Groundwater in the Canadian Prairies:

Trends and Long-term Variability

A Thesis

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ABSTRACT

Groundwater could be an increasingly important water supply in the Canadian interior with global warming and declining summer runoff; however, not enough is known about the behaviour of groundwater under climatic variability. A network of over 33 wells is analyzed in order to document variability of groundwater levels and their sensitivity to climatic events. Groundwater wells are spread through the three Prairie Provinces with median monthly groundwater level records spanning up to 40 years. The aquifers are mostly in sand and sandstone which make them highly sensitive to climatic variations. In addition, these wells have not been affected by human activities such as pumping. Multiple analyses, such as the Mann-Kendall non parametric test to detect trends in groundwater levels, are carried out in order to determine and understand the dynamics of groundwater in the Prairie Provinces. Strong correlations ($r > 0.7$, $p < 0.01$) between tree-ring chronologies and seasonal and annual groundwater levels enable the reconstruction of 11 annual groundwater level records for more than 90 years in Saskatchewan and more than 300 year in Alberta. Results of the application of the Mann-Kendall trend test suggest that groundwater levels in north central areas show either no or decreasing trend, in contrast, groundwater levels in southern areas are dominated by increasing trend. The spatial distribution of trends coincides with increasing and decreasing trends in evaporation during the warm season. The reconstructions of historical groundwater levels suggest that the range of variability in water levels is greater than the variability recorded in the instrumental period. Also, the magnitude and duration of impacts of historical droughts on groundwater vary between different aquifers. Results of spectral analysis suggest that oscillation modes at ~10, ~15, ~20, and ~25 years explain most of the variability in groundwater in Alberta and Saskatchewan.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1 Background

Sea levels are rising, average air and ocean temperatures are increasing, permanent snow and ice coverage are melting and there is no uncertainty that the global climate is warming (IPCC, 2007). This warming could bring new climate conditions that could vary broadly affecting our daily activities. Among the possible impacts is variation of the hydrological cycle, which could have consequence for water availability in Canada.

The Canadian Prairies have been historically affected by droughts of varying magnitude and duration. The instrumental records have registered at least 1 one-year drought in each decade which might not have caused strong impacts as droughts of three, four or even more years in duration. Three decades in the twentieth century were characterized by droughts of five or more years, 1910-20, 1930-39 and 1980-89 (Nkemdirim and Weber, 1999). Most recently the Prairies faced the 1999-2002 multi-year drought which is considered the most severe of all (Bonsal and Wheaton, 2005). Droughts are characterized by a lack of precipitation, higher air temperature than normal, low soil moisture and deficits of water supplies (Wheaton et al., 2005; Nkemdirim and Weber, 1999).The population and economy growth have increased the demand for water, increasing vulnerability to hydrological droughts (Wheaton et al., 2005). It is likely that droughts will become more frequent under global warming (Kharin & Zweirs, 2000).

Historically most of the water required for human activities (housing, industry, agriculture, mining etc.) has been obtained from rivers or lakes and thus most cities, towns, and villages have been set near rivers or lakes and the reason is evident. In

Canada there is no exception to this, mostly the major cities extract their water from surrounding lakes or rivers, however, there is an important percentage of the population that depends on groundwater.

Groundwater is an important component of the hydrological cycle; however, it has not received great attention by scientists studying the effects of climate change and its variability. The Intergovernmental Panel on Climate Change (IPCC) has recognized the importance of groundwater in arid and semi arid regions and the lack of studies of the impacts of climate change on groundwater (IPCC, 2007).

A decreasing trend in annual precipitation has been observed in the Canadian Prairies during the last 40 years (Gan, 1998) and some studies suggest that the new climate could cause less water availability in the Canadian Prairies (Lewis, 1998; Schindler et al. 1996), which would increase the demand on groundwater.

All the above reasons make necessary the understanding of the current dynamic and the natural variability in groundwater levels. This thesis uses the Mann-Kendall trend test to identify trends in mean annual groundwater levels and moisture sensitive tree-ring chronologies to reconstruct historical groundwater levels. The long-term variability is analyzed using spectral methods.

Tree-ring reconstructions of groundwater levels are based on the fact that both trees and groundwater respond to precipitation, and recognize that these responses are often lagged in time. Geologic structures and aquifer characteristics are important factors when relating groundwater levels and tree rings, therefore in this study all aquifers considered have high hydraulic conductivity, an important requirement when studying the effects of climatic variability on groundwater.

1.2 Objectives

The two main goals of this study are to 1) analyze trends in groundwater levels in the Prairies, and 2) study the long-term variability in groundwater levels linking groundwater levels with tree growth.

The specific objectives are to:

a) Identify trends in mean annual groundwater levels using Mann-Kendall test and Trend Free Pre-whitening widely used in detection of trends in stream flow time series with significant auto or serial correlation.
b) Identify spatial patterns of trends.
c) Find linkages between groundwater levels and tree growth.
d) Reconstruct historical groundwater levels using tree-ring chronologies (crossdated tree growth) and multiple regression models.
e) Identify main changes in mean groundwater levels using the regime shift technique.
f) Detect dominant oscillation modes of variability using wavelet analysis.
g) Extract the most dominant oscillation modes of variability using singular spectrum analysis.
h) Identify and attribute effects of these modes of groundwater level variability.

1.3 Study area

The study area is the three Prairie Provinces (Alberta, Saskatchewan and Manitoba).

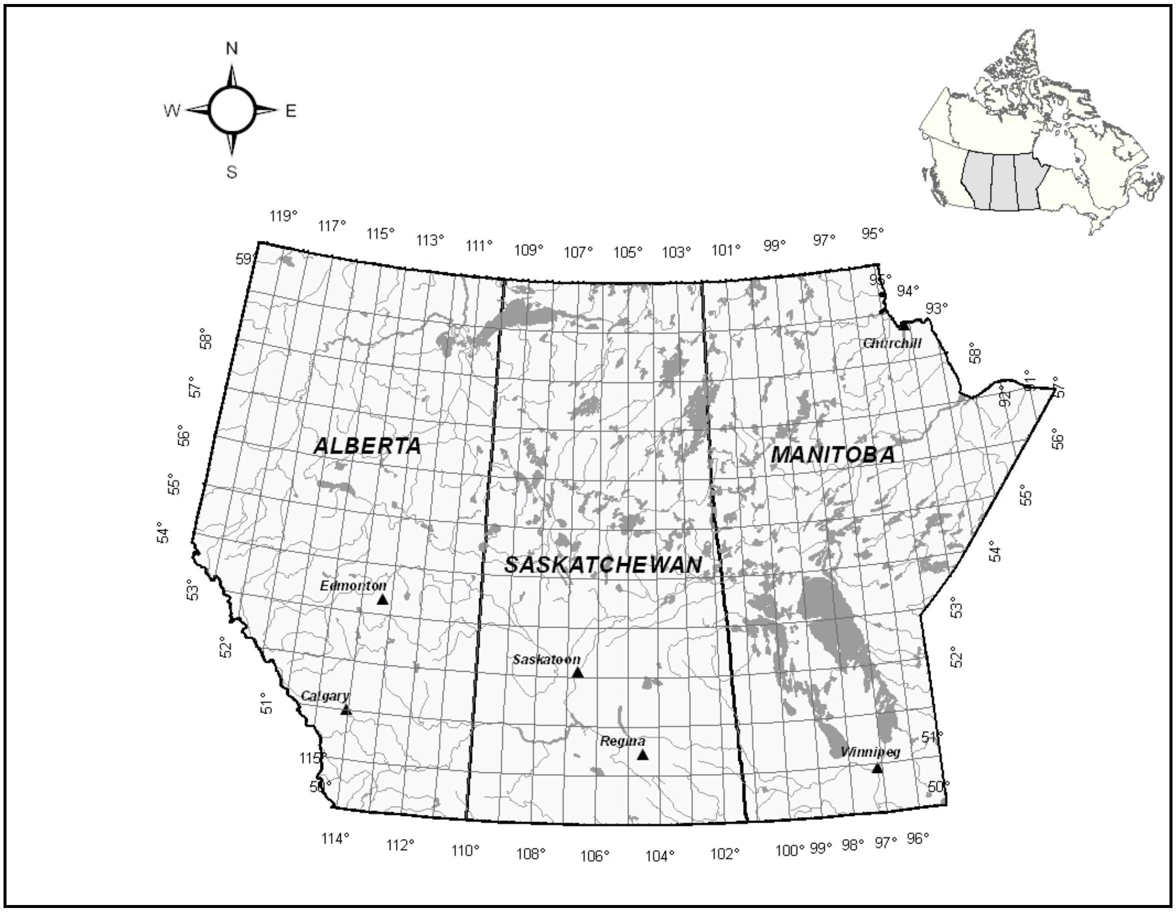

Figure 1.1: Study area

1.3.1 Precipitation and temperature

Temperature in the Canadian Prairies varies drastically from winter to summer. In the cities of Calgary, Regina and Winnipeg the mean winter temperatures (1961-1990) are -8.0°C, -14.3°C and -16.5°C with mean minimum of -17.0°C, -19.6°C, and -21.2°C, respectively. On the other hand, mean summer temperatures reach over 15°C (15.4°C; 17.9°C; 17.9°C) with mean maximum of 17.6°C in Calgary, 20.3°C in Regina, and 20.6°C in Winnipeg. Historically and in contrast to what people think (thought biased by the long winters in the Prairies) autumns are warmer than spring with temperatures that ranges from 3.8°C to 4.4°C in comparison with the 2.4°C to 3.7°C in spring. Mean annual temperature increases towards the south west (Fig. 1.2a), although, summer temperatures increase to the east. Southern Alberta is the warmest area in the Prairies with mean annual temperature from 5.0°C to 6.0°C. Calgary, Regina and Winnipeg have mean annual temperatures of 3.9°C, 2.6°C and 1.9°C.

The annual precipitation in the Prairies varies from just over 300 mm in the southeastern Alberta and southwestern Saskatchewan (Fig. 1.2b) to over 900 mm in the Rocky Mountains. Mean annual precipitation for the period 1961-1990 at Calgary, Regina and Winnipeg are 466 mm, 467 mm, and 596 mm respectively. Most of the annual precipitation occurs in summer, 49%, 39%, and 41 % at Calgary, Regina, and Winnipeg respectively. In general, spring and summer register over 60% of the annual precipitation. However, winter precipitation (snow) is the major source of water to recharge surface and groundwater systems. From the distribution of the precipitation and the temperature through the Prairies, south central areas are under moisture stress conditions and supplied with water from the surrounding Rocky Mountains and foothills, and northern and eastern boreal forest (Sauchyn and Kulshreshtha et al., 2008).

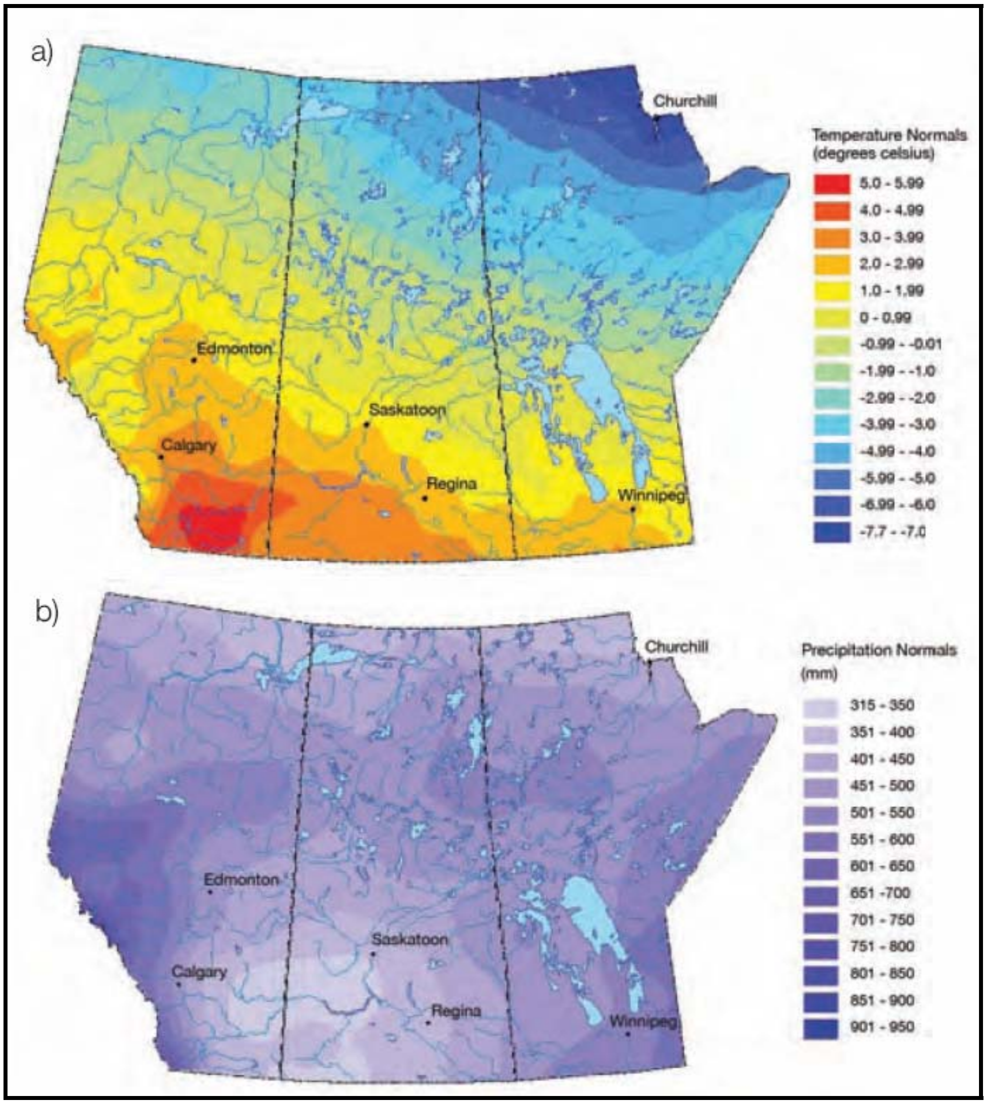

Figure 1.2: Mean annual temperature (a) and mean annual precipitation for the period 1961-1990 for the Canadian Prairies (extracted from Sauchyn, 2008).

Most of the water supply for human activities comes from the Rocky Mountains and drains north and east through the driest areas in the Prairies and into Hudson Bay (Fig. 1.3). The northwest basins of the Prairies drain into the Arctic Ocean, and a small area in the southern Prairies drains to the Gulf of Mexico.

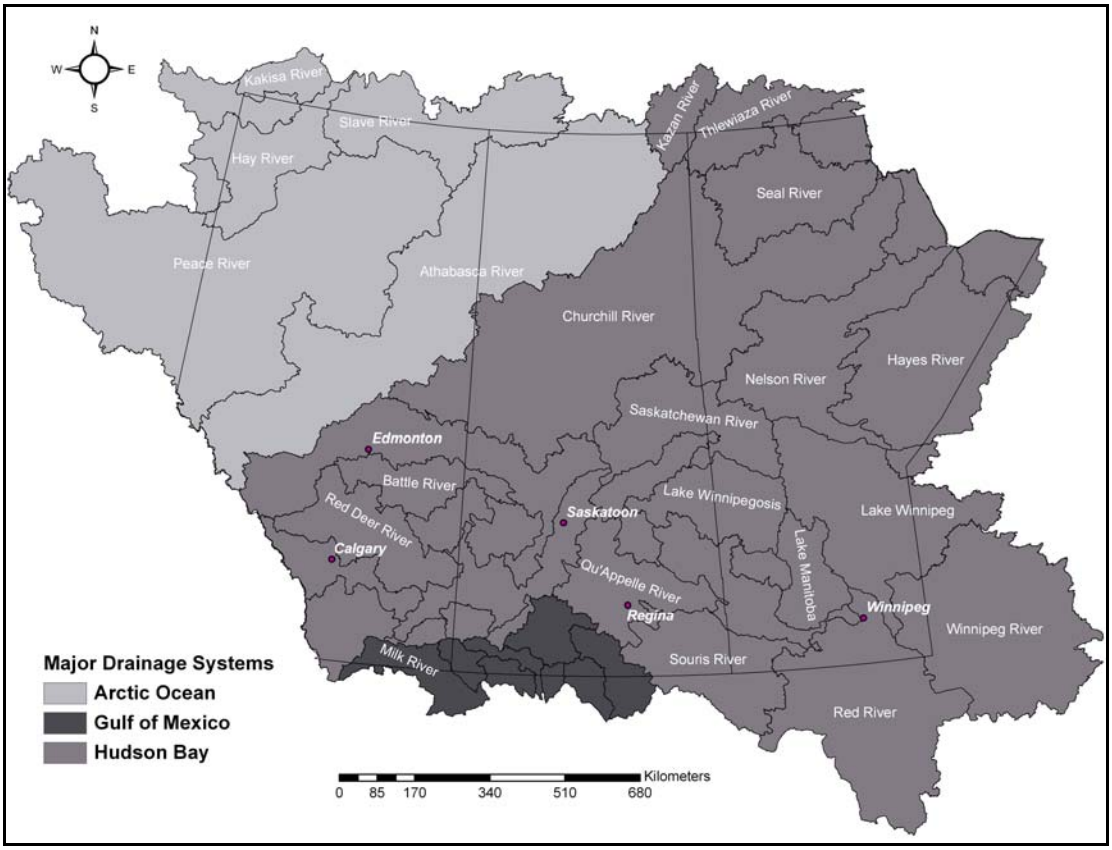

Figure 1.3: Major Drainage systems in the Canadian Prairies (PFRA, 1983).

1.3.2 Hydrogeology

Aquifers have been defined as geologic units with capacity to store and transmit water at sufficient rates to supply reasonable amounts to wells (Fetter, 1994). In the Prairie Provinces aquifers have been classified as bedrock aquifers and Quaternary aquifers. Bedrock aquifers are formed by sediments that range in age from Ordovician to Tertiary. Quaternary aquifers occur between the bedrock surface and the ground surface and are classified into buried valley, intertill and surficial aquifers (Maathius, 2000).

Major bedrock aquifers in the prairies include the Ribstone Creek and Judith Rivers Aquifers within the Bearpaw, Horseshow Canyon, Paskapoo, and Eastend to Ravenserag formations, and Odanah member of the Pierre Shale. Maathius (2000) defined Buried

Valley aquifers as “pre-glacial valleys cut into bedrock sediments that contain extensive thicknesses of coarse sand and gravel deposits”. Intertill aquifers “are composed of glacial graves, sands and silts positioned between layers of till” and Surficial aquifers are formed by stratified deposits of sand, gravel, silt and clay and they are found near the surface. Unfortunately, to date there are no hydrogeological maps showing the location of the aquifers throughout the Prairie Provinces; although, Maathius (2000) collected a series of maps that describe the location of the main groundwater systems in the Prairies.

The geological and hydrogeological setting of the sedimentary basin in the Canadian Prairies includes an impermeable base followed by a basal aquifer systems and an upper aquitard Maathius (2000) (Fig. 1.4). The basal aquifers systems are formed by four different geological units: the basal clastic unit, the Carbonate and evaporative unit, Triassic and Jurassic sediments, and the unit formed by sediments of the Mannville aquifer.

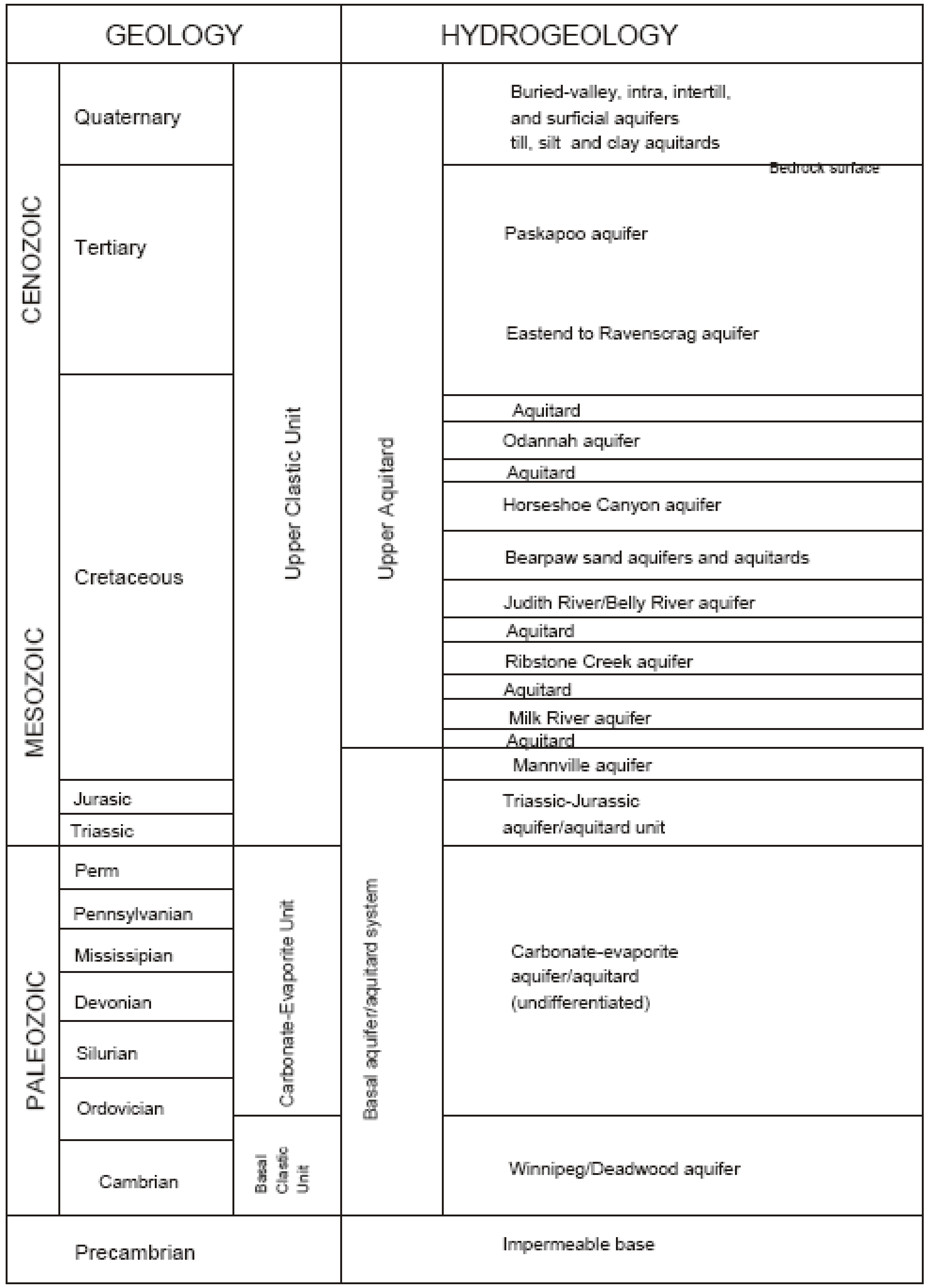

Figure 1.4: Geological and hydrogeological setting of the sedimentary basin in Western Canada (extracted from Maathiuss 2000).

1.4 Previous studies

In general there are few studies of climate change, climate variability and trends in groundwater. Most of the research has focused on surface water resources given the greater dependence on these water resources than on groundwater. This dependence has made possible the gathering of information since at least the beginning of the 1900s; as a result, there is much more information and data to study surface water than groundwater records starting in the mid 1960s in the Canadian Prairies. In addition, most aquifers register anthropogenic effects making them unsuitable for the study of groundwater trends and natural variability. All of this contributes to few studies on groundwater variability and trends; this the first comprehensive study in the Canadian Prairies.

1.4.1 Climate change and groundwater

Even though there is less data for groundwater there are a few studies of climate change and variability on groundwater in Canada.

Allen et al. (2004) used changes in recharge and river stage according to different climate change scenarios to model the recharge of the Grant Forks aquifer, BC. The results obtained show minimum differences or changes in water levels driven by changes in recharge. The highest recharge simulated increments in groundwater levels of 0.05 meters and under low recharge groundwater levels dropped by 0.025 meters. Major changes were observed in water levels driven by changes in stream flow levels. Increments of river level of 20 and 50 percent over peak flows increased groundwater levels by 2.72 and 3.45 meters. On the other hand, river levels of 10 and 50% below base flow resulted in 0.48 and 2.10 meters of groundwater level decrease. Allen et al. (2004) demonstrated that the Grand Forks aquifer is a stream driven system.

Loaciga (2000) modelled the effects of climate change in the Edwards aquifer in Texas using average climate scenarios at 2xCO2, for a dry climate and historical pumping. The results obtained suggest with protracted droughts the aquifer will not supply enough water for human and ecological use. Woldeamlak et al. (2007) simulated the effects of climate change on groundwater systems in the Grote-Nete aquifer, Belgium using dry and wet scenarios and a three dimensional finite difference model (MODFLOW). Results of the simulation suggest that under wet climate change scenarios there will be an increment in groundwater levels of up to 0.79 m and under dry scenarios water levels will drop between 0.5 and 3.1 meters.

1.4.2 Groundwater trends

There is only one western Canadian study on trends in groundwater quantity (Moore et al. 2007).There are many studies on trends in groundwater quality, however, this topic is not addressed in this study.

Moore et al. (2007) studied climate change and low streamflows in BC. Groundwater was addressed by indentifying different types of response of aquifers and trends in groundwater levels. The trend analysis resulted in mostly negative trends in either rain- and snow-melt driven aquifer levels.

There are various studies analysing trends in stream flow, precipitation and evaporation in North America and Europe. Studies in the Canadian Prairies are relevant for this study since stream flow, precipitation and evaporation have a direct relation with groundwater recharge; therefore the main findings of these studies are summarized below.

Burn and Hag Elnur (2002) applied the Mann-Kendall non parametric test to detect trends in a network of 248 Canadian catchments. The trend test was applied to records with at least 25 years of information and the study considered 18 hydrologic variables, including mean monthly and annual flow, date of starting and ending ice conditions and others. The results suggest that in the Canadian Prairies the ice conditions are lasting less giving a decreasing trend. Also, they found an increasing trend in flows from January to March which might be related to an earlier onset of spring runoff.

Mann-Kendall trend test was used by Burn and Hesch (2006) to detect trends in evaporation at 48 sites in the Canadian Prairies. The test was applied to 30, 40 and 50 year periods of record. Significant mostly decreasing trends were found in the warm season (June through October) for the 30 year record (1971-2000). Also a spatial distribution was observed. Northern areas of the Prairies are dominated by no or increasing trends while southern areas by decreasing trends.

Akinremi and McGinn (1999) calculated trends in precipitation records on the Canadian Prairies. They analyzed 37 records of precipitation with 75 years of information using regression analysis to identify linear trends. This studied reported that there has been an increase in the amount of precipitation and the events which means that is raining more and more often.

1.4.3 Reconstruction of groundwater levels

To date, few studies have modeled or reconstructed future and past groundwater levels in the Canadian Prairies. Chen et al. (2002) developed an empirical model linking climate variables to groundwater levels in the Carbonate Rock aquifer in southern Manitoba. Water levels were reconstructed considering a groundwater flow and a water budget model which considers the recharge rate as function of precipitation and evaporation. The statistical model was able to explain 85% of the groundwater variability. Ferguson and St. George (2003) used stepwise multiple regression models to estimate changes in average groundwater levels at shallow aquifers in the Upper Carbonate Aquifer in Manitoba. Precipitation, temperature and tree rings were used as proxy to reconstruct historical levels and evaluate trends in groundwater. Average groundwater levels were reconstructed back to 1907. The model explains 72 % of the variance in groundwater levels and was calibrated using 32 years of information. As a result, no significant changes were observed between averaged observed water levels and reconstructed, a 13 year period of low water levels was identified (1930-1940), decreasing and below average water levels started in 1966 and prolonged to 1991 which might be related to a warming in the Winnipeg area and a low mode shift occurred in the precipitation in 1978. Water levels started to rise in the early 1990s.

1.4.4 Groundwater variability

Van der Kamp and Maathuis (1991) studied the annual fluctuation of groundwater levels in deep and confined aquifers in southern Saskatchewan. They demonstrated that the annual variability is caused by changes in the mechanical load on the aquifer. These changes are driven mainly by moisture conditions raise groundwater levels from October through May/June and decrease groundwater levels from May/June through October, during high evaporation in summer.

Fleming and Quilty (2006) used composite analysis to study the effect of El Niño-Southern Oscillation (ENSO) on groundwater levels at four shallow wells in the Fraser Valley, British Columbia. The results of this study show that there is a direct effect of

ENSO on groundwater levels. During La Niña years water levels are above average and below average during El Niño years reflecting variability in winter and spring precipitation that recharges the aquifer systems. Precipitation tends to be higher and below normal in La Niña and El Niño years respectively. This study is the only one that has investigated the relationship between tele-connection patterns (ENSO) and groundwater levels in Canada; although, there are other studies focused on the variability and dominant oscillation modes in precipitation and stream flow records within the Canadian Prairies which are also summarized since they have direct relation with groundwater.

Coulibaly and Burn (2004) used wavelet to study the variability in annual stream flows in Canada. They applied wavelet techniques to 79 mean annual stream flow records spanning from 1911 to 1999. They showed that stream flows are dominated by activity in the 2-3 and 3-6 years bands. Strong correlations between tele-connection patterns (ENSO) and mean annual stream flow were detected for western stream flows. Results of correlation analysis showed two inflection points or shifts (changes in the sign of the correlation) in 1950 and 1970.

More recently, Gan et al. (2007) applied wavelet analysis to precipitation records at 21 climate stations in southwestern Canada. The objective of this study was to detect the main modes or drivers of variability in precipitation. The results suggest that there is a relation between precipitation and tele-connection patterns such as ENSO, PDO, and indices of Pacific/North America, East Pacific, West Pacific and Central North Pacific sea surface temperatures or pressure. Among all those patterns ENSO has the major and strongest influence on winter precipitation with increase and decreases of 14 and 20 % during El Niño and la Niña phases, respectively.

2. DATA SETS

2.1 Groundwater data

Groundwater data was obtained through the project Drought Research Initiative from Alberta Environment, Saskatchewan Watershed Authority and Manitoba Stewardship for the three provinces respectively. Initially, hourly, daily and monthly information for 876 wells was acquired. The number of observation wells per province varied; Alberta had the major number of wells (677) followed by Manitoba with 138 and Saskatchewan with 61 wells (Figure 2.1). Despite the large number of wells with information not all of them were suitable for the study of trends and climate variability.

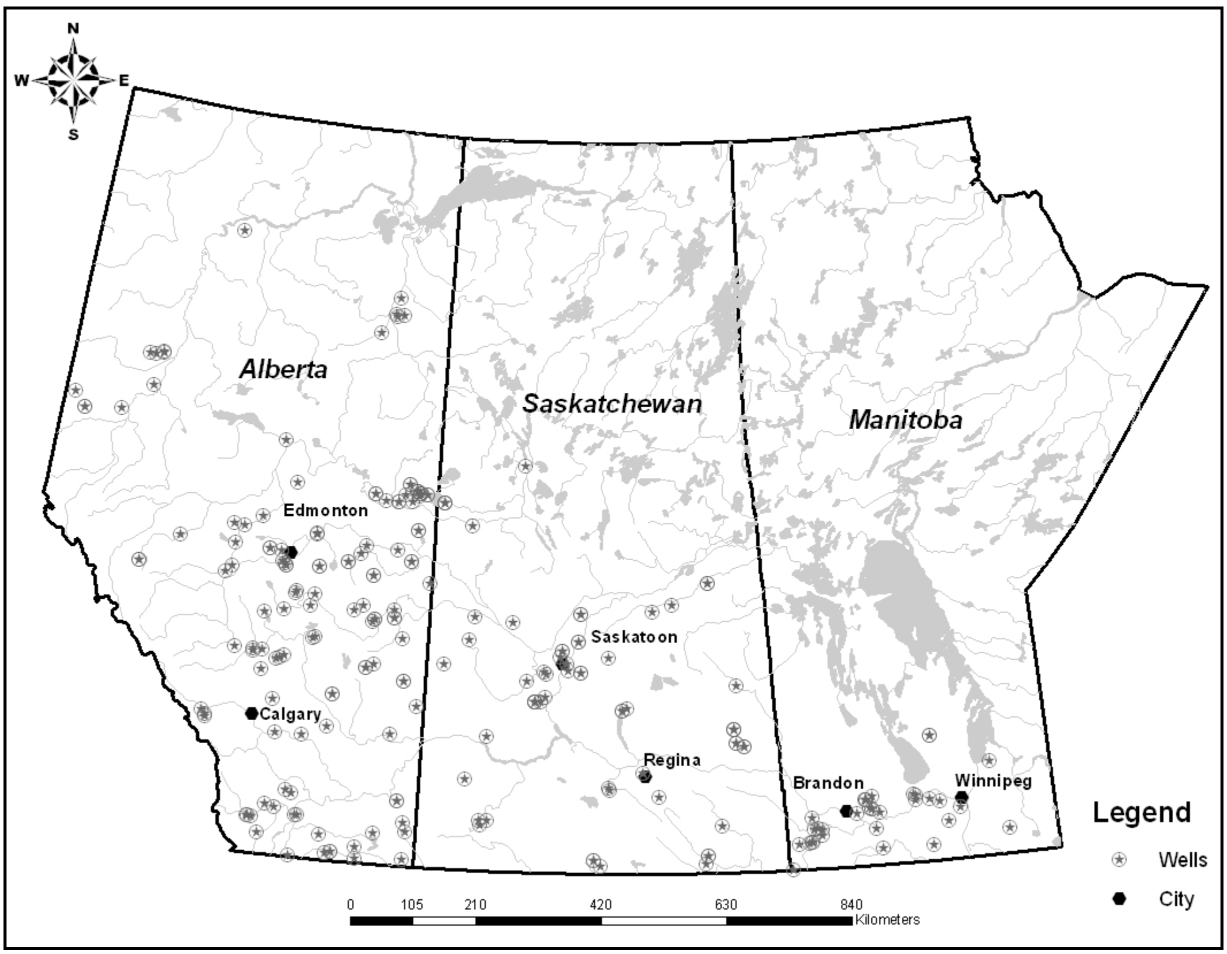

Figure 2.1: Location of groundwater wells through the Prairies.

To study trends and variability in groundwater the data had to satisfy some criteria, specifically more than 20 years of information and no anthropogenic effects (pumping). Hourly and daily data was reduced to median monthly values where the median monthly was calculated among 20 or more days with records.

In Alberta the number of wells with records for more than 20 years is 136. Only 39 of these have not been affected by pumping. The entire time span is 51 years from 1957 to 2007.The Manitoba data initially considered in this study was based on 33 wells from which 27 are affected by pumping. There is 45 years of data from 1963-2007. In Saskatchewan there are 61 groundwater records, covering the period 1964-2007, with 20 or more years with information. However, only 28 wells have not been affected by pumping.

Once the anthropogenic criterion was satisfied the percentage of missing data was calculated for each time series. Those with more than 20% of missing data were not considered for further analysis; this reduced the data set to 39 wells records. Alberta (19) continues being the Province with most of the groundwater information used in this study followed by Saskatchewan (16) and Manitoba (4). Missing data were filled in using correlation with records nearby and median values when the first method was not possible. Table 2.1 summarizes the information for each well and Figure 2.2 shows the location of them.

