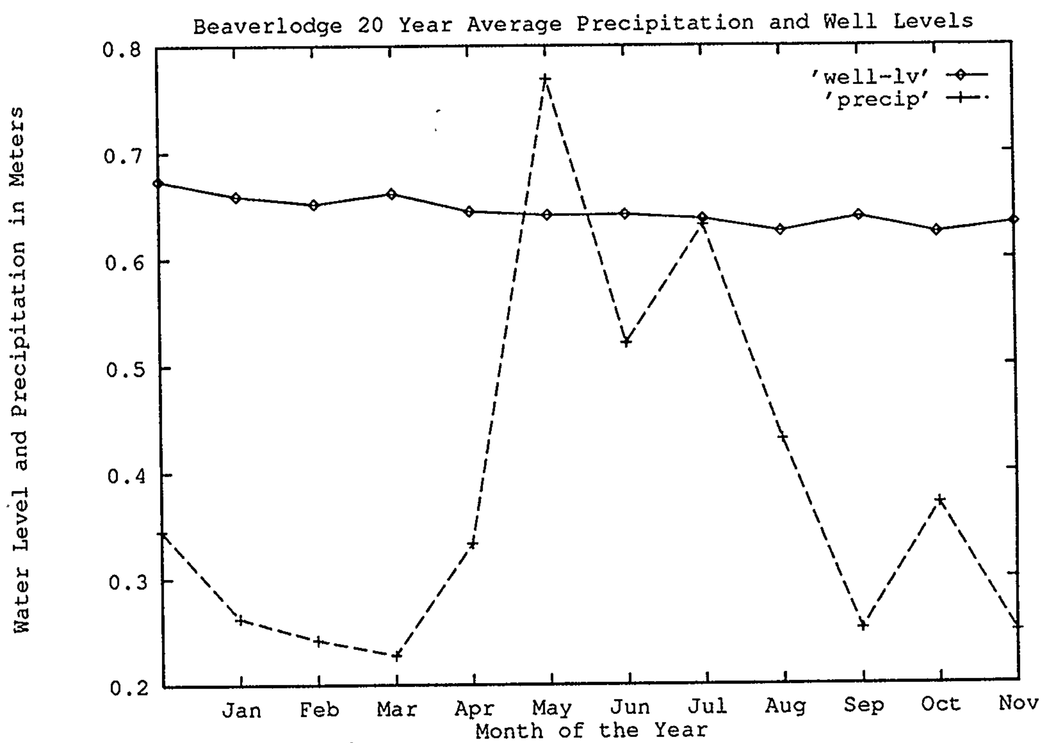


FIGURE 16

LONG TERM (20 YEAR) PLOT OF MONTHLY WELL AND PRECIPITATION DATA, BEAVERLODGE SITE of the water table is taking place (after Freeze, 1969). In the Milk River case, the lag period of 8 months required before response in the water table elevation is noted is probably attributable to the period of time required for water to move from the recharge to the discharge area, where the discharge rate then exceeds evapotranspiration rates, and a positive fluctuation is recorded. A negative correlation between water table levels and precipitation data (as at Drayton Valley) indicates that the rate of discharge is less than the rate of evaporation to the saturated zone.

TABLE 7

CROSS CORRELATION OF MONTHLY WELL AND PRECIPITATION DATA*

Well Site	**Lag Zero (Sig)**	**Max. Correlation (Sig)**
Milk River	0.23 (4.6)	0.29 @ 11 Months (5.9)
Lethbridge	-0.05 (-.94)	-0.06 @ -1 Months (-.99)
Barons	0.07 (.94)	0.13 @ 1 Months (1.7)
Elnora	0.19 (3.5)	0.20 @ 1 Months (3.7)
Stettler (#6)	0.04 (.69)	0.13 @ 5 Months (2.4)
Stettler (137)	0.03 (-.56)	0.03 @ 1 Months (-.56)
Leduc	-0.01 (-.28)	0.05 @ 3 Months (1.0)
Devon #2	0.19 (3.3)	0.23 @ -2 Months (4.1)
Drayton Valley	-0.24 (-4.7)	-0.25 @ -2 Months (-4.8)
Grimshaw	0.07 (1.3)	0.08 @ 1 Months (1.3)
Beaverlodge	0.02 (.31)	0.04 @ 5 Months (.70)

* Significance of correlation in parenthesis ().

TABLE 8

CROSS CORRELATION OF MONTHLY WELL AND TEMPERATURE DATA*

Well Site	Lag Zero (Sig)	Max. Correlation (Sig)
Milk River	0.04 (.79)	-0.43 @ 3 Months (-9.4)
Lethbridge	0.04 (.66)	0.04 @ 4 Months (.79)
Barons	-0.04 (-.56)	-0.09 @ 5 Months (-1.3)
Elnora	0.27 (5.0)	0.27 @ 0 Months (5.0)
Stettler (#6)	-0.04 (-.04)	-0.04 @ -1 Months (-.84)
Stettler (137)	0.04 (.79)	0.06 @ 2 Months (1.0)
Leduc	-0.01 (-.01)	0.08 @ 3 Months (1.5)
Devon #2	0.35 (6.3)	0.38 @ -1 Months (7.0)
Drayton Valley	0.02 (.47)	0.04 @ 2 Months (.70)
Grimshaw	0.07 (1.2)	0.08 @ 1 Months (1.4)
Beaverlodge	0.03 (.65)	0.04 @ 5 Months (.73)

* Significance of correlation in parenthesis ().

7.2 Results of Correlation Analysis

Examining the relationship of well level to precipitation events, Elnora and Devon show the strongest correlation (r=0.19), and the introduction of lag does little to improve correlation strength. Both wells are within shallow surficial sand aquifers, 5.2 and 7.6 meters deep respectively. The closeness of the water table to the surface may account for the higher correlation between levels and precipitation data through reduced time required for percolation to the water table. Milk River has similar aquifer characteristics, a well depth of 7.6 meters, but does not achieve a similar correlation response to precipitation until after a lag of 8 months. The eight month lag requirement is likely the result of the operation of a well defined recharge / discharge system. Correlations achieved by wells within discharge zones of surficial sand aquifers represent the highest achieved between simple well and precipitation data sequences.

Barons and Stettler #6 are both bedrock aquifer sites. Correlation is very low at lag zero, but rises to .11 and .12 respectively after a lag period is observed. Lags 1 and 6 months for the respective wells produce the highest correlation. The low correlations are valid in view of the persistent seasonality present in the cross correlation coefficient series (see Figure 17). The seasonal recurrence of the coefficients suggests the correlations are not due to chance. Time required for groundwater flow from the recharge to these discharge areas is certainly responsible for a portion of the lag. Stettler #6 is twice as deep, and leads to the conclusion that the longer lag period required at the Stettler site for the optimum response is due also to the increased percolation time inferred by the additional depth at this site.

Lethbridge, Stettler 1960-4, Grimshaw and Beaverlodge are similar in that they have very low correlation between water level data and precipitation data. Lagging does not improve correlation strength at these sites. These wells are

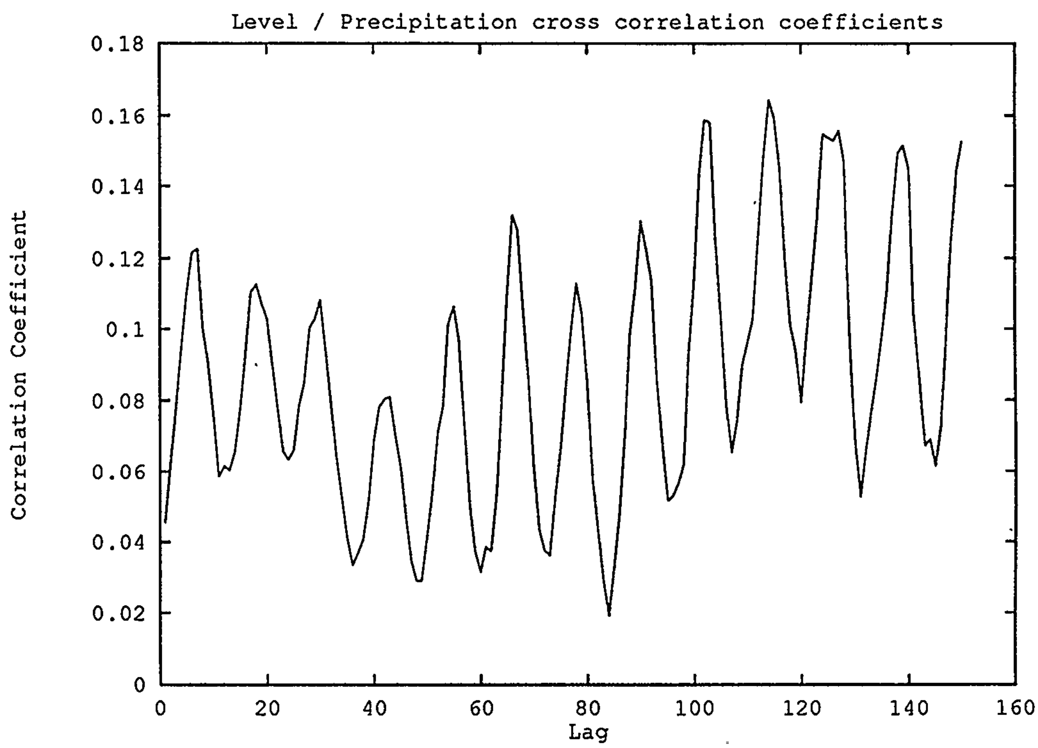


FIGURE 17

SEASONALITY DISPLAYED WITHIN CROSS CORRELATION COEFFICIENTS AT THE STETTLER SITE moderately deep bedrock wells with the exception of Grimshaw, which is a buried gravel aquifer. All wells are located at discharge zones. The extremely low correlations occurring at these well sites are likely due in part to depth, the presence of impermeable layers over the aquifer deposits and the distance of these sites from the recharge areas. Lethbridge can be further isolated as a unique case considering it is a surficial sand aquifer, and should respond in some fashion to precipitation. A possible explanation may lie in considering that the well receives recharge from an artesian source thereby forfeiting significant dependence on the local climatic regime. The depth (21 meters) at this site is also consistent with this theory. It will be discussed further on that water table fluctuations at these sites are dependent upon long term cycle activity in climatic data.

