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GROUND WATER TRENDS AND VARIABILITY IN THE CANADIAN PRAIRIES

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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 ($r > 0.7$, $p < 0.05$) between tree-ring chronologies and seasonal and annual groundwater levels enable the reconstruction of 12 annual groundwater level records for more than 90 years in Saskatchewan and more than 300 year in Alberta. Different modes of climate variability are detected in Alberta and Saskatchewan.

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INTRODUCTION

Groundwater is one 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).

To date, few studies of have modeled or reconstructed future and past groundwater levels. Chen et al. (2002) used an empirical model to predict groundwater levels, while Ferguson and St. George (2003) used precipitation, temperature and tree rings to reconstruct historical levels of groundwater. Tree rings have been widely used to reconstruct components of the hydrological cycle, such as stream flow and precipitation (Watson and Luckman, 2001; Woodhouse, 2001; St. George and Nielsen, 2002; Case and McDonald, 2003 and others), however there is only one study which has investigated the relationship between tree rings and groundwater within the Prairies (Ferguson and St. George, 2003).

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 affects of climatic variability on ground water.

Previous studies have examined trends in stream flow (Burn and Elnur, 2002; Yue et al., 2003; Abdul and Burn, 2006), precipitation (Gan, 1998), evaporation (Burn and Hesch, 2007),; however, this is the first study to analyse long-term ground water trends and variability within the Canadian Prairies, and does so by adopting established techniques used for detecting trends in stream flow and applying them to ground water time series. This study, “Ground water in the Canadian Prairies: Trends, variability and its relationship with tree rings”, is in partial fulfillment for a Master of Applied Science in Engineering degree.

METHODS

Restrictions on the length of this paper permit only a brief description of the methodology and techniques.

Trends analysis

Trend analyses were carried out using detrending and prewhitening methods proposed by Yue et al (2002) in order to prepare the time series for a Mann-Kendall test of trends. This procedure involved calculating the Sen’s slope of the time series; if the Sen’s slope is different from zero then the slope is removed from the data, otherwise no trend is detected. Once the slope is removed, first-order autocorrelation is calculated and removed. After the serial correlation is removed, the Sen's slope is reintegrated into the time series. This last procedure produces a time series that conserves the trend but has no autocorrelation of order 1. Finally the Mann-Kendall test was applied to all the time series using a macro in MINITAB.

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).The Mann-Kendall non-parametric test to detect trends (Mann, 1945; Kendal, 1975) has been widely applied to hydrological time series (Yue et al. 2002; Yue and Pilon, 2003; Burn et al. 2004; Adbul and Burn, 2006; Burn and Mesch, 2007; among others).

Tree-ring reconstruction and analysis post reconstruction

The high correlations found between groundwater levels and tree-ring chronologies makes possible the use of regression techniques based on a predictand (ground water levels) and predictors (standard chronologies). The regression model has the form of Equation [1] below.

[1] $Y_t = a + b_1X_{1t} + b_2X_{2t} + ... + b_kX_{kt} + e_t$

Where Y_t is the predictand, for our case groundwater level, a is the regression constant, X_k are the predictors used in the models, b_k the regression coefficients and e is the error of the regression.

A criterion for the regression models is a period of calibration of at least 30 years. Using this criterion a total of 11 groundwater records could be used.

A series of over 30 different regression models were computed using a MATLAB script which gives parameters such as the R^2 and R^2_{adj} RE among others. Eleven reconstruction models proved useful and are considered in this paper.

Post reconstruction analysis of the 11 proxy groundwater records included: the bar code, which is a simple plot of percentiles to illustrate periods of low water level; intervention analysis to detect shifts in the mean groundwater levels; wavelet analysis to identify different spectral signals through time and Singular Spectrum Analysis to decompose signals into different modes.

DATA

Ground water records

The groundwater network used in this study is based on 33 observations wells. These 33 records were extracted from a groundwater data base (compiled previously) derived from more than 200 well records across the three Prairie Provinces. The data were obtained from the Alberta Environment, the Saskatchewan Watershed Authority and Manitoba Water Stewardship.

The criterion used in choosing the 33 well records was the length and continuity of the record in first instance. Twenty or more years of record was considered appropriate to carry out the analysis in this paper. Anthropological effects, lithology (Table 1), and missing data (see table 1) for each aquifer were also considered in the selection of the well.