Table 2.1: Summary of groundwater wells

Well name	Well ID (used)	Depth (m)	Aquifer	Lithology	Prov	Lat	Long	Elev (m)	Years of record
Cressday 85-2	102	80.00	Belly River	Sandstone	AB	49.104	-110.251	887.1	22
Pakowki 85-1	104	69.00	Medicine Hat Valley	Sand, gravel	AB	49.472	-110.969	886.6	22

Well name	Well ID (used)	Depth (m)	Aquifer	Lithology	Prov	Lat	Long	Elev (m)	Years of record
Cypress 85-1	106	30.00	Upper Bearpaw	Sandstone	AB	49.524	-110.218	1188	22
Elkwater 2294E	108	33.50	Surficial	Sand & Gravel	AB	49.661	-110.288	1220	23
Mud Lake 537E	112	36.58	Mud Valley	Gravel	AB	49.757	-113.511	944	30
Ross Creek 2286E	114	73.70	Irvine Valley	Sand	AB	49.988	-110.461	726	23
Barons 615E *	117	19.80	Horseshoe Canyon	Sandstone	AB	49.993	-113.077	964.5	36
Hand Hills #2 South *	125	40.54	Paskapoo	Sandstone	AB	51.505	-112.205	1015	41
Ferintosh Reg Landfill 85-1	147	35.10	Horseshoe Canyon	Sandstone & Shale Frac.	AB	52.786	-112.955	800.5	23
Devon #2 (North) *	159	7.62	Surficial	Sand	AB	53.388	-113.691	693.3	42
Bruderheim 2340E (S)	176	47.90	Beverly Valley	Gravel	AB	53.877	-112.975	640.0	21
Marie Lake 82-1	192	144.80	Helina V Empress 1	Sand	AB	54.607	-110.253	593.2	25
Marie Lake 82-2 (West)	193	72.50	Muriel Lake (upper)	Sand	AB	54.607	-110.253	593.3	22
Milk River 85-1 (West)	212	73.00	Milk River	Sandstone, light grey	AB	49.144	-111.890	990.0	21
Kirkpatrick Lake 86-1 (West)	228	84.70	Bulwark	Sandstone	AB	51.953	-111.442	774.5	20
Kirkpatrick Lake 86-2 (middle)	229	33.50	Bulwark	Sandstone	AB	51.953	-111.442	774.5	20
Narrow Lake	252	26.80	Channel or surficial	Sand	AB	54.600	-113.631	640.0	21
Milk River 2479E	260	25.90	Buried Valley	Sand	AB	49.115	-112.011	1040	19
Duvernay 2489E	270	20.70	Belly River	Sandstone	AB	53.773	-111.700	580	20
Atton *	Atto	16.15	Surficial	Sand	SK	52.816	-108.869	536.4	38
Baildon 059	B059	30.42	intertill	Sand	SK	50.296	-105.510	583.3	28
Bangor A	Ban A	39.16	Buried Valley	Sand	SK	50.899	-102.287	527.5	32
Bangor B *	Ban B	15.27	Intertill	Sand	SK	50.899	-102.287	527.6	32
Conq 500	C 500	19.16	Intertill	Sand	SK	51.574	-107.174	555.2	31
Conq 501 *	C 501	8.24	Surficial	Sand/silt	SK	51.579	-107.315	572.6	31
Duck Lake 1 *	Duc 1	13.26	Surficial	Sand	SK	52.916	-106.224	502.9	38
Duck Lake 2	Duc 2	124.60	Buried Valley	Sand	SK	52.916	-106.224	502.9	38
Lilac	Lila	122.53	Buried valley	Gravel/sand	SK	52.757	-107.916	548.6	37
M0-5	OG003	9.14	Assiniboine Delta	Limestone or Dolomite	MB	49.768	-97.300	236.9	41
Poplarfield #3	LN001	NA	Assiniboine Delta	Limestone or Dolomite	MB	50.875	-97.855	278.6	40

Well name	Well ID (used)	Depth (m)	Aquifer	Lithology	Prov	Lat	Long	Elev (m)	Years of record
Riceton	Rice	22.40	Emp.	Sand	SK	50.164	-104.317	579.1	34
Sandilands #1	OE001	13.11	Assiniboine Delta	Sand & Gravel	MB	49.240	-97.999	NA	41
Simpson 13-04	SI13	7.22	surficial	Sand	SK	51.457	-105.193	496.6	34
Smokey A *	Smoa	37.12	Bedrock	Sand	SK	53.367	-103.058	319.1	32
Swanson *	Swan	9.18	Surficial	Sand	SK	51.650	-107.066	534.9	30
Tyner	Tyne	113.69	buried valley	Sand	SK	51.024	-108.424	591.3	37
Unity *	Unit	26.72	Intertill	Sand/gravel	SK	52.465	-108.955	673.6	35
Verlo	Verl	12.80	surficial	Clay/silt	SK	50.373	-108.897	737.6	38
Winkler#5	OB005	6.71	Assiniboine Delta	Sand & Gravel	MB	50.875	-97.855	278.7	45

* Groundwater levels reconstructed using tree rings

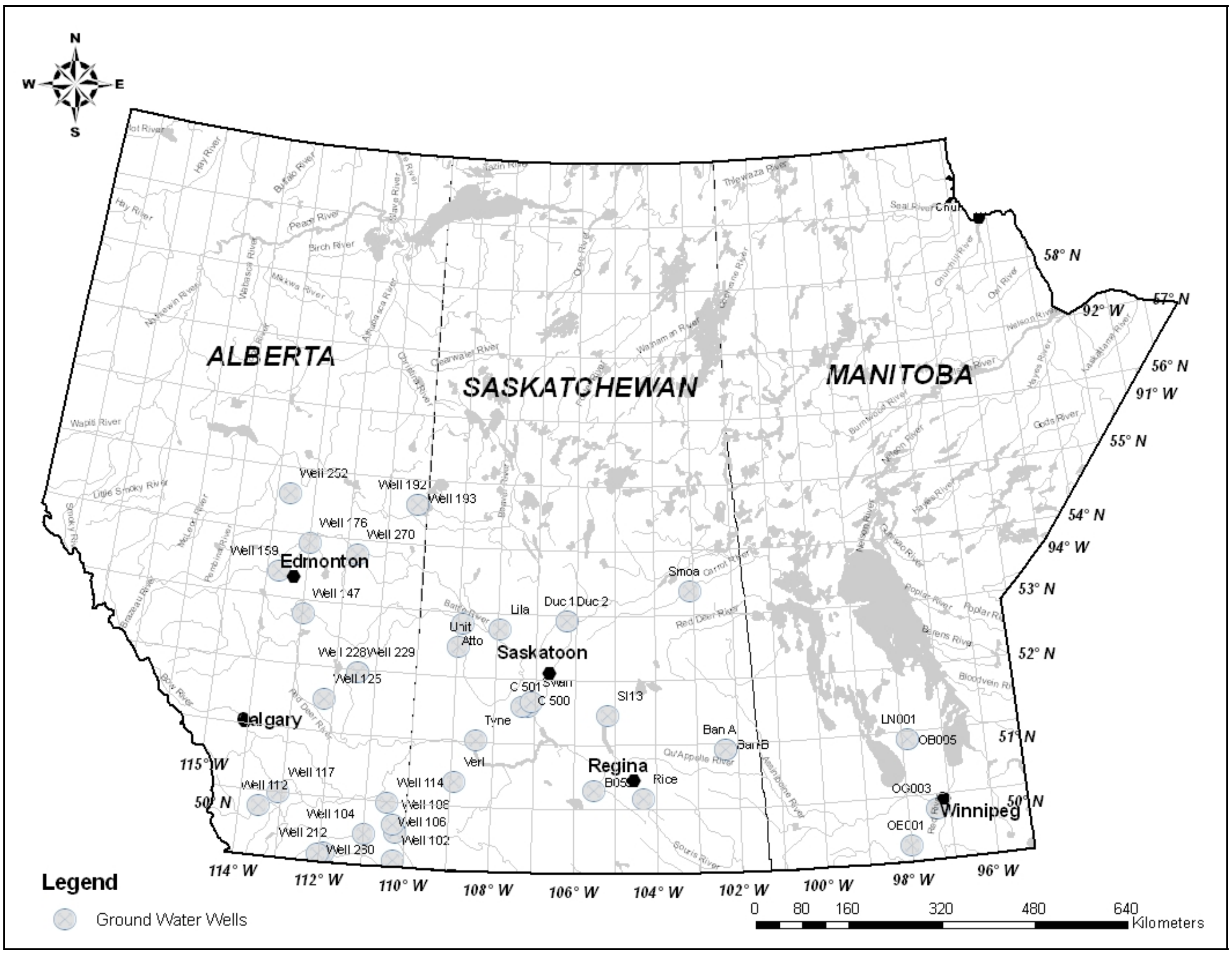

Figure 2.2 Location of the 39 groundwater wells used in this study.

2.1.1 Historical hydrographs

Historical hydrographs were plotted for the 39 well records used in this study. The plots show the original record the whole period of observation, including missing data. The plots are presented for each province.

2.1.1.1 Alberta hydrographs

Hydrographs for 19 wells in Alberta are shown in Figure 2.3. Inter-annual variability is seen mostly in shallow wells (117, 159, 252, 260 and 270). Some inter-annual variability can also be seen in deeper and confined aquifers but this variability is most likely because of the mechanical loading or unloading related to variations in soil moisture (van der Kamp and Maathuis, 1991). Inter-decadal variability is clearly seen in most hydrographs, although it is more evident in wells 114 and 125 that show a clear lower-frequency signal. Large upward trends are obvious for wells 102, 104, and 125. On the other hand, wells 112, 228, 229, 252 show a downward trend. In Chapter V the statistical significance of these trends will be evaluated.

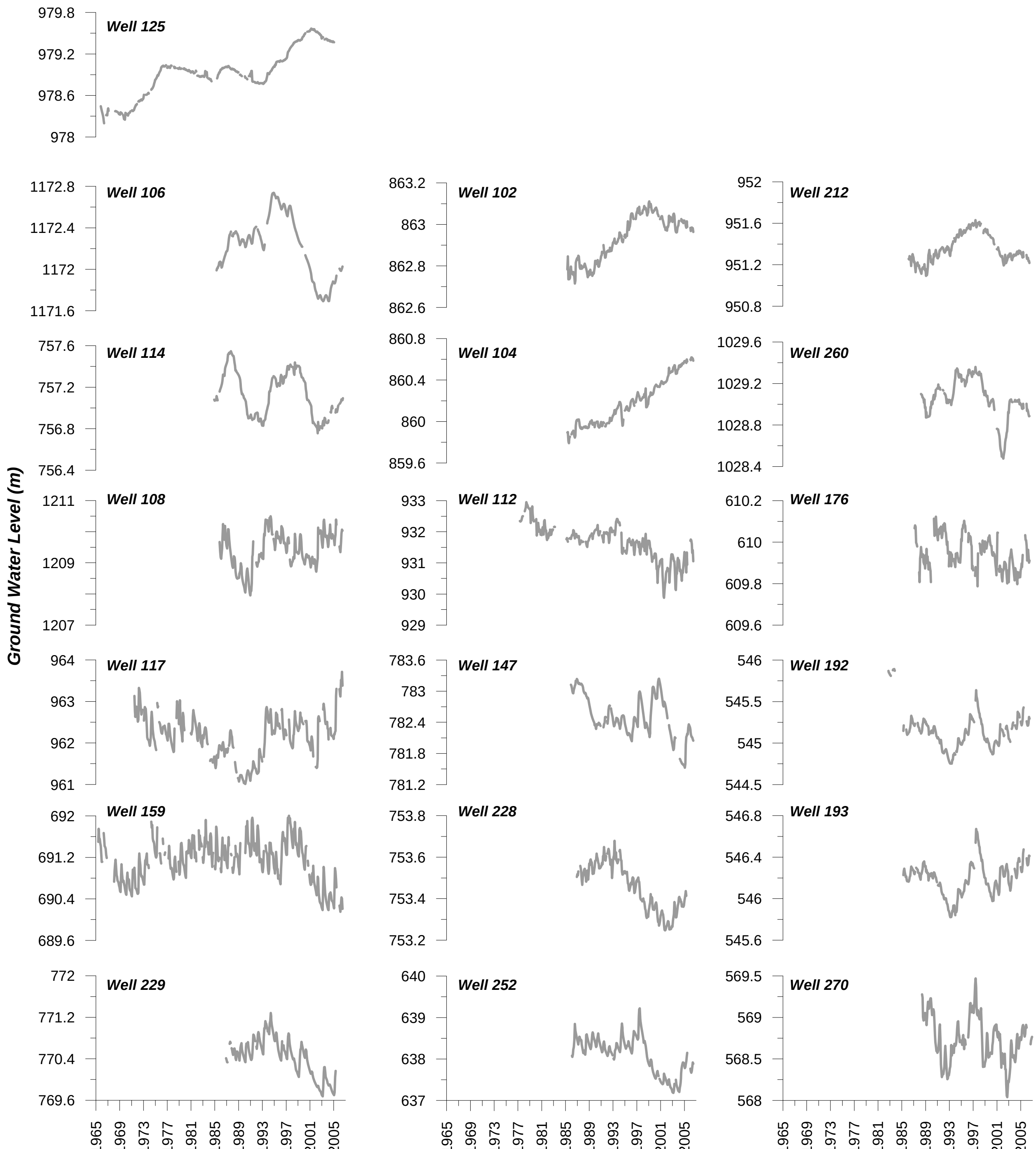

Figure 2.3: Historical groundwater hydrographs for Alberta.

2.1.1.2 Saskatchewan hydrographs

Records for Saskatchewan show that groundwater levels also are subject to some inter-annual and inter-decadal variability. As with the Alberta records, the greater magnitude of inter annual variability is found in shallow wells (depth<30 m; C501, Duc1, and Swan), since depth of the aquifer and degree of confinement have a smoothing effect on groundwater records (van der Kamp and Maathuis, 1991). Downward trends are identified in wells SmoA, Atto, Verl, and Swan, and upward trends in Rice, Lila, Tyne, and C 500 (Fig. 2.4).

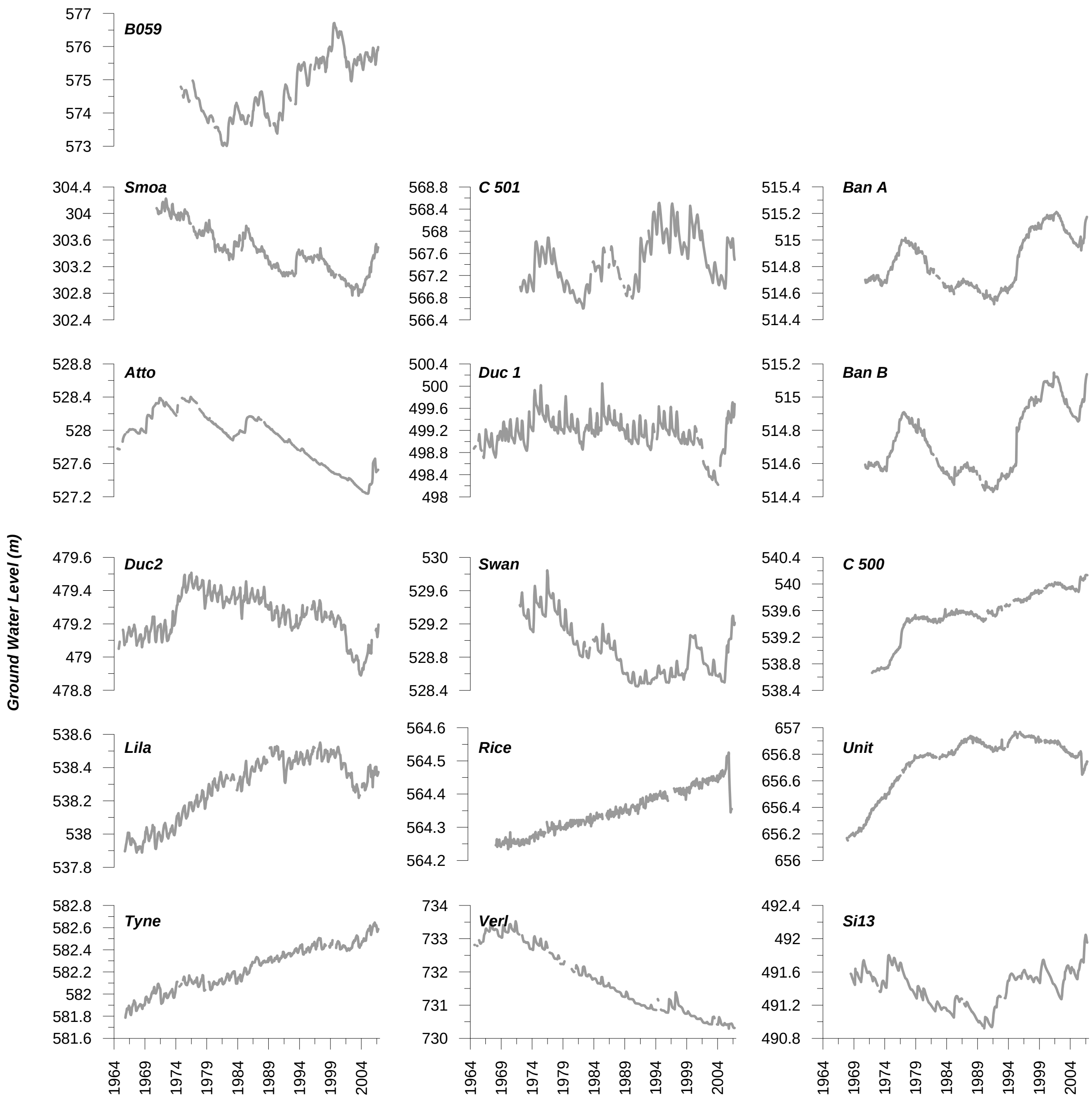

Figure 2.4 Historical hydrographs for Saskatchewan

2.1.1.3 Manitoba hydrographs

Manitoba hydrographs are plotted in Figure. 2.5. Shallow wells show some inter-annual variability and some signal of inter-decadal variability. No trends with a significant magnitude can be seen for the whole period. However, an increasing trend in groundwater levels is identified from 1991 at wells OE001, OB005, and OG003.

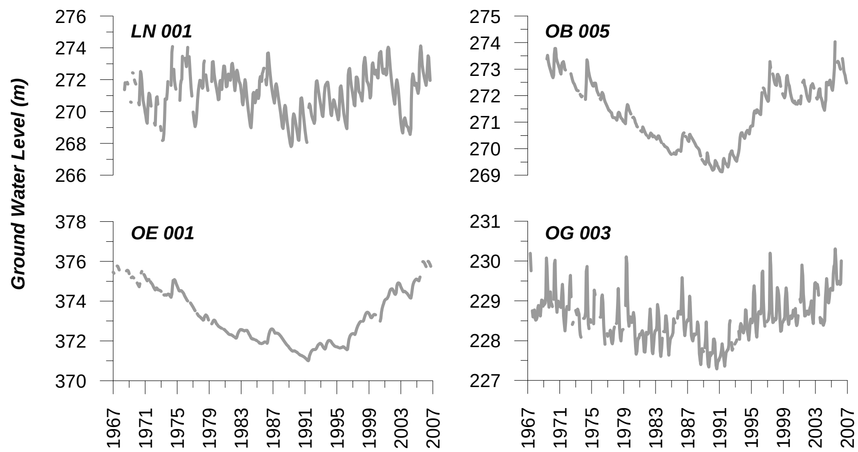

Figure 2.5 Historical hydrographs for Manitoba.

2.1.2 Summary of statistics for groundwater levels

Summary of statistics for mean annual groundwater records are given in Tables 2.2, 2.3, and 2.4. The main statistics calculated for the whole period of record are: the mean, standard deviation and variance, and the median, minimum and maximum and range of groundwater levels. Mean annual groundwater levels were tested for normality using the Shapiro-Wilk test. In Alberta, where the range of groundwater levels has been between 0.3 and 1.7 meters during the last 45 years, six of nineteen records did not pass the normality test. Among these records are the three longest (wells 117, 125, and 159) and best for calibrating and validating tree-ring (linear regression) models of reconstructed groundwater levels.

Table 2.2: Groundwater statistics for wells in Alberta

Well	Mean	Stdev	Var	Median	Min	Max	Range	N	Normal	ACF at p<0.05
w102	862.935	0.103	0.011	862.966	862.768	863.080	0.312	22	Yes	2
w104	860.165	0.195	0.038	860.114	859.908	860.544	0.635	20	Yes	2
w106	1172.234	0.283	0.080	1172.275	1171.721	1172.690	0.969	20	Yes	1
w108	1209.400	0.476	0.227	1209.501	1208.356	1210.090	1.734	20	Yes	1
w112	931.519	0.464	0.216	931.644	930.545	932.157	1.612	20	No	1
w114	757.141	0.208	0.043	757.165	756.813	757.476	0.664	20	Yes	1
w117	962.113	0.444	0.197	962.228	961.146	962.863	1.716	33	No	1
w125	979.040	0.244	0.059	978.962	978.612	979.549	0.938	32	No	1
w147	782.516	0.349	0.122	782.425	781.811	783.143	1.333	20	Yes	1
w159	691.120	0.337	0.114	691.205	690.367	691.715	1.347	38	No	1
w176	609.943	0.058	0.003	609.926	609.839	610.046	0.207	20	Yes	1
w192	545.113	0.144	0.021	545.145	544.801	545.384	0.584	20	Yes	1
w193	546.185	0.137	0.019	546.217	545.872	546.461	0.588	20	Yes	1
w212	951.359	0.127	0.016	951.321	951.157	951.590	0.433	20	Yes	1
w228	753.457	0.112	0.013	753.479	753.268	753.601	0.333	18	Yes	1
w229	770.446	0.328	0.108	770.531	769.833	770.970	1.137	18	Yes	1
w252	638.123	0.410	0.168	638.268	637.381	638.780	1.398	19	No	1
w260	1029.061	0.191	0.037	1029.060	1028.646	1029.305	0.659	17	No	2
w270	568.730	0.230	0.053	568.727	568.322	569.175	0.854	18	Yes	1

In Saskatchewan, the range of variation of water levels is less than in Alberta. Most of the levels vary between 0.22 and 1.5 meters with the exception of well B059 which shows a larger range of variation than the rest (3.92 m). The results of the normality test show that nine time series of groundwater levels do not follow a normal distribution, which has to be considered at the time of multiple regression modeling.

Table 2.3: Groundwater statistics for wells in Saskatchewan

Well	Mean	Stdev	Var	Median	Min	Max	Range	N	Normal	ACF at p<0.05
Atto	527.907	0.309	0.095	527.992	527.319	528.368	1.049	40	No	3
B059	574.721	0.857	0.734	574.594	573.192	576.384	3.192	32	Yes	3
BanA	514.833	0.192	0.037	514.769	514.557	515.188	0.632	35	No	3
BanB	514.731	0.199	0.040	514.685	514.447	515.107	0.660	35	No	2
C500	539.547	0.350	0.123	539.559	538.695	539.999	1.304	34	No	2
C501	567.455	0.400	0.160	567.418	566.742	568.237	1.494	34	Yes	1

Well	Mean	Stdev	Var	Median	Min	Max	Range	N	Normal	ACF at p<0.05
Duc1	499.162	0.252	0.064	499.161	498.345	499.611	1.266	39	No	1
Duc2	479.252	0.126	0.016	479.254	478.953	479.460	0.506	39	Yes	2
Lila	538.282	0.181	0.033	538.323	537.926	538.498	0.571	41	No	3
Rice	564.348	0.063	0.004	564.346	564.252	564.472	0.221	38	Yes	3
Si13	491.422	0.211	0.045	491.467	491.029	491.830	0.801	38	Yes	2
SmoA	303.435	0.343	0.117	303.387	302.867	304.119	1.252	35	Yes	2
Swan	528.883	0.318	0.101	528.867	528.494	529.535	1.041	34	No	2
Tyne	582.234	0.193	0.037	582.257	581.854	582.581	0.727	41	Yes	3
Unit	656.741	0.214	0.046	656.812	656.188	656.938	0.750	38	No	2
Verl	731.735	0.917	0.841	731.666	730.411	733.342	2.930	41	No	3

Water levels in Manitoba had the largest inter-annual variability in the Prairies in the range of 1.9 and 4.0 meters (Table 2.4) and three out of four time series passed the normality test.

Table 2.4: Groundwater statistics for wells in Manitoba

Well	Mean	Stdev	Var	Median	Min	Max	Range	N	Normal	ACF at p<0.05
Ln001	271.150	1.109	1.229	271.042	268.798	272.864	4.066	30	Yes	1
Ob005	271.257	1.067	1.139	271.322	269.336	273.208	3.873	36	Yes	2
Oe001	372.981	1.138	1.296	372.709	371.215	374.820	3.604	35	No	2
Og003	228.501	0.433	0.187	228.491	227.645	229.622	1.976	38	Yes	2

In addition to these basic statistics, autocorrelation functions (ACF) were calculated for all the records. The structure in the autocorrelation functions is important for trends analysis, since first order autocorrelation might have an effect on the detection of trends.

In general groundwater levels in the Prairies are significantly auto-correlated for up to three years. Overall, water levels in Alberta have significant auto-correlation of order 1, at some wells second order autocorrelation was detected but mostly the first order is statistically significant at $p < 0.05$. In Saskatchewan, second and third order auto-correlation is more common than in Alberta, and the few water records for Manitoba show significant auto-correlation of first and second order. Considering the values of auto-correlation in the table A1 (Appendix), the lack of significance of second and third order autocorrelation might be due to the length of the record which in most cases just exceeds 20 years. No relationship between higher order auto-correlation and depth or geology was observed.

2.1.3 Groundwater response

Groundwater in the prairies responds to snow melt and spring and summer precipitation. The peak level varies according to the aquifer and is reached either in early spring or late fall.

The analysis of groundwater response is carried out according to the province where the well is, even though, climate and geology are similar. In addition to groundwater response all further analysis will be carried out according to the Prairie Provinces since the data was obtained from different organization from the provinces.

2.1.3.1 Alberta

Four different kinds of groundwater response have been identified in the nineteen groundwater records. Wells 108, 117, 159, 192, 193, 229, 252, and 270 have a clear response to snow melt and spring and summer precipitation (Fig. 2.6). Groundwater levels start to rise during March and April reaching the peak in the late spring and summer. Water levels decline after this peak period reaching the minimum level during winter. The second kind of groundwater response identified in six wells (Wells 102, 104, 112, 114, 176 and 228) is rising groundwater levels in late winter reaching the peak in early March or April. These wells might have a connection with surface water such that groundwater levels start to decline during spring and reach the minimum levels during the summer. A third kind of response was detected in four wells (106, 125, 147 and 212). In this response water levels start to rise with the spring precipitation and snow melt reaching a peak during the late spring, levels then decline in early summer, and continue increasing through the summer and fall reaching the peak in the fall. A unique case of response was detected for well 260, where in this well as most of the others, groundwater levels start to rise during the spring reaching a peak at the end of the spring, to decline after. However, the highest peak is reached in December.

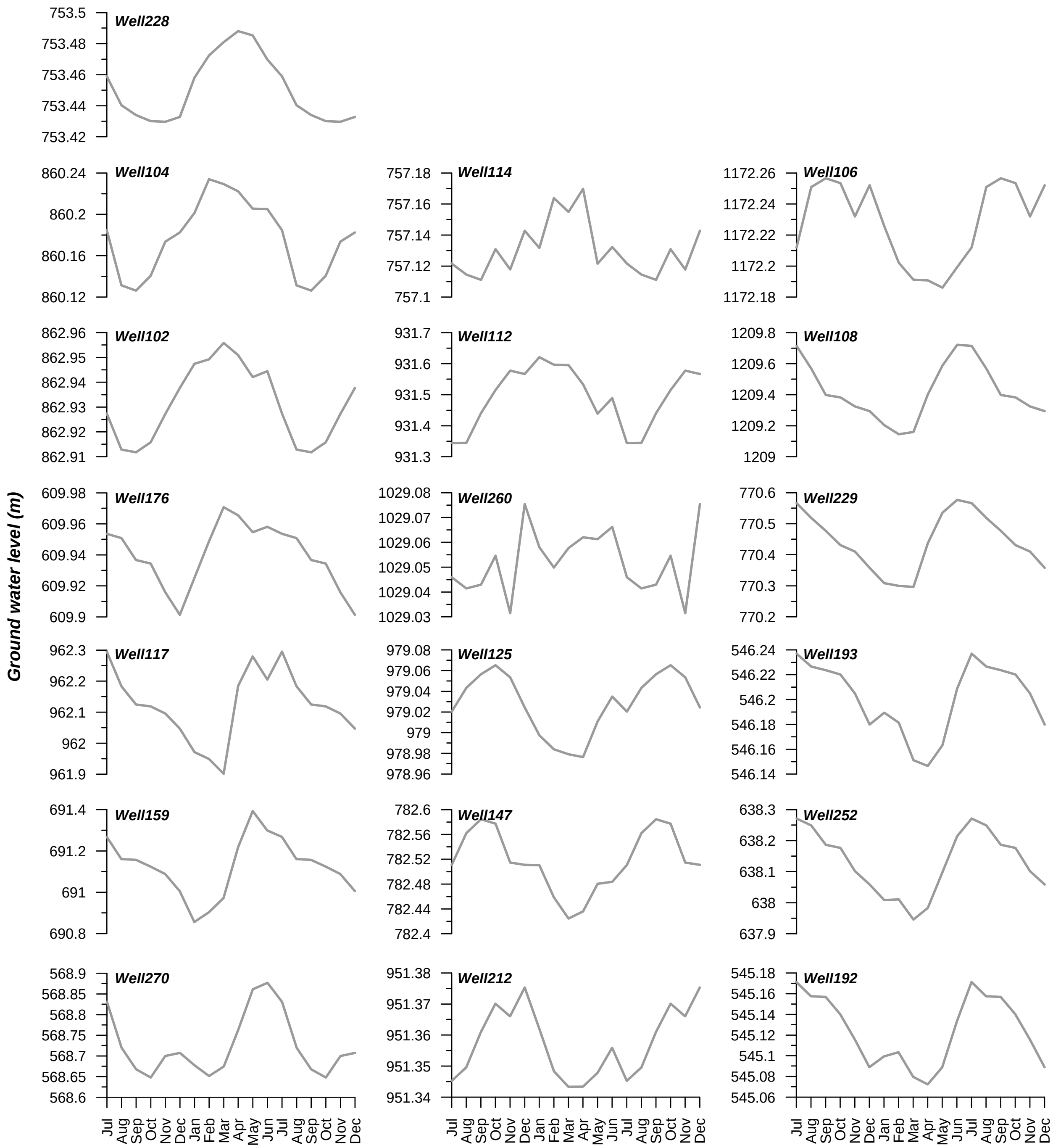

Figure 2.6: Monthly groundwater levels in Alberta.

2.1.3.2 Saskatchewan

Four different types of groundwater response were identified in Saskatchewan. The dominant response is found in eight wells and consists of a fast response to snow melt during spring. Groundwater levels at wells Atto, Ban A, Ban B, C501, Duc1 Si13, Swan, and Verl start to rise in spring reaching the peak in the late spring or summer. Water levels then decline to the lowest levels in winter (Dec-Jan). A second group of three wells (Smoa, Unit, Rice) respond mostly to precipitation. In these wells, peaks are seen in spring, summer, and fall suggesting that precipitation is the main driver of the water level variability. The first peak in spring might be caused by the interaction of snow melt and precipitation; after this peak water levels decline in early summer to increase again and reach a second peak in late summer and continue increasing to the highest level in the fall. The lowest water levels found with this kind of response are in early summer. A different kind of response is found in deep aquifers (Duc 2, Lila, and Tyne). It is characterized by a gradual and constant increasing of water levels starting in the fall, continuing in winter, and reaching the highest level in spring decreasing after to the lowest level in late summer and early spring. Finally, wells C500 and B059 seem to respond to fall precipitation. Water levels begin to rise during the summer reaching the highest level in fall. The lowest water levels in these wells are during the winter at well C500 and early spring at well B059. The depths of these wells are 19.16 and 30.42 meters which suggest that there is some degree of delay in the response. This delay can be seen in Figure 2.7 in which there is a lag for the highest and lowest groundwater levels.

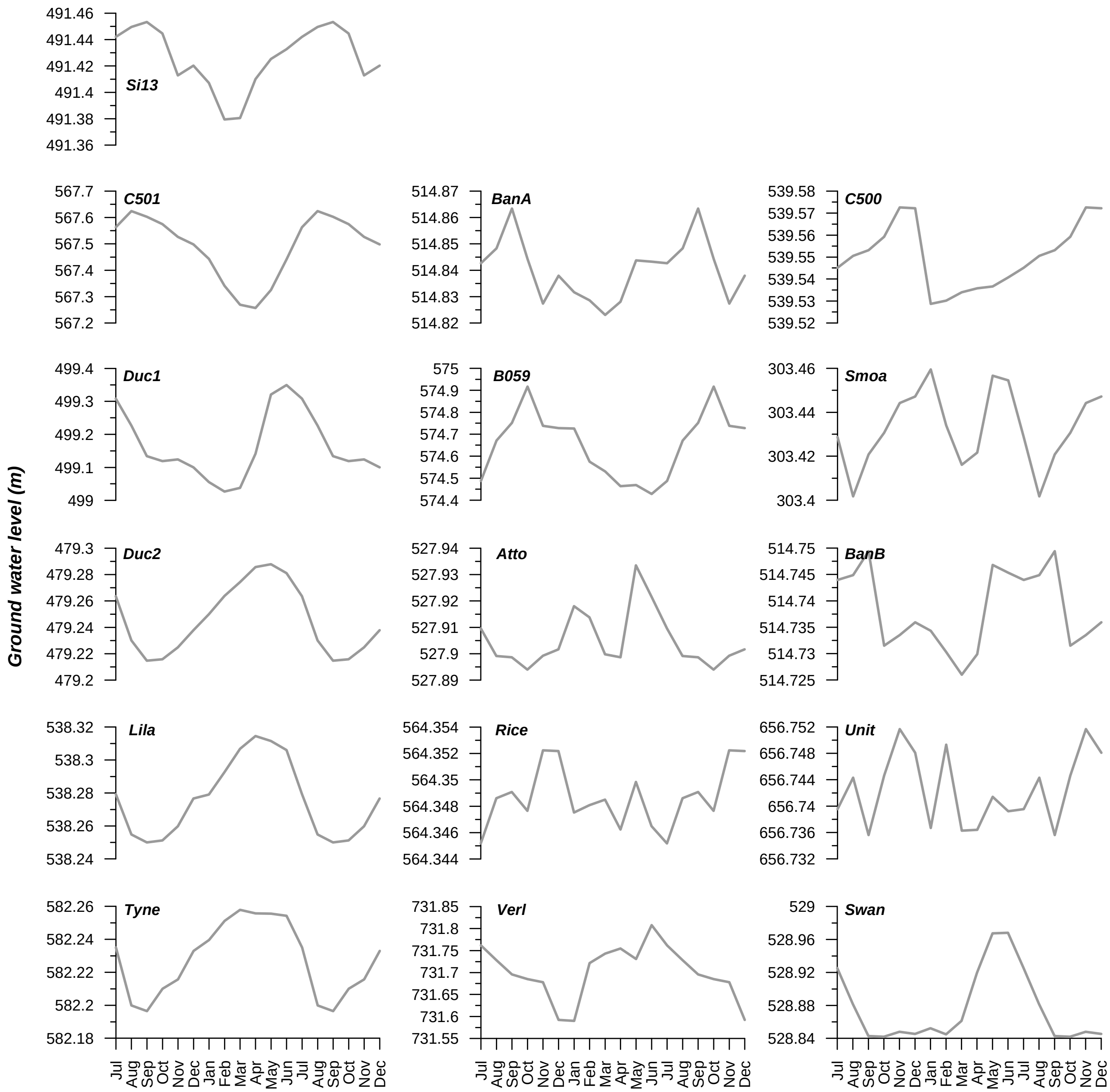

Figure 2.7: Monthly groundwater levels in Saskatchewan.

2.1.3.3 Manitoba

Monthly hydrographs (Fig. 2.8) for the four wells in Manitoba show three different kinds of response. Wells LN001 and OB005 clearly respond to the snow melt during the spring and precipitation during spring and summer. In both wells the highest levels are reached in summer and decrease constant after that. The lowest levels are seen in late winter.

Wells OE001 and OG003 have a different kind of response. The first one presents a response to fall precipitation reaching a peak in this season. Water levels decline until winter, the season in which they start to rise again reaching the second highest peak in the year driven by the snow melt. A small response to spring and summer precipitation is detected in this well increasing water levels in early summer. However, the lowest water level is reached in the middle of the summer. Well OG003 has a fast response to snow melt and precipitation in spring, the season with peak levels. The lowest groundwater level is seen in the middle of the fall.

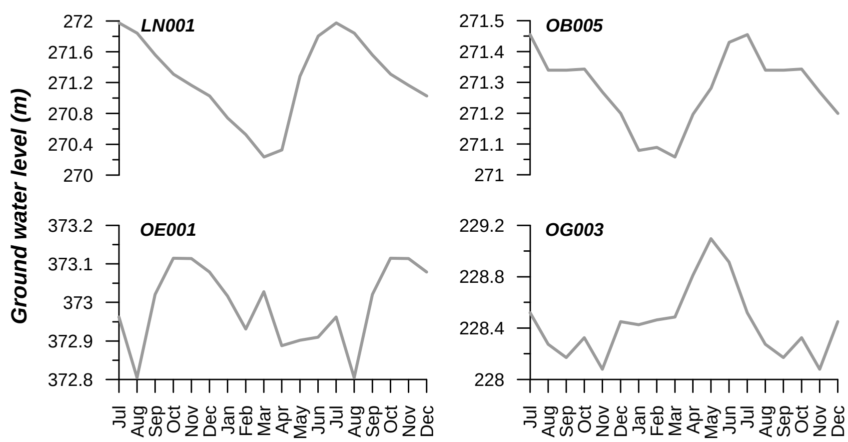

Figure 2.8: Monthly groundwater levels in Manitoba.

2.2 Tree-ring chronologies

A network of 31 tree-ring chronologies was used in this study. Six species of trees (Picea Glauca, Pseudotsuga Menziessi, Pinus Flexilis, Pinus Banksiana, Pinus Contorta, and Quercus Macrocarpa) at 31 sites (Table 2.5) were sampled and processed in the Tree Ring Laboratory of the University of Regina during the last 10 years. Standard dendrochronological methods (Stokes and Smiley 1968; Fritts 1976; Cook 1985; Cook and Kairiukstis 1990) were used in the construction of the chronologies. Conservative detrending (negative exponential or a smoothing spline 67%) was used to remove the growth trends. Cross-dating of the time series, to detect missing or false rings, was verified with COFECHA (Holmes, 1983). For more detail in dendrochronology methods see Axelson (2007).

Table 2.5: Tree-ring chronologies

Site name	ID	Study Area	Pro	Specie Name	Elev	Lat	Lon	Period	Yrs	Cores
Beauvais Lk.- Marna Lk,, Mt. Baldy	BEL	Alberta Foothills	AB	*Picea glauca*	1427	49.4	-114.1	1627-2004	378	34
Beaver Dam Creek - Whalebacks	BDC	Alberta Foothills	AB	*Pseudotsuga menziesii*	1661	49.9	-114.2	1482-2004	523	44
Blackstone Gap	BSG	Alberta Foothills	AB	*Picea glauca*	1810	52.6	-116.6	1668-2003	336	36
Cabin Creek - Porcupine Hills	CAB	Alberta Foothills	AB	*Pseudotsuga menziesii*	1395	49.7	-114.0	1375-2004	630	44
Callum Creek - Whalebacks	CAL	Alberta Foothills	AB	*Pseudotsuga menziesii*	1677	50.0	-114.2	1572-2004	433	36
Dutch Creek	DCK	Alberta Foothills	AB	*Pseudotsuga menziesii*	1648	49.9	-114.4	1618-2004	387	42
Emerald Lake - Crowsnest Pass	ELK	Alberta Foothills	AB	*Pinus flexilis*	1384	49.6	-114.6	1450-2004	555	38
Fighting Lake	FLK	Northern Alberta	AB	*Pinus banksiana*	516	56.63	-119.6	1860-2006	147	34
Highway 88	H88	Northern Alberta	AB	*Pinus banksiana*	Na	57.24	-115.2	1856-2007	152	32
Little Bob Creek - Whalebacks	LBC	Alberta Foothills	AB	*Pseudotsuga menziesii*	1602	49.9	-114.2	1509-2004	496	46
Marten Mountain	MTM	Northern Alberta	AB	*Picea glauca*	NA	55.47	-114.8	1817-2004	188	12
Old Man River - WhaleBacks	ORPF	Alberta Foothills	AB	*Pinus flexilis*	1427	49.8	-114.2	1203-2004	802	64
Onion Creek - Porcupine Hills	OCPc	Alberta Foothills	AB	*Pinus contorta*	1280	49.7	-114.1	1684-2003	320	18
Ruby Ridge	RBR	Alberta Foothills	AB	*Pseudotsuga menziesii*	Na	Na	Na	1854-2006	153	12
Stoney Indian Park - Stoney Indian Reserve	SIP	Alberta Foothills	AB	*Pseudotsuga menziesii*	Na	51.1	-115	1597-2003	407	26
Swan Hills - Swan River	SW1	Northern Alberta	AB	*Picea glauca*	Na	54.8	-115.6	1752-2004	253	10
Swan Hills - Swan River	SW2	Northern Alberta	AB	*Pinus banksiana*	Na	54.8	-115.6	1733-2004	272	22
West Sharples Creek	WSC	Alberta Foothills	AB	*Pseudotsuga menziesii*	1575	49.9	-114.1	1525-2004	480	62
Wildcat Hills	WCH	Alberta Foothills	AB	*Pseudotsuga menziesii*	1351	51.3	-114.7	1341-2004	664	40
Boland Lake - Wollaston Lake	WLPg	Churchill River	SK	*Picea glauca*	474	57.8	-103.8	1852-2002	151	28

Site name	ID	Study Area	Pro	Specie Name	Elev	Lat	Lon	Period	Yrs	Cores
Boland Lake - Wollaston Lake	WLPb	Churchill River	SK	*Pinus banksiana*	474	57.8	-103.8	1817-2002	186	22
Cypress Hills	CHPc	Cypress Hills	SK	*Pinus contorta*	1000	49.7	-110	1872-2001	130	60
Doupe Bay - Jan Lake	DBY	Churchill River	SK	*Picea glauca*	315	54.9	-102.8	1839-2001	163	48
Devon Farm	DEV	Qu'Appell e Valley	SK	*Quercus macrocarpa*	440.4	50.47	-101.8	1853-2005	153	26
Fraser Bay - Otter Lake	FBY	Churchill River	SK	*Picea mariana*	355	55.6	-104.7	1854-2001	148	50
Fleming Island	FIL	Churchill River	SK	*Pinus banksiana*	510	57.4	-106.9	1766-2002	237	36
Hillside	HIL	Qu'Appell e Valley	SK	*Quercus macrocarpa*	450.4	50.53	-102.0	1909-2005	97	12
Holt Lake	HLK	Churchill River	SK	*Pinus banksiana*	470	56.3	-106.8	1943-2002	60	16
Ithingo Lake	ILK	Churchill River	SK	*Pinus banksiana*	500	56.8	-107.6	1875-2002	128	28
Kinapik Lake	KIL	Churchill River	SK	*Picea glauca*	390	55.7	-106.4	1840-2001	162	54
McGugan Island	MIL	Churchill River	SK	*Pinus banksiana*	540	57.1	-105.5	1832-2002	171	32
MacIntyre Lake	MLK	Churchill River	SK	*Pinus banksiana*	500	57.4	-106.1	1854-2002	149	30
Otter Rapids	ORP	Churchill River	SK	*Picea glauca*	360	55.63 3	-104.7	1979-2002	124	42
Patterson Peninsula	PPN	Churchill River	SK	*Picea glauca*	370	55.2	-104.5	1827-2001	175	48
Sanford Island - Reindeer Lake	SIL	Churchill River	SK	*Pinus banksiana*	410	56.5	-103.0	1878-2002	125	38

The tree-ring records used are part of a larger network of moisture-sensitive tree-ring chronologies spanning the Northwest Territories, Alberta, Montana and Saskatchewan. Moisture stressed trees were sampled mostly on dry south-facing slopes. Annual and seasonal moisture conditions for more than 800 years are obtained from these trees (Figure 2.9). The 31 standard index chronologies used are from sites in the foothills and boreal forests of Alberta, northern Saskatchewan and the Qu'Apelle Valley, and cover the period 1203 to 2006. The oldest trees (longest chronologies) are found in south-western Alberta, whereas the shortest chronologies are located in Saskatchewan (Fig. 2.9; 2.10), and give information of moisture conditions for the past 200 years.