Drayton Valley displays an unusually high, negative correlation with precipitation data. As was discussed previously, classification of this site in terms of recharge / discharge area was not possible. Well 321 is a very deep well, located within Paskapoo Sandstone, but is also being affected by pumpage. Apart from this well being different from the other observation wells in the ways described, not enough is known of the aquifer system to conclude why the relationship between precipitation and water table elevation is negative.

The cross correlation coefficients contained in tabular form (Tables 7 and 8) are subjected to a K-means clustering analysis, the results presented in Table 9. In computing a cluster analysis, much subjectivity is avoided in determining groups or clusters of similar well site response based upon cross correlation characteristics. The inclusion of the lag time variable in the classification allows for the classification to be based partially upon recharge / discharge characteristics of the aquifer system. I.e., long lag periods hint at a recharge / discharge system of considerable geographic extent.

TABLE 9

CLUSTER ANALYSIS OF CROSS CORRELATION COEFFICIENTS FROM WELL AND PRECIPITATION DATA

WITH LAG

Cluster

1	2	3
103 136 341	109 117 131 137 153 159 339	321

WITHOUT LAG

Cluster

1	2	3	4
131 159	321	109 137 153 339 341	117 136 103

When clustering using the lag variable, wells belonging to cluster 1 represent those achieving maximum correlation at a lag of approximately 6 months. Cluster 2 wells achieve maximum lag around a lag of 1 month, and cluster 3 well shows a strong negative correlation. Geography, aquifer lithology, or geology does not seem to play a role in this cluster classification. Classification by k-means clustering (above) therefore groups the wells partially according the effect of lag. Care must be taken in using this approach however as low lag periods required for maximum correlation may lead to the conclusion that they have spatially limited recharge areas. In fact the opposite is probably true, owing to the depth and low correlation of the wells, it is possible that the wells are of an artesian nature. Proof of this is provided by examining the clustering without the lag variable. In the 3 cluster scheme, wells in cluster 1 represent the shallow surficial sand aquifers, cluster 3 wells the deeper, generally bedrock wells.

High correlations between water table elevation and temperature data are noted at Milk River, Elnora, and Devon. Again these surficial, shallow (not exceeding 7.6 meters in depth) sand aquifers produce the highest correlation coefficients among the observation wells (.43, .27, and .38). All correlation coefficients are positive, the highest computed correlation strength occurs almost immediately (within 2-3 months) in all cases. In terms of groundwater movement, evapotranspiration is exceeding discharge in the area. The immediate response of the water table to temperature suggests evapotranspiration (and [base]flow to streams) occurs in concert with temperature fluctuations at these sites. The positive correlation must be interpreted as a rise in the water table (discharge in keeping with the concept of the discharge area) occurring with evapotranspirative demand.

Wells remaining are deeper than 20 meters, and all wells have very low (near to zero) correlations with temperature data, and improve only slightly with the introduction of lag. It is therefore suggested that temperature, and the variable it represents, actual evapotranspiration, is not an effective driver for (immediate) discharge in deeper aquifer systems.

Table 10 presents results of the cluster analysis of the well data - temperature correlation coefficients :

TABLE 10

CLUSTER ANALYSIS OF WELL AND TEMPERATURE DATA CORRELATION COEFFICIENTS

(Lag variable used)

Cluster

1	2	3
103	137	117
131	153	136
159	321	109
	341	
	339	

Cluster analysis of the well data and temperature coefficients produce categories similar to those developed using the correlation coefficients derived from well data and precipitation (without consideration of the time lag variable.). Cluster 1 of the 3 cluster scheme (considering lag) again includes the shallow sand aquifers, cluster 2 contains deep bedrock wells, while cluster 3 contains moderately deep wells displaying very low correlation strength in these variables. Clusters 2 and 3 are also roughly distinguished on basis of their geographical location; approximately north and south for clusters 2 and 3 respectively.

On the basis of correlation between water table levels, precipitation and temperature data, it is possible to discuss two broad categories of well response :

1) Surficial (shallow) aquifer system response is characterized by moderate (.20 - .30) correlation strength between well levels and precipitation, at lags likely not exceeding 6 months; high correlation strength (.20 - .40) between well levels and temperature data at lags likely not exceeding 2 months.

2) Deep buried alluvial material aquifer and deep bedrock aquifer response is characterized by low (.05 - .10) correlation strength between well levels and precipitation, possibly improving to strengths near .15 - .20 after a lag likely not to exceed 6 months; very low correlation strengths (.00 - .04) between well levels and temperature improving only slightly at lags not exceeding 6 months.

7.3 Results of Harmonic and Factor Analysis

As the simple correlation does little to reveal the complex harmonic relationships which may exist within and between climate and groundwater, time series analysis was used to explore the harmonic structure of the data sets. Harmonic analysis was performed on all the available data (well levels, precipitation, and temperature) in monthly and annual resolutions. Using monthly and annual data, both short term (monthly) and long term (years) cycles are computed for comparison among the data sets. Periodograms generated from Milk River data are shown as an illustration in Figure 18. Table 11 summarizes dominant cycles appearing within all data sets based upon visual inspection of the periodograms.

In the monthly well level and monthly precipitation periodograms, the 1 year harmonic or cycle is noted as a dominant cycle. The one year dominant cycle is common in many natural systems, and, likely reflects the annual cycle of water availability characteristic of Alberta. The periodogram of precipitation data generated from annual data shows dominant peaks at 5.5 and 3.6 years.

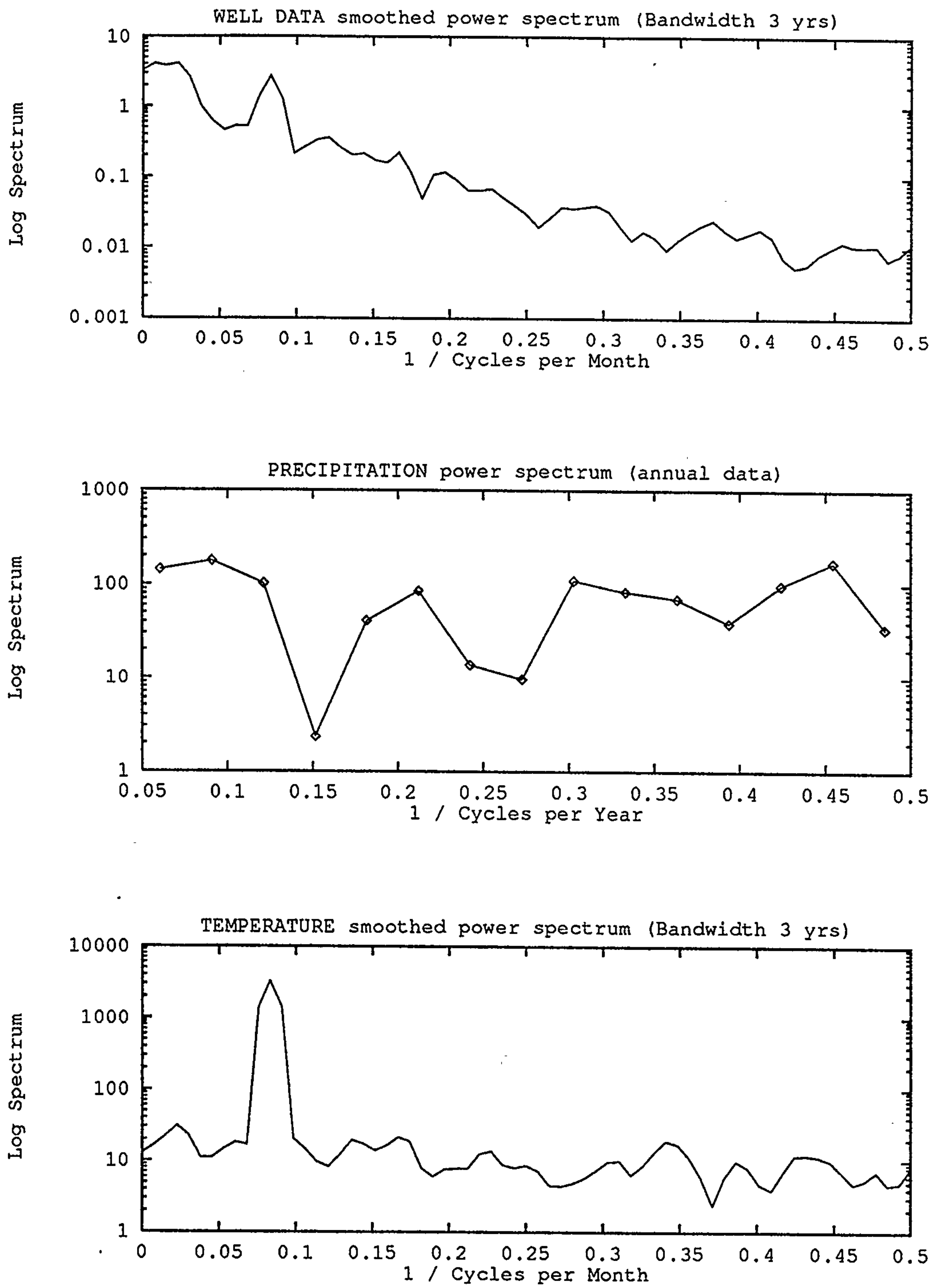


FIGURE 18

PERIODOGRAMS GENERATED FROM MILK RIVER SITE DATA

TABLE 11

DOMINANT HARMONIC CYCLES PRESENT WITHIN ANNUAL WELL, PRECIPITATION, AND TEMPERATURE DATA (Determined Through Visual Inspection)