Table 1: Observation wells used in this paper. All the wells have been not affected by man

Well name	Well ID (used)	Depth of the well (m)	Aquifer	Lithology	Province	Latitude (degrees)	Longitude (degrees)	Elevation (m)	Years of record
Cressday 85-2	Well 102	80.00	Belly River	Sandstone	AB	49.104	-110.251	887.12	22
Pakowki 85-1	Well 104	69.00	Medicine Hat Valley	Sand, gravel	AB	49.472	-110.969	886.60	22
Cypress 85-1	Well 106	30.00	Upper Bearpaw	Sandstone	AB	49.524	-110.218	1188.00	22
Elkwater 2294E	Well 108	33.50	Surficial	Sand & Gravel	AB	49.661	-110.288	1220.00	23
Mud Lake 537E	Well 112	36.58	Mud Valley	Gravel	AB	49.757	-113.511	944.00	30
Ross Creek 2286E	Well 114	73.70	Irvine Valley	Sand	AB	49.988	-110.461	726.00	23
Barons 615E *	Well 117	19.80	Horseshoe Canyon	Sandstone	AB	49.993	-113.077	964.54	36
Hand Hills #2 South *	Well 125	40.54	Paskapoo	Sandstone	AB	51.505	-112.205	1015.18	41
Ferintosh Reg Landfill 85-1	Well 147	35.10	Horseshoe Canyon	Sandstone & Shale Frac.	AB	52.786	-112.955	800.50	23
Devon #2 (North) *	Well 159	7.62	Surficial	Sand	AB	53.388	-113.691	693.30	42
Bruderheim 2340E (S)	Well 176	47.90	Beverly Valley	Gravel	AB	53.877	-112.975	640.00	21
Marie Lake 82-1	Well 192	144.80	Helina V Empress 1	Sand	AB	54.607	-110.253	593.26	25
Marie Lake 82-2 (West)	Well 193	72.50	Muriel Lake (upper)	Sand	AB	54.607	-110.253	593.29	22
Milk River 85-1 (West)	Well 212	73.00	Milk River	Sandstone, light grey	AB	49.144	-111.890	990.00	21
Kirkpatrick Lake 86-1 (West)	Well 228	84.70	Bulwark	Sandstone	AB	51.953	-111.442	774.50	20
Kirkpatrick Lake 86-2 (middle)	Well 229	33.50	Bulwark	Sandstone	AB	51.953	-111.442	774.50	20
Narrow Lake	Well 252	26.80	Channel or surficial	Sand	AB	54.600	-113.631	640.00	21
Milk River 2479E	Well 260	25.90	Buried Valley	Sand	AB	49.115	-112.011	1040.00	19
Duvernay 2489E	Well 270	20.70	Belly River	Sandstone	AB	53.773	-111.700	580.00	20
Atton *	Atto	16.15	Surficial	Sand	SK	52.816	-108.869	536.45	38
Bangor A	Ban A	39.16	Buried Valley	Sand	SK	50.899	-102.287	527.51	32
Bangor B *	Ban B	15.27	Intertill	Sand	SK	50.899	-102.287	527.63	32
Conq 500	C 500	19.16	Intertill	Sand	SK	51.574	-107.174	555.20	31
Conq 501 *	C 501	8.24	Surficial	Sand/silt	SK	51.579	-107.315	572.62	31
Duck Lake 1 *	Duc 1	13.26	Surficial	Sand	SK	52.916	-106.224	502.92	38
Duck Lake 2 *	Duc 2	124.60	Buried Valley	Sand	SK	52.916	-106.224	502.92	38
Smokey A *	Smoa	37.12	Bedrock	Sand	SK	53.367	-103.058	319.10	32
Swanson *	Swan	9.18	Surficial	Sand	SK	51.650	-107.066	534.92	30
Unity *	Unit	26.72	Intertill	Sand/gravel	SK	52.465	-108.955	673.61	35
POPLARFIELD #3	LN001	NA	Assiniboine Delta	Limestone or Dolomite	MB	50.875	-97.855	278.56	40
WINKLER #5	OB005	6.71	Assiniboine Delta	Sand & Gravel	MB	50.875	-97.855	278.73	45
SANDILANDS #1	OE001	13.11	Assiniboine Delta	Sand & Gravel	MB	49.240	-97.999	NA	41
M0-5	OG003	9.14	Assiniboine Delta	Limestone or Dolomite	MB	49.768	-97.300	236.91	41

* Ground water levels reconstructed using tree rings

Historical hydrographs for nine wells are shown in Figure 1. Interannual variability can be seen in all hydrographs, although the magnitude varies among the records. Wells 117 and 159 in Alberta, and LN001 and OG003 in Manitoba have a higher interannual variability than the wells shown for Saskatchewan. Interdecadal variability is most prominent in the Saskatchewan wells and in wells 125 and OB005 in Alberta and Manitoba respectively. These wells also show a small magnitude of inter annual variability.

The ground water in the prairies seems to respond 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.