Different periods of dry conditions can be identified from the tree-ring chronologies; for example, the historical droughts of the 1920s-30s are perfectly identified in the chronologies from Alberta (Fig. 2.9). This correlation between ring width and available moisture allows us to identify many other periods of dry conditions that are even longer than the 1920s-30s (i.e. 1475-1525, 1610-1660, periods in which there is no instrumental record of any climatic variable).

The northern Saskatchewan chronologies show different periods of dry conditions than the chronologies in Alberta, given the different regional climate conditions. The Fleming Island (FIL) chronology shows the 1810- 1855 period as being very dry, however, this is not seen in the Alberta chronologies. The location of the 31 moisture sensitivity tree-ring chronologies is shown in Figure 2.11.

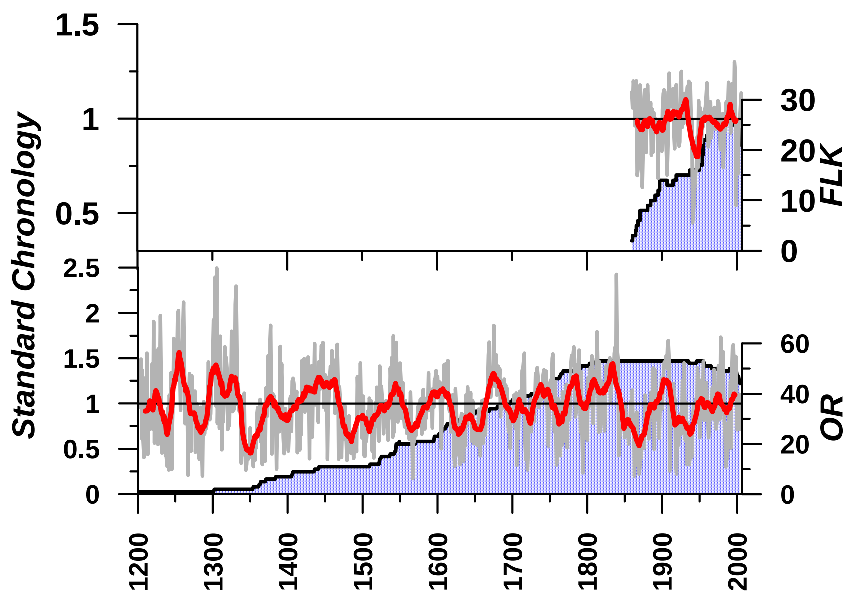

Figure 2.9: Standard chronology index (grey line) for the Fighting Lake (FLK) and Oldman River (OR) sites. The red line depicts a 15-year running average. Index values below and above one represent dry and wet conditions respectively. Notice in the Oldman River chronology that there are several periods of prolonged dry conditions. The right vertical axis shows the sample depth, which is the number of samples trough time.

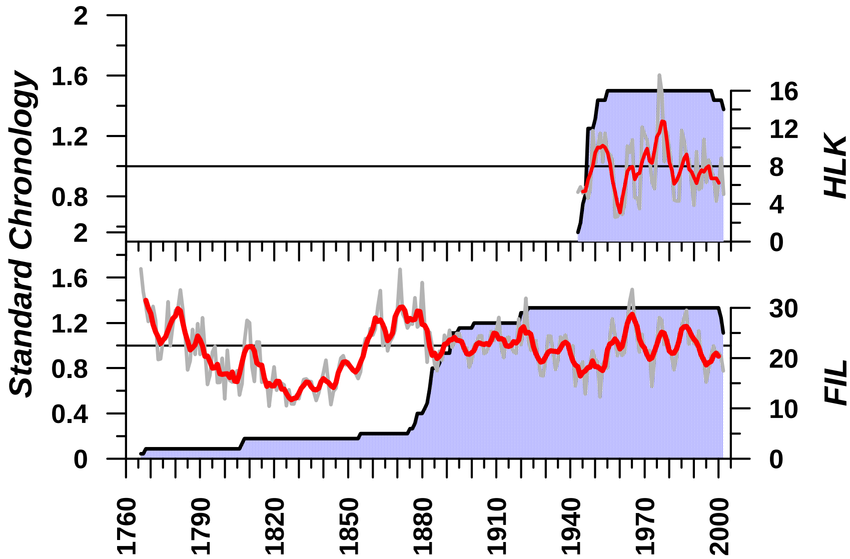

Figure 2.10: Standard chronology index (grey line) for the Hot Lake (HLK) and Fleming Island (FIL) chronologies. The red line depicts a 5-year running average. Index values below and above one represent dry and wet conditions respectively. Chronologies in Saskatchewan record different climate events than in Alberta (i.e. 1800-1860 period).

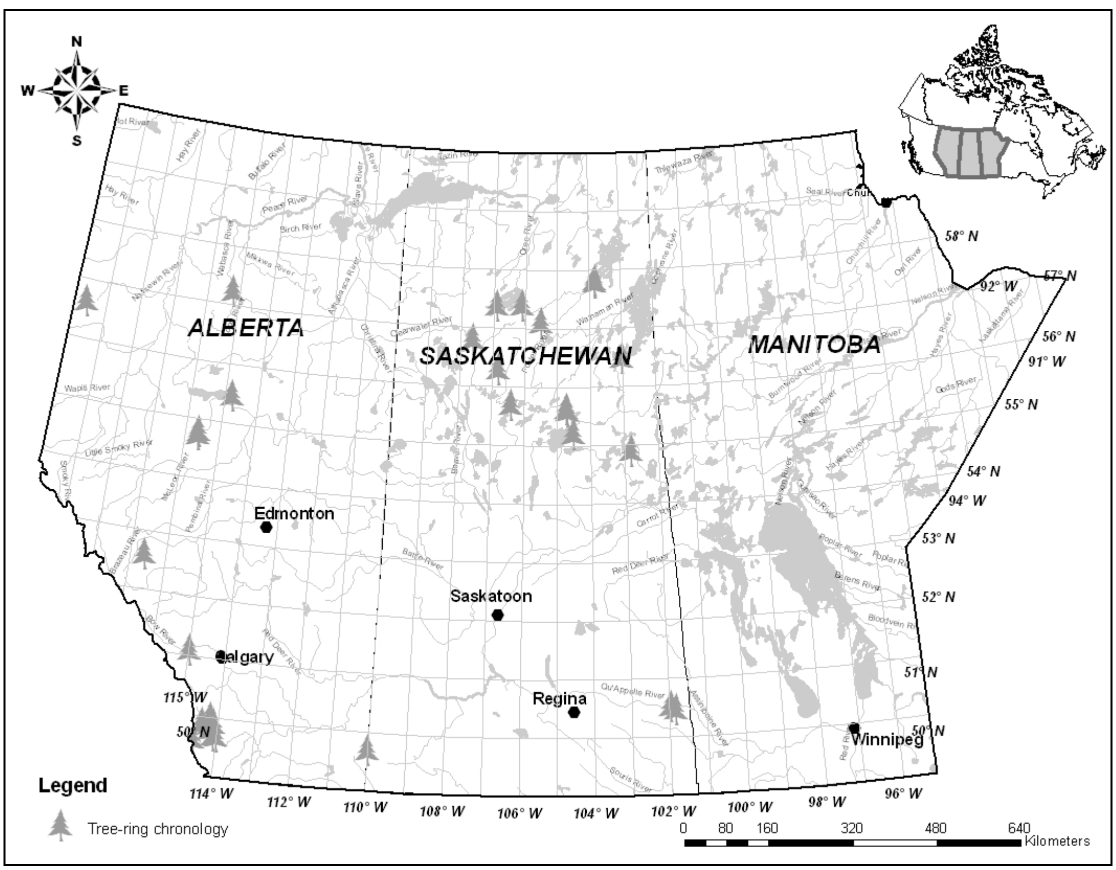

Figure 2.11 Location of the 31 tree-ring chronologies in the Prairies.

2.3 Precipitation and temperature data sets

Gridded precipitation and temperature were obtained for western Canada from the CRU TS 2.1 data set (Mitchell and Jones, 2005) that extends from 1901-2002 and is based on 1224 monthly grids of observed climate of 0.5 degrees of resolution. There are nine climate variables in this data set, but only temperature and precipitation were used in this study.

3. GROUNDWATER, CLIMATE AND TREE-RING RELATIONSHIPS

This chapter explores the linear relationship of groundwater levels with precipitation, temperature and tree-ring variables by calculating simple bi-variate correlations and plotting correlations maps. Monthly, seasonal, and annual correlations were computed using different lags. For example, monthly correlations were calculated with lags of up to 18 months, seasonal with lags of up to 4 seasons, and annual with lags of up 2 years. This chapter summarizes some of the most significant results of this correlation analysis.

3.1 Groundwater and climate

Correlation maps were generated using the climate explorer tool from Royal Netherlands Meteorological Institute available at http://climexp.knmi.nl/start.cgi?someone@somewhere. The number of groundwater wells explored using this tool was limited to the wells selected to reconstruct groundwater levels which are three in Alberta and eight in Saskatchewan. They were selected since their records extend for more than 30 years and have high significant correlations with tree-ring chronologies. This was due to the limited number of correlation maps that can be created using different correlation periods and lags. The use of correlation maps make possible the identification of the area of influence that precipitation and temperature have on groundwater levels at different wells, therefore, significant positive and negative correlations are plotted.

3.1.1 Groundwater levels and precipitation

In Alberta, significant correlations between water levels and precipitation were found at the three wells studied. Spring (Mar.-May) groundwater levels at well 117 have a significant ($p < 0.05$) positive correlation ($r > 0.3$) with winter (Dec.-Feb.) precipitation in the area nearby (Fig. 3.1). Same order correlations were found in a similar area for summer (Jun.-Aug.) groundwater levels with winter precipitation. However, the strongest relationship ($0.4 < r < 0.6$, $p < 0.05$) was found for January groundwater levels with December precipitation (not shown). Strong negative correlations ($r < -0.4$) were found between fall (Sep.-Nov.) groundwater levels for well 125 and the precipitation for the period Mar-Nov. (Fig. 3.2). Fall water levels correlates with $Dec_{(-1)}$-Aug. precipitation with a higher and significant negative relationship ($r < -0.6$) at well 125 (correlation not shown). Summer groundwater levels at well 159 correlate significantly with spring precipitation ($r > 0.2$), although, May precipitation has an important effect on groundwater levels for the months of May, June and September ($r > 0.5$). Figure 3.3 shows September groundwater levels correlated with May precipitation at well 159.

In Saskatchewan, summer groundwater levels at well Atto have a strong correlation ($r > 0.5$) with Dec-May precipitation. The same magnitude of relationship is found for spring water levels with winter precipitation (Fig. 3.4).

No significant correlation between water levels and precipitation was found at well Ban B. December precipitation has a significant negative effect ($r > -0.4$) on groundwater levels in January, February, March and April at well C 501. Figure 3.5 shows correlations for March groundwater levels at well C501 with December precipitation. March precipitation has a significant correlation ($r > 0.4$) with April and May groundwater levels at well Duck 1 (Fig. 3.6). A smaller correlation ($r > 0.3$) is found for August precipitation and water levels during September and October. Summer groundwater levels correlate with precipitation for the periods of Dec-May and March-May. Also, spring water levels correlate with winter precipitation ($r > 0.2$). Well Duck 2 shows low correlations for summer groundwater levels with spring precipitation ($r > 0.3$). Higher correlations for Duck 2 are found between May precipitation and June groundwater levels (Fig. 3.7). Seasonal significant correlations ($r > 0.4$) are found at well SmoA for spring and summer groundwater levels with winter precipitation (Figure 3.8). Negative correlations ($r < -0.4$) are detected for spring water levels with winter precipitation at wells C 501 and Unit (Fig 3.10). The effects of winter precipitation carry on to summer groundwater levels correlating negatively. Finally, at well Swan winter precipitation correlated with water levels in summer ($r > 0.3$) and to a lesser extent spring (Fig. 3.9).

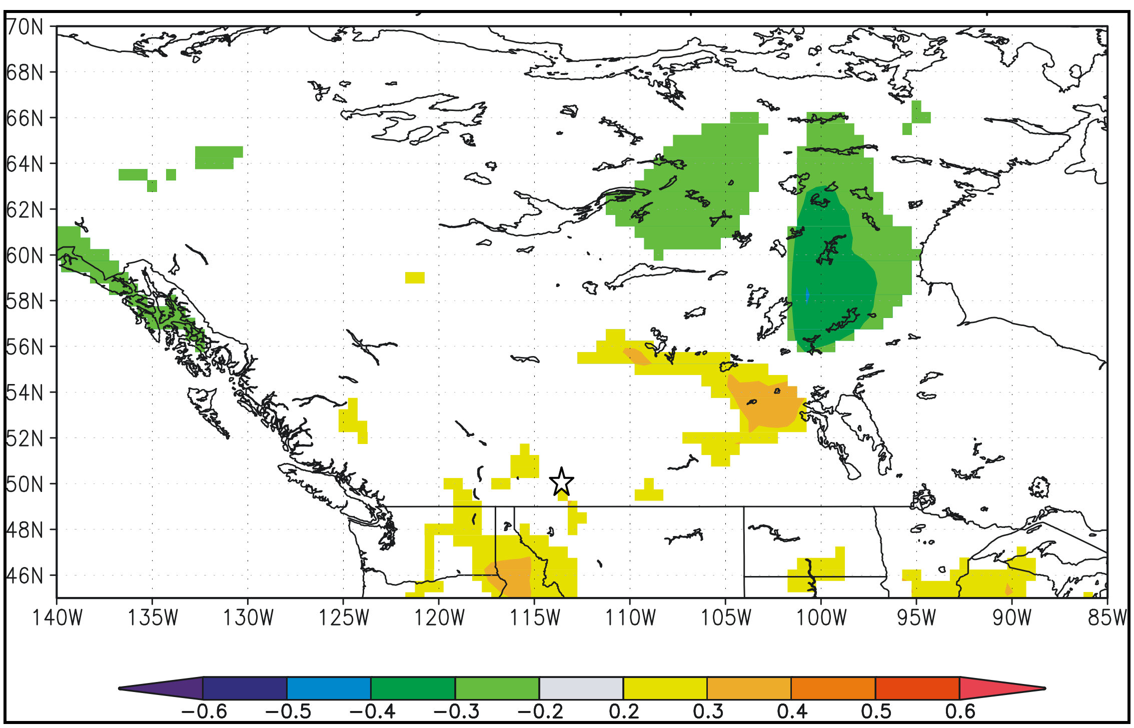

Figure 3.1: Correlation map between Mar-May groundwater level at well 117 (star) and Dec-Feb precipitation for the period 1971-2002 ($p < 0.05$).

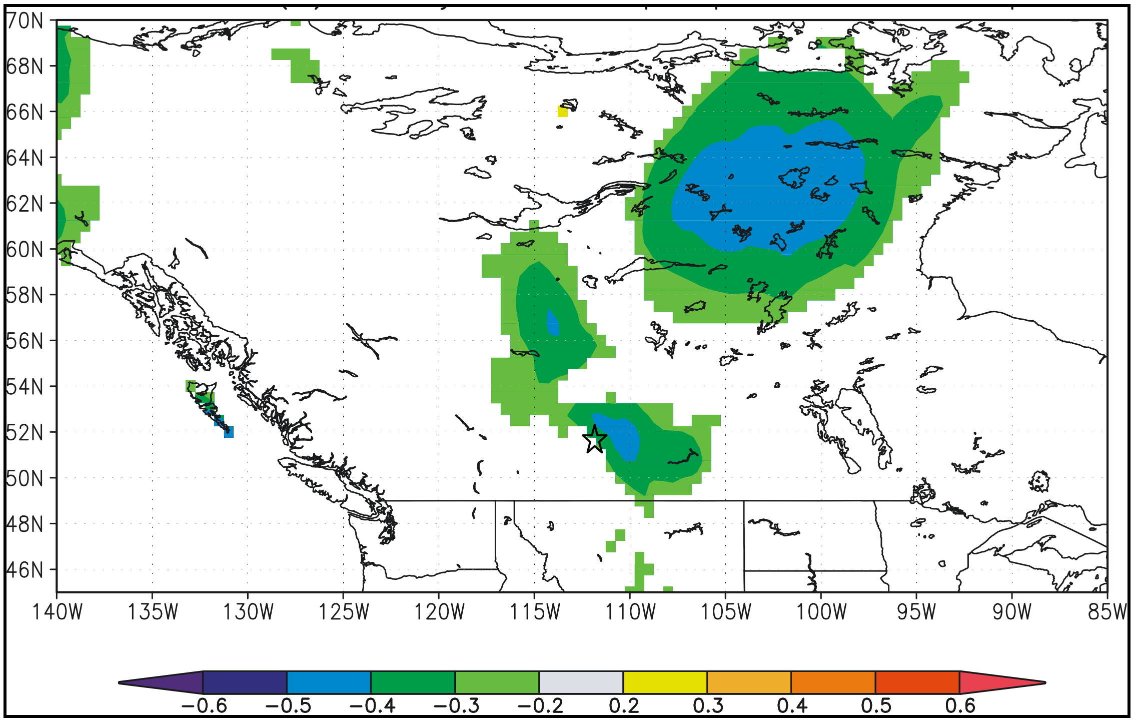

Figure 3.2: Correlation map between Sep-Nov groundwater level at Well 125 (star)and Mar-May precipitation for the the period 1975-2002 ($p < 0.05$).

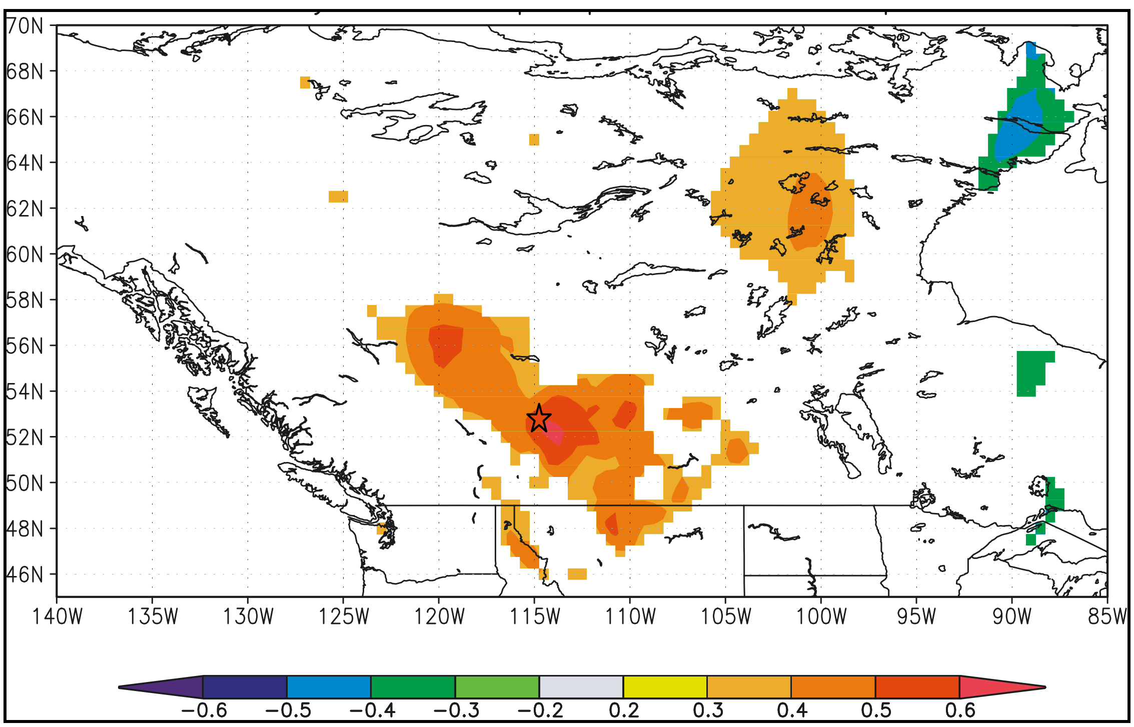

Figure 3.3: Correlation map between Sep. groundwater level at well 159 (star) and may precipitation for the period 1967-2002 ($p < 0.05$).

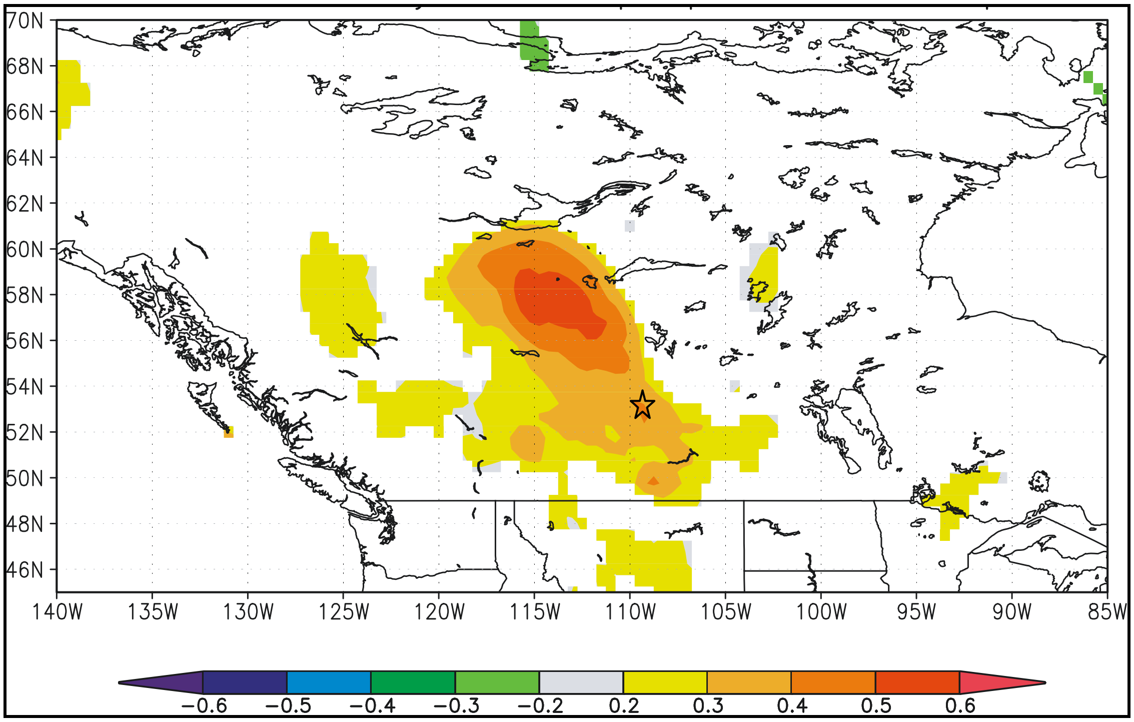

Figure 3.4: Correlation map between spring (Mar-May) groundwater level at Atto (star) and winter (Dec-Feb) precipitation for the period 1965-2002 ($p < 0.05$).

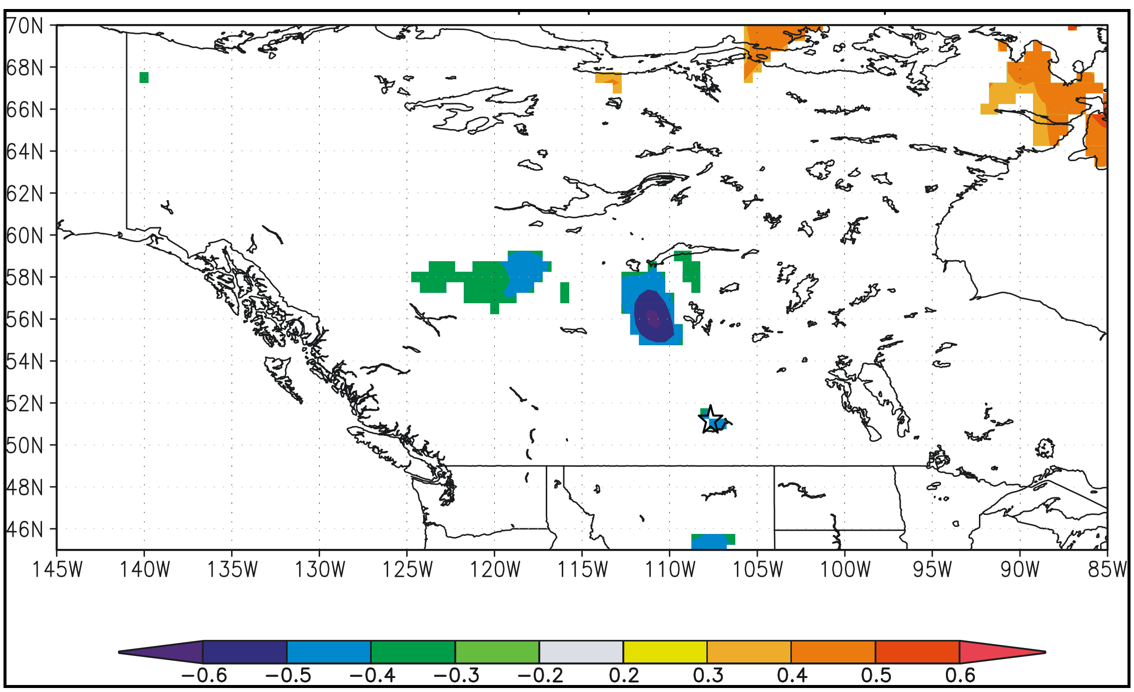

Figure 3.5: Correlation map between Mar groundwater levels at well C501 (star) and Dec precipitation for the period 1972-2002 ($p < 0.05$).

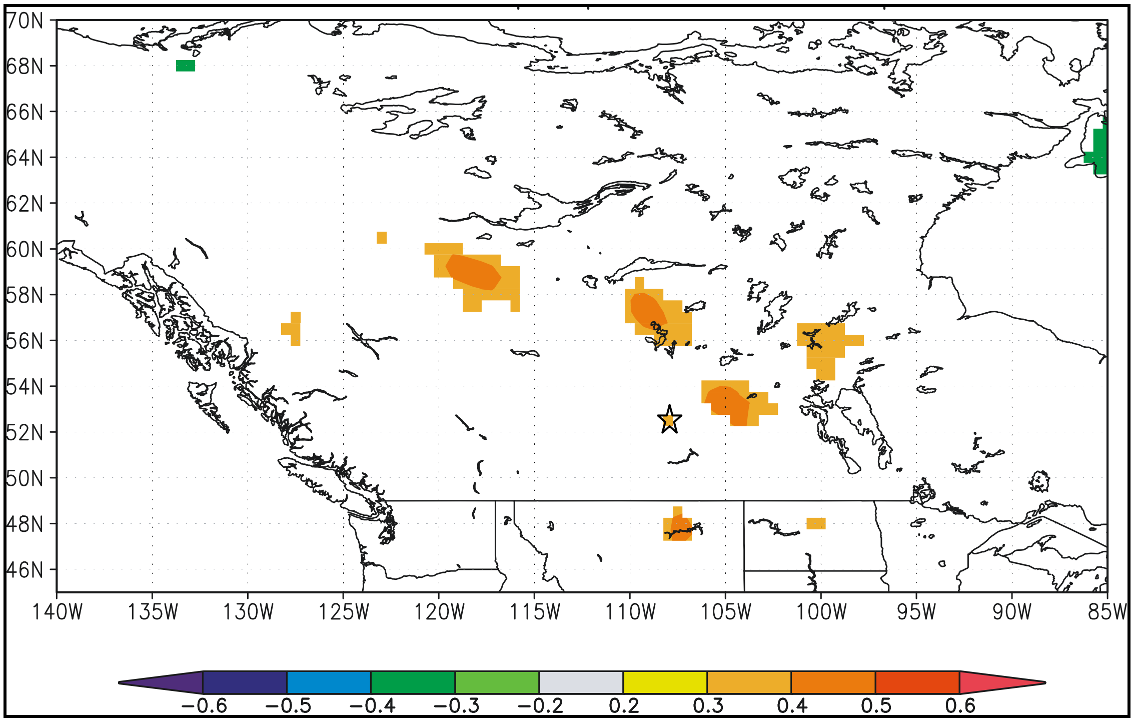

Figure 3.6: Correlation map between May groundwater levels at well Duck 1(star) and Mar precipiation for the period 1966-2002 ($p < 0.05$).

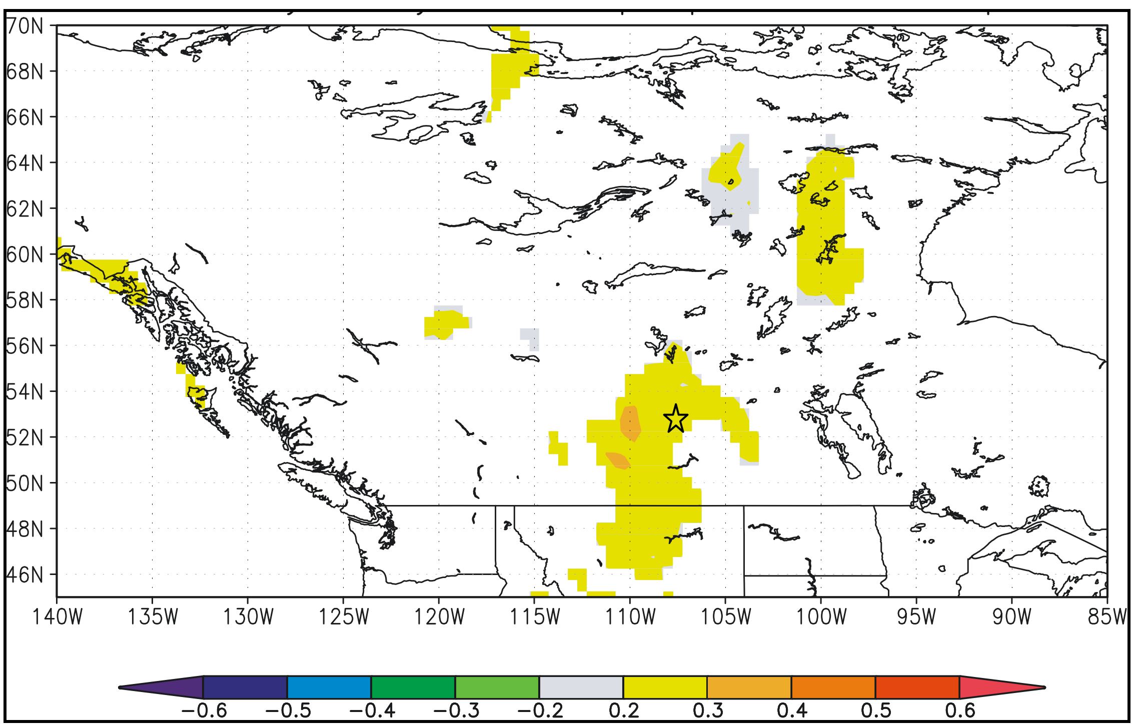

Figure 3.7: Correlation map between summer (Jun-Aug) groundwater levels at Duck 2(star) and spring (Mar-May) precipitation for the period 1966-2002 ($p < 0.05$).

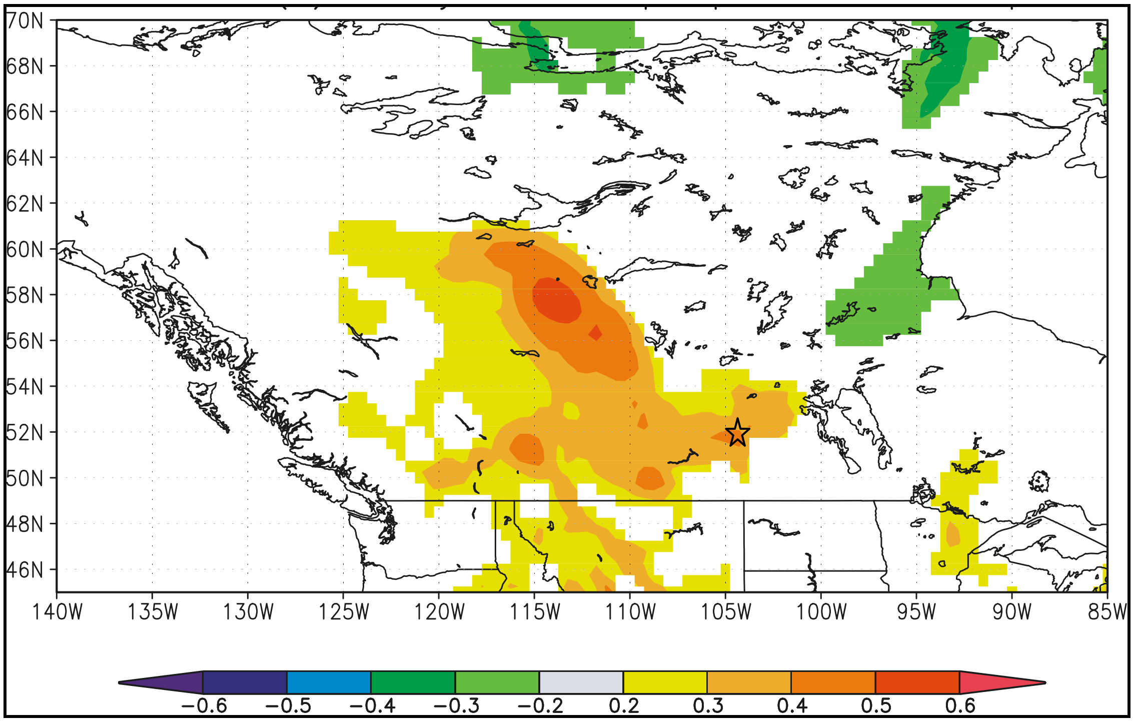

Figure 3.8: Correlation map between summer (Jun-Aug) groundwater levels at SmoA (star) and winter precipitation for the period 1970-2002 (p<0.05).

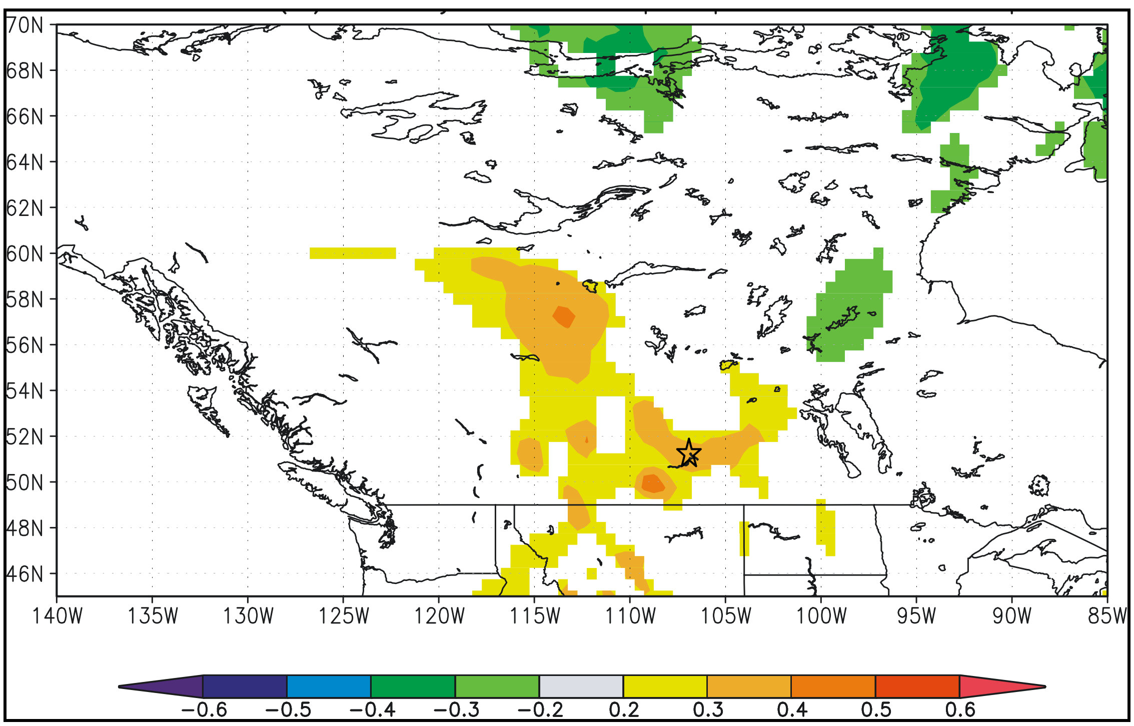

Figure 3.9: Correlation map between summer groundwater level at Swan(star) and winter precipitation for the period 1971-2002 (p<0.05).