Well Site	**Dominant Cycles (Years) from Visual Insp.** WELL	PRECIP	TEMP
Milk River	3.4	2.4	3.0
Lethbridge	3.0	14.3, 3.9, 3.0 2.4	14.3, 4.7, 3.6 2.5
Barons	3.5	2.8	6.9, 3.5
Elnora	11.8, 3.9, 3.0	12.5, 3.8, 2.5	5.9, 3.4, 2.6
Stettler #6	4.0, 2.9, 2.3	10, 5.1, 3.2	6.2, 3.2, 2.4
Stettler 137	6.9, 3.3, 2.6	See 136	See 136
Leduc	4.7, 3.6	8.0, 3.6, 2.2	8,4.7,3.6,2.5
Devon #2	8.0, 3.9, 2.8	8.1, 3.3,	5.9, 3.4,
Drayton Val.	6.3, 4.4, 3.2	4.4, 3.6, 2.2	8.0, 4.4, 3.1
Grimshaw	3.9, 2.6	6.1, 3.9, 2.6	6.1, 2.6
Beaverlodge	8.0, 2.6	5.9, 3.0	5.9, 3.4, 2.6

The modified Fisher's test of significance is used to determine if cycles present within the data set are significant or coincidental (could have arisen by chance) (Tables 12-14). Fisher testing harmonics extracted from observation well data reveal that none of the cycles extracted were significant at the 95 percent level other than cycles whose length approaches infinity (the portion of the data unresolveable into frequencies) and annual cycles within precipitation and temperature data at some sites. The small sample sizes used in generating the harmonics (length of record is less than 30 years at all sites) is believed responsible for the low significance of the generated cycles. It is logical to assume that cycles revealed in the data samples represent those present in the natural system, and that larger sample sizes would generate the same cycles at a higher significance. The representative nature, and the consistent appearance of certain cycles (as the annual and 3.6 year) make harmonic investigation of the data imperative.

TABLE 12

SIGNIFICANT HARMONICS WITHIN WELL DATA DETERMINED THROUGH THE USE OF A MODIFIED FISHER'S TEST OF SIGNIFICANCE

Well Site	**Significant Cycles at 95 % probability**
Milk River	Infinity.
Lethbridge	Infinity.
Barons	Infinity.
Elnora	Infinity.
Stettler (#6)	Infinity, 32 Years.
Stettler (137)	Infinity.
Leduc	Infinity, 33 Years.
Devon #2	Infinity.
Drayton Valley	Infinity, 31 Years.
Grimshaw	Infinity, 23 Years.
Beaverlodge	Infinity, 29 Years.

TABLE 13

SIGNIFICANT CYCLES WITHIN PRECIPITATION DATA DETERMINED THROUGH THE USE OF A MODIFIED FISHER'S TEST OF SIGNIFICANCE

Well Site	**Significant Cycles at 95 % probability**
Milk River	Infinity.
Lethbridge	Infinity.
Barons	Infinity.
Elnora	Infinity, 1 Year.
Stettler (#6)	Infinity, 1 Year.
Stettler (137)	(See Well 136)
Leduc	Infinity, 1 Year.
Devon #2	Infinity, 1 Year.
Drayton Valley	Infinity, 1 Year.
Grimshaw	Infinity.
Beaverlodge	Infinity.

TABLE 14

SIGNIFICANT CYCLES WITHIN TEMPERATURE DATA AS DETERMINED THROUGH THE USE OF A MODIFIED FISHER'S TEST OF SIGNIFICANCE

Well Site	**Significant Cycles at 95 % probability**
Milk River	1 Year.
Lethbridge	1 Year
Barons	1 Year.
Elnora	1 Year.
Stettler #6	1 Year.
Stettler (137)	1 Year.
Leduc	1 Year.
Devon #2	1 Year.
Drayton Valley	1 Year.
Grimshaw	1 Year.
Beaverlodge	1 Year.

The lithology / aquifer type of the observation wells is of two very general types : Surficial sand / gravel deposits, and sandstone / shale bedrock formations. Factor analysis of water table fluctuation data (Table 15) reveals that well site grouping based upon aquifer lithology is possible. Leduc, Stettler #6, and Beaverlodge are similar in their factor 1 loadings, and all monitor bedrock type aquifer formations. Elnora, Grimshaw, and Devon show loadings on factor 2, and are similar in that they monitor unconsolidated sands or gravels.

Lethbridge, Milk River, and Devon are all surficial sand aquifers, and load on factor 3.

TABLE 15

SORTED ROTATED FACTOR LOADINGS
(Factor analysis based on observation well data)

Well Site	FACTOR 1 (Bedrock)	FACTOR 2 (Sand / Gra.)	FACTOR 3 (Sand)
Leduc	-0.927	0.000	0.000
Stettler	0.911	0.000	0.000
Beaverlodge	0.868	0.000	0.000
Lethbridge	0.785	0.000	-0.335
Elnora	0.000	0.871	0.000
Grimshaw	0.290	0.789	0.000
Milk River	0.000	0.000	0.831
Devon	0.418	0.387	0.598

An initial well site distinction can be made based upon factor loadings of water table fluctuation data. Barons, Stettler 1960-4, and Drayton Valley were not included in the factor analysis as data was missing from these sites. It can be assumed however, that the behaviour of these wells would be consistent with wells of similar lithology. In keeping with the factor analysis, these wells would be expected to behave as bedrock type aquifers.

Factor analysis was used to establish rough groupings of cyclical behaviour within water table elevation data according to well site. Factor analysis was performed using harmonics extracted from 8 well sites for which there was complete data. The first harmonic (harmonic zero) was removed from the matrix prior to performing factor analysis thus removing the overwhelming effect of that harmonic and providing for better factor separation. The sorted factor loadings suggest two groupings of wells based upon the harmonics : Beaverlodge, Leduc, Stettler, and Grimshaw; Lethbridge, Devon, Milk River, and Elnora (see Table 16).

TABLE 16

SORTED ROTATED FACTOR LOADINGS
(Factor analysis based on observation well harmonics)

Well Site	FACTOR 1	FACTOR 2
Beaverlodge	0.995	0.000
Leduc	0.993	0.000
Stettler	0.965	0.000
Grimshaw	0.961	0.000
Lethbridge	0.945	0.298
Devon	0.750	0.570
Milk River	0.000	0.922
Elnora	0.372	0.875

The division of wells suggests a north-south provincial split (although Leduc and Devon lie within a few degrees of one another). The split may also be viewed upon the basis of aquifer lithology, the wells loading upon factor 2 are all surficial sand aquifers. Interestingly, well 109 (Lethbridge) which was unique in its insensitivity to simple climate data being a surficial sand aquifer, is now classified with the remaining surficial sand aquifers. This may offer further evidence of the artesian nature of this aquifer, as the harmonic response is deemed similar to the other surficial sand aquifers.

Factor analysis is performed both upon the climate data sequences drawn from each well site, and upon their corresponding harmonic series. This will allow for the similarities in factor loadings (using well data and climate data) to be evaluated. The precipitation data subjected to factor analysis results in the following groupings : Leduc, Devon, Grimshaw, and Beaverlodge; Stettler #6, Elnora, Milk River, and Lethbridge (see Table 17).

TABLE 17

SORTED ROTATED FACTOR LOADINGS
(Factor analysis based on precipitation data)

Well Site	FACTOR 1	FACTOR 2
Leduc	0.906	0.000
Devon	0.903	0.253
Grimshaw	0.812	0.000
Beaverlodge	0.804	0.000
Stettler	0.797	0.381
Elnora	0.742	0.480
Milk River	0.000	0.928
Lethbridge	0.000	0.914

The benefit of performing harmonic analysis with the precipitation variable in light of relatively poor results obtained using correlation is immediately evident. A clear distinction is drawn in the factor loadings making discussion in terms of well site behaviour possible.

The factor separation is almost certainly based upon geography, as a sharp north-south provincial split is indicated. Of note also that there is a great similarity in the factor loadings of precipitation and of well level harmonics (not raw well levels). Such similarity suggests that cyclical behaviour taking place within observation wells may be characterized according to broad provincial precipitation regime.

Factor analysis of the harmonics computed from the precipitation data sequences show the following divisions : Devon, Leduc, Stettler, Grimshaw, Elnora, and Beaverlodge; Lethbridge and Milk River. Factor loadings using harmonic data again suggest a north-south provincial split, with only the very southward wells forming a category (see Table 18).

TABLE 18

SORTED ROTATED FACTOR LOADINGS
(Factor analysis based on precipitation data harmonics)

Well Site	FACTOR 1	FACTOR 2
Devon	0.966	0.000
Leduc	0.963	0.000
Stettler	0.939	0.000
Grimshaw	0.893	0.000
Elnora	0.875	0.000
Beaverlodge	0.852	0.000
Lethbridge	0.000	0.888
Milk River	0.000	0.874

Factor analysis of temperature data and harmonics derived from temperature data results in loadings upon a singular factor, and thus little distinction can be drawn on a provincial basis using factor analysis.

Considerable similarity exists in the factor loadings of well level harmonics and factor loadings of raw precipitation data. Examination of factor loadings in this fashion has thus enabled rough categorization of well harmonic response on the basis of geographical precipitation regime. (north or south). It is therefore logical to state that the broad harmonic structure and characteristics present within well data are influenced in large part by the harmonic structure and characteristics of the precipitation regime in the local area.