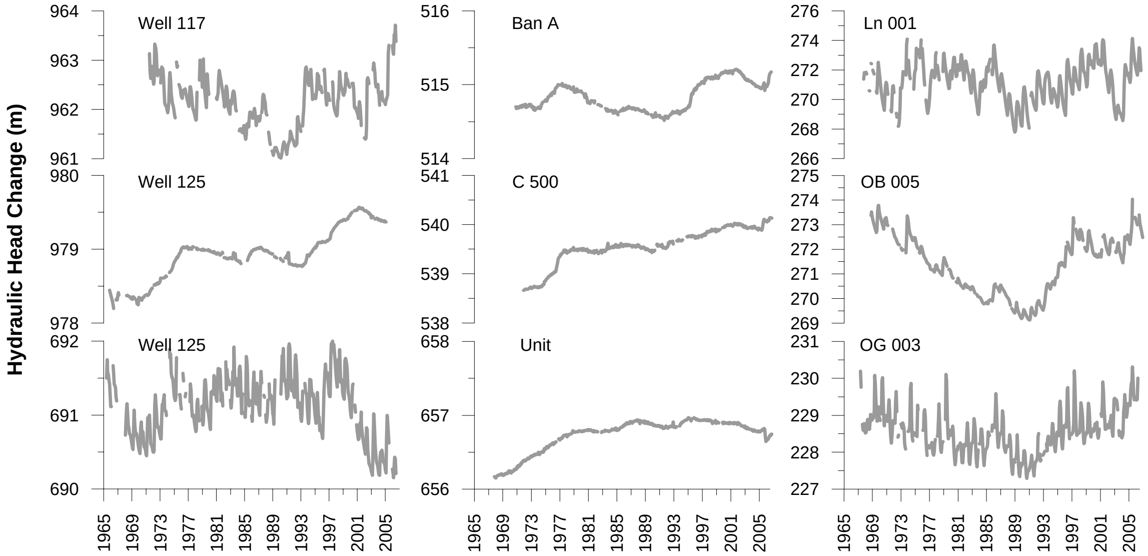


Figure 1: Sample groundwater hydrographs type for the three Prairie Provinces

Tree-ring records

A network of 31 tree-ring chronologies was used in this study. The sampling and processing of the tree rings have been carried out during the last 10 years in the Tree Ring Laboratory of the University of Regina. 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). The 31 standard chronologies used are from sites in the foothills and boreal forests of Alberta and northern Saskatchewan 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, and give information of moisture conditions for the past 200 years.

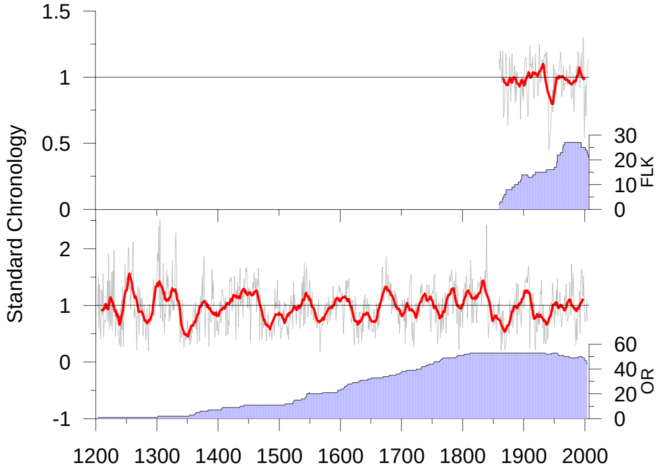


Figure 2: Standard chronology index (grey line) for the Fighting Lake (FLK) and Oldman River (OR) sites. The red line depicts a 15-year running average. Index values below and above one