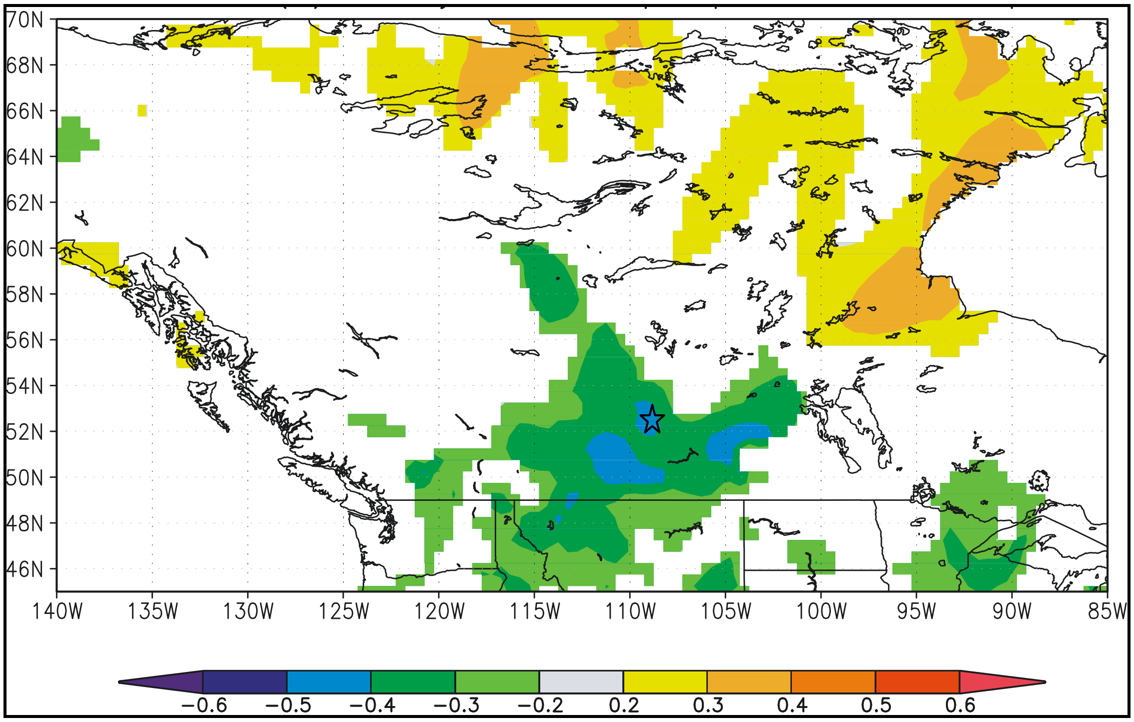

Figure 3.10: Correlation map between summer groundwater levels at Unit and winter precipitation for the period 1968-2002 ($p<0.05$).

3.1.2 Groundwater and temperature

Significant positive and negative correlations were found between groundwater levels and temperature. In Alberta, fall groundwater levels at well 117 have significant negative correlation ($r < -0.2$) with summer temperature (Fig. 3.11). At well 125, there is a positive correlation between November temperature and groundwater levels in January and February ($r > 0.4$; Fig. 3.12) and there is a negative correlation ($r < -0.3$) between water levels in the period June-July at well 159 with May temperature (Fig. 3.13).

Groundwater levels in Saskatchewan also correlate significantly with temperature. June groundwater level has a positive correlation ($r > 0.3$) with May temperature at well Atto (Fig.3.14). September temperature correlates with Sep.-Oct. and Dec. groundwater levels at well Ban B ($r > 0.4$; Fig. 3.15). A negative correlation ($r<-0.4$) between July temperature and September groundwater levels is found for well C 501 (Fig. 3.16). At

Duck 1 October temperature correlates with November, December, and January water levels (r>0.5), however, negative correlations are observed between August temperature with September and October groundwater levels (r < -0.4; Fig. 3,17). October temperature correlates with October, November, and December water levels at Duck 2 (r > 0.2; Fig. 3.18). March temperature has an immediate and positive effect on groundwater levels during March, April, May and June (r>0.4) at well Unit (Fig. 3.19). October, November and December water levels have a negative correlation (r < -0.5) with September temperature at well SmoA (Fig. 3.20) despite the positive correlation between October temperature and November groundwater levels. No relationship between temperature and groundwater levels is detected at well Swan.

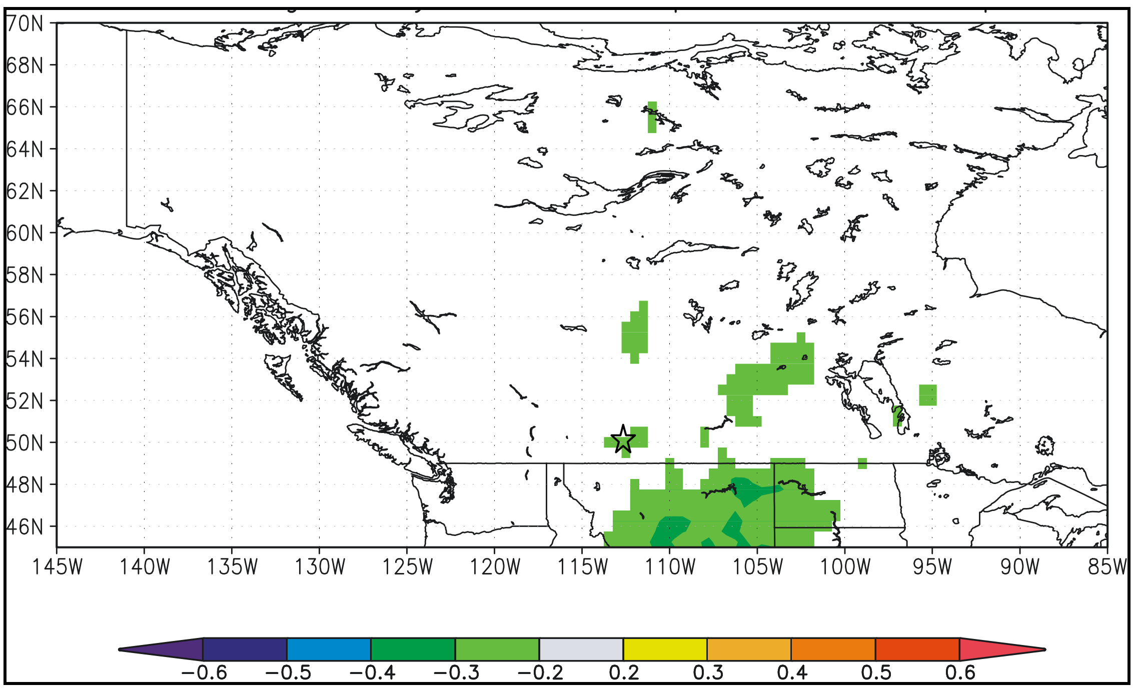

Figure 3.11: Correlation map between fall (Sep-Nov) groundwater levels at well 117 (star) and summer (Jun-Aug) mean temperature for the period 1972-2002 ($p < 0.05$).

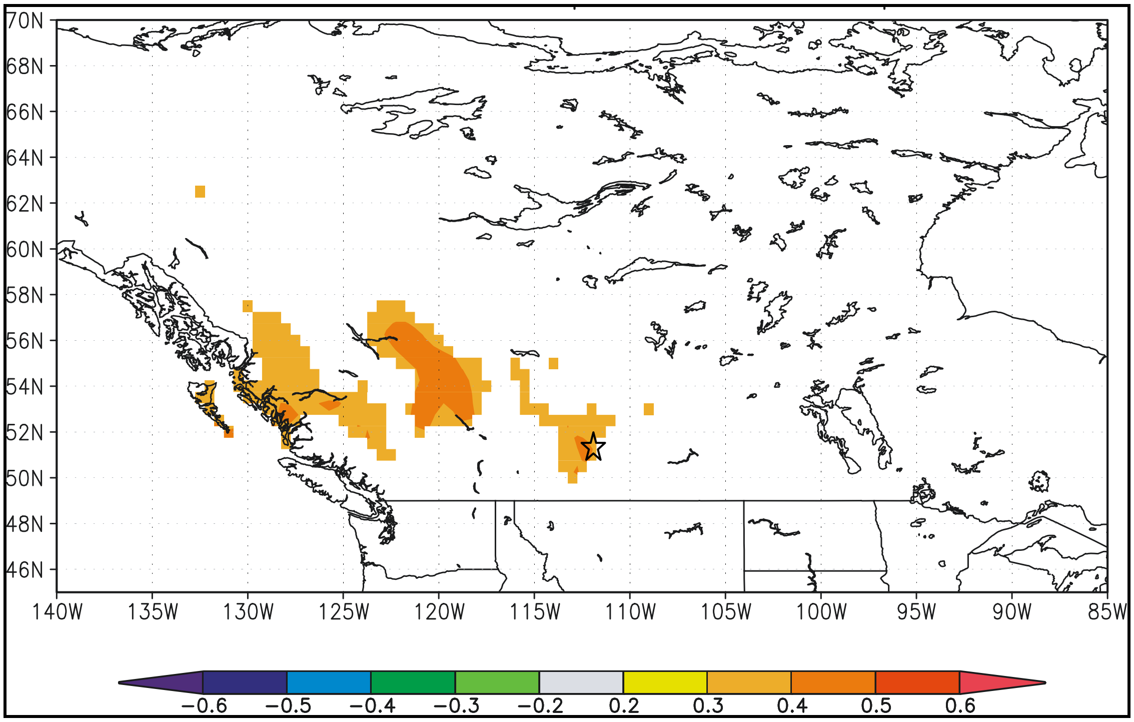

Figure 3.12: Correlation map between Jan. groundwater levels at well 125 (star) and Nov. mean temperature for the period 1972-2002 ($p < 0.05$).

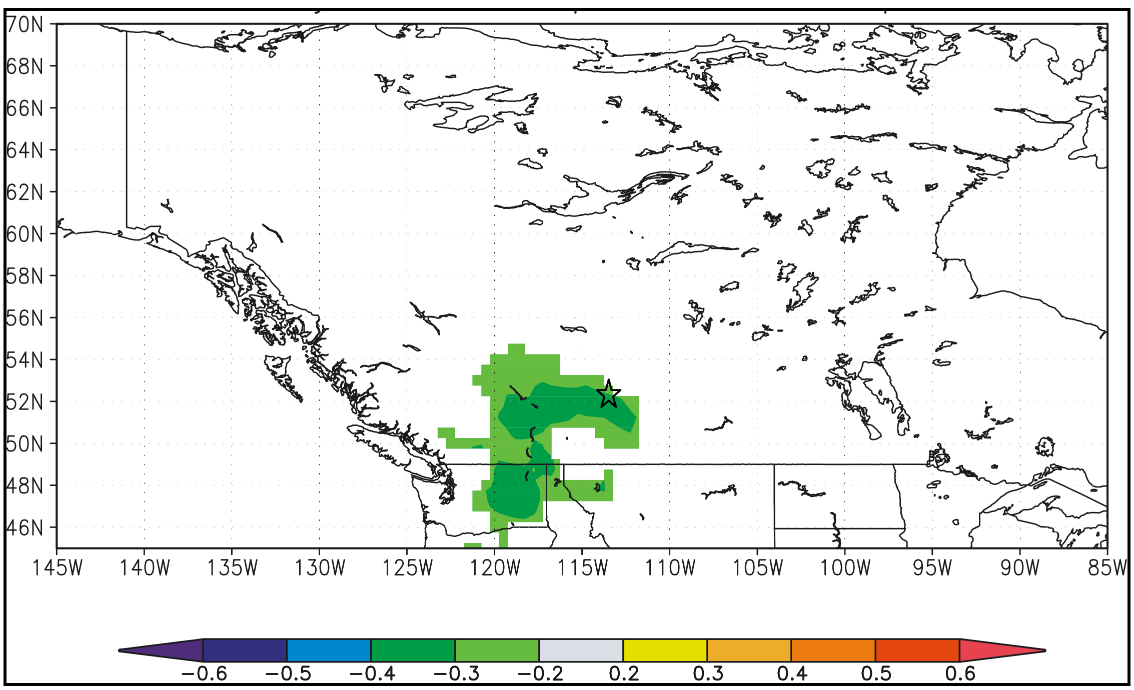

Figure 3.13: Correlation map between Jun-Jul groundwater levels at well 159 (star) and May temperature for the period 1969-2002 ($p < 0.05$).

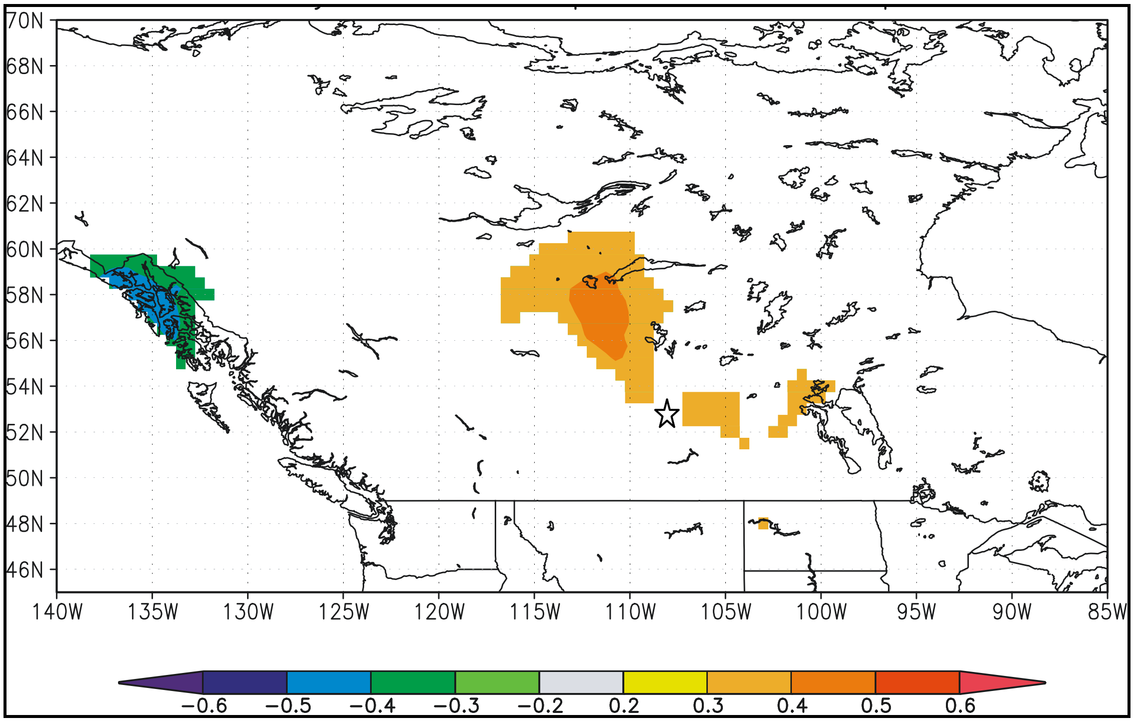

Figure 3.14: Correlation map between Jun groundwater levels at well Atto (star) and may temperature for the period 1965-2002 ($p < 0.05$)

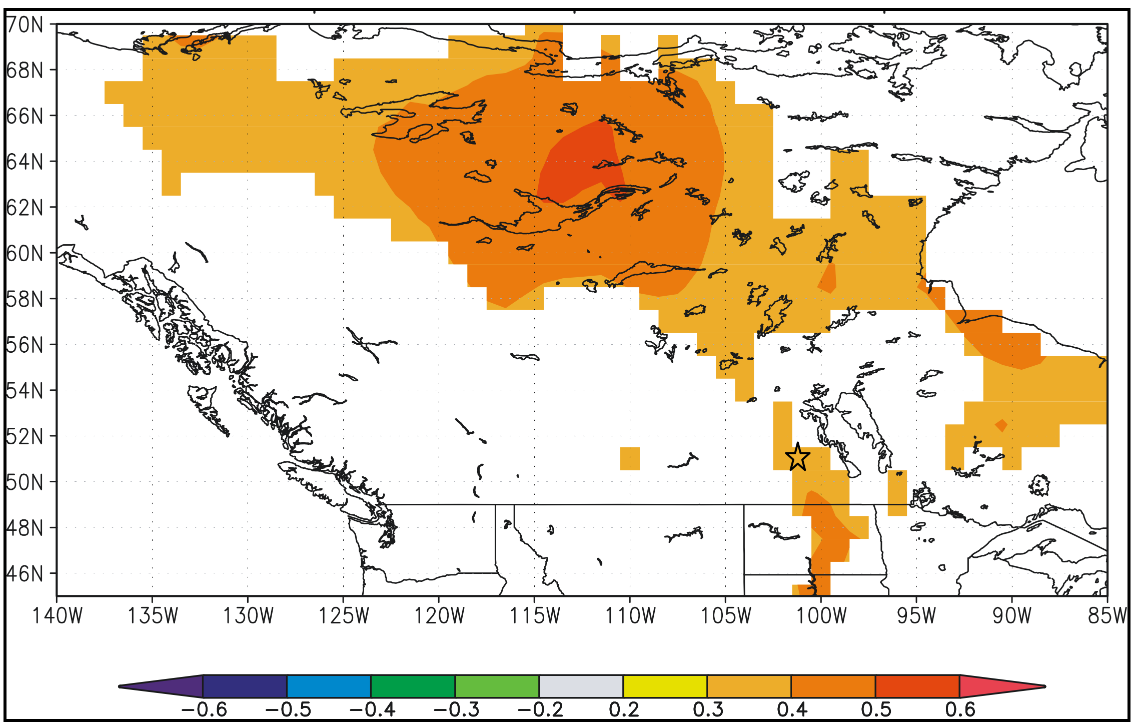

Figure 3.15: Correlation map between Sep. groundwater levels at Ban B (star) and Sep. temperature for the period 1971-2001 ($p < 0.05$).

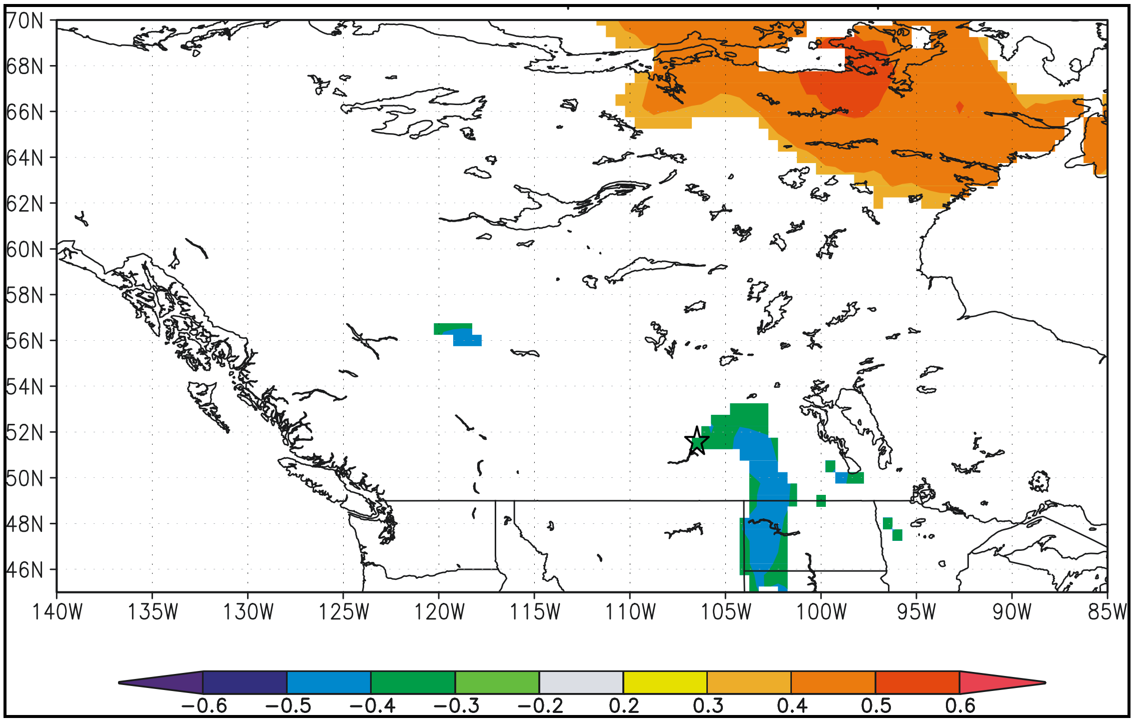

Figure 3.16: Correlation map between Sep. groundwater levels at C501 (star) and Jul. temperature for the period 1972-2002 ($p < 0.05$).

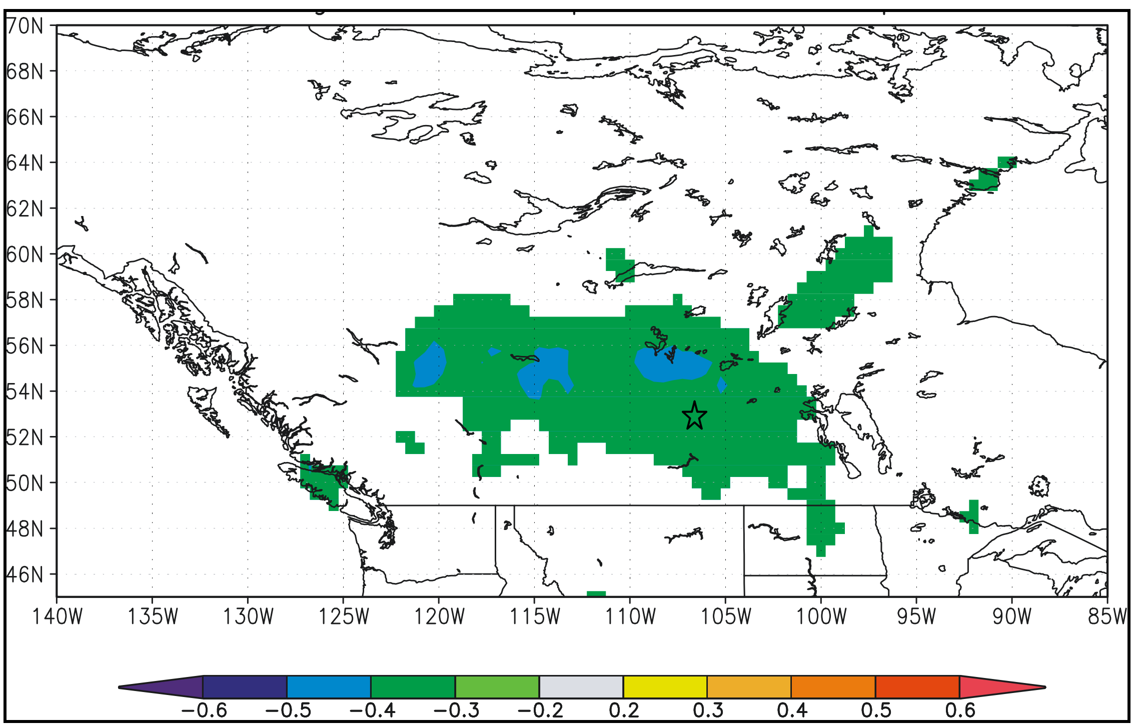

Figure 3.17: Correlation map between Oct groundwater levels at Duck 1 (star) and Aug. temperature for the period 1966-2002 ($p < 0.05$).

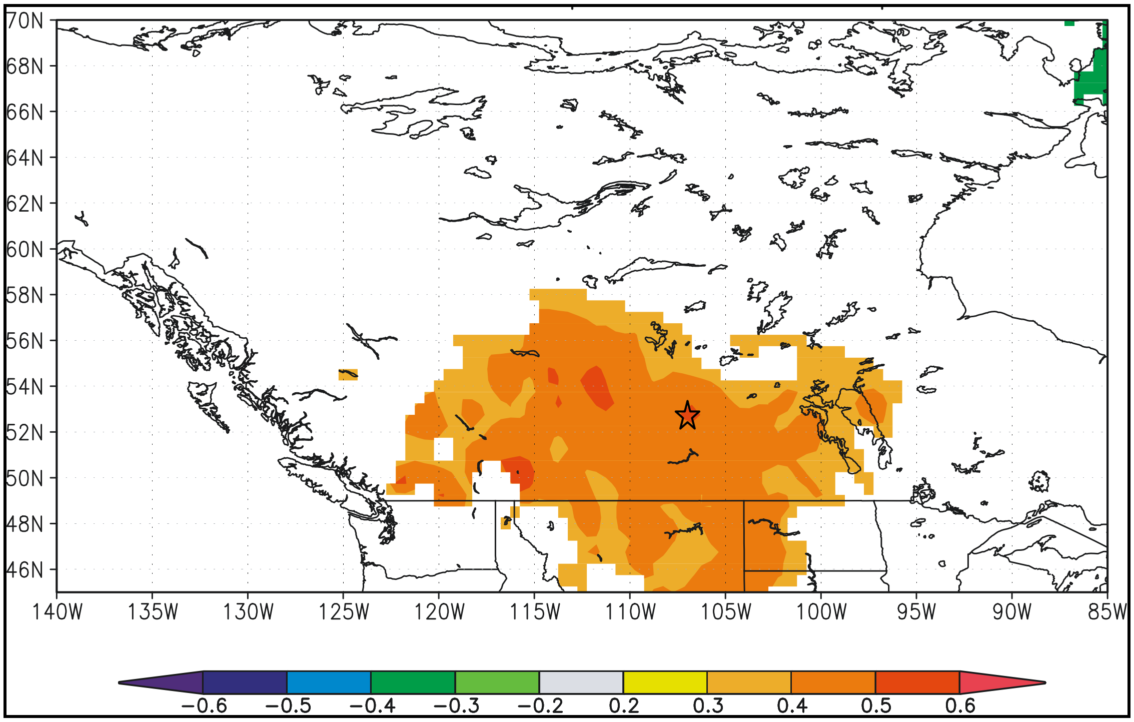

Figure 3.18: Correlation map between Oct. groundwater levels at Duck 2 (star) and Oct. temperature for the period 1966-2002 ($p < 0.05$).

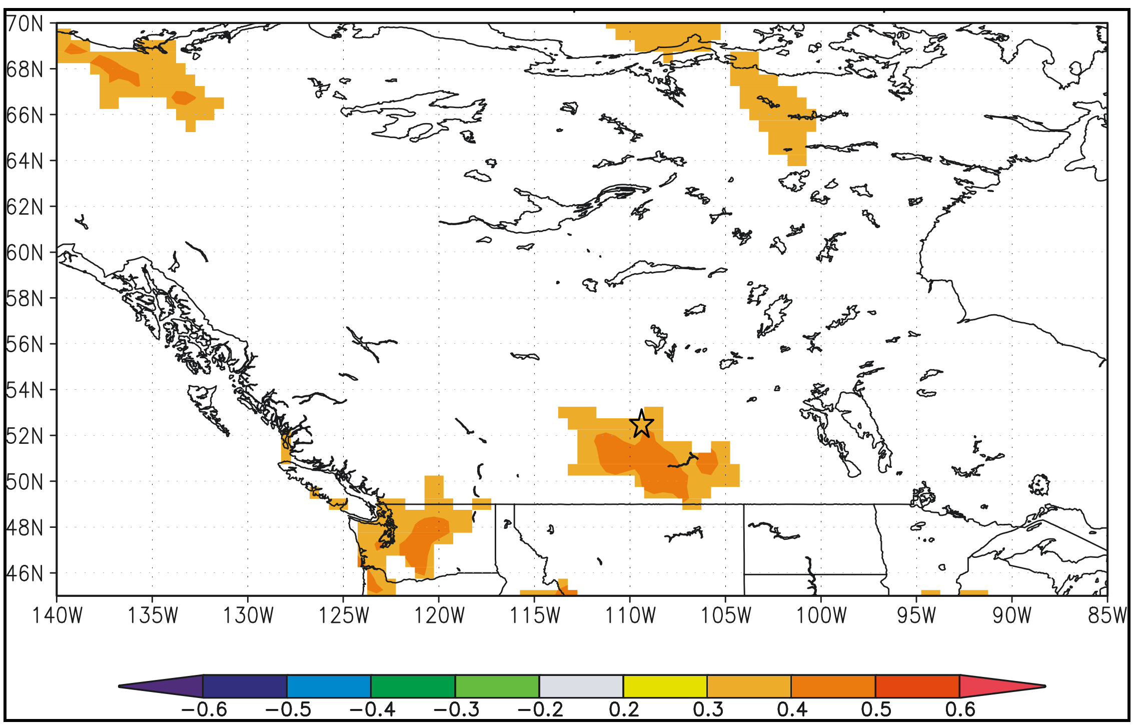

Figure 3.19: Correlation map between May groundwater level at Unit (star) and Mar. temperature for the period 1968-2002 ($p < 0.05$).

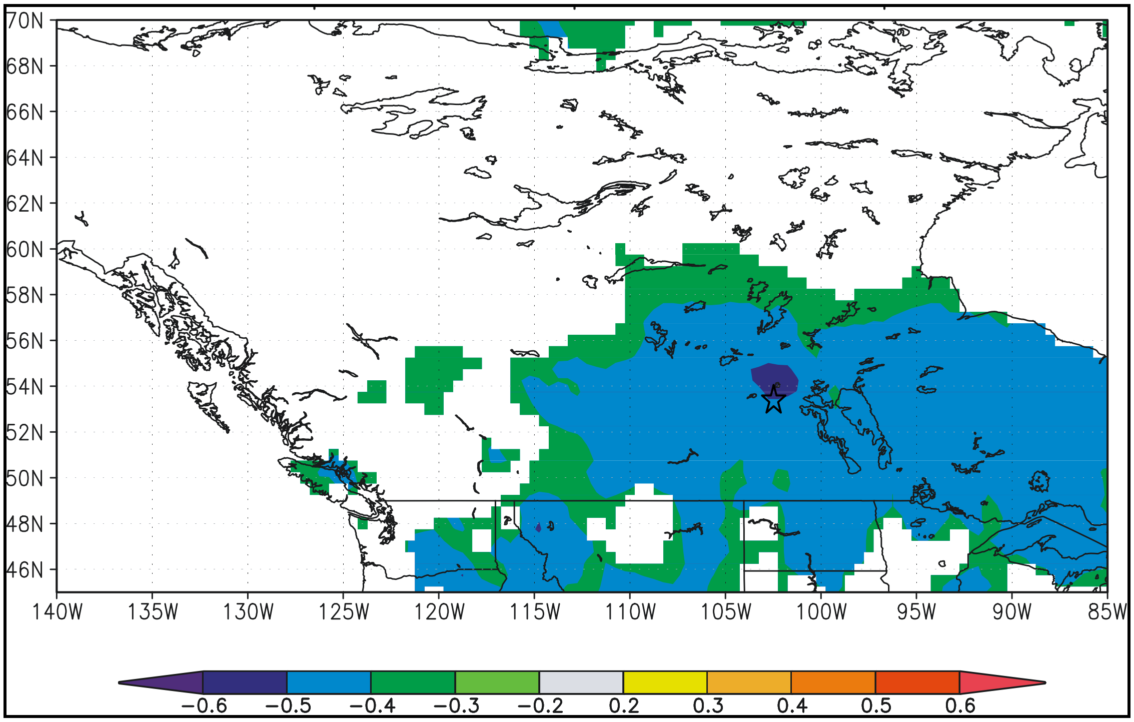

Figure 3.20: Correlation map between Oct. groundwater levels at well SmoA (star) and Sep. temperature for the period 1970-2002 ($p < 0.05$).

3.2 Groundwater and Tree-ring Chronologies

To assess the utilization of tree-ring chronologies for reconstructing groundwater levels exploratory analysis were carried out based on simple bi-variate correlations between the groundwater data and standard tree-ring chronologies. The tree-ring network was divided between Alberta and Saskatchewan for calculating correlation coefficients with groundwater levels.

In Alberta, groundwater levels had a slightly less strong relationship with tree-ring chronologies. The highest correlation found is between water levels at well 117 and the chronology highway 88, which is a negative correlation of 0.72 (Table 3.1). The highest positive correlation is also found at well 117 with the chronology West Sharples Creek ($r = 0.68$). Significant negative correlations are detected for well 125 with Swan Hills, Onion Creek at Porcupine hills and Blackstone Gap. Negatives correlations are observed for groundwater levels and precipitation at well 125 therefore this might be due to local conditions and aquifer characteristic. Water levels at well 159 have a few significant correlations with tree-ring chronologies. They are good enough to be used in further analysis. Figure 3.21 shows mean annual groundwater levels for well 117 and 125 and tree-ring chronologies for the same period.

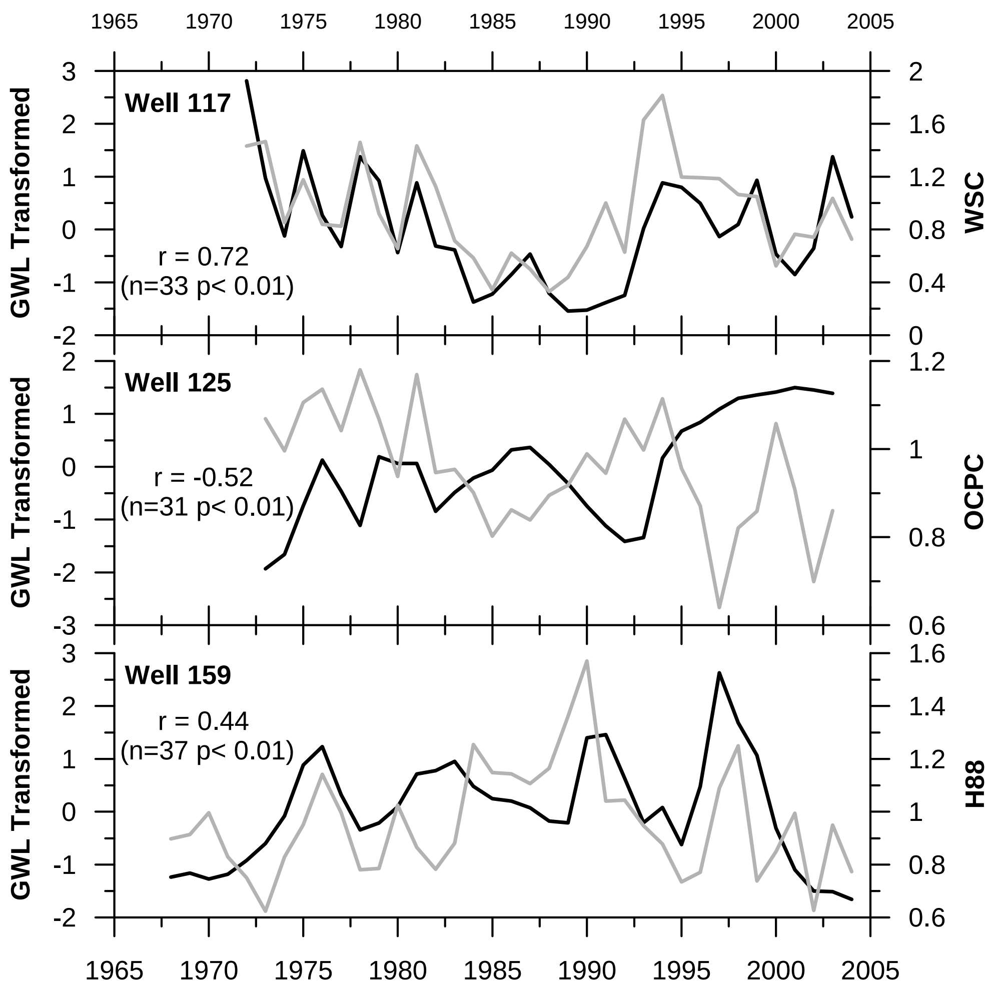

Figure 3.21: Simple correlation between groundwater levels at well 117 and the West Sharples Creek chronology, groundwater levels at well 125 with Onion Creek chronology, and water levels at well 159 and Highway 88 chronology.

Table 3.1: Correlations between groundwater levels and tree-ring chronologies in Alberta. *, ** represent significant correlations at p< 0.05 and p< 0.01 respectively.

Chronology	w117	w125	w159
Wch	0.26	0.00	0.16
Wsc	0.72**	-0.15	0.03
Sw2	-0.10	-0.10	0.14
Sw1	0.28	-0.40*	0.44*
Sip	0.34	-0.31	0.19
Or	0.57**	0.01	0.10
Ocpc	0.25	-0.52**	0.09
Mtm	0.60**	0.26	0.04
Lbc	0.61**	-0.16	0.13
Elk	0.04	-0.14	0.18
Dck	0.24	-0.27	0.30
Cal	0.46**	-0.14	0.18
Cab	0.54**	-0.12	0.01
Bsg	-0.18	-0.43*	0.20
Bdc	0.61**	-0.24	0.15
Bel	0.20	-0.29	0.25
Flk	-0.18	-0.20	0.31
H88	-0.72**	0.00	0.44*
Rbr	-0.33	-0.22	0.58**

Groundwater levels in Saskatchewan have a strong and significant relationship with tree-rings at p-values of 1% and 5% (Table 3.2). Most of water levels correlate positively with the chronologies in SK, however, groundwater levels at well Unit correlate negatively with all the chronologies at p-values of 5% and even 1%. Significant correlation coefficients range from -0.39 to -0.70. The reason for this negative correlation is unknown but I believe that is due to local conditions and aquifer characteristics and the possible interaction between streamflow-groundwater. Positive correlations coefficients are detected for the rest of the groundwater levels in Saskatchewan except at well Atto that shows a negative significant (p<0.01) correlation (r=0.52) with the Devon Farm chronology. The highest correlation is between water levels at SmoA and the chronology

Otter Rapids (Orp), the correlation coefficient is 0.81. Figure 3.22 shows mean annual groundwater levels at Atto and C 501 with the Orp and Dev chronologies.

Table 3.2: Correlations between groundwater levels and tree-ring chronologies in Saskatchewan. *, ** represent significant correlations at p< 0.05 and p< 0.01 respectively.