7.4 Harmonic Cycling

Cycles of lengths from between 2 months to approximately 12 years were examined from the data sets. Arbitrary frequency bands are discussed :

The 2.0 - 2.9 Year Frequency Bands :

The 2.0 - 2.9 year frequency band is proven significant by frequent and widespread geographic occurrence. Similar cycle length is reported to exist within African rainfall by Rhode and Virji, (1976), Kraus (1976), Klaus (1978) and Ogallo, (1979). Similar fluctuations are noted in the spectra of Indian (Jagganathan and Parthasarathy, 1973); Jagganathan and Bhalme, 1973; Parthasarathy and Dhar, 1974, 1976; Bhalme, 1975; Bhalme and Mooley, 1980), Californian

(Granger, 1977), Central American-Carribean (Hastenrath and Kaczmarczyki, 1981), Brazilian (Kousky and Chu, 1978) and English (Tabony, 1979) rainfall series. Higher spectral density in this frequency band is noted within temperature and precipitation records for most of the well sites, and within well data at about half of the well sites (Table 11). It is also noted that the 2.0 - 2.9 year frequency band within well data is occurring mostly within deep aquifers, shallowest being Beaverlodge (35 meters). Oladipo (1987) states the cause(s) of this quasi 2 year oscillation is still unclear, but that it is generally recognized as a pulsation of the general atmospheric circulation with particular relation to reversals in the tropical stratospheric winds. Oladipo (1987) also suggests the oscillation is related to large flux variation of the ultraviolet emission from the sun because the neutrino flux from the sun has been shown by Sakurai (1981) to vary with a period almost equal to 26 months.

It is unclear why the deeper wells appear to support oscillations in water table level of this frequency. Discounting pulsations in the atmospheric circulation for the moment, it is logical to speculate that deeper aquifers have larger water volumes and greater geographic extent, and will therefore respond to changes in pore volume and gravitation brought about by the orbit of astronomical bodies as the sun and moon. Deeper (non-surficial) wells are more likely to develop and maintain an artesian recharge / discharge system.

Pulsations in the atmospheric circulation are more likely to affect an artesian groundwater aquifer through pressure changes as the aquifer more closely approximates a "closed" system.

The 3.0 - 3.9 Year Frequency Bands :

The 3.0 - 3.9 year frequency band is represented at most sites within all data sets. Included in this frequency band is the 3.6 year frequency which was found to be a dominant cycle (with significant predictive power) in many well sites. The significance of the 3.0 - 3.9 year cycle is as yet unknown. Oladipo (1987) suggests it to be close to the first modal peak of the Southern Oscillation, and therefore would infer persistence of large-scale atmospheric pressure patterns during dry / wet conditions.

The 5.0 - 5.9 Year Frequency Bands :

The 5.0 - 5.9 year frequency bands appear in few of the data sets and are limited to climate data. A 5 year oscillation in rainfall in Indian, Indonesian, African, and South American rainfall series have been verified (Oladipo, 1987).

Dominant cycles extracted from the monthly data sets (well levels, precipitation, and temperature) range from 2.6 - 12.6 years. Cycle resolution of harmonics derived from monthly data is limited to 1 month.

7.5 Explaining Cycle Occurrence

To explain the occurrence of cycles within observation well data, climate data may be examined for the presence or absence of similar dominant cycles as those computed within well data. One such means of evaluating the similarity of cycle pattern belonging to well data and climate data is to cross correlate the power spectra cycles from each data set. Doing this results in near perfect correlations (.95 - .99) being computed at lag zero. An examination of the data sets being correlated quickly provides explanation for the high correlation. Within the harmonic series from each data set, the first harmonic (harmonic 0) tends to contain a very large portion of the variance within the series, while the actual cycles account for considerably less of the total variance. Thus correlating two "lopsided" data sets results in the very high (and meaningless) correlations. Recognizing this, the first harmonic was removed from the series of harmonic cycles and cross correlation again performed. The result is a truer indication of the similarity in cyclical pattern of the data sets, and considerably lower correlation coefficients result. Correlation coefficients are quite low for all sets correlated (.1 - .2). It is therefore concluded that the harmonic structural pattern within climate data is not imitated within well level fluctuations, but in light of similar factor loadings, the collective structure is deemed similar between precipitation and well level fluctuation harmonic structure.

I.e., the co-occurrence of 1 or two cycles within the power spectra of precipitation and well fluctuation data may be enough to classify them in similar fashion when factor analysis is used. The existence of a dominant cycle within both periodograms may also suggests that one is dependent upon the other.

The time series were divided into 3 segments and Fourier analysis performed on each portion. In doing so, it was possible to examine the changing harmonic structure of the series through time. It was revealed at most sites that the harmonic structure of the time series was dynamic through time, and that certain cycles in particular displayed considerable variability in the amount of spectral density they owned in terms of the power spectrum. Table 19 illustrates the change in spectral density within the 3.6 year cycle at the Milk River site, at the expense of the annual cycle :

TABLE 19

SELECTED FREQUENCY BANDS FROM POWER SPECTRA OF WELL LEVELS AT MILK RIVER

Time Period	Frequency	% Variance Explained
1957-1971	3.6 Years 1.0 Years	1.1 6.4
1964-1978	3.6 Years 1.0 Years	2.9 5.3
1974-1988	3.6 Years 1.0 Years	9.4 1.2

The unusual behaviour of the 3.6 year cycle might lend credibility to the notion of an ENSO association with the 3.6 year cycle (Oladipo, 1987). ENSO events during the last decade were some of the strongest observed (WMO, 1986).

A more direct means of examining the behaviour of a particular frequency band within the data is provided for by the computation of the log gain.

7.6 GAIN - Complex Demodulation

To this point, discussion has focused upon the similarity of well data and harmonics occurring within well data and climate data as a culmination of data time period. i.e., the idea of the "dynamic cycle" has not been discussed. In terms of a dynamic cycle, a cycle goes through stages of potential. In simple terms, the cycle can be described as having a crest, a trough, and an origin, or point at which the amplitude of the wave form is equal to zero. In terms of this study, the concept of wave form in terms of hydrologic balance must be described.

Using the idea of temperature for any given site, it is likely that the 1 year cycle will be the dominant cycle, and will represent a large portion of the explained variance within the data set. This is conceptually easy to understand in terms of Alberta's climate as the seasons bring about a somewhat constant pattern in temperature variation; temperature from one year to the next can be determined in large part through use of the annual temperature cycle. The annual (and other) cycles must not be thought of as being static in time. At any given point in time, the annual gain cycle can account for different proportions of the explained variance within the series of computed harmonics. The changing portion of variance accounted for by a harmonic frequency is referred to as the GAIN of that cycle. It can be useful to compute the gain of a cycle over the length of data record, noting when cycle achieves the highest gain, or accounts for greater portions of variance of the harmonic series (at that moment in time.). Similar response may then be looked for within water table fluctuation. The closer the covariance of gain cycles between time series, the safer it is to assume that one cycle influences the status of the other. Using this approach, the effectiveness of a single (climate) cycle upon water table fluctuation will be examined.

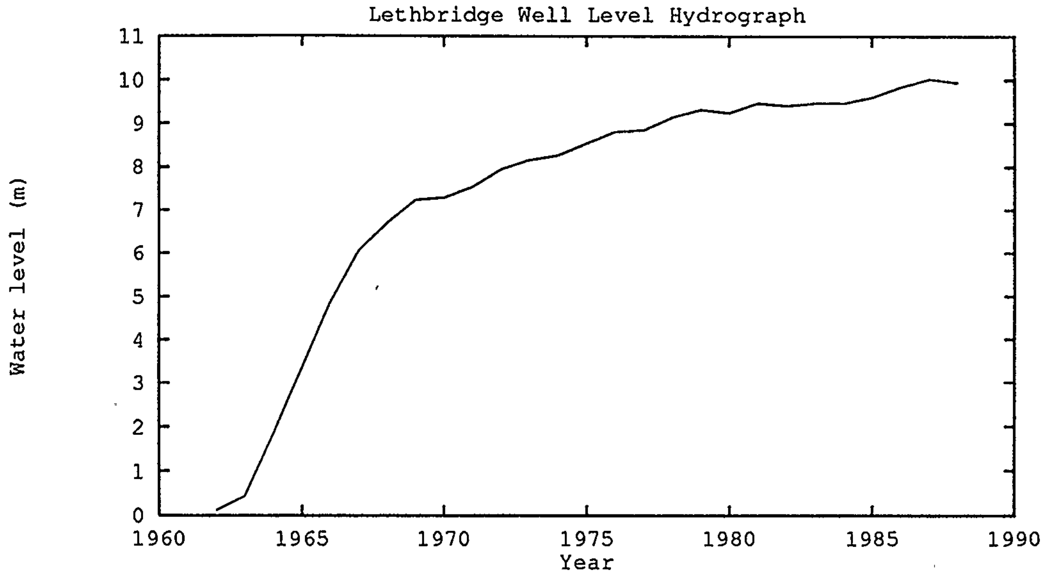
The log gain may be calculated for any valid cycle length occurring within the data set, but for practicality, only certain cycles have been "extracted" as gain sequences. Examination of the dominant cycles within the harmonic series (Table 11) is used to select those cycles which may be of interest to analyze in this fashion.

It was decided to extract annual and 3.6 year cycles from the available data sequences owing to the appearance of these cycles within several well site data sequences. Cross correlation has been used to evaluate the similarity of cycle gain (mainly the annual and 3.6 year) occurring within water table elevation fluctuations and climatic parameters. The premise is that a groundwater aquifer being influenced by a long term cycle within precipitation for example, should manifest a cycle of similar length to that suspected to be active within the precipitation data, and that the cycles themselves should display a certain degree of similarity in terms of spectral density variation through time. "Raw" well data representing water table fluctuation has also been cross correlated with selected (climate) cycle extractions. Correlating these two data sequences is slightly different in concept. High correlations between the two data sets represent a maxima in water table response occurring at points where the cycle being examined is also at a maxima (highest or lowest point). This technique thus provides a means of measuring the effectiveness a particular cycle length has upon simple water table fluctuations. Results obtained from this procedure will be similar to those obtained through the correlation of gain cycles from both data sequences, but the meaning of the results is different for both cases.