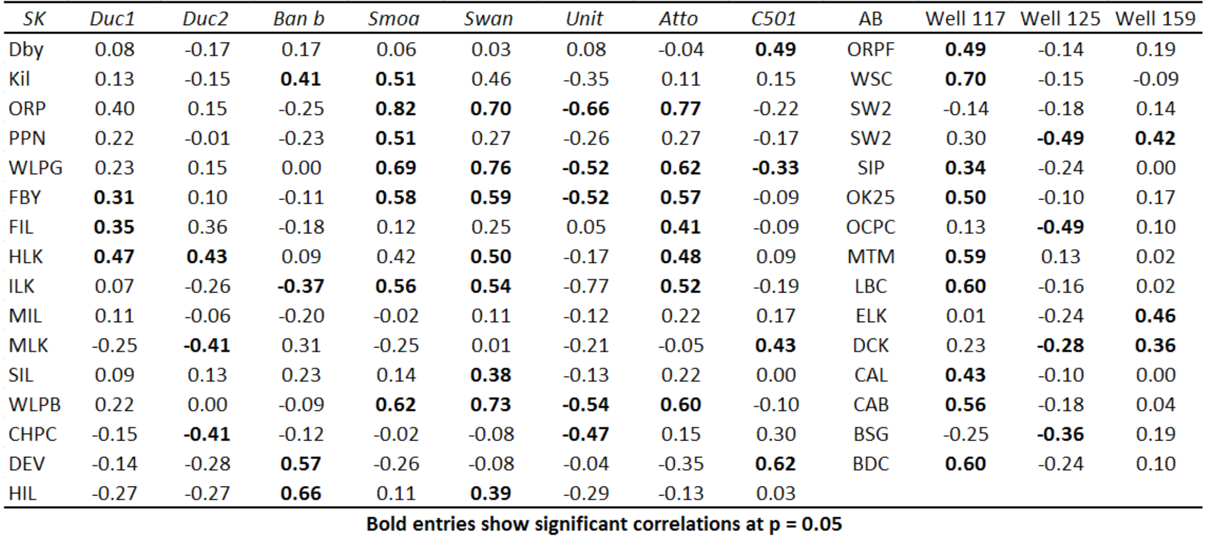
represent dry and wet conditions respectively. Notice in the Oldman River chronology that there are several periods of prolonged dry conditions. The right vertical axis shows the sample depth, which is the number of samples trough time.

GROUND WATER / TREE RINGS RELATIONSHIPS

Simple correlations (Table 2) were calculated between the 33 well records and the 31 chronologies available. This analysis shows highly significant correlations between tree growth and groundwater level. Trees and groundwater do not have an instantaneous response to precipitation; therefore tree growth indices and water levels lag behind variations in precipitation.

The highest correlations are found in Saskatchewan ($r = 0.82$ and $r = 0.77$, $p < 0.05$). Correlations in Alberta are not as high as in Saskatchewan ($r = 0.70$, $p < 0.05$) but their significance suggests that tree-ring chronologies can be used as predictors in the reconstruction of historical groundwater levels. Negative relationships between water levels and tree growth were also found. This inverse relationship might be due to anomalous aquifer characteristic, although further research is needed.

Table 2: Correlations between mean annual groundwater levels and standard chronologies, colums are groundwater levels and rows are tree-rings chronologies



SK	*Duc1*	*Duc2*	*Ban b*	*Smoa*	*Swan*	*Unit*	*Atto*	*C501*	AB	Well 117	Well 125	Well 159
Dby	0.08	-0.17	0.17	0.06	0.03	0.08	-0.04	**0.49**	ORPF	**0.49**	-0.14	0.19
Kil	0.13	-0.15	**0.41**	**0.51**	0.46	-0.35	0.11	0.15	WSC	**0.70**	-0.15	-0.09
ORP	0.40	0.15	-0.25	**0.82**	**0.70**	**-0.66**	**0.77**	-0.22	SW2	-0.14	-0.18	0.14
PPN	0.22	-0.01	-0.23	**0.51**	0.27	-0.26	0.27	-0.17	SW2	0.30	**-0.49**	**0.42**
WLPG	0.23	0.15	0.00	**0.69**	**0.76**	**-0.52**	**0.62**	**-0.33**	SIP	**0.34**	-0.24	0.00
FBY	**0.31**	0.10	-0.11	**0.58**	**0.59**	**-0.52**	**0.57**	-0.09	OK25	**0.50**	-0.10	0.17
FIL	**0.35**	0.36	-0.18	0.12	0.25	0.05	**0.41**	-0.09	OCPC	0.13	**-0.49**	0.10
HLK	**0.47**	**0.43**	0.09	0.42	**0.50**	-0.17	**0.48**	0.09	MTM	**0.59**	0.13	0.02
ILK	0.07	-0.26	**-0.37**	**0.56**	**0.54**	-0.77	**0.52**	-0.19	LBC	**0.60**	-0.16	0.02
MIL	0.11	-0.06	-0.20	-0.02	0.11	-0.12	0.22	0.17	ELK	0.01	-0.24	**0.46**
MLK	-0.25	**-0.41**	0.31	-0.25	0.01	-0.21	-0.05	**0.43**	DCK	0.23	**-0.28**	**0.36**
SIL	0.09	0.13	0.23	0.14	**0.38**	-0.13	0.22	0.00	CAL	**0.43**	-0.10	0.00
WLPB	0.22	0.00	-0.09	**0.62**	**0.73**	**-0.54**	**0.60**	-0.10	CAB	**0.56**	-0.18	0.04
CHPC	-0.15	**-0.41**	-0.12	-0.02	-0.08	**-0.47**	0.15	0.30	BSG	-0.25	**-0.36**	0.19
DEV	-0.14	-0.28	**0.57**	-0.26	-0.08	-0.04	-0.35	**0.62**	BDC	**0.60**	-0.24	0.10
HIL	-0.27	-0.27	**0.66**	0.11	**0.39**	-0.29	-0.13	0.03				

Bold entries show significant correlations at p = 0.05

RESULTS

Trends

Results of the application of the Mann-Kendall test show that 67% of the wells have a trend statistically significant at $p < 0.10$. A decreasing trend is detected in most of the wells studied (12); slopes range from 0.5 % to 5.9% (Table 3). Increasing trends were found in 10 wells, with slopes ranging from 0.7% to 3.3%. No significant trends were found in the 11 remaining wells studied.