Chronology	Duck1	Duck2	BanB	SmoA	Swan	Unit	Atto	C501
Dby	0.07	-0.20	0.17	0.05	0.03	0.04	-0.01	0.49**
Kil	0.19	0.00	0.45*	0.47**	0.46*	-0.44*	0.04	0.15
Orp	0.60**	0.45*	-0.19	0.81**	0.70**	-0.70**	0.77**	-0.23
Ppn	0.22	0.06	-0.20	0.44*	0.27	-0.39*	0.24	-0.17
Wlpg	0.35	0.43*	0.04	0.70**	0.77**	-0.68**	0.67**	-0.33
Fby	0.44*	0.35	-0.09	0.56**	0.59**	-0.53**	0.56**	-0.09
Fil	0.32	0.49**	-0.13	0.06	0.22	0.13	0.41*	-0.10
Hlk	0.47**	0.50**	0.17	0.36*	0.49**	-0.13	0.46*	0.08
Ilk	0.43*	0.31	-0.36	0.50**	0.54**	-0.48**	0.65**	-0.19
Mil	0.21	0.12	-0.20	-0.05	0.11	0.05	0.18	0.16
Mlk	-0.17	-0.15	0.33	-0.32	0.01	0.35	-0.25	0.44*
Sil	0.11	0.23	0.24	0.15	0.39*	-0.20	0.23	0.00
Wlpb	0.33	0.32	-0.01	0.57**	0.72**	-0.55**	0.62**	-0.11
Chpc	-0.10	-0.20	-0.09	-0.11	-0.08	-0.09	0.00	0.30
Dev	-0.17	-0.35	0.58**	-0.25	-0.06	0.19	-0.52**	0.65**
Hil	-0.17	-0.10	0.69**	0.22	0.50**	-0.29	-0.04	0.08

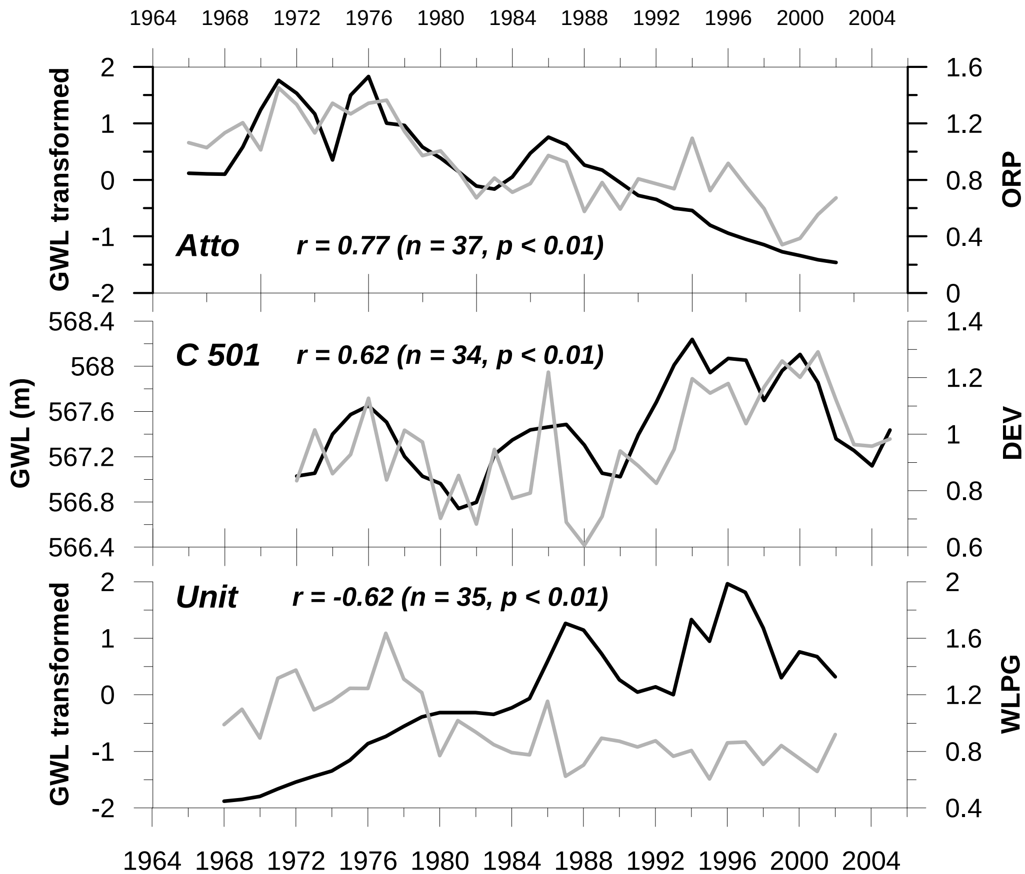

Figure 3.22: Simple correlations between groundwater levels at well Atto and Otter rapids chronology, groundwater levels at well C 501 and Devon farm chronology, and water levels at well Unit with the Wollaston Lake chronology.

4. METHODS OF TIME SERIES ANALYSIS

Previous studies have examined trends in stream flow (Burn and Elnur, 2002; Yue et al., 2003; Abdul and Burn, 2006), precipitation (Gan, 1998), and evaporation (Burn and Hesch, 2006); however, this is the first to study trends in groundwater levels and analyze the long term variability within the Canadian Prairies, and does so by adopting established techniques such as the Mann-Kendall trend test, Regime shifts, Wavelet analysis, and Singular spectrum analysis.

4.1 Trend analysis

The Mann-Kendall non-parametric test to detect trends (Mann, 1945; Kendal, 1975) has been widely applied to hydrological time series particularly non-normally distributed data (Hirsch and Slack, 1984; Yue et al. 2002; Yue and Pilon, 2003; Burn et al. 2004; Adbul and Burn, 2006; Burn and Mesch, 2007; among others).This rank based test works under two hypothesis, usually called hypothesis null or zero (H_0) and hypothesis one (H_1). The assumptions for the null hypothesis is that the data or time series (a vector X_j, j = 1, 2, …,n) are independent and identically distributed. On the other hand, the hypothesis one assumes that there is a monotonic trend in the vector X.

The test statistic is given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sgn(Xj - Xi) \qquad (4.1)$$

Where X_i and X_j are data values and n is the length of the time series.

$$Sgn(\emptyset) = \begin{cases} +1 & \emptyset > 0 \\ 0 \text{ if } & \emptyset = 0 \\ -1 & \emptyset < 0 \end{cases} \qquad (4.2)$$

When n ≥ 8, S is normally distributed with mean and variance described by equations 4.3 and 4.4 (Mann, 1945; Kendall, 1975)

$$E(S) = 0 \qquad (4.3)$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{m=1}^{n} t_m m(m-1)(2m+5)}{18} \qquad (4.4)$$

Where t_m is the number of ties of extent m. The standardized test statistic is calculated using equation 4.5 below.

$$Z = \begin{cases} \frac{s-1}{\sqrt{V(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & S < 0 \end{cases} \qquad (4.5)$$

The Mann-Kendall statistic "Z" follows a standard normal distribution with a mean of zero and variance of 1. Therefore the probability value (p) of the statistic S is calculated using the normal cumulative distribution described by equation 4.6

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{\frac{-t^2}{2}} dt \qquad (4.6)$$

A p value of 0.5 signifies no trend in independent sample data. Positive trends should have p values close to one and negative trends have values close to zero.

In addition von Storch (1995) suggested that positive auto or serial correlation (Order 1) in the data makes the identification of trends difficult because it increases the probability that the test will detect a significant trend (von Storch, 1995). Yue et al. (2002) developed a method to avoid the higher probability of detecting trends caused by autocorrelation. This method is called Trend Free Pre-Whitening (TFPW) and is applied to mean annual groundwater levels in this study.

In order to carry out the TFPW approach a series of steps are necessary. They are described below.

a) Calculate the slope of each trend using the Sen method (1968) expressed in equation 4.7 (Helsel and Hirsch, 1992).

$$\beta = Median\left(\frac{Yj \quad Yi}{Xj - Xi}\right)\ for\ all\ i < j\ and\ i = 1,2,\ldots(n-1)\ \ j = 2,3,\ldots n \qquad (4.7)$$

Where X is the vector recording the number of data (n) and Y is the data vector.

b) Remove the trend using equation 4.8

$$y_t = x_t - \beta t \qquad (4.8)$$

Where x_t is the time series value at time t and y_t is the de-trended time series.

c) Once the series has been de-trended the auto or serial correlation (Order 1) is calculated. If there is no significant autocorrelation in the time series the Mann-Kendall test is applied to the original data. Time series with significant ($p<0.05$) autocorrelation have to be pre-whitened using steps d and e.

d) Auto or serial correlation is removed using equation 4.9

$$y'_t = y_t - r_1 y_{t-1} \qquad (4.9)$$

Where y'_t is the de-trended and pre-whitened time series and r_1 is the first order autocorrelation. Removing the autocorrelation (order 1) is recommended because, when using the Mann-Kendall test, the probability of finding a trend where one may not exist, is increased by the serial autocorrelation (Yue et al. 2002).

e) Reincorporate the trend into the time series using equation 4.10

$$y''_t = y'_t + \beta t \qquad (4.10)$$

Where y''_t is the trend free pre-whitened time series.

f) Mann-Kendall trend test is applied to the y''_t time series.

The execution of all the steps mentioned above was completed using a combination of Excel spread sheets and Macros in Minitab.

Groundwater trends were calculated for the 39 mean annual water level records selected previously. Trends were analyzed for the whole period of record of each well; there is no common period.

4.2 Tree-ring reconstruction

The high correlations found between groundwater levels and tree-ring chronologies makes possible the use of regression techniques based on a predictand (groundwater levels) and predictors (standard chronologies) to reconstruct historical groundwater levels. Multiple linear regression models have been used to reconstruct past climate (Fritts, 1976; Guiot, 1990; Loaiciga et al., 1993; and others) and will be used here to reconstruct historical groundwater levels. Multiple linear regression models have the form described by equation 4.11.

$$Y_t = a + b_1 X_{1t} + b_{2t} X_{2t} + \dots + b_k X_{kt} + e_t \qquad (4.11)$$

Where Y_t is the predictand, for our case groundwater level, *a* is the regression constant, $X_1, X_2, \dots X_{kt}$ are the predictors used in the models, b_k the regression coefficients and e_t is the error of the regression (Ostrom, 1990). Multiple regression models are subject to the following assumptions:

a) There is a linear relationship between Y and X.

b) Non-stochastic X

$E[e_t X_t] = 0$ (4.12)

c) Zero Mean

$E[et] = 0$ (4.13)

d) Constant variance

$E[e_t^2] = \sigma^2$ (4.14)

e) Non-autoregression

$E[e_t e_{t-m}] = 0 \ (m \neq 0)$ (4.15)

f) Error has to be normally distributed

In addition to the assumptions above multiple regression models have to be checked for non-multicollinearity. When all the assumptions mentioned above are met, the regression model is unbiased, efficient and consistent (Ostrom, 1990).

4.2.1 Reconstruction models

Linear regression models were developed using a MATLAB function written by Meko (2005). Step-wise and cross-validation stopping rules are the two characteristics of the code. The function chooses the predictors in the model from a pool that have been previously selected through simple correlations between predictors and the predictand. Predictors can be lagged positively or negatively for up to three years and the linear regression model statistics are calculated.

4.2.1.1 Statistics

a) Coefficient of determination. The R^2 statistic indicates the amount of variance that the model is describing through the regression.

b) Standard error of estimate is the standard deviation of the differences between the actual values of the dependent variables (results) and the predicted values.

c) The F-ratio (F) estimates the statistical significance of the regression equation, taking into account degrees of freedom, and the size and number of predictors.

d) Adjusted R-squared (R^2_{adj}.) compensates for an artificial increment of R-squared caused by the addition of more predictors in the model. The addition of predictors increments the difference between the R^2 and R^2_{adj}.

In order to make sure that the linear regression assumptions are satisfied plots and some statistics are analyzed.

e) The Variance inflation factor (VIF) is used to detect multicollinearity in the models. It indicates how much of the variance explained in the model is increased by the addition of a predictor that is correlated with the others predictors.

The MATLAB function builds plots of the time series residuals, a scatter plot of residuals against predicted values and individual predictors, a histogram of residuals, an autocorrelation function of residuals, lag-1 scatterplots of residuals, and Durbin Watson statistic tests for autocorrelation of residuals and Portmanteaus test.

4.2.1.2 Validation

In the development of models there are two defined stages: 1) the selection of the variables, and creation and calibration of the model and 2) the validation of the model. Methods of validation compare the predictions from the model to records of some proxy for the predictand. A cross validation method uses a time series segment of the predictand withheld from calibration (Meko, 2005).

Two cross-validation techniques are: a) the split-sample methods, where data is divided into two equal segments and the model is calibrated with one half and validated with the another half (Hughes et al, 1982; Briffa, 1999) and b) where the cross-validation is executed using the technique of leave-n-out in which the model is validated repeatedly using observations that are left out sequentially (Hueghes et al., 1983). The leave-n-out technique makes the utilization of the whole period of record possible. Thus it is recommended when the data sets are too short to be split using the split-sample method of cross-validation.

Some validation statistics are:

Root mean squared error of validation (RMSEv) is the average size of the prediction error for the validation period.

Reduction of error (RE) measures the predictive capacity of the model; values range from negative infinite to plus one. A value of one represents a theoretical perfect estimation of the model therefore RE values close to 1 validate the predictive capacity of the model (Fritts, 1976; Fritts, *et al.*, 1990).

4.3 Post reconstruction methods

Regime shifts, wavelet analysis and singular spectrum analysis were applied to the reconstructed groundwater levels to identify changes in the mean, detect main oscillation modes and extract and identify these modes. In this section the methods are explained briefly since most of them are complex and advanced. These methods have been explained and used in many other studies, therefore, for more detail references are cited and recommended.

4.3.1 Regime shifts

A Regime shift (Rodionov, 2004) method was used to detect significant changes in mean groundwater levels at the 11 wells reconstructed. Regime shifts is based on statistical tests and a sequential data processing technique where observations are in time series and the hypothesis of the existence of a regime shift or discontinuity is tested for each new observation (Rodionov, 2004).

The method is based on the Student's test. Rodionov (2004) describes the methods as follows:

Let x1, x2, ..., xi, ... be a time series with new data arriving regularly. When a new observation arrives, a check is performed to determine whether it represents a statistically significant deviation from the mean value of the "current" regime ($\bar{x}_{cur}$). According to the t-test, the difference between and the mean value of the new regime ($\bar{x}_{new}$) to be statistically significant at the level p should satisfy the conditions $diff = |\bar{x}_{new} - \bar{x}_{cur}| = t\sqrt{2\bar{s}_l^2/l}$ *where t is the value of the t-distribution with 2l – 2 degrees of freedom at the given probability level p. It is assumed here that the variances for both regimes are the same and equal to the average variance for running l-year intervals in the time series {x_i}. It means that diff remains constant for the entire session with the given time series. At the "current" time t_{cur} , the mean value of the new regime* $\bar{x}_{new}$ *is unknown, but it is known that it should be equal or greater than the critical level* $\bar{x}^{\uparrow}_{crit}$ *, if the shift is upward, or equal or less than* $\bar{x}^{\downarrow}_{crit}$ *, if the shift is downward, where:*

$$\bar{x}^{\uparrow}_{crit} = \bar{x}_{cur} + diff \quad (4.16)$$

$$\bar{x}^{\downarrow}_{crit} = \bar{x}_{cur} - diff \quad (4.17)$$

If the current value $\bar{x}_{cur}$ is greater than or less than $\bar{x}^{\uparrow}_{crit}$ or less than $\bar{x}^{\downarrow}_{crit}$, the time t_{cur} is marked as a potential change point c, and subsequent data are used to reject or accept this hypothesis. The testing consists of calculating the so-called regime shift index (RSI) that represents a cumulative sum of normalized anomalies relative to the critical level $\bar{x}_{crit}$:

$$RSI = \frac{1}{l\sigma_l} \sum_{i=tcur}^{m} (xi - \bar{x}_{crit}) \;, m = |tcur, tcur + 1, \ldots, tcur + l - 1| \qquad (4.18)$$

If at any time during the testing period from t_{cur} to t_{cur} + l " 1 the index turns negative, in the case of , or positive, in the case of , the null hypothesis about the existence of a shift in the mean at time t_{cur} is rejected, and the value x_{cur} is included in the "current" regime. Otherwise, the time t_{cur} is declared a change point c.

Regime shifts is a Visual Basic Application (Macro) that is added to Excel and then used to calculate the shifts in reconstructed mean annual groundwater levels.

4.3.2 Continuous wavelet analysis (CWT)

Wavelet analysis is a relatively new technique in signal processing and can be used on stationary or non-stationary time series (Daubechies, 1998; Meyer et al., 1993). It locates the periodic signal in time and identifies the frequency or period (Torrence and Compo, 1998; Jevrejeva et al., 2003).

Continuous wavelet analysis (CWT; Torrence and Compo, 1998; Grinsted et al., 2004) was used to identify the dominant oscillation modes of variability in groundwater levels. Among all the wavelet families, Morlet wavelet (w_0=6) was chosen and applied to groundwater levels since it has a good balance between time and frequency domains and it is recommended when the purpose is to extract quasi-periodic signals (Grinsted et al. 2004). The statistical significance was assessed against a red noise background at 95%.

The Morlet wavelet is defined as follows:

$$\varphi_0(\mu) = \pi^{-1/4} e^{i w_0 \mu} e^{-\frac{1}{2}\mu^2} \qquad (4.19)$$

Where w_0 is dimensionless frequency and μ is dimensionless time.

The application of the convolution theorem to a time series (X_n, n=1,..., N) defines the continuous wavelet transform (X_n) with uniform time steps δt. Then, the local phase is defined by $W_n^X(s)$ where:

$$W_n^X(s) = \sqrt{\frac{\delta t}{s}} \sum_{n'=1}^{N} x_{n'} \varphi_0\left[\left(n' - n\right)\frac{\delta t}{s}\right] \qquad (4.20)$$

And the wavelet power is defined as $|W_n^X(s)|^2$.

In order to deal with the cyclic assumption in a wavelet, a cone of influence has been introduced. This delimits the time domain where edge effects are important (Grinsted et al., 2004).

Wavelet analysis was carried out in MATLAB using a MATLAB package.To get more details of the wavelet method used see Torrence and Compo (1998) and Grinsted et al. (2004)

4.3.3 Singular spectrum analysis (SSA)

Singular spectrum analysis is used to extract information from a short and noisy time series using principal components techniques (Vautard and Ghil, 1989; Dettinger et al., 1995). Basically this method extracts the eigenvalues and eigenvectors from the time series and reconstructs the cyclical components of the time series that are statistically significant.

A description of the method is given by Vautard et al. (1992) is summarized below. For a time series X_i (i=1, ..., N) and a maximum lag M, the elements of a Toeplitz matrix are defined by C_j where:

$$C_j = \frac{1}{N-j}\sum_{i=1}^{N-j} x_i x_{i+j} \qquad 0 \le j \le M-1 \quad (4.21)$$

Principal components are calculated to determine the eigenvalues λ_k and eigenvectors E_j^k. Eigenvectors are sorted in decreasing order according their eigenvalue; eigenvalues greater than 1 are considered statistically significant. The k_{th} principal component is given by a_j^k where:

$$a_j^k = \sum_{j=1}^{M} x_{i+j} E_j^k \qquad 0 \le i \le N \quad M \qquad (4.22)$$

The components of the signal identified by SSA are reconstructed using equation 4.23.

$$(R_A x)_i = \frac{1}{M}\sum_{j=1}^{M}\sum_{k \in A} a_{i-j}^k E_j^k \qquad for\ M \le i \le N - M + 1 \qquad (4.23)$$

Where $(R_A x)_i$ is the component reconstructed and $\sum_{k \in A}$ represents the addition of one or more components to the reconstruction.

4.3.4 Percentile analysis

Simple percentile analysis was used in this study to identified periods of low levels in reconstructed groundwater levels. The time series data are classified by percentiles and then plotted, generating a barcode to visualize the sequences using colors. For example water levels in the lowest and highest ten percentile will be illustrated with red and blue respectively.

5. RESULTS AND DISCUSSION

This chapter presents results of several methods used to study trends and long term variability in groundwater levels. It is divided into three main sections which are results of: trend analysis, groundwater levels reconstructions, and groundwater variability.

5.1 Mann-Kendall trend test

Results of the application of the Mann-Kendall test show that 67% of the wells have a trend statistically significant at $p < 0.05$. A decreasing trend is detected in most of the wells studied (12), and slopes range from -0.5 % to -5.9% (Table 5.1). Increasing trends were found in 10 groundwater time series, with slopes ranging from 0.7% to 7.5%. No significant trends were found in the 11 remaining wells studied. The magnitude of decreasing trends is greater than the rate of increasing trends. For example, a moderate trend of between 0 and 2 percent applies to 39 percent of the wells with a decreasing slope in comparison to 60% of the wells with increasing slopes in the same range. For slopes between 2 and 4 percent the percentages of wells are in the same range for increasing and decreasing groundwater levels. However, the main difference is where slopes are greater than 4 percent; in this category there is a 30.5% of the wells with decreasing trends in comparison with 7% with increasing trends.

Figure 5.1 shows the spatial distribution of the significant ($p < 0.05$) trends. Central Alberta is characterized by negative slopes or no trends. In the southern part of the province some upward and downward trends are found. The trend test results for Saskatchewan suggest that all the wells studied have significant trends either positive or negative. Most wells studied in Manitoba present no trend; only one was found to have a significant upward trend. The spatial distribution of trends across the Prairies shows a distinct pattern, in which northern and central areas are dominated by negative or no trends, whereas southern areas, in the Prairie Ecozone, show positive trends, with the notable exception of three wells in or near the forested Cypress Hills.

Table 5.1: Groundwater trends statistics. Slopes entries in bold indicate that they are significant at a 5% level ($p < 0.05$), * are groundwater levels reconstructed in section 5.2.

Name	ID	Depth	Slope	Z statistic	trend p-value
Cressday 85-2	Well 102	80.00	**1.3%**	5.284	0.000
Pakowki 85-1	Well 104	69.00	**3.3%**	5.738	0.000
Cypress 85-1	Well 106	30.00	**-1.3%**	-3.708	0.000
Elkwater 2294E	Well 108	33.50	**3.1%**	2.309	0.010
Mud Lake 537E	Well 112	36.58	**-5.9%**	-3.988	0.000
Ross Creek 2286E	Well 114	73.70	**-1.1%**	-1.819	0.034
Barons 615E *	Well 117	19.80	-0.6%	-0.081	0.468
Hand Hills #2 South *	Well 125	40.54	**2.0%**	6.119	0.000
Ferintosh Reg Landfill 85-1	Well 147	35.10	**-3.0%**	-2.169	0.015
Devon #2 (North) *	Well 159	7.62	0.2%	-1.190	0.117
Bruderheim 2340E (S)	Well 176	47.90	-0.5%	-1.609	0.054
Marie Lake 82-1	Well 192	144.80	0.2%	0.980	0.164
Marie Lake 82-2 (West)	Well 193	72.50	0.2%	0.560	0.288
Milk River 85-1 (West)	Well 212	73.00	0.8%	1.469	0.071
Kirkpatrick Lake 86-1 (West)	Well 228	84.70	**-1.8%**	-4.572	0.000
Kirkpatrick Lake 86-2 (middle)	Well 229	33.50	**-4.2%**	-3.419	0.000
Narrow Lake	Well 252	26.80	**-5.2%**	-3.337	0.000
Milk River 2479E	Well 260	25.90	-0.3%	-0.855	0.196
Duvernay 2489E	Well 270	20.70	-1.6%	-0.855	0.196
Atton *	Atto	16.15	**-2.7%**	-7.936	0.000
Baildon 059	B059	30.42	**7.5%**	5.915	0.000
Bangor A	Ban A	39.16	**0.8%**	4.655	0.000
Bangor B *	Ban B	15.27	**0.9%**	4.657	0.000
Conq 500	C 500	19.16	**2.7%**	7.112	0.000
Conq 501 *	C 501	8.24	**2.1%**	3.486	0.000
Duck Lake 1 *	Duc 1	13.26	**-0.6%**	-3.394	0.000
Duck Lake 2 *	Duc 2	124.60	**-0.5%**	-6.537	0.000
Lilac	Lila	122.53	**1.4%**	8.097	0.000
M0-5	OG003	9.14	**0.7%**	2.393	0.008
Poplarfield #3	LN001	NA	0.0%	0.882	0.189

Name	ID	Depth	Slope	Z statistic	trend p-value
Riceton	Rice	22.40	0.6%	8.174	0.000
Sandilands #1	OE001	13.11	-2.9%	-1.186	0.118
Simpson 13-04	SI13	7.22	**0.2%**	1.896	0.029
Smokey A *	SmoA	37.12	**-3.1%**	-6.612	0.000
Swanson *	Swan	9.18	**-2.6%**	-5.965	0.000
Tyner	Tyne	113.69	**1.6%**	8.214	0.000
Unity *	Unit	26.72	**1.2%**	7.363	0.000
Verlo	Verl	12.80	**-7.6%**	-8.191	0.000
Winkler #5	OB005	6.71	-1.2%	0.710	0.239

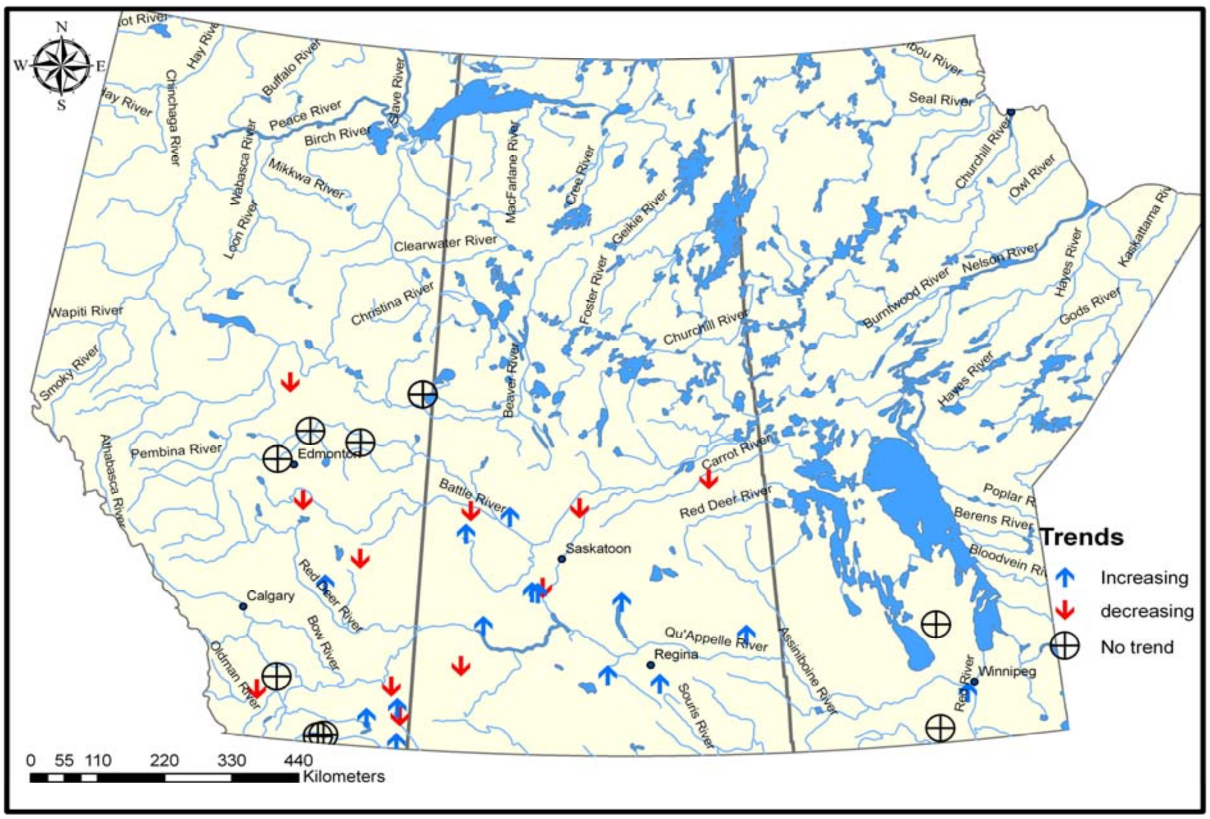

Figure 5.1: Spatial distribution of trends statistically significant at p<0.05.

Spatial analysis of the magnitude of the slope did not show a spatial pattern, although groundwater levels in the north central areas dominated by negative trends are minimal in magnitude (Figure 5.2). As expected from the spatial distribution of trends, the greatest magnitudes are declines in north central areas. On the other hand, even though the slope of increasing trends mostly do not exceed the 2% there are some areas(i.e. south east Alberta) dominated by positive slopes between 2-4 percent.

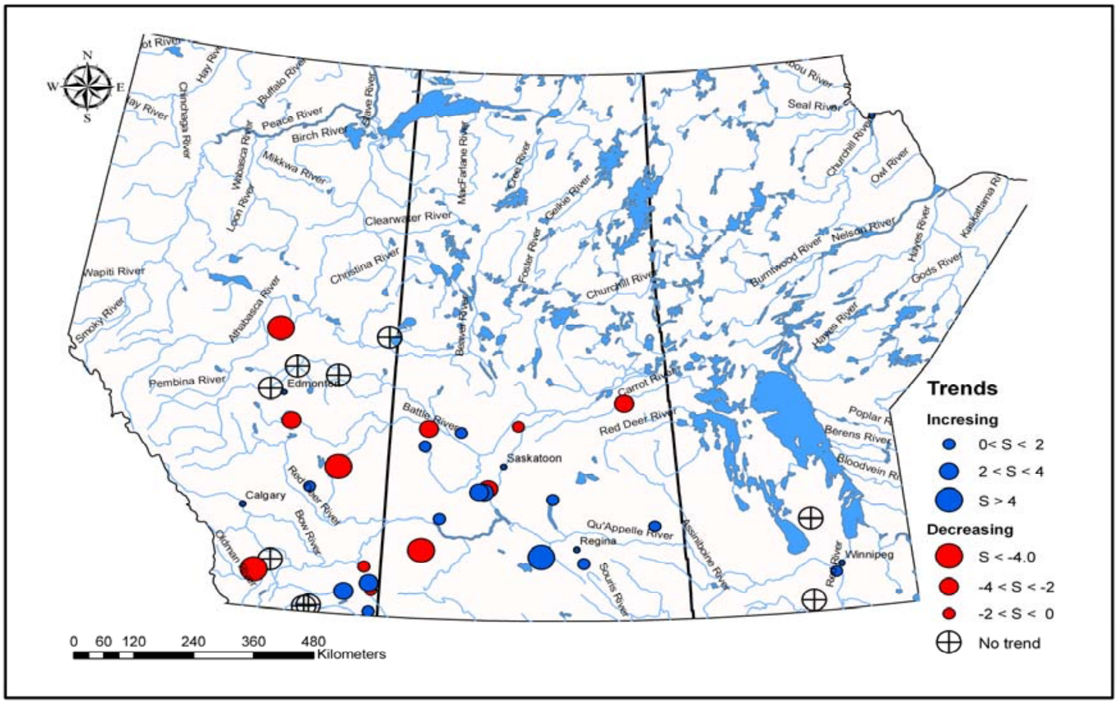

Figure 5.2: Spatial distribution of the slope magnitude for statistically significant trends.

No relationship was found between groundwater levels depth or aquifer lithology and trends or even the magnitude of the trend.

Spatial comparison between trends in groundwater levels and trends in evaporation (Burn and Hesh, 2007) suggest that there is spatial coherence between these hydroclimatic parameters. Trend in evaporation for the warm season (1971-2000) showed that north central areas of the Canadian Prairies are dominated by no or increasing trends which is consistent with decreasing groundwater recharge and the results of this study.

Assuming that the aquifer recharge is function of precipitation and evaporation, increased evaporation will lead to decreased recharge (not considering changes in precipitation), that is reflected by the negative trends that dominate the groundwater levels in north central areas in the Prairies. Southern areas of the Prairies are dominated by decreasing trend in evaporation during the warm season (1971-2000) which coincides with the increasing trends in groundwater domination in this area.

Precipitation in the Canadian Prairies has increased during the last 75 years, although, this increment is largely rainfall with decreasing snowfall (Akinremi and McGinn, 1999c). No spatial coherence was found between groundwater trends and these changes in precipitation. Although there might exist a relationship between trends in seasonal groundwater levels and winter precipitation which has not been explored in this study.

Overall, evaporation rates seem to play a major role in groundwater recharge, even though, total precipitation has increased in the Prairies there is a significant number of negative trends in water levels.

The methods used to calculate trends in groundwater levels have been widely used on stream flow time series with first order autocorrelation. Thus, it would be necessary to explore the influence of second and third order autocorrelation in the Mann-Kendall trend test. As it was pointed out in chapter two, groundwater time series generally have significant autocorrelation of second and third order.

Independent of the methods applied, the use of common periods of time, such as 1971-1990, 1971-2000 and 1981-2000, is recommended. Seasonal and annual trends should be examined in order to make better comparisons with trends in precipitation and evaporation.

5.2 Tree-ring reconstructions

Using tree-ring chronologies as predictors of groundwater levels, regression models were built for 11 groundwater wells across Alberta and Saskatchewan. The models expand annual water level records by more than 300 years in Alberta (Wells 117 and 125) and for at least 93 years in Saskatchewan. The length of the reconstruction was limited by the chronologies used in the model where the shortest chronology determines the length of the reconstruction. Most of the regression models are for wells located in Saskatchewan where there are longer groundwater records for calibrating the regression models. As discussed earlier, only three groundwater records in Alberta have the length and continuity to be used in this study.

In the process of finding the optimal and best reconstruction models for groundwater levels over 50 models were created (not reported). These models were developed using different predictors, number of predictors, and positive and negative lags for up to two years. Selecting the best models was not easy since some regression models presented better statistics for short periods of reconstruction than for longer periods, which gives information statistically more reliable. On the other hand, longer reconstructions provide more information through time but the reliability decreases.

Statistics of the 11 final regression models are presented in table 5.2. All the models have a positive skill of cross validation indicated by the reduction of error.

Residual analysis indicates that most of the regression models did not have significant autocorrelation in the residuals. The Durbin-Watson statistic was in the uncertain range for three regression models (Duc1, Duc2, and Swan). In statistical terms the best reconstruction model explains 82% of the instrumental variance in annual groundwater levels for the Unit observation well; in contrast, the regression model for well Duck Lake 1 explains the lowest percent of variance (40%). Other models in Saskatchewan explain high amounts of variance (over 70%). Even though intuitively tree growth driven by soil moisture should correlate best with shallow groundwater levels, the statistics obtained from the regression model for the deepest groundwater record reconstructed in this study, Duck Lake 2 (Duc2), are better than for a few shallow wells, which suggests the possible utilization of tree growth to reconstruct groundwater levels in deep aquifers.

In terms of length, Alberta models allowed reconstruction of groundwater levels for up to 387 years (w117) which even exceeds some tree-ring reconstructions of stream flow and precipitation in the area (Watson and Luckman, 2001; Case and McDonald, 2003; Axelson, 2007) . The shortest reconstruction, but the best in terms of instrumental variance explained, is well 159. Also, this is the only model has tree-ring variables with positive and negative lags as predictors. This shortest reconstruction for Alberta exceeds the longest reconstruction in Saskatchewan.

Table 5.2: Statistics of the optimal regression models

Name	Period	Length (yrs)	Calibration Period	Lag	# of Predictors	R^2	R^2_{adj}	RE	SE	AC_1	Max VIF
w 117	1618-2003	387	1972-2003	0	3	0.73	0.71	0.640	0.57480	H0	2.8
w125	1684-2003	320	1973-2003	0	6	0.60	0.52	0.360	0.70470	H0	5.5
w159	1859-2002	144	1968-2001	±2	7	0.80	0.76	0.630	0.46630	H0	1.7
Atto	1879-2001	123	1966-2001	0	5	0.81	0.79	0.730	0.41263	H0	5.5
Ban B	1909-2001	93	1971-2001	0	4	0.77	0.75	0.580	0.48250	H0	1.5
C 501	1862-2001	140	1972-2001	0	4	0.61	0.56	0.450	0.28390	H0	2.5
Duc 1	1909-2001	93	1967-2001	0	5	0.47	0.40	0.270	0.63710	U	1.6
Duc 2	1875-2001	127	1966-2001	0	5	0.74	0.71	0.640	0.05510	U	2.8
Smoa	1879-2001	123	1971-2001	0	5	0.80	0.77	0.690	0.15130	H0	4.5
Swan	1875-2001	127	1972-2001	0	4	0.67	0.63	0.520	0.62110	U	1.6
Unit	1875-2001	127	1968-2001	0	2	0.82	0.81	0.780	0.09890	H0	1.5

H0: No first order autocerrelation in residual. U: Uncertain

One important assumption in linear regression modeling is the normality of the predictands. The normality test showed that most mean annual groundwater levels are not normally distributed and therefore they need to be transformed. Common and widely used transformations in hydrological time series did not work on groundwater levels hence the complex Johnson transformation was used. Once the time series were transformed they were tested for normality again. The results of this second test showed that the Johnson transformation succeeded one hundred percent. Transformation and linear regression equations are listed in Table 5.3.

Table 5.3: Transformation and regression equations

Well	Johnson transformed	Linear regression model
w117	1.33505 + 0.977974*Asinh[(x-962.543) / 0.147662]	0.5128 + 2.2440*DBY - 1.8548*WLPG + 2.5679*FIL - 4.4372*ILK
w125	-0.422957 + 0.580869*Asinh[(x-978.919) / 0.0460879]	3.5958 + 1.3604*WCH - 1.8532*SIP + 1.5203*OK24 - 1.9671*OCPC - 1.9214*DCK - 1.3258*BSG
w159	1.60130 + 1.40428*Asinh[(x-691.530) / 0.230649]	-2.2684 + 1.3660*WCH_{-1} - 2.3403*$OCPC_{-1}$ + 4.0188*$H88_{-1}$ - 1.2779*SW_{-2} + 1.6914*$H88_{+1}$ + 3.1735*$SW2_{+2}$ - 4.1839*FLK_{+2}
Atto	1.79953 + 1.94815*Asinh[(x-528.362) / 0.376]	-0.6029 - 1.2790*KIL + 3.3523*ORP - 1.9445*FBY - 1.0310*MLK + 1.8361*WLPB
BanB	0.241646 + 0.587977*Ln[(x-	-1.0863 - 1.6735*ILK - 2.1332*CHPC + 2.1463*DEV +

Well	Johnson transformed	Linear regression model
	514.436) / (515.133-x)]	2.36836*ILL
C501	No	565.9887 + 0.7104*DBY - 0.946*WLPG + 0.6886*WLPB + 1.1463*DEV
Duc1	0.295628 + 1.08316*Asinh[(x-499.249) / 0.187576]	-0.6089 + 1.7761*ORP + 1.5138*FIL - 2.6282*CHPC + 1.4661*DEV - 1.4543*HILL
Duc2	No	479.1639 - 0.1535*DBY + 0.2077*FBY + 0.5481*FIL - 0.2832*ILK - 0.2702*MLK
SmoA	No	303.3906 + 1.0191*ORP + 0.3268*WLPG - 0.5081*FBY - 0.2264*FIL - 0.4572*DEV
Swan	0.515740 + 0.526811*Ln[(x-528.487) / (529.576-x)]	-2.0288 + 1.3115*KIL + 1.7886*WLPG + 2.4068*ILK - 2.8036*CHPC
Unit	2.35697 + 0.990162*Asinh[(x-656.946) / 0.0209937]	0.5128 + 2.2440*DBY - 1.8548*WLPG + 2.5679*FIL - 4.4372*ILK

5.2.1 Calibration of Alberta models

Plots of observed and reconstructed groundwater levels are shown below for wells 117, 125, and 159 (Fig. 5.3, 5.4, and 5.5, respectively). The models capture a large part of the inter-annual variability for wells 117 and 159 following a similar pattern. In general, these two models estimate well extreme groundwater levels. The regression model for well 117 initially overestimates water levels but then is in-phase with observed water levels until the 1980s; the models underestimate water levels in late 1980s and 1990s (Fig. 5.3). Well 159 underestimates water levels at the beginning of the record and reconstructs greater inter annual variability than observed from the late 1970s until late 1980s. Afterwards low and high levels are well estimated excluding the low level in the late 1980s (Fig. 5.4). As stated before, the regression model for well 125 has the worst statistics of the three models as evident in Figure 5.5. The model gives greater inter annual variability than the water levels observed that seem to be driven by an inter-decadal climate variability; however, the model is picking up relatively well low and high levels. Generally, it is overestimating the lows excepting water levels in 2000.

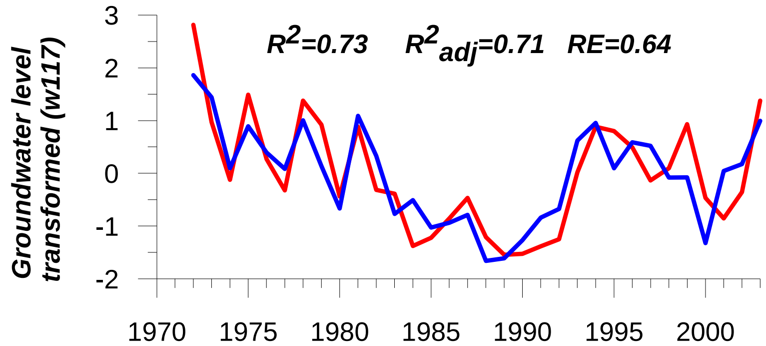

Figure 5.3: Calibration period for well 117. Blue and red lines are groundwater levels reconstructed and observed respectively.