Cross correlating a cycle's gain with the source data set provides a very direct means of determining the significance of selected cycle lengths to the expression of well data. For example, Lethbridge well data and the 3.6 year gain cycle correlate almost perfectly (Table 31). Well levels at this site are therefore directly tied to the spectral density status of the 3.6 year cycle. Further research is then required to determine the source(s) of the 3.6 year cycle within the well data. Climate and temperature data are naturally turned to for explanation. Figure 19 illustrates the remarkable similarity in shape of the Lethbridge well level hydrograph to the 3.6 year gain cycle.

Interpretation of the correlation coefficients derived from gain cycles shall proceed as follows : When considering the positive correlation between raw well levels and a gain variable sequence, higher spectral density, (times when the cycle in question accounts for more of the explained variance within its harmonic set) results in the positive fluctuation of the water table through activity of the variable from which the gain is drawn, or feedback mechanisms to other variables resulting from the varying spectral density of the variable in question. A negative correlation is indicative of either a natural negative feedback mechanism, or an out of phase relationship which may be correctly and properly defined as a negative feedback mechanism.

Positive correlations derived from the cross correlation of gain cycles from water table elevation data and climate data are interpreted as measures of similarity which may exist within cycles of similar length within the data sets. This is drawn from consideration of the physical relationship where positive correlation between gain cycles is a measure of the covariance in that cycle length between well and climate data.



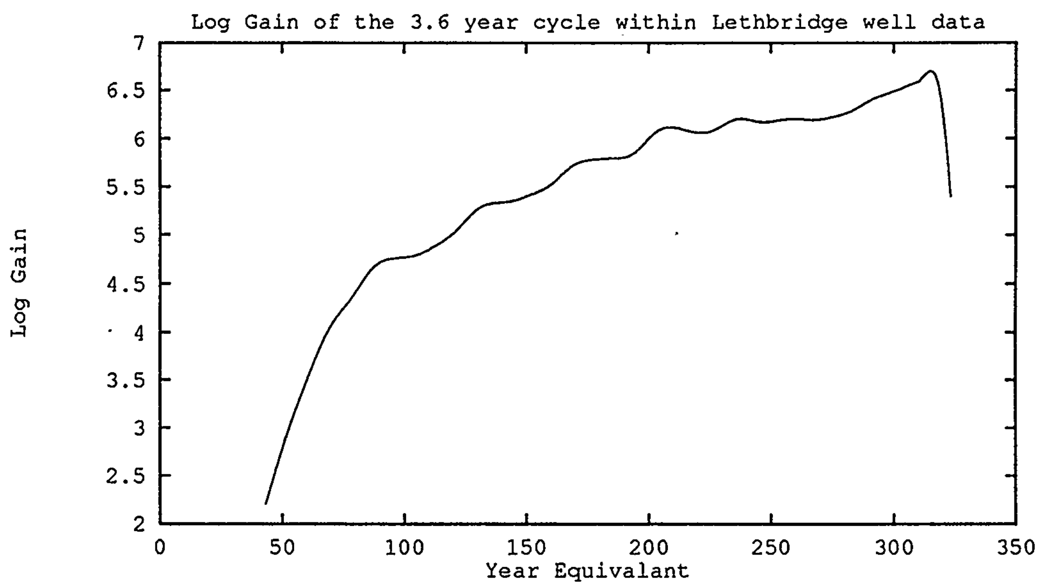


FIGURE 19

VISUAL COMPARISON OF THE LETHBRIDGE SITE WELL HYDROGRAPH AND LOG GAIN OF THE 3.6 YEAR CYCLE

Negative correlations between these two variables suggests an out of phase relationship and the usual implications.

The need for the introduction of time lag to the analysis to produce the highest correlation is a measure of system responsiveness, and an indirect means of measuring system inertia.

7.6.1 Complex Demodulation of Annual Cycles

Cluster analysis of the cross correlation coefficients generated from well data and the annual gain cycles originating from that data indicate a geographic clustering influence is present.

Barons, Elnora, Stettler #6, and Leduc display the highest correlation between raw well data and the annual gain cycle (r= .46 - .73) see Table 20. These wells also form a singular cluster in the 3 cluster scheme when the lag variable is not considered (Table 21). Geographically, this collection of wells represents those centrally located among the set of observation wells, and represent a mixture of aquifer lithology types. Grimshaw and Beaverlodge represent a moderate correlation (.24 - .43) and are both located in the northern portion of the province. The remaining sites, Milk River, Lethbridge, Stettler 1960-4 and Drayton Valley have low correlations (-.07 - .30) and excepting well 321 (Drayton Valley) are located in the southern portion of the province. The lower correlation wells again form separate clusters.

Lagging typically improves the correlation, the maximum strength being computed around 6 months of lag. It will be illustrated later on in this discussion that in general, those wells having a lower correlation (between the annual gain in the well level data and well data) show higher correlations using longer term cycle data.

In the cluster analysis where lag is ignored, cluster 3 represents the well sites for which there is very low correlation.

TABLE 20

CROSS CORRELATION OF ANNUAL GAIN CYCLE DATA FROM WELL LEVELS, AND RAW WELL DATA

Well Site	Lag Zero	Max. Correlation (@ Lag)
Milk River	0.14	0.38 @ 9 Months
Lethbridge	0.07	0.07 @ 0 Months
Barons	0.67	0.73 @ 4 Months
Elnora	0.48	0.59 @ 9 Months
Stettler (#6)	0.46	0.58 @ 1.3 Years
Stettler (137)	0.01	-0.12 @ 7 Months
Leduc	0.47	0.47 @ 0 Months
Devon #2	-0.07	-0.31 @ -2.4 Years
Drayton Valley	0.16	0.30 @ 1.0 Years
Grimshaw	0.24	0.43 @ 1.6 Years
Beaverlodge	0.30	0.30 @ 0 Months

TABLE 21

CLUSTER ANALYSIS OF CROSS CORRELATION COEFFICIENTS FROM ANNUAL WELL LEVEL GAIN CYCLES, AND WELL LEVELS

WITH LAG

Cluster

1	2	3
103 136 321 339	117 153 131	137 159 341 109

WITHOUT LAG

Cluster

1	2	3
117 131 136 153	109 321 339 341	137 159

1 Year Complex Demodulation using Precipitation Data

Cross correlation and cluster analysis performed using well and precipitation cycle data is summarized in Tables 22 - 26.

TABLE 22

CROSS CORRELATION OF ANNUAL GAIN CYCLES FROM WELL AND PRECIPITATION DATA

Well Site	Lag Zero	Max. Correlation (@ Lag)
Milk River	0.23	0.27 @ -5 Months
Lethbridge	-0.05	-0.05 @ 0 Months
Barons	0.16	0.23 @ 2 Months
Elnora	-0.32	-0.35 @ 8 Months
Stettler (#6)	0.18	0.54 @ -1.8 Years
Stettler (137)	0.02	0.31 @ 2.3 Years
Leduc	0.05	0.09 @ - 3 Months
Devon #2	-0.01	-0.03 @ 4 Months
Drayton Valley	0.12	0.23 @ 10 Months
Grimshaw	0.08	0.44 @ 2.2 Years
Beaverlodge	0.86	0.87 @ 3 Months

TABLE 23

CLUSTER ANALYSIS OF RAW WELL DATA AND PRECIPITATION ANNUAL GAIN CROSS CORRELATION COEFFICIENTS

WITH LAG

Cluster

1	2	3	4
159 339	321	131 137 153 109	117 136 341 103

WITHOUT LAG

Cluster

1	2	3	4
103 136 339 341	131 321	117 159	137 153 109

TABLE 24

CROSS CORRELATION OF PRECIPITATION ANNUAL GAIN, AND RAW WELL DATA

Well Site	Lag Zero	Max. Correlation	(@ Lag)
Milk River	0.31	0.35 @	4 Months
Lethbridge	-0.38	-0.41 @	6 Months
Barons	-0.02	0.09 @	4 Months
Elnora	-0.16	-0.25 @	6 Months
Stettler (#6)	0.46	0.58 @	1.3 Years
Stettler (137)	-0.41	-0.41 @	0 Months
Leduc	-0.60	-0.60 @	0 Months
Devon #2	0.13	0.49 @	2 Years
Drayton Valley	-0.33	-0.44 @	3 Years
Grimshaw	0.30	0.70 @	2.6 Years
Beaverlodge	0.29	0.40 @	1.3 Years

TABLE 25

CLUSTER ANALYSIS OF ANNUAL GAIN CYCLES CROSS CORRELATION COEFFICIENTS FROM WELL AND PRECIPITATION DATA
(Lag variable used)

2 Clusters

1	2
131 137 159 321 339 109 153 117	136 341 103

3 Clusters

1	2	3
131 137 159 321 339	341	117 136 153 103 109

4 Clusters

1	2	3	4
341	117 136 153 103	137 321 339	159 131 109

TABLE 26

CLUSTER ANALYSIS OF ANNUAL GAIN CYCLES CROSS CORRELATION COEFFICIENTS FROM WELL AND PRECIPITATION DATA (Lag variable NOT used)

2 Clusters

1	2
103 136 339 341	109 117 131 153 159 321 137

3 Clusters

1	2	3
341	109 131 153 159	136 137 339 103 117 321

4 Clusters

1	2	3	4
341	109 153 159	136 137 339 103 117 321	131

Cluster analysis of the correlation coefficients derived from annual gain cycles in consideration of the lag time variable (Table 25) hints at geographic selectivity. The remaining clustering schemes show little significant clustering attribute. The 4 cluster scheme accomplishes a rough north-south sorting of well sites, clusters 1 and 3 representing predominantly northern well sites, clusters 2 and 4 southern wells. When the lag variable is not considered as part of the classification, the 4 cluster scheme does not show geographic specialization. Cluster 2 is found to represent those wells of nil or minimal correlation, and calls into question the strength of the annual cycle within the well data series. Such low correlation strength may be indicative of artesian characteristics at these well sites. Cluster 3 wells represent those providing a moderate strength of correlation between the gain cycle data sequences. The positive correlations indicate similar response in the spectral density of the annual gain cycle in both data sets, and provide basis for establishing the dependence of water table elevations on the annual precipitation regime. Beaverlodge, the sole member of cluster 3 shows a rapid and high correlation between the gain cycles, and leads to the conclusion the annual gain cycle density is similar, and therefore influenced by the precipitation regime. Elnora displays a significant negative correlation between the gain variables and therefore suggests an out of phase relationship.