Figure 3 shows the spatial distribution of the significant ($p < 0.10$) 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, however, most, if present, are negative. The trend test results for Saskatchewan suggest that all the wells studied have trends both are positive and negative. The spatial distribution of the trends shows that the north-central part of the province is dominated by negative trends and the southern area by positive trends. 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 that northern and central areas are dominated by negative or having no trends, whereas southern areas show positive trends.

Table 3: Slopes in groundwater levels. Entries in bold indicate that slopes are significant at 10% level ($p < 0.10$)

Well ID	102	104	106	108	112	114	117	125	147	159	176	192	193	212	228	229	252
Slope	**1.3%**	**3.3%**	**-1.3%**	**3.1%**	**-5.9%**	**-1.1%**	-0.6%	**2.0%**	**-3.0%**	0.2%	-0.5%	0.2%	0.2%	0.8%	**-1.8%**	**-4.2%**	**-5.2%**
Well ID	260	270	Atto	Ban A	Ban B	C 500	C 501	Duc 1	Duc 2	Smoa	Swan	Unit	LN001	OB005	OE001	OG003	
Slope	-0.3%	-1.6%	**-2.7%**	**0.8%**	**0.9%**	**2.7%**	**2.1%**	**-0.6%**	**-0.5%**	**-3.1%**	**-2.6%**	**1.2%**	0.0%	-1.2%	-2.9%	**0.7%**	

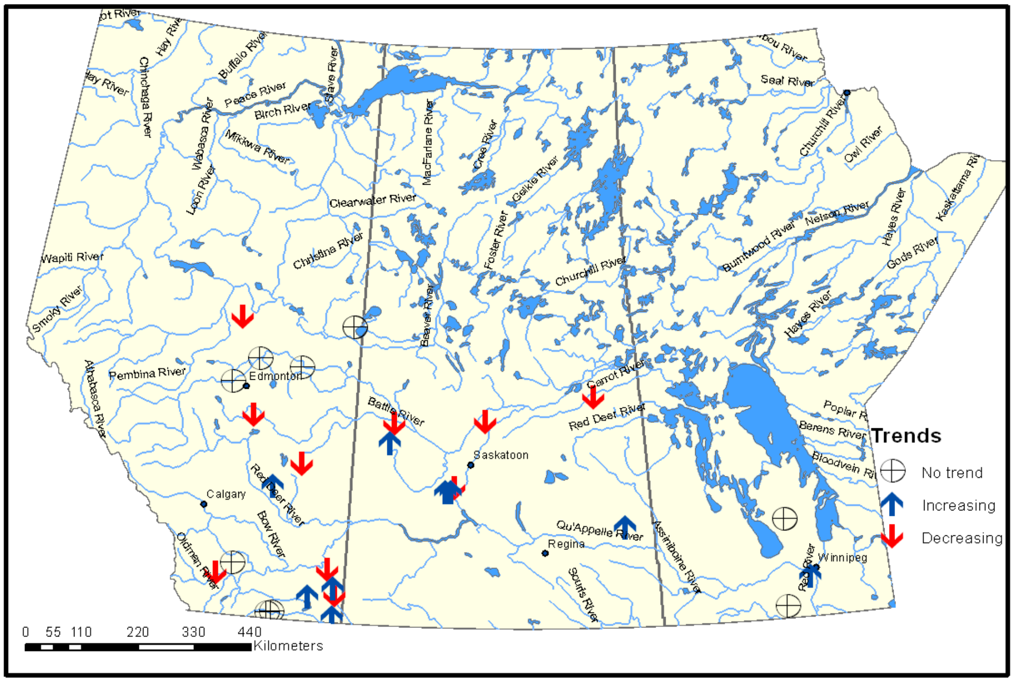


Figure 3: Spatial distribution of trends at 10% significance level.

Reconstructions

Using tree-ring chronologies as predictors of groundwater levels, regression models were built for 11 groundwater wells across Alberta and Saskatchewan. The models expanded 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.

The best reconstruction model is Unit which explains 81% of the variance in annual groundwater levels (Table 4). Other models in Saskatchewan explain high amounts of the variance (over 70%), however, they are relatively short compared to the reconstruction models in Alberta which also have a high variance explained (wells 117 and 159).