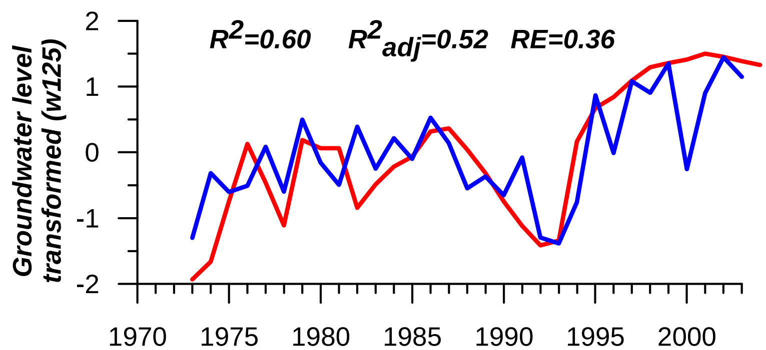

Figure 5.4: Calibration period for well 125. Blue and red lines are groundwater levels reconstructed and observed respectively.

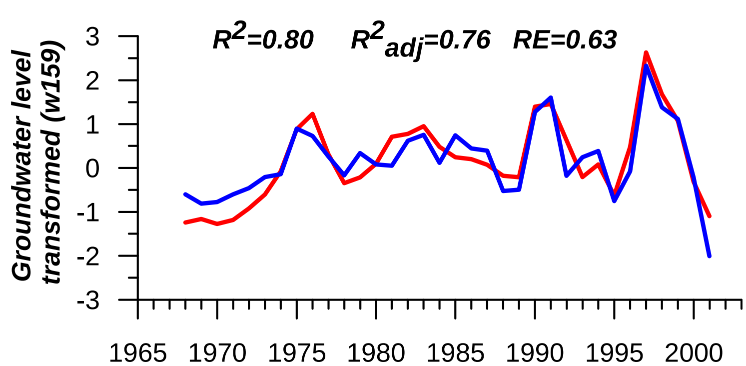

Figure 5.5: Calibration period for well 159. Blue and red lines are groundwater levels reconstructed and observed respectively.

5.2.1.1 Tree-ring reconstructions of groundwater levels in Alberta

The use of tree-rings makes possible the reconstruction of historical groundwater levels at three observation wells in Alberta (Wells 117, 125, and 159). The regression models expand water level records by 387, 320, and 144 years at wells 117, 125, and 159, respectively. Consecutive years of low and high water levels are identified in each of the reconstructions.

The 387-year reconstruction for well 117 shows periods of persistent low and high water levels (Figure 5.6). Major lows are centered on 1698, 1720, 1859, 1920, 1944, and 1985. On the other hand, major highs are centered on 1775, 1825, 1910 and 1975. From smoothing (15 years running average) the reconstructed time series, the period centered on 1859 represents the lowest water levels for the longest period, although the shorter periods centered on 1969, 1720, and 1985 had years with lower water levels than the interval of prolonged low levels centered on 1859. During the last 250 years, a clearly inter-decadal variability and decreasing in water levels are observed in the reconstruction. Table 5.4 summarizes water levels below the 30th percentile. Under this classification there are five periods of five or more consecutive years in which water level are below 30 percent. Also this table shows the 15 years with the lowest water levels; five of these years were in the last 20 years.

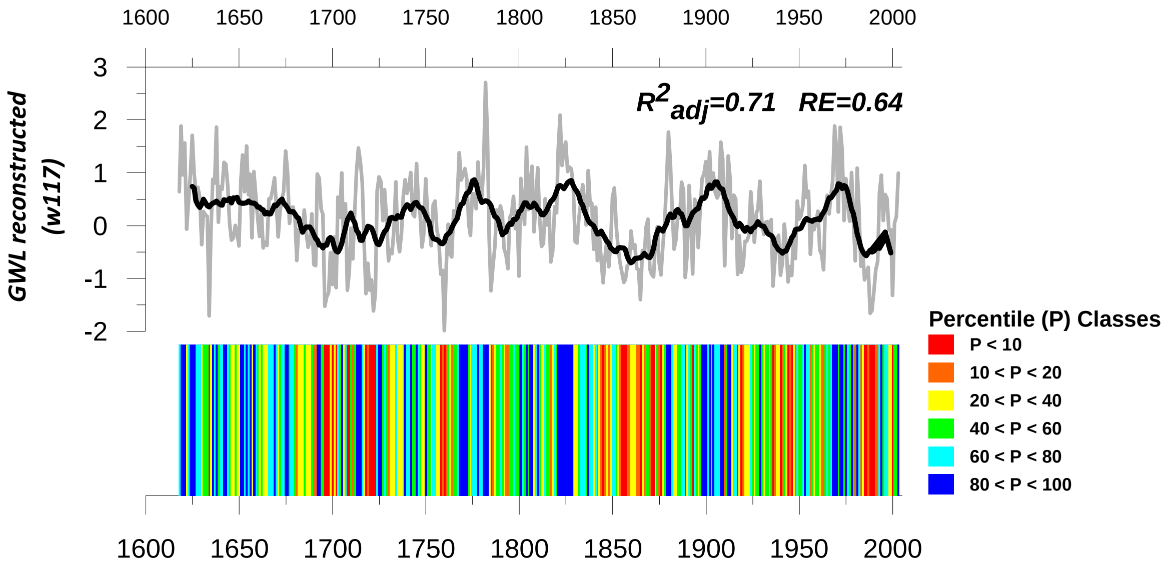

Figure 5.6: Groundwater levels reconstructed at well 117 and the 15-year running mean (grey and black lines respectively). At the bottom is the bar code representing percentile classes of groundwater levels.

Groundwater level reconstructed at well 125 shows less clearly inter-decadal variability (Figure 5.7). Low and high levels are identified, however, the pattern is more diffuse. Fewer periods of extreme low levels are identified, although the longest and most extreme low level period is seen in this reconstruction (~1925-1966). Some high levels are centered on 1775, 1815, and 1875. The least extreme relatively high period, centered on 1910, is followed by decreasing water levels and 40 years of the lowest water levels in the 320 years. Seven of the lowest annual water levels are found in this period (Table 5.5). As with well 117, before 1750s water levels show less variability (a relatively stable 15-year running average).

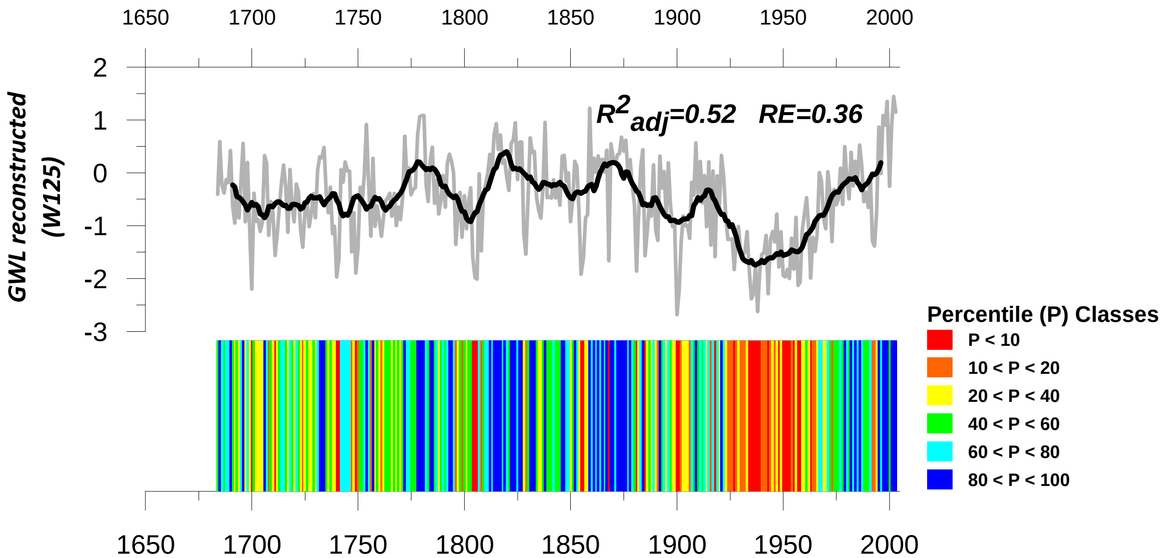

Figure 5.7: Groundwater levels reconstructed at well 125 and the 15-year running mean (grey and black lines respectively). At the bottom is the bar code representing percentile classes of groundwater levels.

Mostly one or two consecutive years with low levels are identified in the reconstruction at well 159. The longest period of consecutive years (5) is centered on 1970. There are other periods of low level, such as the one centered on 1920, that include a few years of high levels. The inter-decadal variability is also seen but not to the same degree as previously. High levels are centered on 1870, 1940 and 1960 (Fig. 5.8). The period centered on 1980 is relatively stable showing less variability.

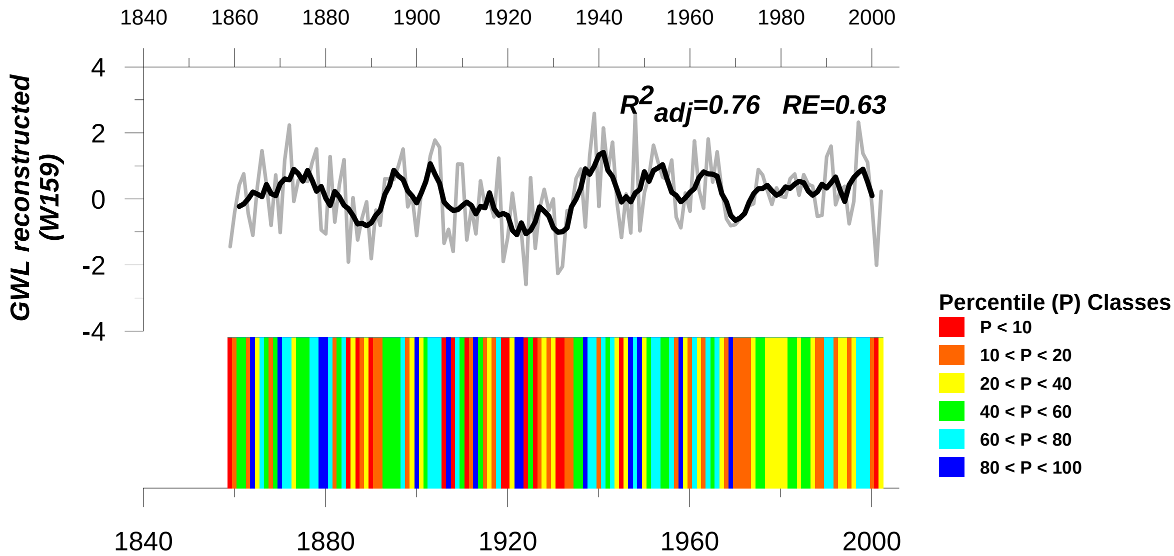

Figure 5.8: Groundwater levels reconstructed at well 159 and the 15-year running mean (grey and black lines respectively). At the bottom is the bar code representing percentile classes of groundwater levels.

Nkemedirin and Weber (1999) compared the 1930s and 1980s droughts. The 1930s drought was characterized as the driest and more prolonged drought of the two, although winter and springs were wetter than normal while during the 1980s drought winter and spring precipitation was below average. In both there were dry summers. The impact of these droughts on groundwater levels vary at the different wells studied. The 1930s drought had a stronger impact on water levels at wells 125 and 159 than at well 117. This drought had as a consequence low water levels at well 125 for more than 40 years which is probably related to aquifer conditions and the longer period of recovery for deeper aquifers. During this period water levels were mostly in the lowest 20 percent, the lowest water levels reconstructed occurred during this period. The major impact of the 1930s drought can be attributed to the high evaporation rate during this decade. This highlight the impact of evaporation on groundwater levels during the warm season (seen previously in trends).On the other hand, the 1980s drought produced greater impacts on water levels at well 117 than at the other sites.

Some other common periods of low surface water levels have been previously recognized for the Canadian Prairies, for example the period centered on 1860 (St. George and Nielsen, 2002), This dry period had the strongest and longest impacts on groundwater levels at well 117 (Fig. 5.6b).

Table 5.4: Groundwater levels < 30th percentile at Well 117 (1618-2003). Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two major droughts in the Canadian Prairies.

Single Year	More than 2 and less than 5 years	5 or more consecutive years	Lowest GWL (increasing order)
1630,**1634**,1650,	1663,1664,1665	**1696,1697,1698**,1699,**1700**	1760,1634,1988*,1722,1989*, 1696,1865,1697,2000*,1718, 1723,1990*,1698,1785,1720
1681,1**702**,1706, 1711,1736,1748,	1687,1688	**1718**,1719,**1720,1721,1722,** **1723**	
1753,**1800**,1840,	1690,1691	1853,1854,**1855,1856,1857**,	
1842,1883,**1893**,	**1708,1709**	1858,1859	
1896,1910,**1917**,	1730,1731,1732	1861,1862,1863,1864,**1865**,	
1926,1948,1956,	**1758**,1759,**1760**,1761	1866,1867	
1980,**2000**	1763,1764	1983,1984,**1985,1986**,1987,	
	1785,1786,1787	**1988,1989,1990,**1991,1992	
	1792,1793,1797		
	1812,1813		
	1817,1818		
	1830,1831		
	1844,**1845**,1846		
	1848,1849		
	1870,**1871,1872**		
	1875,**1876**,1877		
	1889,1890		
	1919,1920,1921,1922		
	1936,1937		
	1940,1941		
	1943,**1944**,1945,**1946**		
	1961,1962,1963		

Table 5.5: Groundwater levels < 30th percentile at Well 125 (1684-2003). Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two major droughts in the Canadian Prairies.

Single year	More than 2 and less than 5 years	5 or more consecutive years	Lowest GWL (increasing order)
1692,1697,1708,1717,1720,1727,1747,1756,1758,1761,1768,1796,1799,1801,1808,1850,**1868**,**1881**,1914,1916,**1918,**1970,1973	1699,**1700** 1704,1705 **1711**,1712 1723,1724 1738,1739,**1740,1741** **1749**,1750 **1804,1805,1806** 1828,1829 **1855,1856** **1885**,1886 1890,1891 1904,1905,1906 **1957,1958**,1959 1992-93	1898,1899,**1900**,**1901,**1902 1924,1925,1926,**1927**,1928,1929,1930,1931,1932,1933,**1934,1935,1936,1937,1938,1939**,1940,1941,1942,**1943**,1944,1945,1946 **1948,**1949,**1950,1951,1952,1953,**1954,**1955** 1962,**1963**,1964,1965,1966	1900,1938,1935,1943,1936,1901,1700,1957,1958,1806,1953,1963,1805,1740,1951

Table 5.6: Groundwater levels < 30th percentile at Well 159 (1859-2002). Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two major droughts in the Canadian Prairies.

Single year	More than 2 and less than 5 years	5 or more consecutive years	Lowest GWL (increasing order)
1868,1870,1882, **1885**,**1890,**1892, 1900,**1911**,1913, 1917,**1926**,1937, **1945**,1947,1949, 1995,**2001**	**1859**,1860 1863,1864,1879,1880 **1887**,1888 **1906,**1907,**1908** **1919,1920** 1922,1923,**1924** **1931,1932** 1957,1958 1988,1989	1968,1969,1970,1971,1972	1924,1931,1932,2001*, 1885,1919,1890,1908, 1926,1859,1906,1911, 1887,1945,1920

5.2.2 Calibration Saskatchewan

As in Alberta, regression models in Saskatchewan show a greater inter-annual variability than observed groundwater records, although they show a relatively similar pattern.

The calibration period for well Atto (Fig. 5.9) shows that observed and reconstructed groundwater levels have a decreasing trend. There is some under estimation of low and high water levels in the early 1980s and 1990s. Overall the model captures well low and high water levels and the model explains 79% of the instrumental variance. Regression models for wells BanB and C501explain 75% and 56% of the instrumental variance respectively. Both of them underestimate water levels in the early 1990s and after that show an increasing trend that coincides with observed water levels (Fig. 5.10 and 5.11). Duc1, as pointed out before is the worst of the regression models in statistical terms explaining just 40% of the instrumental variance (Fig. 5.12). The under and overestimation plus the out of phase peaks account for the unexplained variance. Water levels at Duc2 show a continuously increasing trend from 1965 to 1976 afterwards decrease. This pattern is captured by the regression model which explains 71% of the instrumental variance. The model has two clear overestimations of water levels in the early 1970s and 1990s (Fig. 5.13). Regression models for wells SmoA and Swan explain 77% and 63% of the instrumental variance. Both models follow the decreasing trend of water levels but show a certain degree out of phase especially for high water levels (Fig. 5.14 and 5.15). Overestimation of low levels in the early 1990s is evident in the model for well Swan. Finally, the best regression model in statistical terms is for water levels at well Unit. This model explains 82% of the instrumental variance and has the longest calibration period (1966-2001). The increasing trend is followed by the model adding some inter-annual variability that is not seen in the well record. It captures high and low levels relatively well; however, there is an underestimation of high water levels in late 1990s (Fig. 5.16).

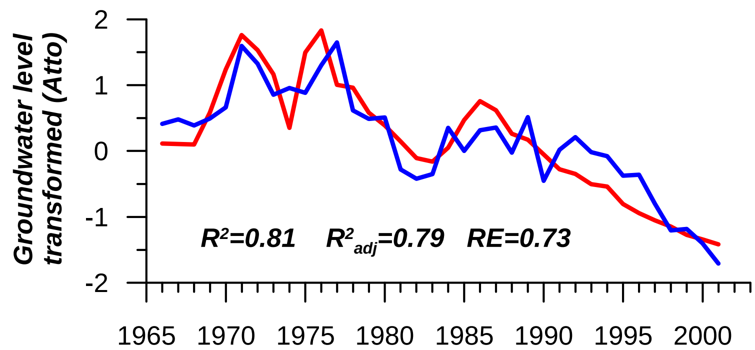

Figure 5.9: Calibration period for well Atto. Blue and red lines are groundwater levels reconstructed and observed respectively.

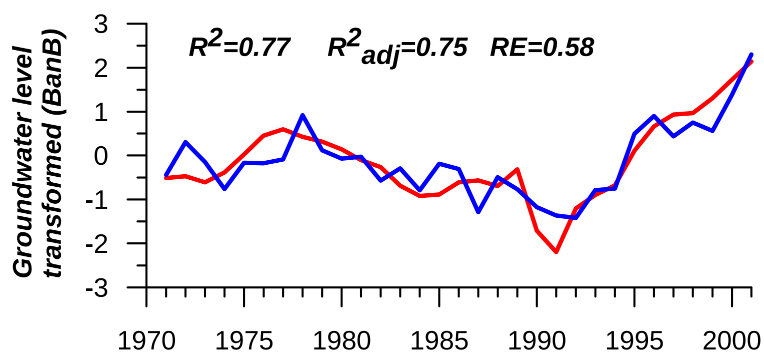

Figure 5.10: Calibration period for well BanB. Blue and red lines are groundwater levels reconstructed and observed respectively

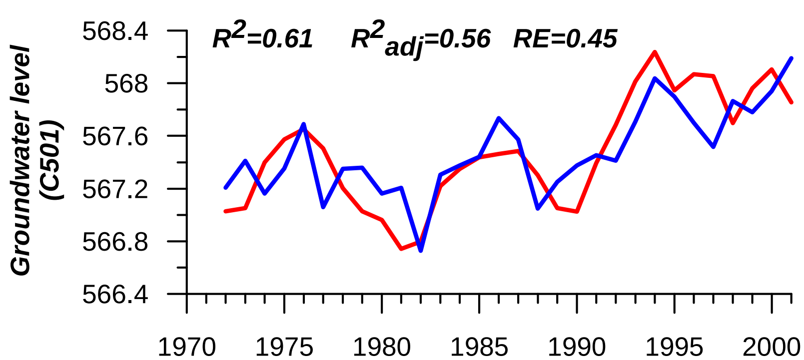

Figure 5.11: Calibration period for well C501. Blue and red lines are groundwater levels reconstructed and observed respectively

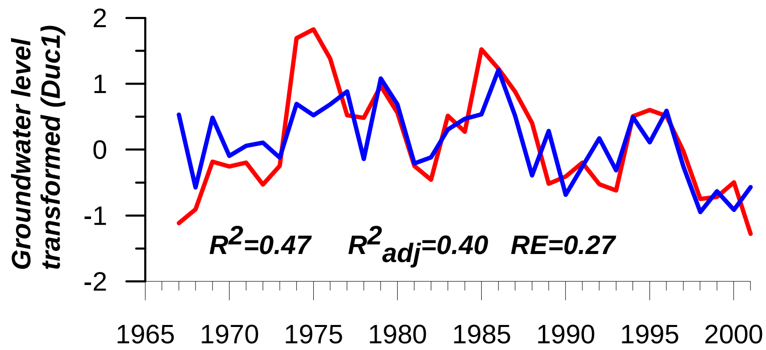

Figure 5.12: Calibration period for well Duc1. Blue and red lines are groundwater levels reconstructed and observed respectively

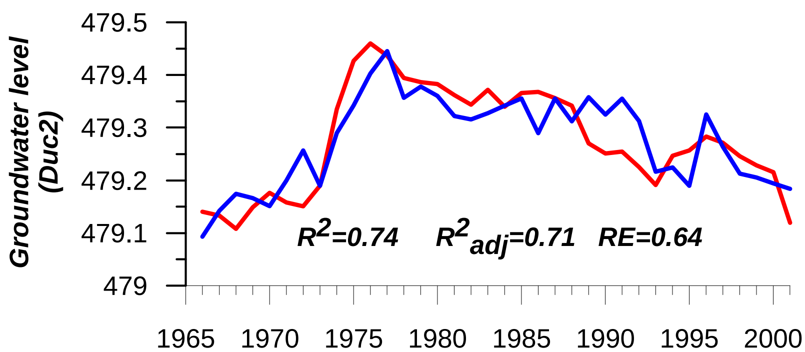

Figure 5.13: Calibration period for well Duc2. Blue and red lines are groundwater levels reconstructed and observed respectively

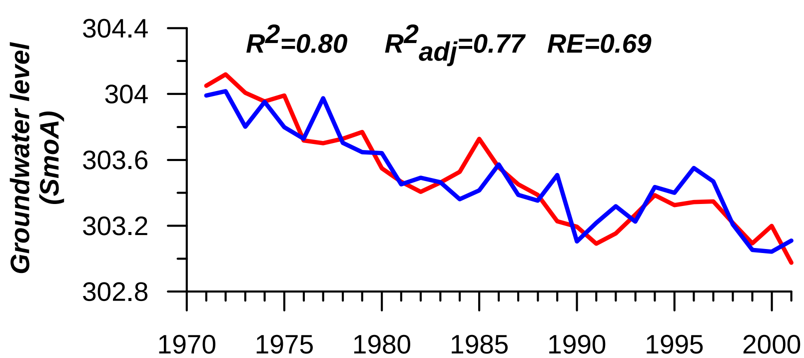

Figure 5.14 Calibration period for well SmoA. Blue and red lines are groundwater levels reconstructed and observed respectively

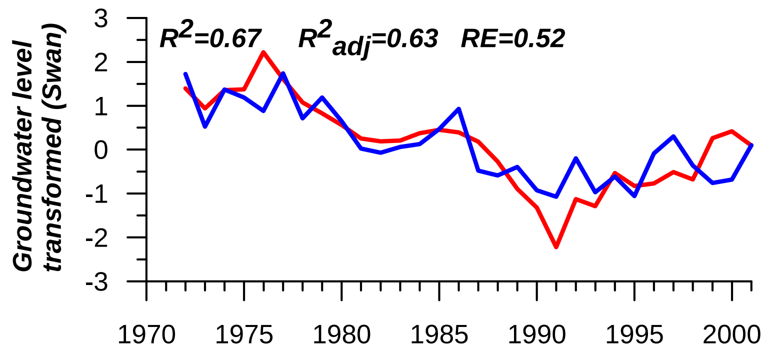

Figure 5.15: Calibration period for well Swan. Blue and red lines are groundwater levels reconstructed and observed respectively

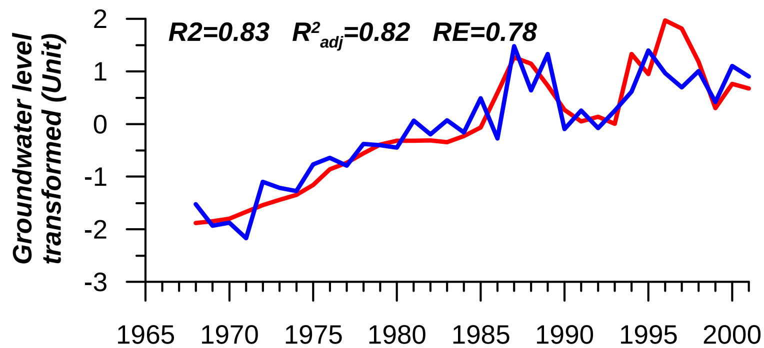

Figure 5.16: Calibration period for well Unit. Blue and red lines are groundwater levels reconstructed and observed respectively

5.2.2.1 Tree-ring reconstructions of groundwater levels in Saskatchewan

The groundwater level reconstructions show a similar pattern of low and high levels for wells Atto, BanB C501, SmoA and Unit; high water levels are centered around the 1950s (Figures 5.17, 5.18, 5.19, 5.22, and 5.24). Another similar period centered on 1970 was detected at wells Atto, Duc2, SmoA and Swan (Figures 5.17, 5.21, 5.22, 5.23).

Common periods of low water levels are reconstructed in the late 1880s, late 1920s and early 1930s at well Atto, where low levels are followed by high levels for around 20 yr (1941-1962), at well C501 where ~10 years are dominated by low levels, and at wells BanB, Duc1, Duc2, SmoA and Unit. During these periods water levels at Swan dropped but not as much as in the rest of the wells. Water levels were low in the early 1960s at wells BanB, C501, Duc2 and Unit extending for around 20 consecutive years (1951-1971). Wells Atto, BanB, C501, Duc1, SmoA and Swan had low levels during or shortly following the drought in 1988. Also, effects of the 2000-01 drought are observed on Atto, Duc1, Smoa, and Swan water levels, which have been decreasing since the late 1960s.

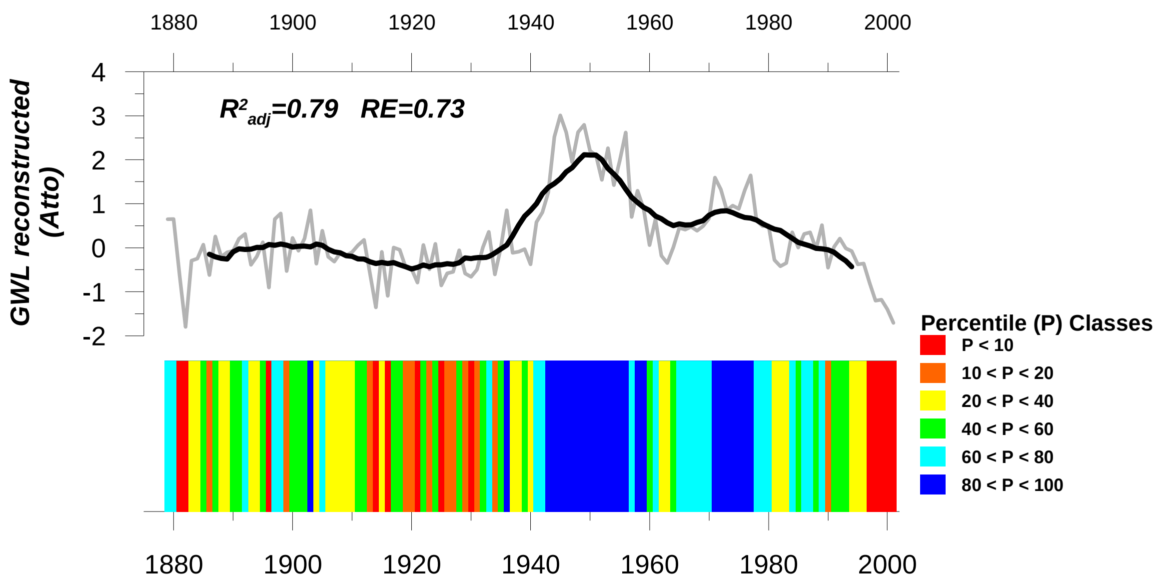

Figure 5.17: Groundwater levels reconstructed at well Atto and the 15-year running mean (grey and black lines respectively). At the bottom is the bar code representing percentile classes of groundwater levels.

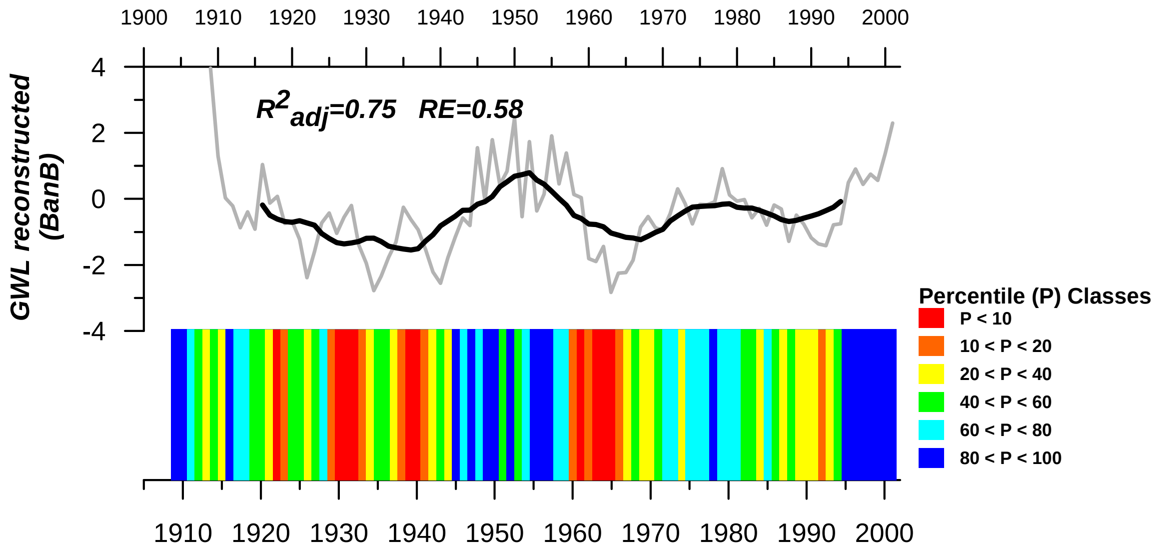

Figure 5.18: Groundwater levels reconstructed at well BanB and the 15-year running mean (grey and black lines respectively). At the bottom is the bar code representing percentile classes of groundwater levels.

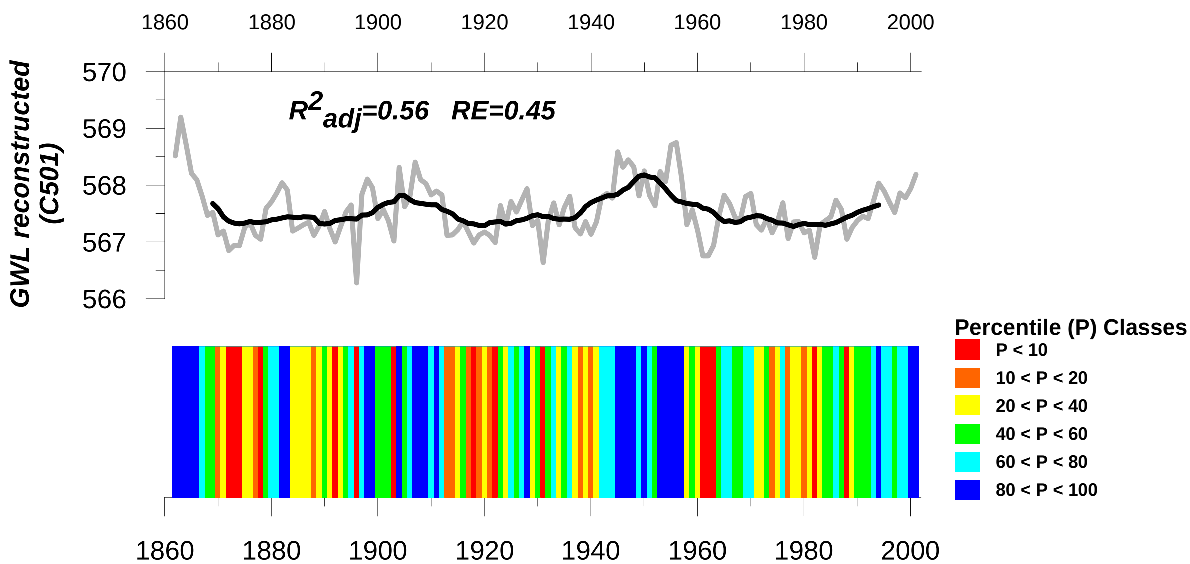

Figure 5.19: Groundwater levels reconstructed at well C501 and the 15-year running mean (grey and black lines respectively). At the bottom is the bar code representing percentile classes of groundwater levels.

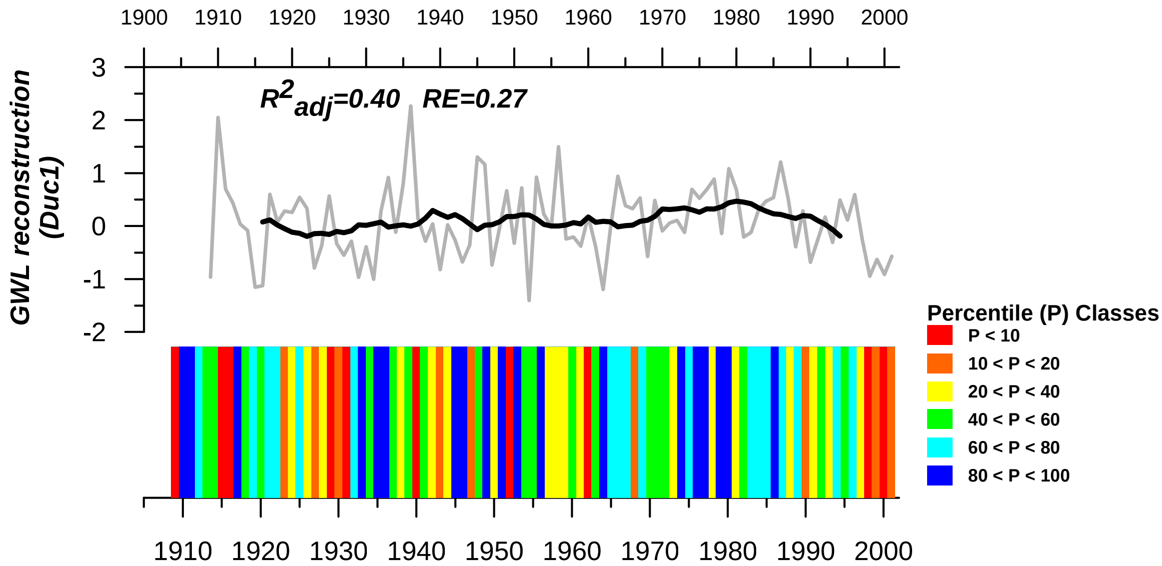

Figure 5.20: Groundwater levels reconstructed at well Duc1 and the 15-year running mean (grey and black lines respectively). At the bottom is the bar code representing percentile classes of groundwater levels.

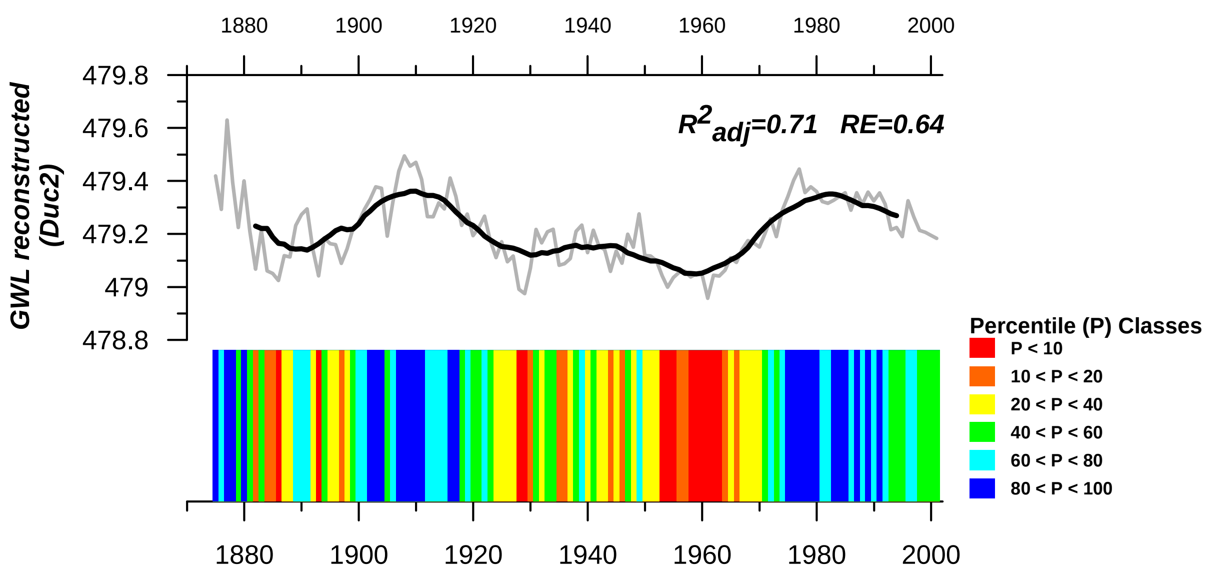

Figure 5.21: Groundwater levels reconstructed at well Duc2 and the 15-year running mean (grey and black lines respectively). At the bottom is the bar code representing percentile classes of groundwater levels.

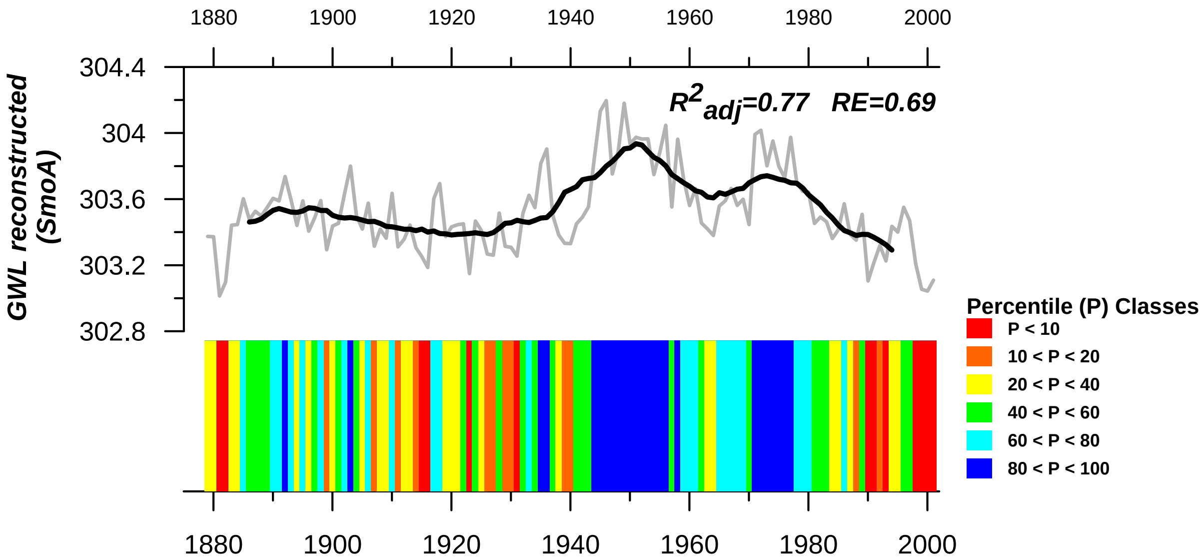

Figure 5.22: Groundwater levels reconstructed at well SmoA and the 15-year running mean (grey and black lines respectively). At the bottom is the bar code representing percentile classes of groundwater levels.