The geographic clustering noted as lag is considered in the clustering scheme outlines the effect upon the relationship between annual gain cycles of precipitation and well level geography has.

1 Year Complex Demodulation using Temperature Data

Temperature data is examined in the same fashion. The cross correlation coefficients and cluster analysis are shown.

TABLE 27

CROSS CORRELATION OF ANNUAL GAIN CYCLES
FROM TEMPERATURE AND RAW WELL DATA

Well Site	Lag Zero	Max. Correlation		(@ Lag)
Milk River	0.19	0.22	@	3 Months
Lethbridge	-0.26	-0.65	@	-6 Years
Barons	0.22	0.22	@	0 Months
Elnora	-0.06	-0.40	@	1.8 Years
Stettler (#6)	-0.39	-0.50	@	- 1.3 Years
Stettler (137)	0.01	-0.77	@	3.8 Years
Leduc	0.54	0.57	@	1 Year
Devon #2	-0.42	-0.44	@	6 Months
Drayton Valley	-0.40	-0.41	@	3 Months
Grimshaw	-0.17	-0.37	@	1.8 Years
Beaverlodge	-0.39	-0.39	@	0 Months

TABLE 28

CLUSTER ANALYSIS OF RAW WELL DATA AND TEMPERATURE
ANNUAL GAIN CROSS CORRELATION COEFFICIENTS

WITH LAG

Cluster

1	2	3
103	131	136
117	137	159
153	339	321
		341
		109

WITHOUT LAG

Cluster

1	2	3
103	131	136
117	137	159
153	339	321
		341
		109

TABLE 29

CROSS CORRELATION OF ANNUAL GAIN CYCLES FROM WELL AND TEMPERATURE DATA

Well Site	Lag Zero	Max. Correlation		(@ Lag)
Milk River	0.46	0.47	@	-2 Months
Lethbridge	-0.29	-0.29	@	0 Months
Barons	0.30	0.30	@	0 Months
Elnora	0.15	0.33	@	1.5 Years
Stettler (#6)	-0.08	-0.26	@	1.3 Years
Stettler (137)	-0.30	-0.52	@	1.8 Years
Leduc	0.46	0.62	@	1.1 Years
Devon #2	0.02	0.25	@	5 Months
Drayton Valley	-0.37	-0.37	@	0 Months
Grimshaw	0.01	0.2	@	2 Years
Beaverlodge	-0.51	-0.51	@	0 Months

TABLE 30

CLUSTER ANALYSIS OF ANNUAL GAIN CYCLES FROM TEMPERATURE AND WELL DATA CROSS CORRELATION COEFFICIENTS

WITH LAG

Cluster

1	2	3	4
131 153 339	117 159 103	321 341 109	136 137

WITHOUT LAG

Cluster

1	2	3	4
103 117 153	109 136	131 159 339	137 321 341

The clusters show no preference for geologic structure or aquifer lithology. There is however the suggestion of geographical preference in examining the 4 cluster scheme derived without consideration of the lag variable. Clusters 1 and 2 may represent wells in the southern part of the province, wells 3 and 4 those wells in the northern portion of the province.

Clustering of the coefficients derived using annual temperature data and gain data suggest that geographic location and aquifer lithology play important roles in determining the strength and nature of the relationships observed between the data sets.

Annual Gain Data Summary

In general, correlation of well data with the annual gain cycle present within that data averages .30 - .60 for most wells, wells 109 (Lethbridge) and 137 (Stettler 1960-4) displaying distinctly low correlations between these two parameters. The wells for which the correlation coefficient is of reasonable strength therefore display annual seasonality within water table fluctuations, i.e., well levels may be predicted to a certain degree by considering the annual cycle.

Lethbridge, Stettler 1960-4, and Devon display low correlation between well level and the annual gain as described (Devon shows a negative correlation). 109 (Lethbridge) and 137 (Stettler) also show very low correlation with precipitation, temperature, and low correlation when annual well gain is cross correlated with annual precipitation gain. The remaining parameters, the cross correlation of raw well data and the annual gain from temperature and precipitation, and the cross correlation of the annual gain cycles from well and temperature data produce high negative coefficients, usually at long lag periods. This insensitivity of water table fluctuations to an annual gain cycle, and to the annual gain cycle in precipitation suggests isolation of these aquifers from the immediate weather / climate. The strong negative correlation of gain cycles derived from well and climate data suggests a negative feedback mechanism, or more likely, a recharge / discharge system of time length which is a multiple of the lag required for maximum correlation to be recorded. The data suggest these wells are of artesian characteristics. Well 159 (Devon #2) shows a strong correlation between annual gain cycles derived from precipitation, strong negative correlation between gain cycles from well and temperature data. Devon is a surficial sand aquifer, and likely helps to explain the strong correlation between gain cycle variables, especially variables drawn from temperature data.

The remaining wells showing good correlation between the annual gain and well levels may be subdivided according to aquifer lithology and geographic location.

7.6.2 Complex Demodulation of 3.6 Year Cycles

The log gain of the 3.6 year cycle is examined next. The correlation coefficients derived at some well sites for the log gain and the fluctuation sequence are remarkably high, representing almost perfect correlations. Shallow surficial sand aquifers, and wells located in the south of the province show distinctly lower correlation in this analysis (r = .58 to .75). Cluster analysis establishes groupings of the data :

TABLE 31

CROSS CORRELATION OF 3.6 YEAR GAIN CYCLES FROM WELL DATA, AND RAW WELL DATA

Well Site	Lag Zero	Max. Correlation (@ Lag)
Milk River	0.11	0.58 @ 1.21 Years
Lethbridge	0.97	0.99 @ 2.8 Years
Barons	0.58	0.58 @ 0 Months
Elnora	0.16	0.64 @ 2.2 Years
Stettler (#6)	0.86	0.95 @ 1.8 Years
Stettler (137)	0.87	0.94 @ 10 Months
Leduc	0.90	0.95 @ 1.22 Years
Devon #2	0.22	0.74 @ 2.5 Years
Drayton Valley	0.76	0.91 @ 2.4 Years
Grimshaw	0.68	0.91 @ 2.2 Years
Beaverlodge	0.87	0.99 @ 2.4 Years

TABLE 32

CLUSTER ANALYSIS OF RAW WELL DATA AND 3.6 YEAR GAIN CYCLES CROSS CORRELATION COEFFICIENTS

WITH LAG Cluster 1	WITH LAG Cluster 2	WITHOUT LAG Cluster 1	WITHOUT LAG Cluster 2
109	117	109	117
136	131	136	131
137	159	137	159
153	103	153	103
321		321	
339		339	
341		341	

The simple 2 cluster classification (considering lag) groups wells into those that achieve a strong relationship between well levels and their 3.6 year gain cycle (cluster 2), and those wells which display near perfect correlations (cluster 1), and draws a distinction between wells located in the south and north of the province, and aquifers of a bedrock nature versus those of shallow surficial sands.

3.6 Year Complex Demodulation using Precipitation Data

The relationship between the 3.6 year cycle within precipitation and well data is examined next. Well sites showing low correlation between well data and the 3.6 year gain cycle within precipitation are 117 (Barons), 131 (Elnora), and 137 (Stettler). Remaining wells show correlation strength in the r= .30 to .75 range (Table 33).

Wells 109 (Lethbridge), 131 (Elnora), and 159 (Stettler) are 3 of the 4 surficial sand aquifers in the study, and show a negative coefficient in this analysis. The remaining surficial sand aquifer, well 103 (Milk River) shows a positive coefficient with these data sets.

Following is the cross correlation and clustering analysis of the cross correlation between well levels and the 3.6 year gain cycle within precipitation.

TABLE 33

CROSS CORRELATION OF 3.6 YEAR GAIN CYCLES FROM PRECIPITATION, AND RAW WELL DATA

Well Site	Lag Zero	Max. Correlation	(@ Lag)	
Milk River	0.11	0.58	@	14.6 Months
Lethbridge	-0.33	-0.33	@	0 Months
Barons	0.06	0.01	@	-1 Months
Elnora	-0.11	-0.19	@	9 Months
Stettler (#6)	0.06	0.38	@	2.2 Years
Stettler (137)	-0.10	-0.11	@	7 Months
Leduc	0.07	-0.18	@	2 Years
Devon #2	-0.42	-0.46	@	4 Months
Drayton Valley	-0.49	-0.59	@	10 Months
Grimshaw	-0.05	0.75	@	4.3 Years
Beaverlodge	-0.01	0.30	@	3.3 Years

TABLE 34

CLUSTER ANALYSIS OF RAW WELL DATA AND 3.6 YEAR PRECIPITATION GAIN CYCLE CROSS CORRELATION COEFFICIENTS

WITH LAG

Cluster

1	2	3
136 339 341	109 159 321	117 131 137 153 103

WITHOUT LAG

Cluster

1	2	3
117 131 136 339 341	109 137 159	153 321 103

Using the 3 cluster classification scheme which includes the lag variable, cluster 1 contains wells which display a long lag period before maximum correlation is recorded (2-4 years). Cluster 2 wells result in a negative correlation coefficient being computed at lags not exceeding 1 year, cluster 3 contains wells of typically low correlation strength, with the exception of well 103. A geographic classification is suggested. Cluster 1 wells with the exception of 136 (Stettler) representing the northern portion of the province, cluster 2 wells the west central portion of the province (with the exception of Lethbridge 109), cluster 3 wells the south and east central portion of the province. The mixture of aquifer types and well depths suggests the geographic preference in terms of classification does not arise out of coincidence.