Table 4: Statistics of the regression models. RE is the reduction of error and says how good is the capacity of prediction of the model. SE is the standard error of the prediction

Name	Reconstruction Period	Length (yrs)	Calibration Period	Lag	# of Predictors	R2	R2 ad	RE	SE	AC1
Atto	1879-2001	123	1966-2001	0	5	0.81	0.79	0.730	0.41263	H0
Ban B	1909-2001	93	1971-2001	0	4	0.77	0.75	0.580	0.48250	H0
C 501	1862-2001	140	1972-2001	0	4	0.61	0.56	0.450	0.28390	H0
Duc 1	1909-2001	93	1967-2001	0	5	0.47	0.40	0.270	0.63710	U
Duc 2	1875-2001	127	1966-2001	0	5	0.74	0.71	0.640	0.05510	U
Smoa	1879-2001	123	1971-2001	0	5	0.80	0.77	0.690	0.15130	H0
Swan	1875-2001	127	1972-2001	0	4	0.67	0.63	0.520	0.62110	U
Unit	1875-2001	127	1968-2001	0	2	0.82	0.81	0.780	0.09890	H0
Well 117	1618-2003	387	1972-2003	0	3	0.73	0.71	0.640	0.57480	H0
Well 125	1684-2003	320	1973-2003	0	6	0.60	0.52	0.360	0.70470	H0
Well 159	1859-2002	144	1968-2001	±2	7	0.80	0.76	0.630	0.46630	H0

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

Water level reconstructions and the bar codes for Alberta are shown in Figure 4. The bar code illustrate periods of low flow; for example well 125 shows a period of over 40 consecutive years with low level between 1920 and 1960. The same low levels are in the reconstructions of wells 117 and 159 although the magnitude and period of the low levels vary considerably. Another period of low flow can be indentified for well 117 around 1800; however the magnitude of the impact of climate variability varies among the aquifers.

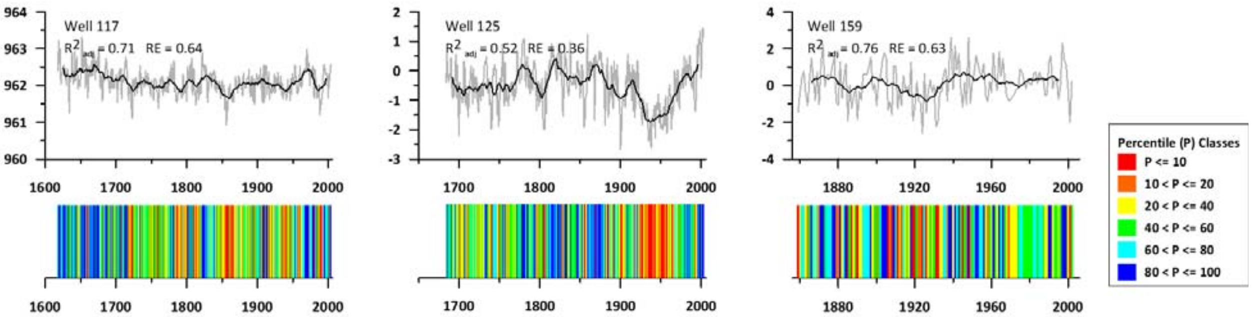


Figure 4: Ground water levels reconstructed for Alberta (grey line). Black line is 15 years running average. At the bottom is the bar code which is the graphic representation of water levels percentiles. Notice that not all the units of water levels are in meters. Where water level units are not in meters, data was transformed in order to meet the normality assumption needed in regression models.

The Saskatchewan reconstructions are (Figure 5) similar to the reconstructions for Alberta, with a period of low levels around the 1920s for all the three wells in

Saskatchewan. Other periods of low levels are in the late 1950s and early 1960s for well Unit, late 1870s for wells c501 and Unit and late 1990s and beginning of 2000s.