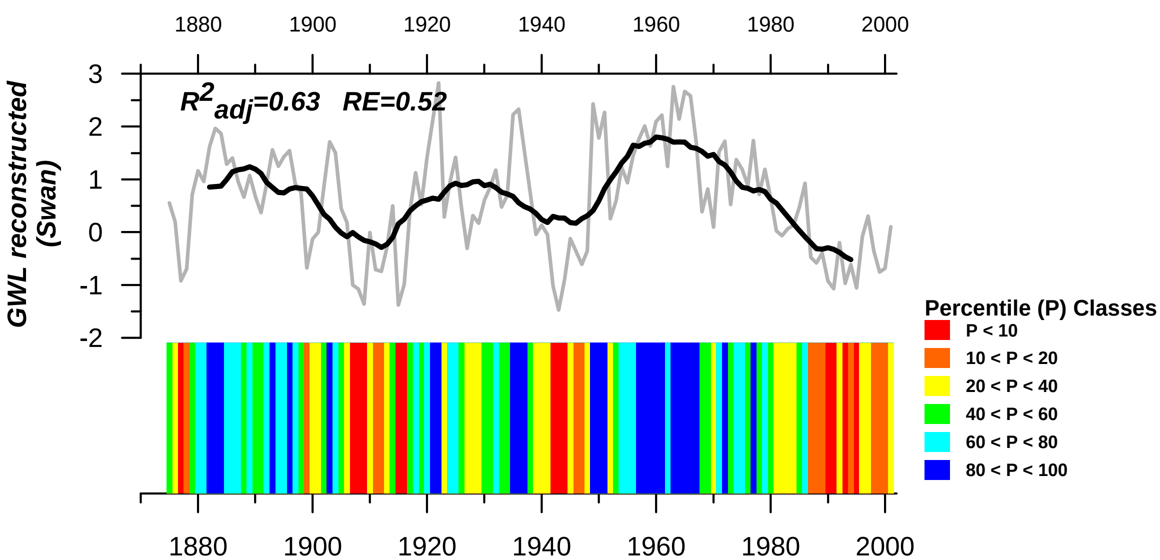

Figure 5.23: Groundwater levels reconstructed at well Swan and the 15-year running mean (grey and black lines respectively). At the bottom is the bar code representing percentile classes of groundwater levels.

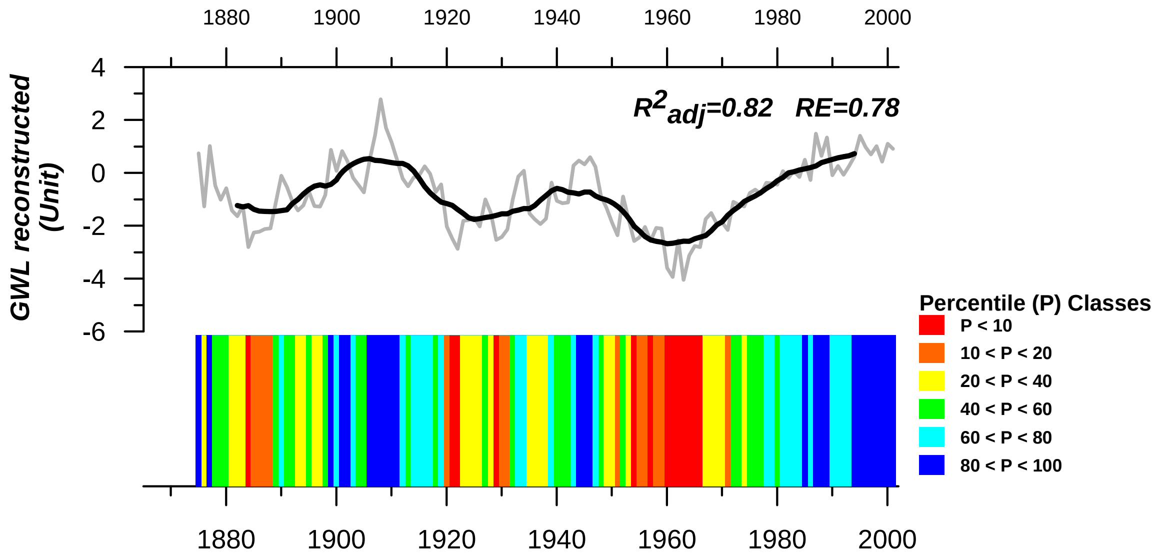

Figure 5.24: Groundwater levels reconstructed at well Unit and the 15-year running mean (grey and black lines respectively). At the bottom is the bar code representing percentile classes of groundwater levels.

Years with water levels in the lowest thirty percentile are summarized by Tables 5.7-5.14. Up to three periods of five or more consecutive years with low levels were reconstructed at wells BanB, Duc2, Swan and Unit during the last century. Several periods with more than two, and less than five, years of low levels are identified where droughts had taken place in the last century. Also, the top 15 years with the lowest water levels are presented in these tables. Only a few years of instrumental records are in this group which suggests that groundwater levels were lower when there is no instrumental record, although four of the 15 lowest water levels occurred during the last 10 years at well Atto and the period 1998-2001 is among the six lowest water levels in 123 years.

Table 5.7: Groundwater levels < 30th percentile at Well Atto. Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two major droughts in the Canadian Prairies.

Single year	More than 2 and less than 5 years	5 or more consecutive years	Lowest GWL (increasing order)
1886, 1893, **1896**, 1899, 1904, 1907, **1916**, 1923, 1934, 1940, 1963, 1990	**1881, 1882**, 1883, 1884 1913, **1914** 1919, 1920, **1921** **1925**, 1926, 1927 1929, **1930**, 1931 1981, 1982, 1983	1995, 1996, **1997, 1998, 1999, 2000, 2001**	1882, 2001*, 2000*, 1914, 1998*, 1999*, 1916, 1896, 1925, 1997*, 1921, 1930, 1881, 1886, 1934

Table 5.8: Groundwater levels < 30th percentile at Well BanB Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two major droughts in the Canadian Prairies.

Single year	More than 2 and less than 5 years	5 or more consecutive years	Lowest GWL (increasing order)
1915, 1926, 1970, 1987	1921, **1922,** 1923 1990, 1991, 1992	1929, **1930, 1931, 1932**, 1933, 1934 1937, 1938, **1939, 1940,** 1941, 1942 1960, **1961**, 1962, **1963, 1964, 1965**, 1966	1963, 1931, 1940, 1922, 1932, 1964, 1965, 1939, 1930, 1961, 1966, 1960, 1941, 1933, 1923

Table 5.9: Groundwater levels < 30th percentile at Well C501 . Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two major droughts in the Canadian Prairies.

Single year	More than 2 and less than 5 years	5 or more consecutive years	Lowest GWL (increasing order)
1896, **1903,** 1929, **1931,** 1940, 1972, 1974, 1977	1877, **1878** 1884, 1885 1891, **1892**, 1893 1913, 1914, 1915 1937, 1938 1960, **1961, 1962, 1963** 1980, 1981, **1982** 1988, 1989	1870, 1871, **1872, 1873, 1874,** 1875 1979, **1918**, 1919, 1920, 1921, **1922**	1896, 1931, 1982*, 1962, 1961, 1872, 1874, 1873, 1963, 1918, 1922, 1892, 1903, 1878

Table 5.10: Groundwater levels < 30th percentile at Well Duc1 Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two major droughts in the Canadian Prairies.

Single year	More than 2 and less than 5 years	5 or more consecutive years	Lowest GWL (increasing order)
1909, 1938, **1940**, 1947, 1950, 1952, 1959, 1968, 1988, 1990, 1993	**1915, 1916** 1923, 1924 1943, 1944 1961, **1962** **1998**, 1999, **2000,** 2001	1926, 1927, 1928, **1929**, 1930, **1931**	1952, 1962, 1915, 1916, 1931, 1929, 1909, 1998*, 2000*, 1940, 1923, 1947, 1990*, 1943, 1999*

Table 5.11: Groundwater levels < 30th percentile at Duc2 . Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two major droughts in the Canadian Prairies.

Single year	More than 2 and less than 5 years	5 or more consecutive years	Lowest GWL (increasing order)
1882, **1893**, 1897, 1924, 1940	1935, 1936, 1937 1943, 1944, 1945, 1946	1884, 1885, **1886**, 1887, 1888 1926, 1927, **1928, 1929**, 1930 1950, 1951, 1952, **1953, 1954, 1955**, 1956, 1957, **1958, 1959, 1960, 1961, 1962, 1963**, 1964, 1965, 1966	1961, 1929, 1928, 1954, 1886, 1955, 1958, 1963, 1893, 1953, 1962, 1960, 1959, 1885, 1956

Table 5.12: Groundwater levels < 30th percentile at SmoA. Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two major droughts in the Canadian Prairies.

Single year	More than 2 and less than 5 years	5 or more consecutive years	Lowest GWL (increasing order)
1896, 18991919, **1923,** 1964, 1995	1879, 1880, **1881, 1882** 1911, 1912 1914, **1915, 1916** 1925, 1926, 1927 1929, 1930, **1931** 1938, 1939, 1940 1984, 1985 1987, 1988 **1990, 1991**, 1992, **1993** **1998, 1999, 2000, 2001**		1881, 2000*, 1999*, 1882, 1990*, 2001*, 1923, 1916, 1998*, 1991*, 1993*, 1915, 1931, 1927, 1926

Table 5.13: Groundwater levels < 30th percentile at Swan. Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two major droughts in the Canadian Prairies.

Single year	More than 2 and less than 5 years	5 or more consecutive years	Lowest GWL (increasing order)
1927, 1939	**1877**, 1878 1899, 1900, 1901	**1907, 1908, 1909**, 1910, 1911, 1912, 1913	1943, 1915, 1909, 1908, 1991, 1995,
	1915, 1916 1981, 1982	1941, **1942, 1943, 1944**, 1945, 1946, 1947, 1948	1942, 1907, 1916, 1993, 1990*, 1877,
	1998, 1999, 2000	1987, 1988, 1989, **1990, 1991**, 1992, **1993**, 1994, **1995**, 1996	1944, 1999*, 1912

Table 5.14: Groundwater levels < 30th percentile at Well Unit Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two major droughts in the Canadian Prairies.

Single year	More than 2 and less than 5 years	5 or more consecutive years	Lowest GWL (increasing order)
1882	**1929**, 1930, 1931	**1884**, 1985, 1986, 1987, 1988	1963, 1961, 1960,
	1936, 1937, 1938	1920, **1921, 1922**, 1923, 1924, 1925, 1926	1964, 1922, 1966, 1884, 1965, 1954,
	1950, 1951 1969, 1970, 1971	1953, **1954**, 1955, 1956, **1957**, 1958, 1959, **1960, 1961, 1962, 1963, 1964, 1965, 1966**, 1967	1957, 1962, 1929, 1921, 1955, 1930

As with the reconstruction of groundwater in Alberta, the models in Saskatchewan reflect changes in mean annual groundwater levels forced by climate, as recorded by trees in Alberta and Saskatchewan.

Tree-ring reconstructions suggest that the range of water levels observed during the last 45 years does not reflect the natural variation in groundwater levels.

5.2.3 Statistical comparison between observed and reconstructed groundwater levels

The main statistics of reconstructed and observed groundwater levels are summarized in Table 5.15. Mean water level for the 1618-2003 at well 117 is higher than recorded over the period of instrumental observations (1972-2003), although the minimum and maximum water levels are lower than the minimum record and the maximum recorded. On the other hand, mean water levels for the periods of 1684-2003 and 1859-2002 at wells 125 and 159 respectively are lower than the recorded over the period of instrumental observations (1973-2003; 1968-2001). Minimum and maximum reconstructed water levels are lower than minimum and maximum observed which suggest the existence of more extreme dry events driving low water levels.

In Saskatchewan, mean water levels for the periods of 1879-2001, 1862-2001,1879-2001, 1875-2001 at wells Atto, C501, SmoA and Swan are higher than means recorded over the periods of 1966-2001, 1972-2001, 1971-2001, and 1972-2002 respectively. Minimum water levels were lower at wells Atto and C501 and higher at wells SmoA and Swan during the reconstruction period than during the instrumental period. At wells BanB, Duc1, Duc2, and Unit mean reconstructed water levels (1909-2001-;1909-2001;1872-2001;1872-2001) are lower than the instrumental means recorded (1971-2001;1967-2001;1966-2001;1968-2001). Minimum and maximum reconstructed water levels are lower and higher than minimum and maximum water levels recorded at the 4 wells.

Table 5.15: Statistical comparison between observed and reconstructed water levels

Well	Mean	StDev	Variance	Median	Minimum	Maximum	Range	N
w117	-0.00239	1.03188	1.06479	-0.12732	-1.54309	2.81647	4.35956	34
w117_rec	0.13301	0.76670	0.58784	0.15074	-1.98388	2.71032	4.69421	386
w125	0.03808	1.00591	1.01186	0.06102	-1.93106	1.49967	3.43073	32
w125_rec	-0.49778	0.80240	0.64384	-0.46918	-2.68069	1.44462	4.12531	320
w159	0.16931	0.92933	0.86365	0.08566	-1.27557	2.63087	3.90644	34
w159_rec	0.11400	1.03975	1.08108	0.16483	-2.59469	2.59495	5.18964	144
Atto	0.15998	0.88505	0.78332	0.13195	-1.41518	1.83135	3.24652	36
Atto_rec	0.25170	0.94714	0.89708	0.01946	-1.79419	3.00877	4.80295	123
BanB	-0.12520	0.94450	0.89208	-0.31177	-2.19437	2.13829	4.33265	31
BanB_rec	-0.42150	1.22129	1.49154	-0.52899	-2.82959	3.95813	6.78772	93

Well	Mean	StDev	Variance	Median	Minimum	Maximum	Range	N
C501	567.476	0.420	0.176	567.450	566.742	568.237	1.494	30
C501_rec	567.558	0.473	0.224	567.460	566.279	569.196	2.917	140
Duc1	0.12054	0.80878	0.65412	-0.18121	-1.27608	1.82438	3.10046	35
Duc1_rec	0.07908	0.69442	0.48221	0.03896	-1.40956	2.26670	3.67626	93
Duc2	479.276	0.100	0.010	479.263	479.108	479.460	0.352	36
Duc2_rec	479.214	0.128	0.016	479.210	478.957	479.630	0.673	127
SmoA	303.496	0.311	0.097	303.452	302.975	304.119	1.144	31
SmoA_rec	303.533	0.248	0.061	303.492	303.013	304.195	1.182	123
Swan	0.12505	1.00740	1.01485	0.23036	-2.22000	2.22000	4.44000	30
Swan_rec	0.60553	1.02680	1.05431	0.60310	-1.47448	2.82553	4.30001	127
Unit	-0.10685	1.08238	1.17155	-0.14776	-1.88141	1.96650	3.84791	34
Unit_rec	-0.83108	1.28877	1.66092	-0.83686	-4.05640	2.78023	6.83662	127

5.3 Analyses post reconstruction: Regime shifts, wavelets and singular spectrum analysis

The utilization of regime shifts analysis to detect shifts in the mean, plus wavelet and singular spectrum analysis (SSA) is a powerful combination to analyze the variability of groundwater levels and enable the identification and attribution of the major changes in mean water levels.

5.3.1 Alberta

Results of the regime shifts analysis suggest that there have been constant changes in mean groundwater levels at well 117 (Fig. 5.25a). Several periods of higher and lower water levels than average are identified from the reconstruction. There are more periods above average than below, although, periods below average are longer.

There are two major periods with low levels: a 36 year period starting in 1842 and a 35 year period starting in 1914. Also a third relatively long period of low water levels starts in 1979 and extends to 1991.

Result of wavelet analysis show significant activity in the 3-6, 6-12, and around 64 year bands (Fig. 5.25b). Most of the activity in the 2-6 yr band occurs in the period 1850-2000. Significant activity in the 6-12 yr band occurs in the early and late 1700s. The ~64 year band presents significant activity from the first quarter of the eighteen century which coincides with the first period of low levels.

Singular spectrum analysis is used to separate different oscillation modes detected by wavelet analysis. Six major waveforms at 6.4, 9.69, 10.8, 14.2, 24.5, and 66.3 years were isolated from the groundwater reconstruction (Fig. 5.25c). These six oscillation modes account for 51.5% of the total variance in the reconstruction. Most of the modes identified by SSA are in the range previously identified by wavelet analysis (6-12 and 64 years). In terms of variance explained the 14.2 yr mode is the most influential explaining 15.8% of the variance. This oscillation mode is followed by the 66.3 year mode which accounts for 11.8% of the variance; both modes show decreased amplitudes during low water levels.

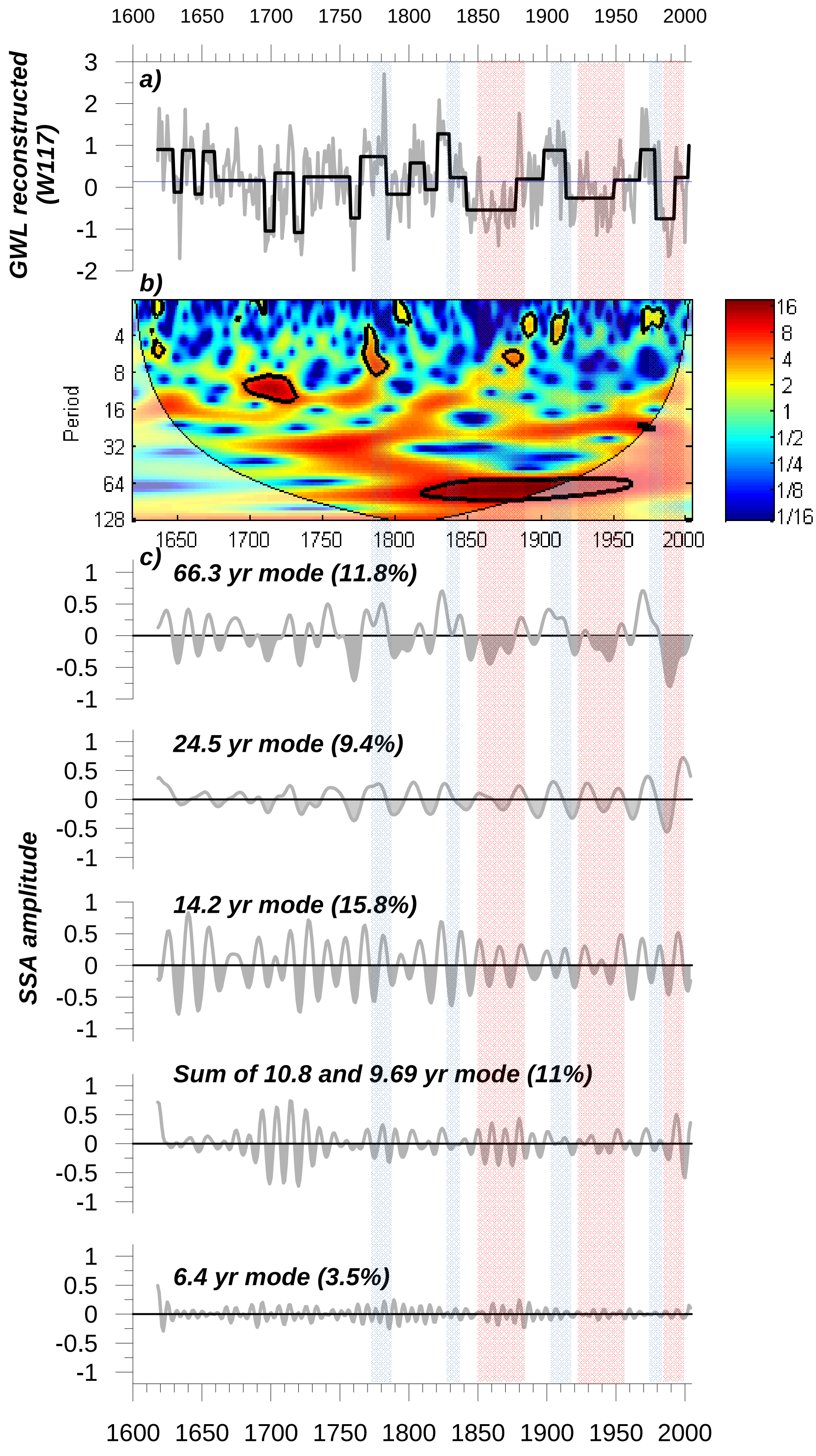

Figure 5.25: a) Well 117 groundwater levels reconstruction (grey line) and regime shifts (black line) which shows significant shifts in the mean. b) Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are significant. The black

contour line shows the 95% confidence interval. c) Singular spectrum analysis shows individual oscillation modes and the variance explained by them. Units are dimensionless. Period is in years and the percentage of variance associated with each waveform is given in brackets.

Results of regime shift analysis for well 125 show that in 168 years water levels have been lower than average (Fig. 5.26a). These low level years are divided into four periods of 73, 13, 28, and 54 years. The longest low level period starts in 1700. Mean annual water levels are just below average.

The second longest period is 1923 to 1976, when water levels reached their minimum level. Periods above average sum a total of 152 years and are divided in to five main periods, including 70 years in the eighteen century and from 1976 to the present. This recent period has the maximum water levels in the whole reconstructions.

Wavelet analysis of water levels at well 125 show some activity in the 2-4, 4-8, 8-16 and 23-64 yr bands (Figure 5.26b). The activity in the 2-4 year band had mostly taken place between 1850 and 1950, and around 1700 and 1750. The most significant activity in the 4-8 yr band occurred in the eighteen century, a period in which some activity is also seen in the 32-64 yr band. The 8-16 yr band shows significant activity around 1750.

Six oscillation modes at 47.5, 29.5, 18.6, 11.9, 11.8, and 9.7 years account for 35.1 % of the variance when isolated using SSA (Fig. 5.27c). Most of the variance (12.8%) is explained by the sum of three modes in the 9-12 yr band; although, changes in the magnitude of these modes seem to produce no changes in mean water levels. The 47.5 and 29.5 yr modes account for 11.2 % and 6.1% of the variance and changes in the amplitude of these modes seem to affect mean water levels. Periods of low water levels coincide with a decreased magnitude of these modes. In addition, water levels above and below average coincide with the maximum positive and negative amplitude of these two modes, respectively. During the low period around 1950 the 47.5 yr mode produced a decreased magnitude reducing the waveform. After this period the mode is present and coincides with the positive trend in water levels.

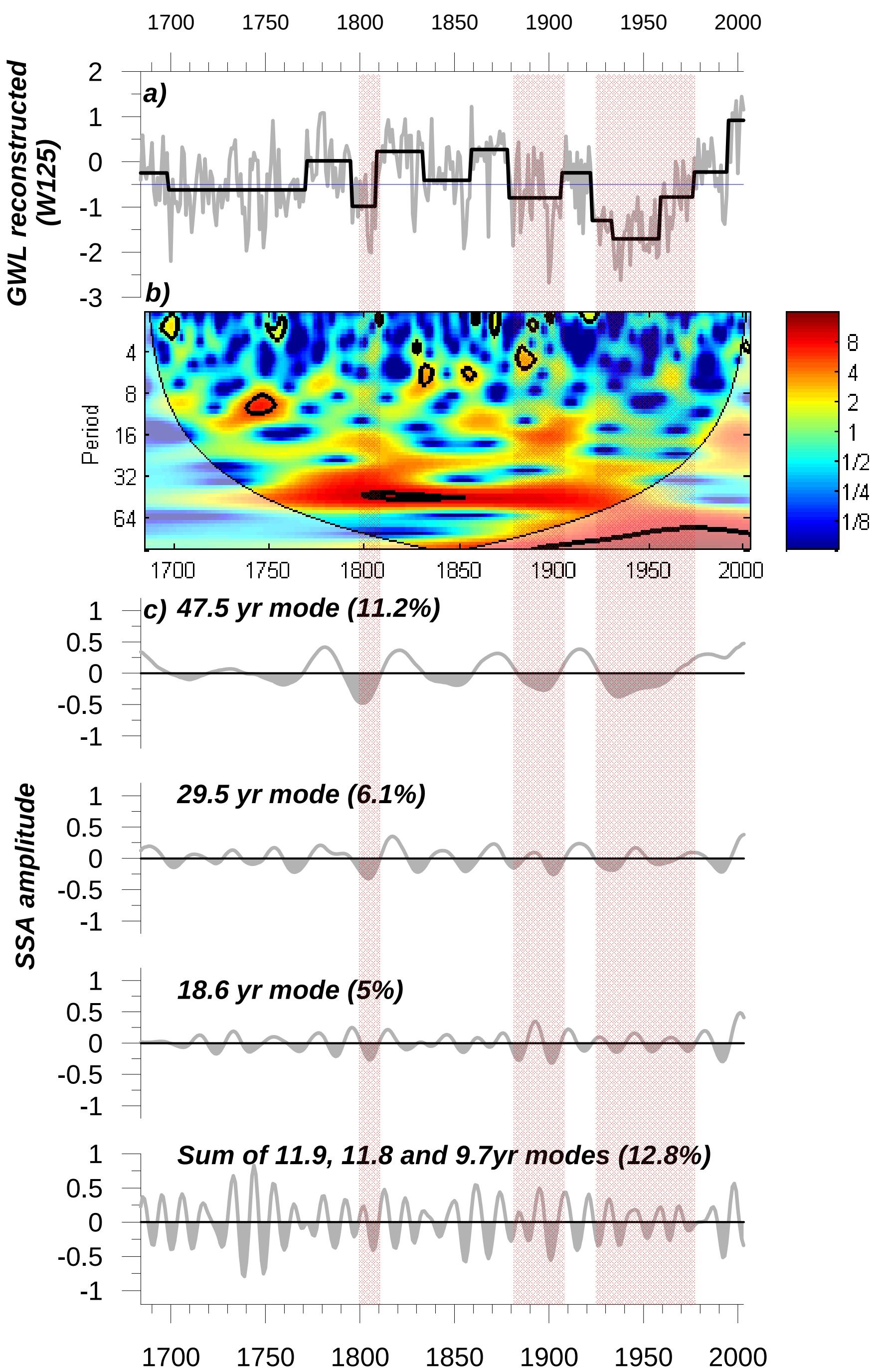

Figure 5.26: a) Well 125 groundwater levels reconstruction (grey line) and regime shifts (black line) which shows significant shifts in the mean. b) Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are significant. The black contour line shows the 95% confidence interval. c) Singular spectrum analysis shows different oscillation modes and the variance explained by them. Units are dimensionless. Period is in years and the percentage of variance associated with each waveform is given in brackets.

Regime shifts identified fewer changes in mean water levels at well 159 than at wells 117 and 125 (Figure 5.27a). Only the 1885-1892 and 1906-1934 periods have water levels below average.

Wavelet analysis shows activity in the 2-4, 4-8, 8-16 and 32 yr bands at different times. The most significant activity in the 2-4 yr band took place around 1880 and 1940. The 4-8 yr band was active around 1900; its relation to changes in the mean during this period is not clear. The period 1940-60 represents significant activity in the 8-16 yr band. This activity does not produce changes in the mean, although, major variability in groundwater level is observed, variability that might be caused by the superposition of this periodicity with the activity in the 2-4 yr band. Finally, significant activity is observed in the 32 yr band during the low water level period centered on 1920.

Application of singular spectrum analysis to water levels at well 159 reveals 13 main oscillation modes (Fig. 5.27c) accounting for 54% of the total variance in the reconstruction. Waveforms were identified and reconstructed at 30 years, and between 2.2-4.3, 5.2-6.3, and 10.9-11.2 years. Modes between 2.2-4.3 yrs explain most of the variance despite the fact that neither increased nor decreased magnitude seems to influence water levels. Decreased magnitudes of the 30 year oscillation mode and waveforms between 5.2-6.3 years coincide with low water levels. During 1970-90 all the oscillation modes have decreased magnitude which is reflected by the less variability in water levels during this period.

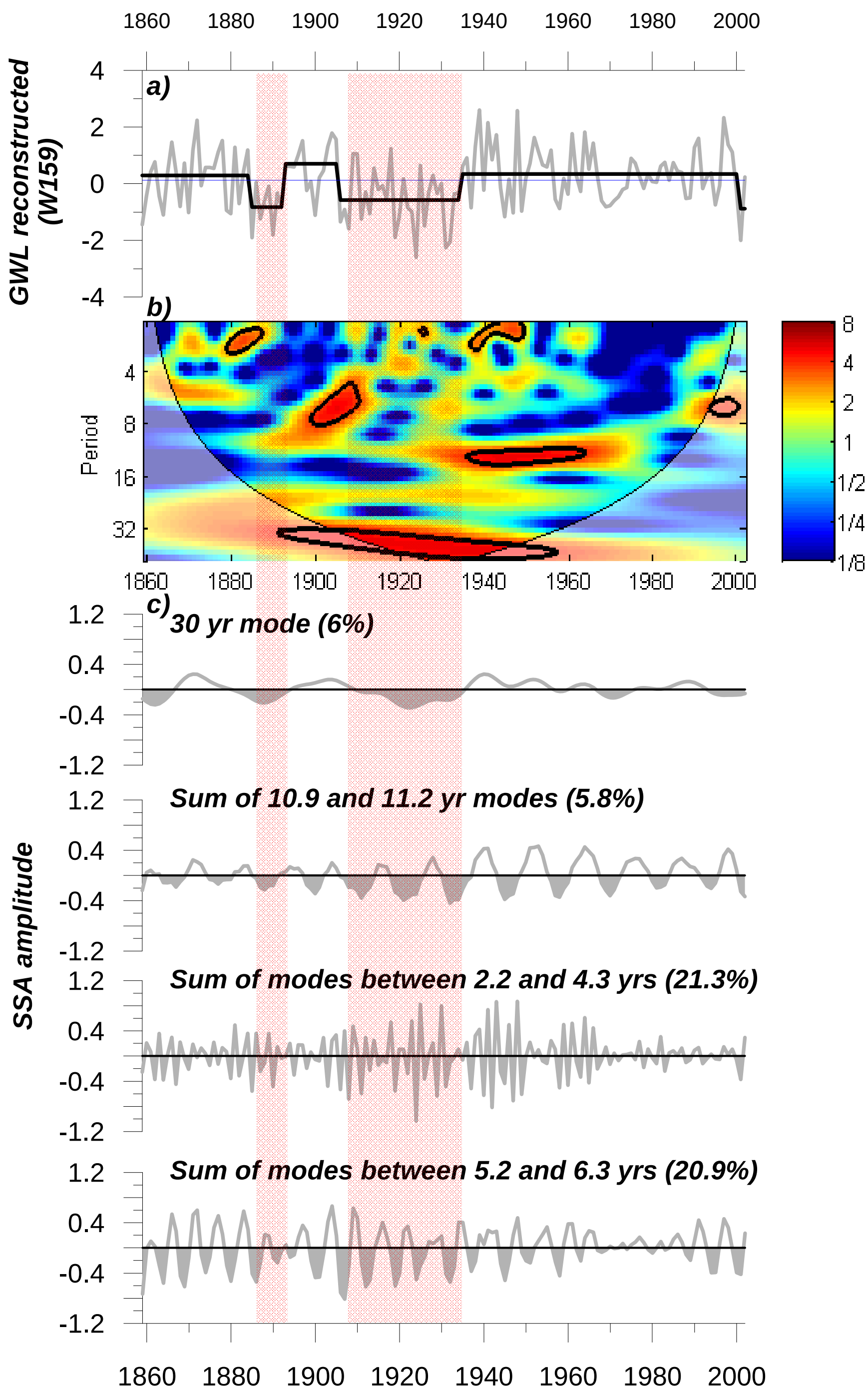

Figure 5.27: a) Well 159 groundwater levels reconstruction (grey line) and regime shifts (black line) which shows significant shifts in the mean. b) Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are significant. The black

contour line shows the 95% confidence interval. c) Singular spectrum analysis shows different oscillation modes and the variance explained by them. Units are dimensionless. Period is in years and the percentage of variance associated with each waveform is given in brackets.

5.3.2 Saskatchewan

No changes in mean water levels at well Atto were detected during the period 1879-1940, when the mean was below average. Positive changes in the mean are observed for the next 40 years. Around 1980 there is a negative shift in the mean and since then water levels have been constantly decreasing. The period 1940-60 represents the maximum reconstructed water levels and therefore the maximum mean (Fig. 5.28a).

Wavelet analysis shows significant activity only in the 2-4 yr band. This activity is significant but does not have high spectral power. More powerful activity is observed in the 8-16 and the 32 yr bands; however, it is not statistically significant (Fig. 5.28b).

Two major wave forms were isolated from the groundwater reconstruction using SSA (Fig. 5.28c). The two oscillation modes account for 16.73% of the variance in the reconstruction. The 24.07 yr mode accounts for 11.04 % and increased magnitudes coincide with periods of above average water levels. Decreased magnitude of this mode and lower values of the 19.53 yr mode coincide with water levels below average during the last 20 years.

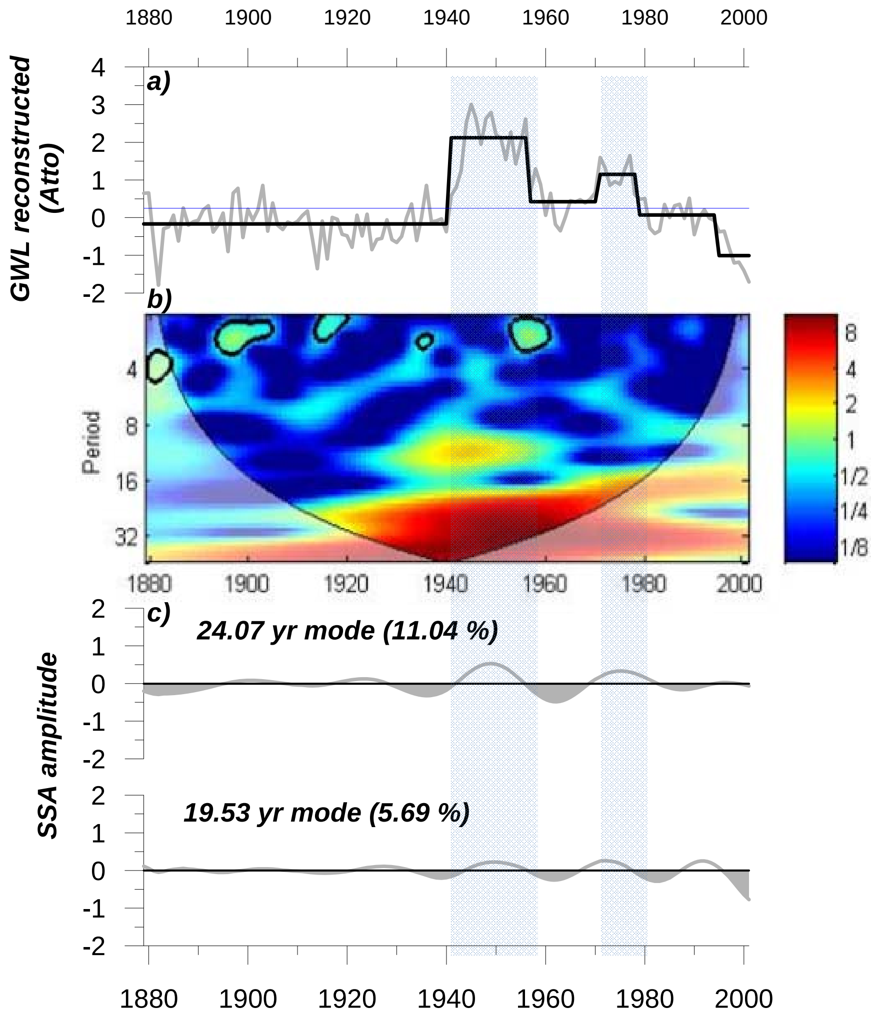

Figure 5.28: a) Well Atto groundwater levels reconstruction (grey line) and regime shifts (black line) which shows significant shifts in the mean. b) Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are significant. The black contour line shows the 95% confidence interval. c) Singular spectrum analysis shows different oscillation modes and the variance explained by them. Units are dimensionless. Period is in years and the percentage of variance associated with each waveform is given in brackets.

Few regime shifts occur at well BanB (Fig. 5.29a). Water levels are above average during the beginning (1909-1918), middle (1945-1957) and the end (1995-2001) of the 20th century. The 1919-1944 period is the longest (26 years) with below average water levels; and the minimum mean water levels in the reconstruction are from 1958 to 1966.

Wavelet analysis shows significant activity in the 2-4 and 16-32 year bands, and some relatively powerful activity in the 8-16 yr band although it is not statistically significant (Fig. 5.29b). The significant activity is centered on the 1950s for both bands and coincides with the period of above average water levels.

Four significant oscillation modes are isolated from the reconstruction of groundwater levels at well BanB using SSA. They account for 45.6% of the total variance with most (25.7%) attributable to the sum of the 24.5 and 26.3 year modes (Fig. 5.29c). Periods of low water levels coincide with a decreased magnitude of these modes and vice versa.