Clusters 1 and 2 (those displaying moderate to high correlation) also contain well sites for which the 3.6 year cycle within well levels correlated very highly with the raw data. The higher correlation of clusters 1 and 2 well site gains with precipitation gains suggests that the correlation of the 3.6 year well data cycle and raw well data is partially derived from the precipitation regime. I.e., spectral density in the 3.6 year cycle of the precipitation regime induces similar variation in spectral density in the same cycle within observation well data. Wells 137 and 153 do display high correlation in the raw well data - 3.6 year precipitation analysis, but appear in cluster 3 as a result of the stability of the correlation coefficient with the introduction of lag (it does not change much).

Cluster 3 wells (using the lag variable) have lower correlation strength between the two variables. Of this grouping, two wells are surficial sand aquifers, and are not likely to be able to sustain a long term cycle within well levels. High correlation noted between well data and the log gain of the 3.6 year cycle in wells 137 (Stettler) and 153 (Leduc) is NOT attributable in large part to similar behaviour noted in the precipitation regime. Influences other than the precipitation regime must be responsible in larger part for the 3.6 year cycle in well data. For these well sites, longer term temperature cycles correlate with greater strength, and will be discussed further in the next section.

The cluster analysis of the cross correlation of the 3.6 year gain cycles from both well data and precipitation is examined next.

TABLE 35

CROSS CORRELATION OF 3.6 YEAR GAIN CYCLES FROM WELL AND PRECIPITATION DATA

Well Site	Lag Zero	Max. Correlation (@ Lag)
Milk River	-0.22	-0.29 @ -4 Months
Lethbridge	-0.29	0.30 @ - 3 Months
Barons	0.20	0.26 @ 5 Months
Elnora	0.29	0.51 @ 8 Months
Stettler (#6)	0.29	0.39 @ 1.4 Years
Stettler (137)	-0.09	0.17 @ 1.9 Years
Leduc	-0.14	-0.15 @ - 4 Months
Devon #2	-0.01	0.44 @ 2.5 Years
Drayton Valley	-0.08	-0.09 @ 2 Months
Grimshaw	0.11	0.41 @ 1.7 Years
Beaverlodge	0.15	0.17 @ 3.4 Months

TABLE 36

CLUSTER ANALYSIS OF WELL AND PRECIPITATION 3.6 YEAR CYCLES CORRELATION COEFFICIENTS

WITH LAG Cluster			WITHOUT LAG Cluster		
1	2	3	1	2	3
137	117	153	117	109	153
159	131	321	131	137	321
339	341	103	136	159	103
	136	109	341		

The clustering of well sites as derived from the cross correlation of the 3.6 year gain cycles is quite different than from the raw data and 3.6 year precipitation cycle. Discussing the clustering using the 3 cluster classification (considering lag), cluster 1 is again composed of wells requiring a long period of time to achieve maximum correlation (2 - 2.5 years). Cluster 2 contains wells which display a moderate correlation strength (.25 - .50), and achieve their maximum strengths of correlation at lags no more than 1 year in length. Cluster 3 contains wells which have a negative correlation between the gain cycles, and maximum correlation strength occurring at lags less than 1 year. Elnora, Stettler #6, Devon, Grimshaw and Beaverlodge record the highest correlation between the two gain cycles. Of these wells, Beaverlodge, Stettler, and Grimshaw scored near perfect correlation between the raw well data and 3.6 year well data cycle, Elnora and Devon score in the r = .60 - .75 range.

Elnora and Devon are surficial sand aquifers, Stettler #6 and Beaverlodge are bedrock aquifers. At this point it may be stated that the 3.6 year cycle within precipitation has a greater influence upon a 3.6 year cycle within water table elevations in bedrock and deep alluvial material aquifers, as opposed to surficial sand aquifers. The 3.6 year cycle within precipitation can therefore be deemed highly effective and influential in determining the long term behaviour recorded in water table elevation in bedrock aquifers.

The coefficients are not clustered according to geography, geology, aquifer lithology, or well depth.

The relationship between the 3.6 year gain variables within precipitation and water table fluctuation data is unique to each well site, and cannot be categorized on the basis of geography, well depth, or aquifer lithology. The relationship of water table level to the status of the 3.6 year gain cycle within precipitation can be categorized on the basis of geography. This leads to the following theorems :

1) That the 3.6 year gain cycle within the series of water table elevations is the result of a combination of factors, not the 3.6 year gain cycle within precipitation alone. Otherwise, the gain cycles would correlate with greater strength, and with heed to geographical and other factors. That the correlation between gain cycles is not stronger, yet considering the very strong correlations achieved between the well level 3.6 year gain cycles and well

levels suggests that there are other mechanism(s) of great influence upon water table elevation.

2) That the correlation between well levels and the 3.6 year gain cycle within precipitation displays a geographic pattern, the concept of geographic variability is introduced into the relationship. The source of the variability may be within the climate or well site characteristics and is likely a combination of both.

3) Aquifer lithology is also of importance in how the 3.6 year cycle will affect water table elevations. Correlation between well levels and the 3.6 year precipitation cycle are typically negative for surficial sand aquifers, the correlation between gain cycles is typically positive.

3.6 Year Complex Demodulation using Temperature Data

The 3.6 year log gain analysis using temperature is carried out. Following is the cross correlation and cluster analysis of raw well data and the 3.6 year cycle present within temperature data from the well sites :

TABLE 37

CROSS CORRELATION OF 3.6 YEAR GAIN CYCLES
FROM TEMPERATURE, AND RAW WELL DATA

Well Site	Lag Zero	Max. Correlation	(@ Lag)
Milk River	0.07	0.26 @	7 Months
Lethbridge	0.40	0.40 @	0 Months
Barons	0.58	0.58 @	0 Months
Elnora	0.31	0.38 @	1.2 Years
Stettler (#6)	0.18	0.32 @	- 1.4 Years
Stettler (137)	0.02	-0.69 @	7.4 Years
Leduc	-0.35	-0.38 @	11 Months
Devon #2	0.35	0.36 @	4 Months
Drayton Valley	0.21	0.26 @	1 Year
Grimshaw	0.46	0.46 @	2.4 Months
Beaverlodge	0.32	0.32 @	0 Months

TABLE 38

CLUSTER ANALYSIS OF RAW WELL DATA AND 3.6 YEAR
GAIN CYCLES FROM TEMPERATURE DATA

WITH LAG

Cluster

1	2	3	4
109 117 159 339	137	153	131 136 321 341 103

WITHOUT LAG

Cluster

1	2	3	4
103 136 339 341	109 159 321	117 153	131 137

Examining the 4 cluster classification scheme (using the lag variable), the cases are clustered rather obviously. Cluster 1 contains wells that achieve a moderately high correlation with the 3.6 year gain in temperature at relatively short lag periods. Cluster 4 contains wells again achieving moderately high correlation, but at lag periods between 7 months to 1 year. Wells 137 and 153 represent a negative correlation and are thus isolated. In this cluster analysis, geology, aquifer lithology, nor geographical location seem to be preferred in determining the clusters.

The highest correlation coefficients are calculated for well sites in cluster 1. Two of these wells (109 and 339) show the near perfect correlation between well level data and the 3.6 year gain cycle in that data. Well 339 belongs also to the cluster representing high correlation between well data and the 3.6 year cycle within precipitation. Well 137 is a cluster unto itself, and although the raw data correlated almost perfectly with a 3.6 year well data cycle, it displays significantly different behaviour when correlated with the 3.6 year cycle gain in temperature, as a negative coefficient is computed. In these wells representing higher correlation it can be concluded that the water table elevation is under the influence of temperature, and that the spectral density of the 3.6 year cycle within temperature has an impact on the expression of water table elevation at these well sites.

Following is the cluster analysis of the 3.6 year gain cycles derived from both well data and temperature data

TABLE 39

CROSS CORRELATION OF 3.6 YEAR GAIN CYCLES FROM WELL AND TEMPERATURE DATA

Well Site	Lag Zero	Max. Correlation		(@ Lag)
Milk River	-0.45	-0.51	@	5 Months
Lethbridge	0.43	0.44	@	- 5 Months
Barons	-0.13	-0.18	@	- 2 Months
Elnora	-0.26	-0.34	@	10 Months
Stettler (#6)	0.06	0.23	@	- 2.4 Years
Stettler (137)	0.03	-0.42	@	3.7 Years
Leduc	-0.42	-0.43	@	8 Months
Devon #2	0.38	0.58	@	- 2.65 Years
Drayton Valley	0.20	0.30	@	- 11 Months
Grimshaw	0.26	0.27	@	1 Month
Beaverlodge	0.36	0.54	@	3.6 Years

TABLE 40

CLUSTER ANALYSIS OF 3.6 YEAR GAIN CYCLES FROM WELL AND TEMPERATURE DATA

WITH LAG

Cluster

1	2	3
321 339 341	117 131 137 153 103	136 159 109

WITHOUT LAG

Cluster

1	2	3
109 136 159 321 339 341	117 137	131 153 103

Wells belonging to cluster 1 have a moderate positive correlation, with the maximum correlation being computed between -1 year and 3.6 years of lag. Cluster 2 wells display negative correlation between the gain variables, and cluster 3 wells show moderate strength correlations at negative lag periods. It is evident from this cluster analysis that geography is playing a major role in the categorization of the wells into their respective clusters. Cluster 1 wells represent those located in the northern part of the province, cluster 2 wells represent those of south and south central Alberta, and cluster 3 wells tend to represent wells predominantly in the central region of the province.