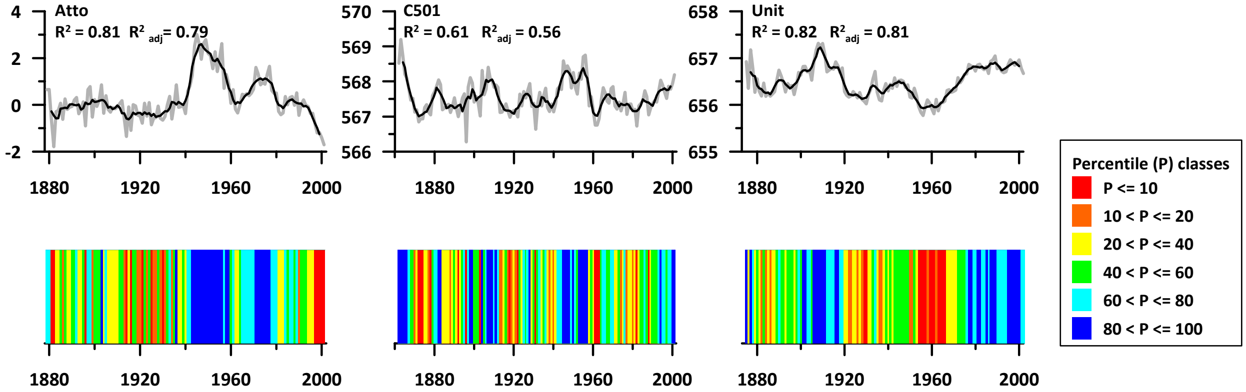


Figure 5: Ground water levels reconstructed for Saskatchewan and bar code. Black line is 5 years running average.

The utilization of intervention analysis to detect shifts in the mean, plus wavelet and singular spectrum analysis (SSA) is a powerful combination to analyse the variability of groundwater levels.The decomposition of the variance through SSA shows that there is a common mode of variability between 10 and 15 years that affects all the aquifers. Other modes indentified are around 25-30 years explaining a considerable amount of variance. A El Nino Southern Oscillation (ENSO) signal, with modes between 2 and 8 years, was identified for well 159. Some ENSO signal is identified in well records 117 and 125 from the wavelet analysis but it is not statistically significant according to SSA.

The combination of these three different methods makes possible the identification and attribution of the major changes in water levels. For example in Figure 6, there are several significant changes in the mean level of well 125 during the period 1775-1960. These significant changes highlighted in blue are due to the superposition of several modes of variability. From left to right the first shift in the mean corresponds to a 47.5 year mode which is also indicated by wavelet analysis. The 28.7 year mode is also forcing some change in the mean but not as significant. The second major shift in mean levels coincides with the superposition of 47.5, 28.7 and 11.9 year modes. Lower means correspond mostly by the absence of the 47.5 year mode.

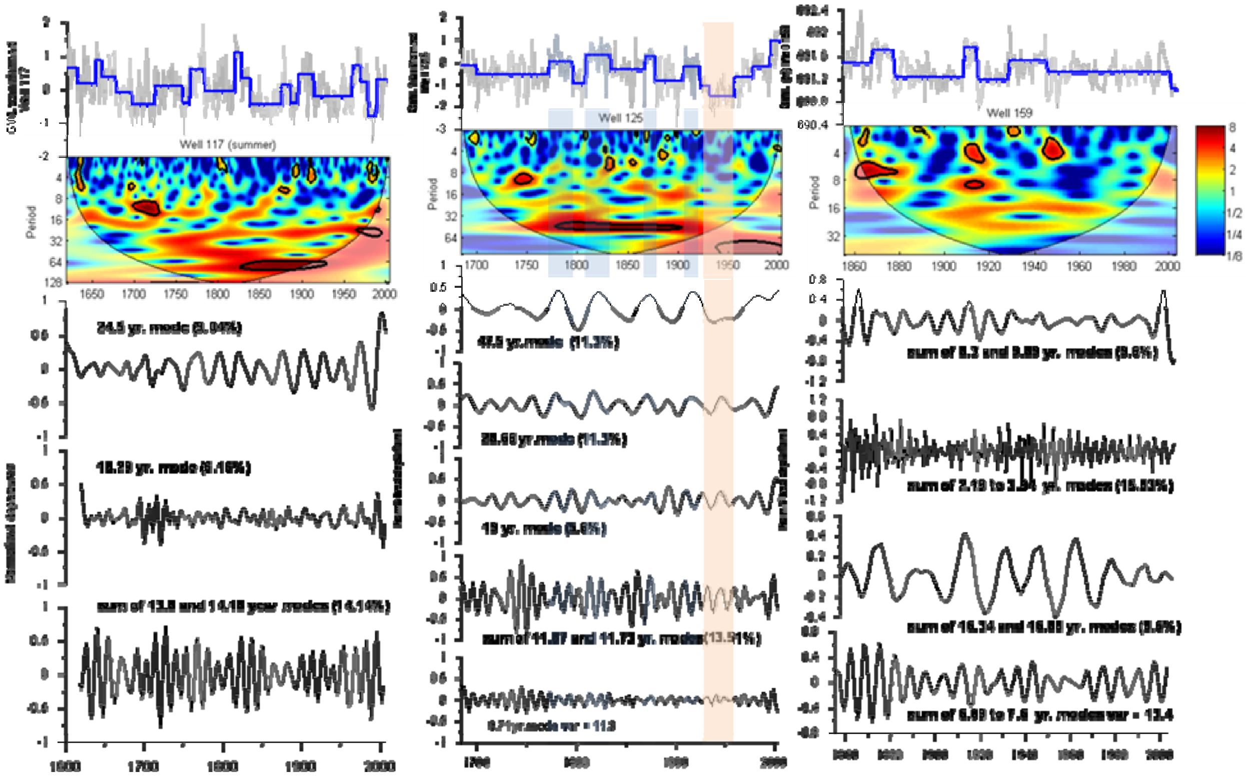


Figure 6: Top: Intervention analysis shows significan shifts in the mean. Next: Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence in which the effects are important. The black contour line shows the 95% confidence. Lower plots: Singular spectrum analysis shows different modes and the variance explained by them.