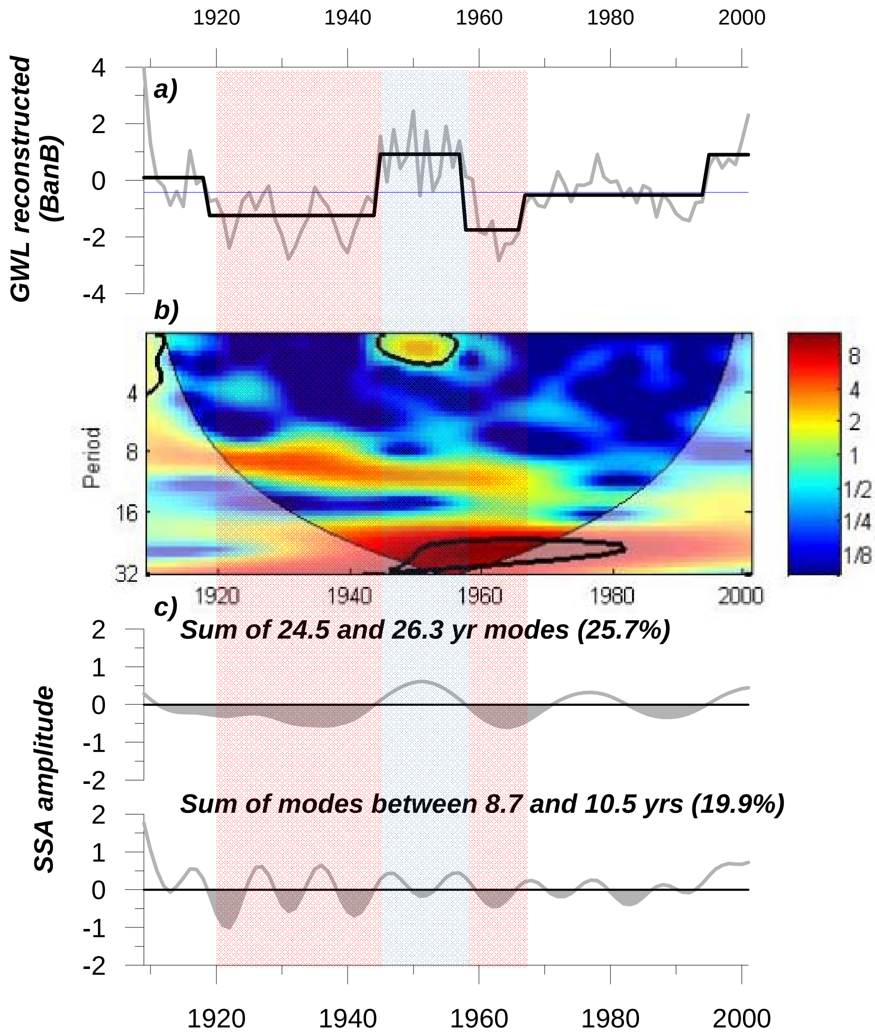

Figure 5.29: a) Well BanB groundwater levels reconstruction (grey line) and regime shifts (black line) which shows significant shifts in the mean. b) Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are significant. The black contour line shows the 95% confidence interval. c) Singular spectrum analysis shows different oscillation modes and the variance explained by them. Units are dimensionless. Period is in years and the percentage of variance associated with each waveform is given in brackets.

Five periods of below average mean reconstructed water levels at well C501 are 1868-1878, 1879-1903, 1913-1922, 1923-1942, and 1958-1992. They all extend for more than 30 years, however, during most of the two first periods mean water levels are relatively close to the mean. The 1958-1992 period is the most extended but does not register the lowest mean. The 1862-1867, 1904-1912, 1942-1957, and 1993-2001 periods have mean water levels above average. Maximum and minimum mean water levels occur in the 1862-1867 and 1923-1941 periods respectively (Fig. 5.30a)

From wavelet analysis, significant activity is identified in the 2-4, 4-8, and 8-16 years bands (Fig. 5.30c). Most of the activity in the 2-4 yr band is around 1900, some significant activity is also seen around 1935 and 1950. The 4-8 yr band also presents significant activity around 1900. 1942-1957 is a period of above average mean water levels coinciding with significant activity in the 8-16 yr band. In addition some activity is seen in the 16-32 yr band but this is not statistically significant.

More than 47% of the total variance in the reconstruction is explained by six oscillation modes at 8.8, 9.6, 9.7, 15.67, 22, and 22.5 years (Fig. 5.30c). The sum of the 22 and 22.5 year modes accounts for most of the variance (26.4%) and another important amount (16.16%) is explained by the modes in the 8-10 yr band. Decreased and increased magnitudes of these modes coincide with periods of mean water levels below and above average. The activity registered by wavelet analysis in the 8-16 yr band coincides with an increased magnitude of the three modes in the 8-10 yr band.

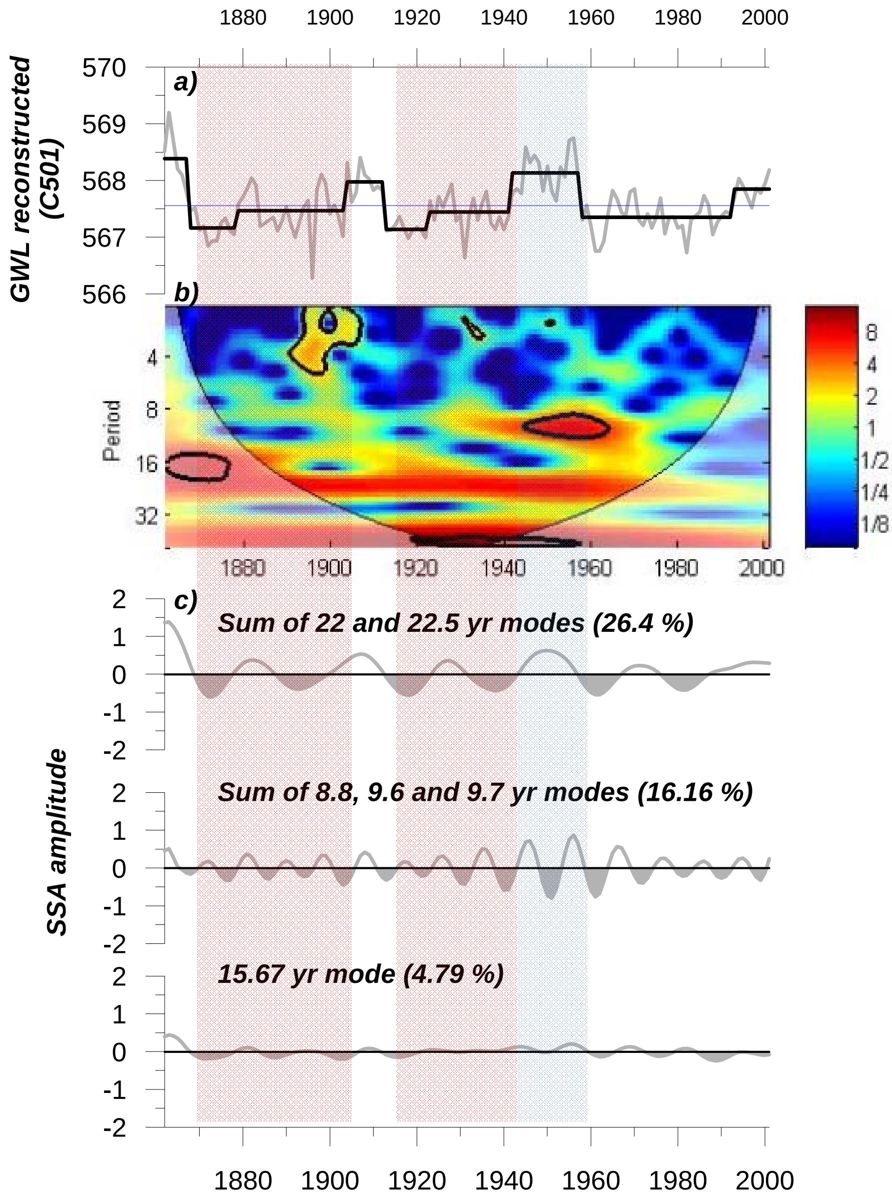

Figure 5.30: a) Well C501 groundwater levels reconstruction (grey line) and regime shifts (black line) which shows significant shifts in the mean. b) Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are significant. The black contour line shows the 95% confidence interval. c) Singular spectrum analysis shows different oscillation modes and the variance explained by them. Units are dimensionless. Period is in years and the percentage of variance associated with each waveform is given in brackets.

The only significant change in mean water levels at well Duc1 is for the period 1998-2001 (Fig. 5.31a).

Wavelet analysis shows significant activity in 2-4, 4-8, and 8-16 yr bands (Fig. 5.31b) and only in the period 1920-1960 resulting in major variability in water levels.

Ten dominant oscillation modes were isolated from the reconstruction using SSA (Fig. 5.31c). Modes at 2.5, 2.6, 3.3, 3.5, 4.8, 4.9, 10, 10.2, 13.6, and 14 years account for 60 % of the total variance in the reconstruction. Modes in the 2-4 year band account for most of the variance (23.7%) corresponding to the results of wavelet analysis. Decreased magnitude of modes in the 2-5 and 10 year bands coincide with a less variability in water levels and below average mean levels in the period 1998-2001.

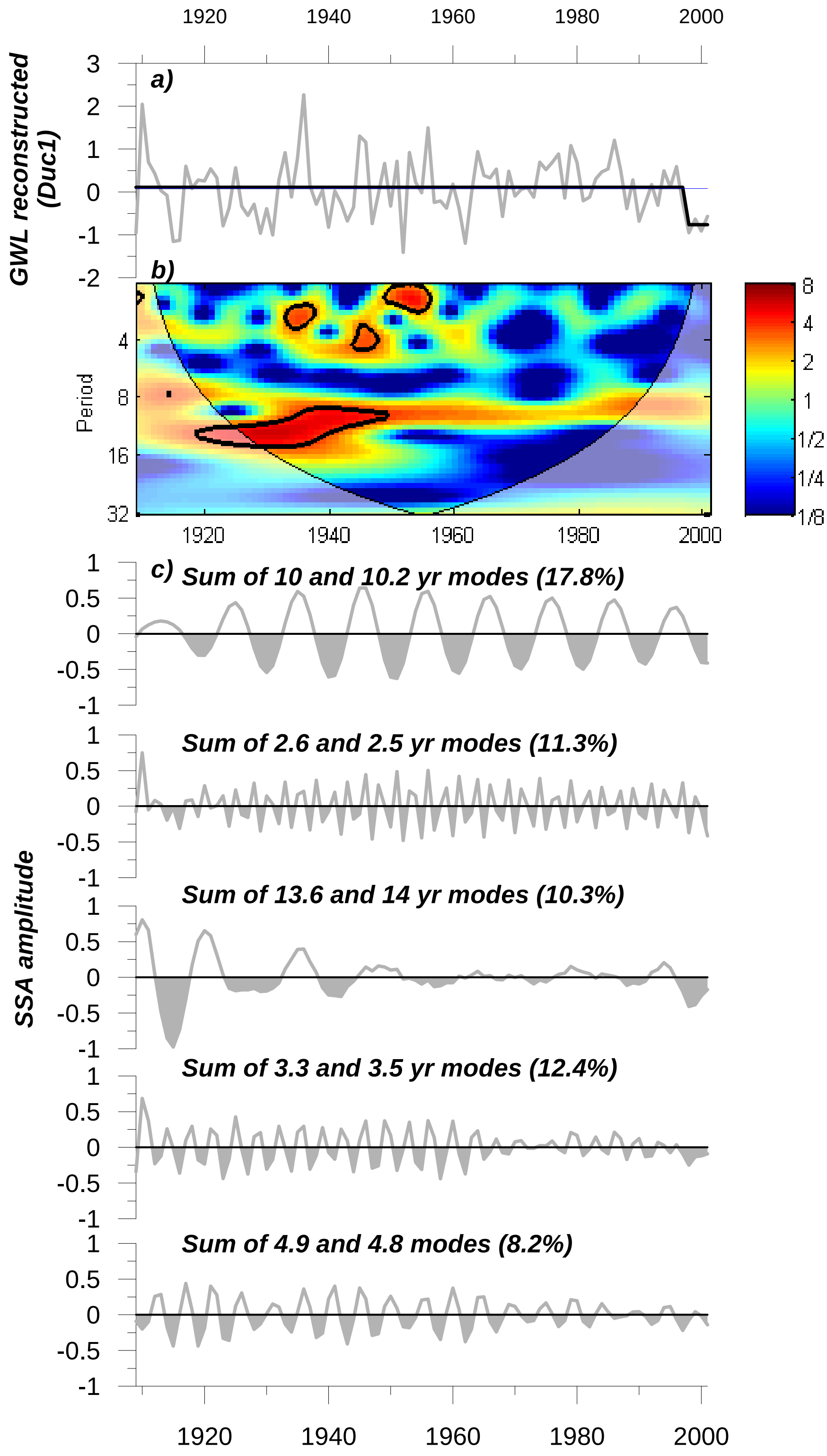

Figure 5.31: a) Well Duc1 groundwater levels reconstruction (grey line) and regime shifts (black line) which shows significant shifts in the mean. b) Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are significant. The black contour line shows the 95% confidence interval. c) Singular spectrum analysis shows different

oscillation modes and the variance explained by them. Units are dimensionless. Period is in years and the percentage of variance associated with each waveform is given in brackets.

There are two main periods of below average mean water levels at well Duc 2 (Fig. 5.32a) centered on 1940 for 66 years and on 1890 for 47 years. Lowest water levels are during 1953-1964. There are three periods (1875-1880, 1899-1917, 1973-1992) with above average mean water levels.

Wavelet analysis suggests some significant activity, in the middle range of the power spectra, in the 2-4 yr band around 1880 and in the 4-8 year band around 1910 (Fig. 5.32b).

SSA isolated modes at 13.7, 14.5, and 32 years accounting for 17.4 % of the total variance in the reconstruction (Fig. 5.32c). The 32-year mode accounts for most of the variance (9.6%) and decreased magnitude in this mode coincides with periods of below average mean water levels.

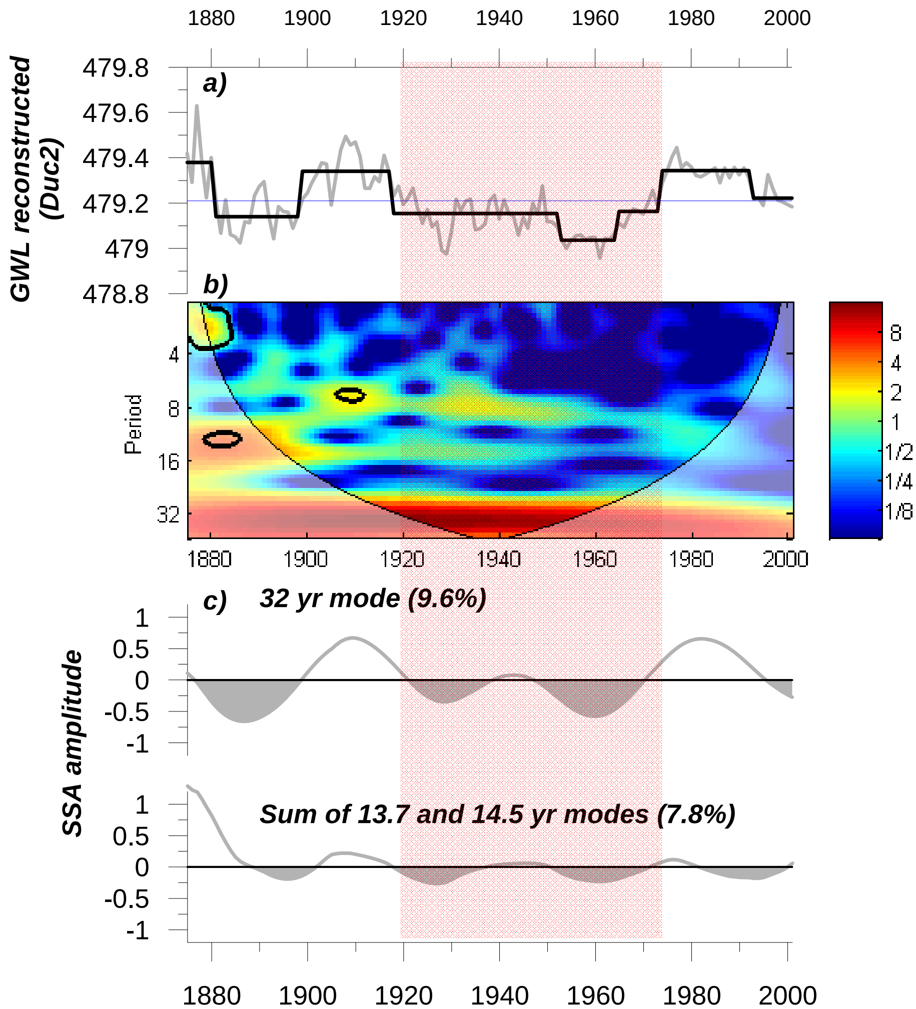

Figure 5.32: a) Well Duc2 groundwater levels reconstruction (grey line) and regime shifts (black line) which shows significant shifts in the mean. b) Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are significant. The black contour line shows the 95% confidence interval. c) Singular spectrum analysis shows different oscillation modes and the variance explained by them. Units are dimensionless. Period is in years and the percentage of variance associated with each waveform is given in brackets.

Mean water levels remained constant and slightly below average at well SmoA during 1879 to 1943 (Fig. 5.33a). Then there are three shifts in mean water levels, all above the average for the next 35 years. Three periods of below average mean water levels occur from 1979 to 2001.

Wavelet analysis suggests that all the significant activity at well SmoA is in the 2-4 and 4-8 year bands (Fig. 5.33b) appearing around 1920, in the period 1940-1960, in the 1970s, and with less magnitude in the early 1990s. Spectra in the 8-16 and 16-32 year bands have high power but are not statistically significant.

Over 31% of the total variance in the reconstruction modes is explained by six oscillation modes (Figure 5.33c). A 25.3 year mode account for most of the variance (10%) and increased magnitude of this mode coincides with above average mean water levels, however, decreased and increased magnitudes of the 15.9 and 8.2-8.4 modes respectively coincide with below average water levels during 1979-2001.

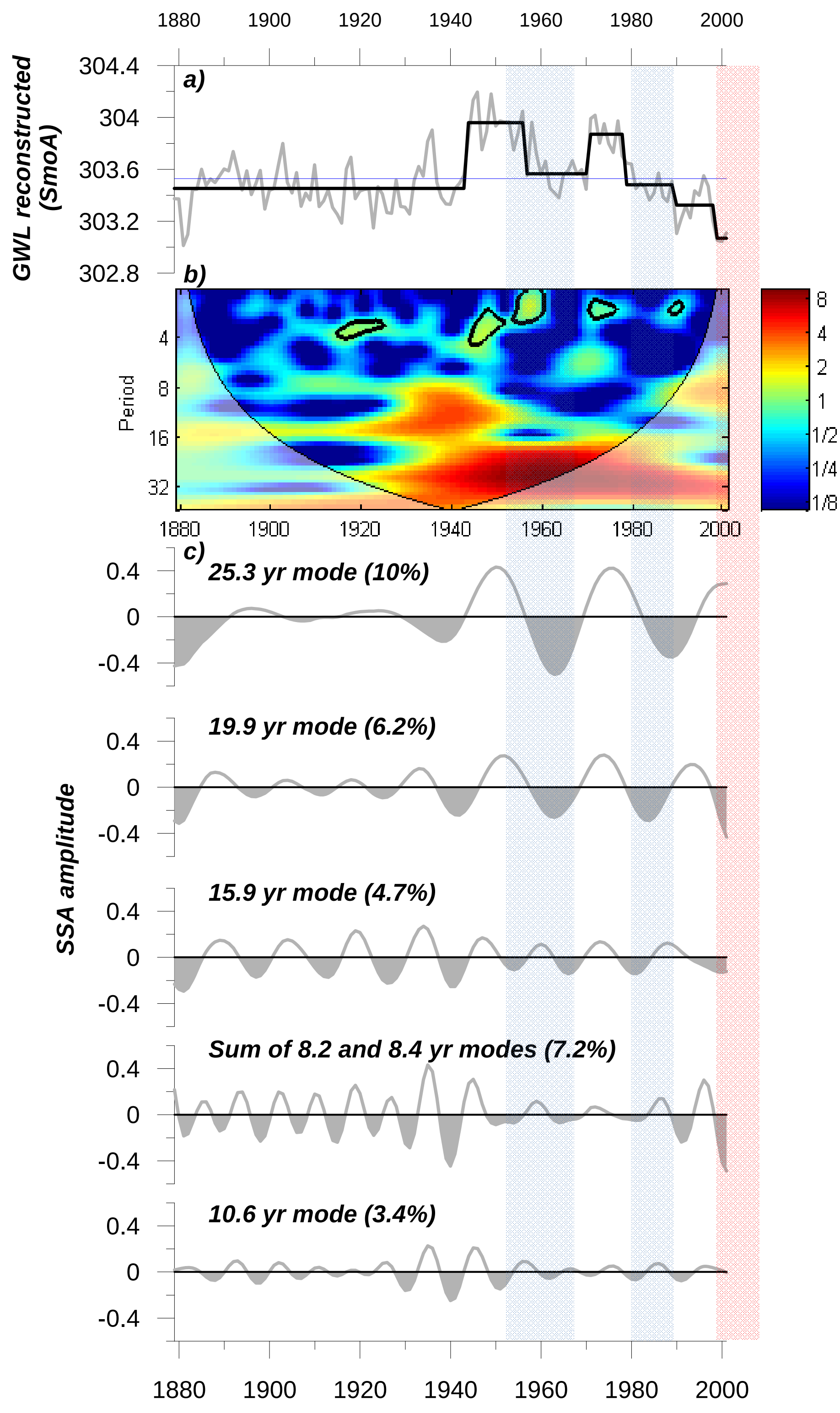

Figure 5.33: a) Well SmoA groundwater levels reconstruction (grey line) and regime shifts (black line) which shows significant shifts in the mean. b) Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are significant. The black contour line shows the 95% confidence interval. c) Singular spectrum analysis, wave forms of

different oscillation modes and the variance explained by them. Units are dimensionless. Period is in years and the percentage of variance associated with each waveform is given in brackets.

Three periods of 11, 10, and 21 years have below average mean water levels are at well Swan (Fig. 5.34a). 1981-2001 is the most extended period, although, does not have the lowest water levels. Mean water levels are highest mean during the period 1949-1967.

Wavelet analysis showed significant and constant activity in various bands during 1890-1950. Significant activity in the 2-4 yr band is observed around 1910, 1950 and 1970, in the 4-8 yr band around 1910 and in the 1940s, in the 8-16 yr band around 1900 and during 1920-1940. Also this period presents activity in the 16-32 yr band (Fig. 5.34b).

SSA of reconstructed water levels revealed seven oscillation modes that account for 53.2 % of the total variance in the reconstruction (Fig. 5.34c); 20 % is in the 12-16 yr band. The 36.4 yr mode account for 19% of the total variance and increased magnitudes of this mode coincide with above average water levels centered on 1960. There is no clear visualization of how all these modes affect and produce changes in mean water levels considering that more than one mode is acting at the same time, which is clearly identified by wavelet analysis.

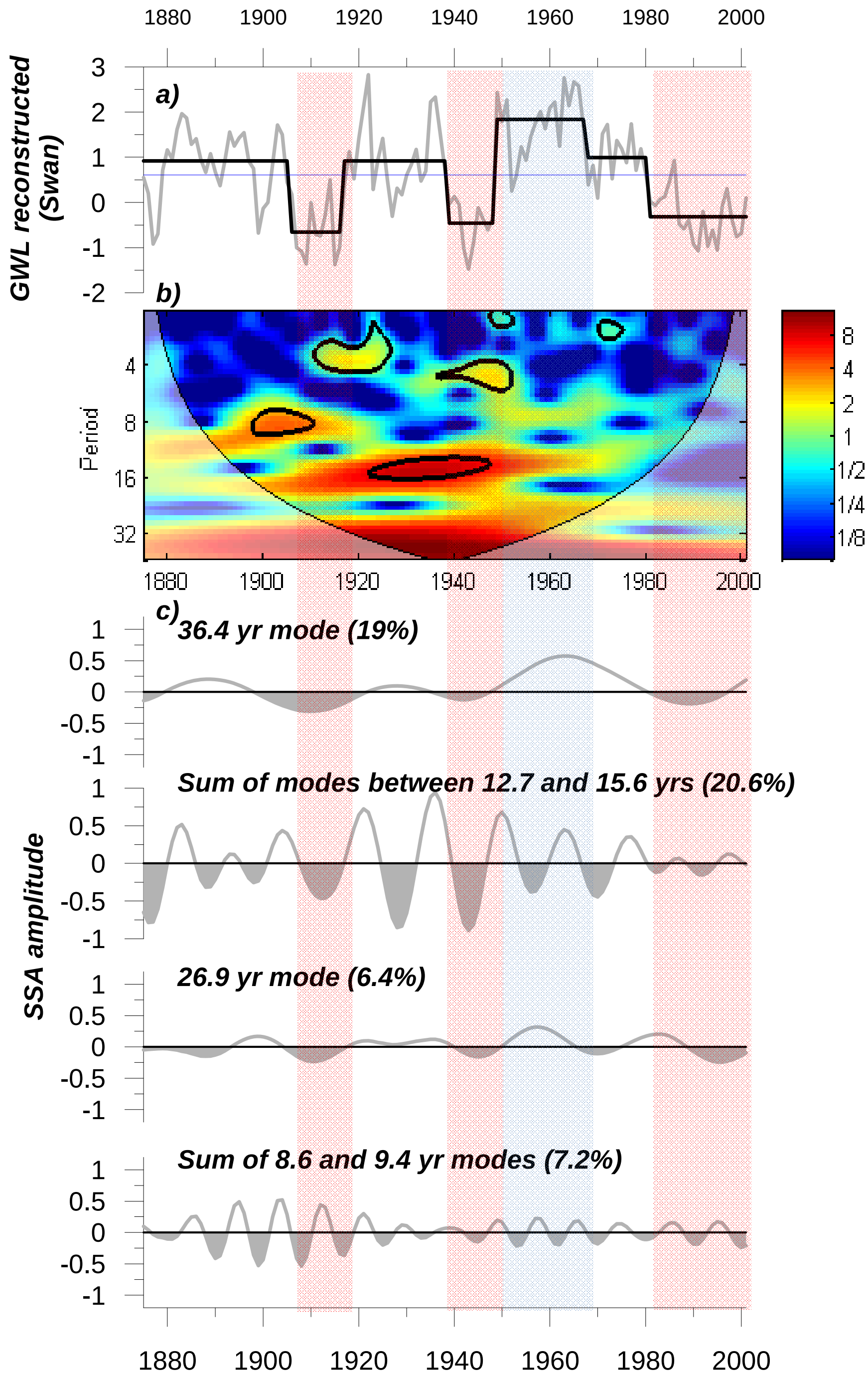

Figure 5.34: a) Well Swan groundwater levels reconstruction (grey line) and regime shifts (black line) which shows significant shifts in the mean. b) Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are significant. The black contour line shows the 95% confidence interval. c) Singular spectrum analysis shows different oscillation modes and the variance explained by them. Units are dimensionless. Period is in years and the percentage of variance associated with each waveform is given in brackets.

At well Unit water levels are below average in several periods, 1884-1889, 1920-1942, 1949-1974, and 1960-1966 which registers the lowest water levels (Fig. 5.35a), the four periods add 36 years of water levels below average. Three main periods (1899-1919, 1943-1948, and 1975-2001) with above average water levels include a six year period (1943-1948) that interrupted what could have been 55 consecutive years with below average mean water levels. The highest mean water level is reached during the fifteen year period 1987-200).

Wavelet analysis shows significant activity at different periods during the first half of the nineteen century (Fig. 5.35b): in the 2-4 yr band around 1880 and 1960, the 4-8 yr band during 1900-1940, the 8-16 yr band during 1900-1935, and in1925-1945 period around the 32 yr band.

Oscillation modes at 8.5, 9, and 30 years account for 16% of the total variance in the reconstruction (Fig. 5.35c). The 30 yr mode account for most of the variance with 8.7% and increased and decreased magnitudes of this mode match periods with mean water levels above and below average.

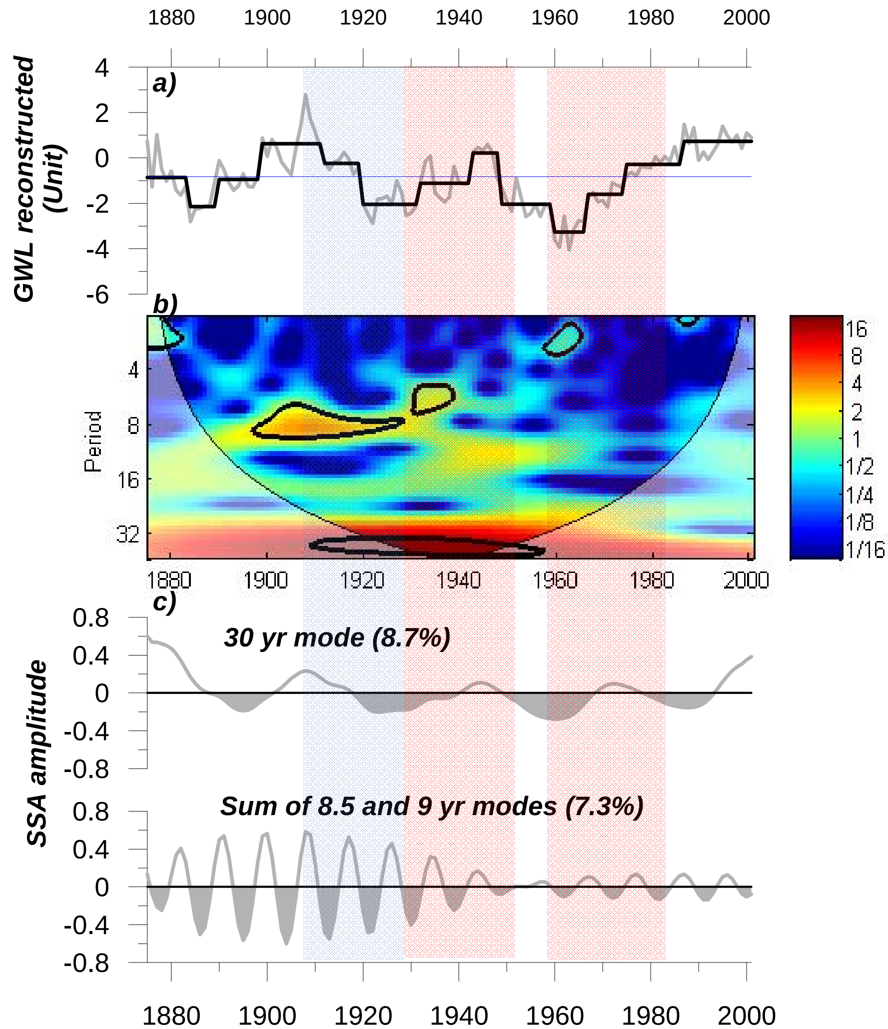

Figure 5.35: a) Well Unit groundwater levels reconstruction (grey line) and regime shifts (black line) which shows significant shifts in the mean. b) Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are significant. The black contour line shows the 95% confidence interval. c) Singular spectrum analysis shows different oscillation modes and the variance explained by them. Units are dimensionless. Period is in years and the percentage of variance associated with each waveform is given in brackets.

Ferguson and St. George (2003) have been the only authors to have used tree growth to reconstruct groundwater levels. Their work reconstructed mean annual groundwater levels in the Upper Carbonate Aquifer near Winnipeg. The results of this study are coherent with their results and ratified the success using tree-ring chronologies to reconstruct groundwater levels. Also, this study achieves better results, with similar variance explained but longer reconstruction periods for most wells. Also, this study only uses tree-ring chronologies as predictors and records from groundwater levels that have been not affected by pumping, and are mostly in sand and sandstone aquifers. In addition, the reconstruction of water levels at various wells allows us to retain the natural variability related to the specific local conditions which is reflected by the differing responses of groundwater levels to known climatic events.

Even though, exploratory analysis showed significant correlations between groundwater levels and temperature, this correlation is not high enough to use temperature as a predictor of groundwater levels as it was used by Ferguson and St. George (2003).Another difference from Ferguson and St. George (2003), is the use in this study of spectral analysis to identify dominant oscillation modes in bands of 2-8, 8-16 and 16-32 years.

In Alberta most of the variability is explained by oscillation modes in the bands 2-8 and 8-16 years. However, most of groundwater levels in Saskatchewan do not have significant oscillation modes in the 2-8 year band and most of the variability is driven by oscillation modes in the 8-16 and 16-32 year bands. Four oscillation modes at ~10, ~15, ~20, and ~25 years respectively explain most of the variance in groundwater levels.

This study has examined and documented trends, shifts and variability in groundwater levels in the Canadian Prairies, however, the study of the drivers is beyond the scope of this study which was to analyze trends and natural variability in groundwater levels. Although some authors (Coulibaly and Burn, 2004; Gan et al. 2007; and others) have linked the hydroclimate of western Canada to sea surface temperature oscillations such as

El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Most of the oscillation modes isolated using spectral methods are in the ENSO band (2-8 years) and the PDO band (15-25 years) which might be the main drivers of the variability in groundwater levels. Table 5.16 summarizes the results of spectral analysis for each well at different bands.

Table 5.16: Results of spectral analysis at different periodicities. Wav and ssa represent the existence of oscillation modes statistically significant using wavelet and singular spectrum analysis respectively.

Well	2-8 years	~10-15 years	~20-25 years	> 25 years
w117	wav/ssa	wav/ssa	-	wav/ssa
w125	wav/ssa	wav/ssa	ssa	wav/ssa
w159	wav/ssa	wav/ssa	-	wav/ssa
Atto	wav	-	ssa	-
BanB	wav	ssa	ssa	ssa
C501	wav	wav/ssa	ssa	-
Duc1	wav/ssa	wav/ssa	-	-
Duc2	wav	ssa	-	ssa
SmoA	wav	ssa	ssa	-
Swan	wav/ssa	wav/ssa	-	ssa
Unit	wav	wav/ssa	-	wav/ssa

6. CONCLUSIONS

6.1 Research findings

This study is the first to examine trends in groundwater levels and long term variability in the Canadian Prairies and it has achieved each one of the objectives described under heading 1.5.

The results indicate that 12 groundwater records present statistically significant decreasing trends, 10 records do not register significant trends and 11 have increasing trends. This study also found a spatial pattern in the distribution of trends through the Prairies. Groundwater levels in north central areas are dominated by decreasing or no trends, in contrast to groundwater levels in southern areas which are dominated by increasing trends. This spatial pattern coincides with the spatial distribution in evaporation trends identified in a previous study, where northern areas have increasing trends and southern areas decreasing trends in evaporation and thus a negative correlation with trends in groundwater levels This result ratifies the importance of evaporation in aquifer recharge.

Strong linear relationships were found between groundwater levels and moisture-sensitive tree-ring chronologies. This relationship made possible the use of multiple linear regression techniques to reconstruct historical groundwater levels in Alberta and Saskatchewan. These reconstructions expand groundwater records for more than 300 years in Alberta and more than 100 years in Saskatchewan. The tree-ring reconstructions account for 40% to 81% of the instrumental variance in groundwater levels.

Longer periods of low groundwater levels than observed were identified in inferred pre-instrumental water levels in Alberta and Saskatchewan. Also, these reconstructions reveal the impact of historical climatic events and in particular droughts. For example the 1980s is the decade with the lowest water levels reconstructed at well 117 in more than 300 years. The Period centered on 1950 is the longest period with low water levels in the 320 year reconstruction at well 125. Mean water levels at well 159 have remained relatively steady during the 144 year reconstruction, even though spectral methods identified significant oscillation modes in the 2-8, 8-16, 16-32 year bands. The activity in the 2-8 year band produces significant inter-annual variability but not always changes in the mean. Activity in the same bands is also observed in groundwater levels at wells 117 and 125 and most of the activity in the 2-8 year band is significant after 1850.

The reconstruction models for Saskatchewan suggest that low water levels in the late 1990s early 2000s at wells Atto, Duc1, and SmoA are the lowest in 123, 93, and 123 years respectively. This is also the period with the lowest mean except at well Duc1 where the lowest period is centered on the 1950s. Groundwater at wells BanB, Duc2, and Unit reached the lowest levels in the 1960s and this is the period with the lowest mean in 93, 127, and 127 years. Water levels at wells Swan reached the lowest level in the 1940s and the period centered on 1910 registers the lowest mean.

Wavelet analysis identified most of the significant activity in Saskatchewan groundwater levels in the 8-16 and 16-32 years bands. Activity in the 2-8 year band was found in at some wells but it was not significant at all wells in Saskatchewan. Oscillation modes in this band cause a greater inter-annual variability but it is not a driver of changes in mean water levels. Oscillation modes in the 8-16 and 16-32 year bands account for most of the variability in water levels in Saskatchewan. Common oscillation modes have been identified at ~10 and ~15 years in the 8-16 year band, and ~20 and ~25 year.

Generally, changes in mean water levels are caused by the superposition of different oscillation modes acting at the same time where different phases of these modes can produce major impacts on groundwater levels.

6.2 Future research

As a result of this study, a groundwater data based has been generated for the Canadian Prairies. This data base has been used for the first time to calculate trends in groundwater levels and study long term climate variability. This study has answered some questions about trends, natural variability, and impacts of historical droughts on groundwater resources but also raises many more questions that lead to more research. These topics for further research include seasonal trends in groundwater levels for a common period, and the identification of spatial patterns as a function of evaporation and precipitation. In addition, historical droughts have had different impacts on groundwater levels at different wells which suggest that the quantification of the impacts climate events such as droughts needs to be studied at aquifer level.

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APPENDIX

Table A1: Coefficients of autocorrelation functions (ACF)

Well	ACF(1)	ACF(2)	ACF(3)	ACF(4)	ACF(5)
w102	0.925*	0.792*	0.645	0.458	0.256
w104	0.850*	0.688*	0.530	0.386	0.240
w106	0.825*	0.540	0.258	-0.013	-0.223
w108	0.677*	0.230	-0.196	-0.459	-0.452
w112	0.825*	0.624	0.488	0.297	0.135
w114	0.764*	0.266	-0.221	-0.541	-0.619
w117	0.681*	0.390	0.273	0.192	0.100
w125	0.597*	0.107	-0.158	-0.309	-0.231
w147	0.330*	-0.119	0.071	0.304	0.061
w159	0.649*	0.059	-0.381	-0.575	-0.474
w176	0.637*	0.092	-0.322	-0.494	-0.418
w192	0.869*	0.626	0.323	0.032	-0.220
w193	0.911*	0.763	0.561	0.339	0.104
w212	0.766*	0.575	0.354	0.131	0.017
w228	0.814*	0.536	0.293	0.024	-0.177
w229	0.632*	0.271	0.065	-0.218	
w252	0.483*	-0.132	-0.239	-0.289	-0.445
w260	0.869*	0.710*	0.567	0.424	0.270
w270	0.804*	0.498	0.195	-0.049	-0.150
Atto	0.921*	0.821*	0.725*	0.641	0.558
B059	0.896*	0.783*	0.693*	0.595	0.536
BanA	0.931*	0.785*	0.594*	0.383	0.182
BanB	0.914*	0.765*	0.579	0.374	0.176
C500	0.857*	0.698*	0.526	0.375	0.265
C501	0.813*	0.524	0.290	0.121	0.066
Duc1	0.749*	0.373	0.167	0.125	0.094
Duc2	0.851*	0.634*	0.419	0.269	0.173
Lila	0.936*	0.850*	0.765*	0.694	0.619
Rice	0.925*	0.834*	0.748*	0.656	0.572
Si13	0.806*	0.611*	0.470	0.337	0.274
SmoA	0.882*	0.725*	0.581	0.450	0.334
Swan	0.888*	0.768*	0.617	0.496	0.397
Tyne	0.889*	0.777*	0.699*	0.628	0.568
Unit	0.891*	0.767*	0.636	0.520	0.415
Verl	0.928*	0.860*	0.804*	0.724	0.630
Ln001	0.504*	0.081	-0.021	0.051	0.073
Ob005	0.867*	0.718*	0.604	0.486	0.331
Oe001	0.870*	0.724*	0.624	0.467	0.278
Og003	0.696*	0.470*	0.308	0.261	0.113