It is interesting to note at this point that the geographic importance of clustering found within the temperature - well 3.6 year cycle gain correlation was not present in the precipitation study, instead the raw well data

- precipitation gain correlation was found to be reliant upon geographic location.

Summary of 3.6 Year Complex Demodulation

The 3.6 year cycle within well data was discovered to have extraordinary predictive power of the shape of the well hydrograph in most wells. Excluding wells 103 (Milk River), 117 (Barons), 131 (Elnora), and 159 (Devon #2), the correlation achieved after a lag period approximating 2 years approaches 1.0 (a perfect correlation). The remaining wells display correlations in the .60 - .75 range, and therefore considerable predictive power still exists.

In general, it is the deeper bedrock / deep alluvial material aquifers that display the higher correlations with the 3.6 year cycles present within well level (longer cycles in general), precipitation, and temperature. Well sites where water table fluctuations are found to be insensitive to annual data have been found to correlate highly with some of the 3.6 year log gain sequences extracted from climate data. A case in point is well 137 (Stettler), which shows little correlation strength with annual data, but high correlation strength with 3.6 year cycle data derived from the temperature regime.

Although 3.6 year cycle activity is found to correlate moderately well with shallow and surficial sand aquifers, it is believed that the deeper bedrock wells are better able to develop longer cycles within aquifer storage. The deeper bedrock aquifers are better able to support "hydrologic momentum" through a more extensive recharge-discharge area, and larger aquifer volume.

7.7 Complex Demodulation Cycle Summary

Only the annual and 3.6 year cycle gains were examined extensively in terms of influence upon well level fluctuations. The 3.6 year cycle was selected for detailed examination due to the unusual behaviour it tends to display at certain sites. Other cycle lengths were also extracted through the course of researching this thesis to get a feel for their influence upon well level fluctuations. It was discovered in general that cycling activity within well levels is largely dependent upon longer term cycles, that is, the log gain of longer term cycles tends to assume the same shape as the well level hydrograph. The 3.6 year cycle most closely describes the shape of the fluctuation in well levels among the possible gain cycles for most sites.

CHAPTER 8

CONCLUSIONS

This thesis has examined the time series of water tables at 10 sites in Alberta. Two climatic parameters, precipitation and temperature were examined for possible linkages to fluctuations recorded in the water table. Cycling was also looked at as a possible related parameter in explaining water table fluctuations, and an explanation of causal links was attempted.

It was shown that in general, the well sites can firstly be categorized into two broad groupings based upon collective well response to climatic parameters : 1) Surficial sand aquifers, and 2) Deep alluvial material and bedrock aquifers. The small sample size of wells used to represent the province could have caused some categorical inaccuracy.

It was also shown that harmonic cycles present within observation well data can be used to develop two rough categories dependent upon aquifer lithology and geography. Both well response and harmonic cycle response categories agree. A north-south provincial split delineates surficial sand versus bedrock aquifers and serves as a basis for the distinction of harmonics based upon the pattern (percentage of total variance of the harmonic series) computed for each well site.

In terms of the precipitation regime it was discovered that the surficial sand aquifers are more sensitive to precipitation (i.e., display higher correlation coefficients with precipitation data). Lower sensitivity was characteristic of bedrock aquifers due in part to generally lower permeability characteristics of the water bearing strata and greater depth of the wells.

The temperature regime was discovered to have considerable influence on water table fluctuations within surficial sand aquifers. When cycling was examined with the temperature variable, it was shown that there was considerable predictive power in the temperature variable at all well sites.

Certain wells, most notably bedrock and deep alluvial material wells show a great similarity in water table fluctuations and the gain of the 3.6 year cycle within that data. Surficial sand aquifers display a slightly weaker correlation strength between these two parameters, but a stronger correlation between the annual gain cycle variable within well data than do the deeper bedrock and deep alluvial material aquifers. Analysis indicate that for the majority of the wells and in particular the bedrock wells, similar cycles within the precipitation and temperature regime are source in part for the expression of these cycles within the well data. Temperature seems to play a more important role in this capacity than do cycles in precipitation.

The dependence of water table fluctuation upon annual and 3.6 year gain cycles in precipitation and temperature can be further subdivided into sub-groupings according to geographic location and aquifer lithology, and has been described in detail in chapter 3.

8.1 Predictability - Groundwater Status for the Future

This thesis has revealed certain relationships which are important in the expression of water table fluctuations, and can therefore be used as an effective means to predict qualitative volume fluctuation of the resource for areas of Alberta.

The 3.6 year oscillation was found to be an important predictor in the expression of well levels. At most well sites, the 3.6 year cycle within well level fluctuations alone could act as a sufficient predictor for determining the general shape of the water table hydrograph. The 3.6 year oscillation appears within precipitation and temperature time series for most sites, and the co-occurrence of this cycle within all data sets would serve to strengthen the predictive ability of the cycle. The log gain of the 3.6 year cycle seems to retain predictive power over the shape of the hydrograph even where spectral density in that frequency band is low. The moderate covariance between the log gain cycles of well levels and climatic time series suggest partial reliance of the water table upon the immediate climate. Long term trends and oscillations in climate therefore may have an impact upon water table fluctuations, and therefore upon groundwater supply.

Correlation and cross correlation techniques were also examined in the thesis as a means of describing well hydrographs. In general, cross correlation techniques would be able to approximate water well levels in the surficial aquifer well sites, although confidence in predictions would likely be quite low.

Although the 3.6 year cycle was found to have considerable predictive power, it would be advised that the use of the techniques described within this thesis be restricted to the province of Alberta. As Oladipo (1987) points out, the occurrence of specific cycles within climatic phenomena is largely a geographic phenomena. Areas significantly removed from the Alberta area should be subjected to a thorough examination of the power spectra within well levels and climatic phenomena before making any statements pertaining to the present or future status of the groundwater resource.

Prediction of well levels and therefore of aquifer water volume may be made effectively on the basis of long term (3.6 year) cycles within climatic parameters, and shorter term (1 year) for aquifers of a shallow surficial nature. Analysis of longer sequences of climate data will allow for the behaviour of these cycles to be understood with greater clarity, and thus enable accurate predictions of water table fluctuation to be made for considerable periods of time into the future.

8.2 Future Study Directives

Much frustration was encountered in gathering and processing data for this thesis. Groundwater observation well data, although generally adequate in terms of quality, is still limited to a data length of around 20 years. This short length of record makes any conclusions and predictions tentative at best when considering that changes in climate occur over periods of time generally many times greater. Climate data was surprisingly difficult to obtain in terms of quality and length of record. Many weather recording sites in Alberta operate on a seasonal basis, and observations for winter periods may be entirely absent. Existing weather stations and weather observation sites if upgraded to provide continuous data would help in this respect.

Drawing quantitative conclusions as to the actual change in groundwater storage which fluctuations in water table elevations represent was not possible due to the lack of information required to compute aquifer volumes. Plentiful and detailed geologic cross sections in water bearing regions would be desirable towards calculating aquifer volumes.

The continued accumulation of ground water data will provide the longer term time series needed to increase accuracy and significance of predictions. In future studies of this nature, it would be desirable to work with data improved in the aspects described above.

It is felt that although the conclusions drawn from the harmonic analysis carry little significance, cycling activity and interactions between the climate and groundwater system are of great importance in understanding how changes in climate will impact upon the groundwater system. As climate and groundwater databases improve in quality and increase in size, more useful knowledge will be gained from studies of this sort.

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APPENDIX

Statistical Analysis

Several commercial statistical packages, and computer routines written by the author were used in generating the statistics which will be presented. Commercial packages used include SPSS (Statistical Package for the Social Sciences), BMDP Statistical Software, routines copyrighted by Davis (1975), and Minitab Statistical Software. Most of the data analysis was completed on a Honeywell DPS 80 mainframe machine running the Multics Operating System.

K - Means Cluster Analysis

The computational steps for computing a K-means cluster analysis as given in the 1983 BMDP Statistical Software manual are as follows :

1) Data is standardized by overall variance or covariance if requested : obtain X_{new} such that

$$(X_{new})\ (M^{1/2}) = X_{input}$$

where $M^{1/2}$ is the Cholesky decomposition of the matrix to standardize with.

2) Classify cases into clusters based on the SEED or CENTER parameters, if they have been stated.

3) If the desired number of clusters have been defined, then step 5 is carried out, otherwise, a cluster is split into two clusters using the following procedure :

a) for each variable **i** in each cluster **c** the variance $\mathbf{var}_{ic}$ is estimated.

b) the indices $\mathbf{i}^*$ and $\mathbf{c}^*$ are found such that the value of variable $\mathbf{i}^*$ at the midpoint of the range of variable $\mathbf{i}^*$ in cluster $\mathbf{c}^*$.

c) cluster $\mathbf{c}^*$ is split into two clusters based on the value of variable $\mathbf{i}^*$ at the midpoint of the range of variable $\mathbf{i}^*$ in cluster $\mathbf{c}^*$.

4) If the number of clusters is less than desired, step 3 is repeated.

5) The data is standardized within clusters variance or covariance matrix.

6) Each case is moved to the cluster whose center is closest to the case.

7) Centers of the clusters (means) are recomputed and step 6 is repeated if any case was moved in step 6.

8) Repetition from step 5 is carried out if any case was moved since the last standardization.

9) Report clusters for the current number of clusters.

10) If a larger NUMBER of clusters has been requested, the procedure is repeated from step 3.