For the Saskatchewan reconstructions (Figure 7), a mode between 20 and 25 years explains most of the variability. Changes in the mean level for the Atto well are caused by the superposition of two modes (24.1 and 19.5 years). The 24 year mode has more infuence on the mean since has a higher amplitude and explains more of the variance. Well C 501 is dominated by three main; the 22 year mode explains 26.4 % of the variance, the 8 to 10 year mode accounts for 16.2 % and the 15.7 year mode explains around 5% of the variance.

Changes in the mean are caused more likely by the superposition of the two first modes where the first mode has more influence. Well Unit is dominated by just one significant mode of 31.2 years explaining around the 10% of the variance. Shifts in the mean correspond to different phases of this mode.

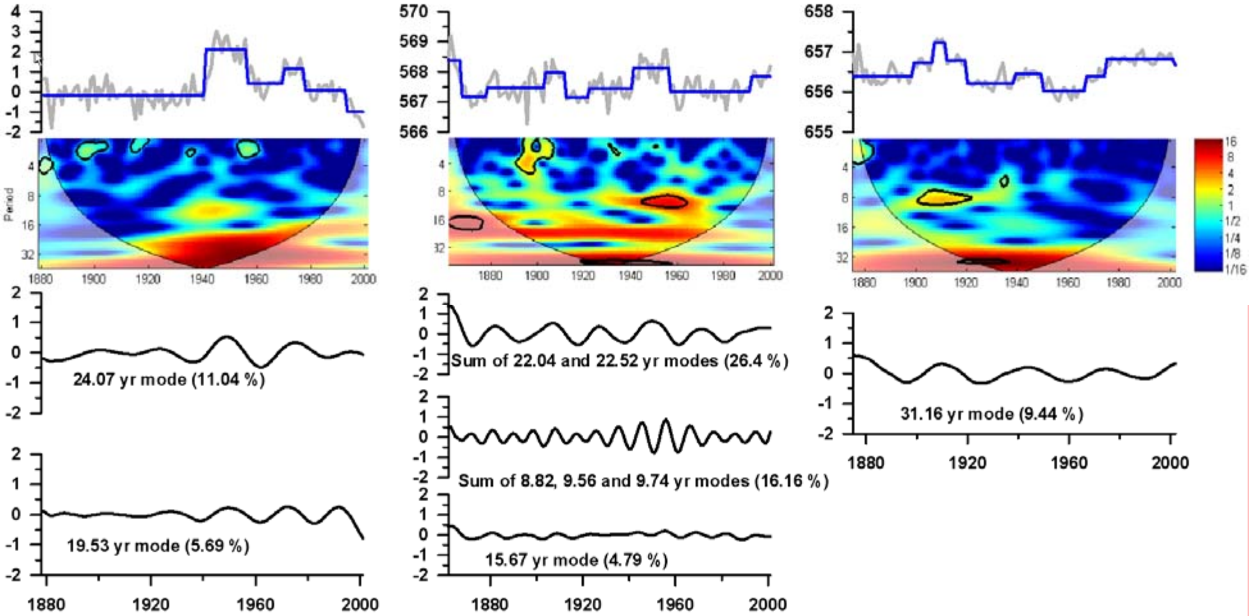


Figure 7: Intervention, wavelet and singular spectrum analysis for the Saskatchewan reconstructions.

CONCLUSIONS

The application of the Mann-Kenndal test to detect trends has resulted in the identification of mostly decreasing and or no trends in groundwater levels. A spatial pattern was observed with negative trends in the north central area of the Prairies Provinces, whereas positive trends are seen in the southern regions. In addition, the slopes for decreasing ground water levels are double in magnitude as compared to the slopes for increasing groundwater levels.

The utilization of moisture sensitive trees proved useful for the reconstruction of historical groundwater levels in Alberta and Saskatchewan making possible the analysis of long-term climate variability. Different modes of variability are detected in groundwater levels, aquifers closer to the surface register higher frequency signals than deeper aquifers; however a strong common signal has been found in all the groundwater level reconstructions in the ranges of 12 to 16 and 20-25 years which explain an important amount of the variability.

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