Dendrochronologia 29 (2011) 41–47

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.de/dendro

Tree-ring reconstruction of groundwater levels in Alberta, Canada: Long term hydroclimatic variability

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ARTICLE INFO

Keywords:
Groundwater levels
Dendrohydrology
Spectral analysis
Oscillation modes

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 behavior of groundwater under climatic variability. Groundwater levels at two wells in southern and central Alberta are analyzed in order to document long-term variability of groundwater levels and their sensitivity to climatic events. The instrumental well records span more than 40 years. Strong correlations ($r > 0.7$, $p < 0.01$) between mean annual groundwater levels and tree-ring chronologies suggested the use of regression models to reconstruct historical water levels for more than 300 years. From the estimated groundwater levels several periods with five or more consecutive years of low levels were identified (i.e. periods centered on 1698, 1720, 1855, and 1863 at well 117; 1887 and 1923 at well 159). The application of a regime shift method revealed periods with more than 30 years with below-average water levels. Spectral analyses, wavelet and multitaper methods, suggest dominant oscillation modes in groundwater levels in the 2–8 and 8–16 year bands.

Introduction

Despite the importance of groundwater as a component of the hydrological cycle and source of potable water, especially in arid and semiarid regions, there is a lack of studies of the impacts of climate change on groundwater (IPCC, 2007) and the response of groundwater levels to climate fluctuations such a drought. Groundwater studies are limited by the quantity and quality of the observations available and in particular limitations caused by anthropogenic effects on water table levels.

In Canada groundwater has a major role supplying fresh water for domestic use for almost 9 million Canadians (30.3% of the population). Most of the groundwater is used in rural areas, 67% or 6 million people that rely on groundwater live in rural areas (Statistics Canada, 1996). In Alberta groundwater resources are used by more than 23% of the population through over 500,000 domestic wells. The groundwater allocations are about 3% of the total water allocation in the province and are mostly used in commercial and industrial activities (53%), agriculture (25%), municipal use (18%) and 4% for other purposes (Alberta Environment, 2005).

To date, few studies have modeled or reconstructed future or past groundwater levels in the Canadian Prairies. 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 in the Upper Carbonate Aquifer in central Manitoba back to 1907. Tree rings have been widely used to reconstruct components of the hydrological cycle, such as stream flow and precipitation (e.g. Watson and Luckman, 2001; St. George and Nielsen, 2002; Case and MacDonald, 2003), however Ferguson and St. George (2003) is the only study which has investigated the relationship between tree rings and groundwater within the Prairies.

Tree-ring reconstructions of groundwater levels are based on the common response of tree growth and groundwater levels to effective precipitation, recognizing that these responses are often lagged in time. Tree rings collected at dry sites are a proxy of available soil moisture. In western Canada, spring snow melt and rainfall are the major sources of groundwater and soil moisture (Pomeroy et al., 2007). Summer precipitation has little influence on groundwater levels because it mostly evaporates; mostly from the unsaturated soil water zone where it is available for annual plant growth. Geologic structures and aquifer characteristics are important factors when relating groundwater levels and tree rings. High hydraulic conductivity is an important requirement when studying the effects of climatic variability on groundwater because it represents the capacity of a rock, aquifer, or earth material to transmit water; higher hydraulic conductivity means a faster movement of the water through that media (Fetter, 1994).

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doi:10.1016/j.dendro.2010.09.001

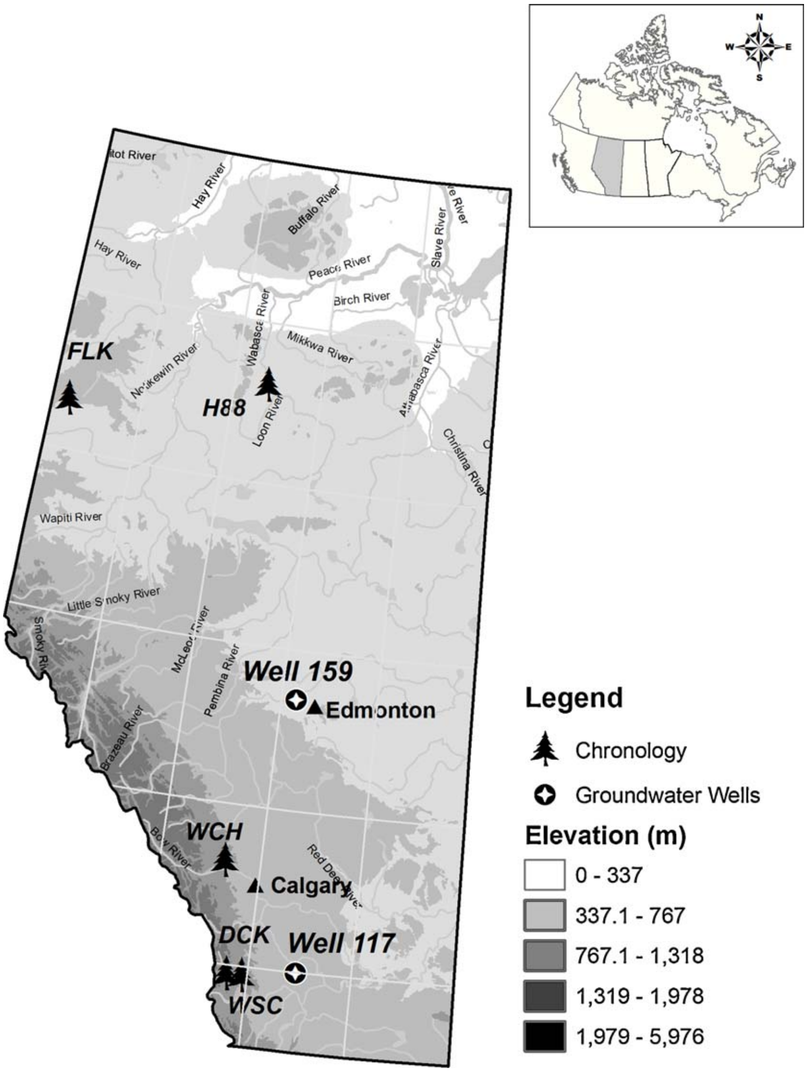

Fig. 1. Study area and location of the tree-ring chronologies and groundwater wells.

This study aims to relate water table variations to climate variability at inter-annual and inter-decadal time scales. Using tree-ring chronologies we reconstruct mean annual groundwater levels, apply regime shift techniques (Rodionov, 2004) to detect discontinuities in mean water levels, and apply spectral analysis, wavelet (Torrence and Compo, 1998) and multitaper (Ghil et al., 2002) methods, to identify the dominant oscillation modes.

Data and methods

Study area

The study area is between 49° and 58° latitude and 120° and 110° longitude in the Canadian Province of Alberta (Fig. 1). The tree-ring sites are in the headwater regions of major river basins in the southwestern foothills of the Rocky Mountains and the boreal forest of north-central Alberta. The two groundwater wells selected for this study are located in the central and southern part of the Province. The Prairie Provinces have a cold and sub-humid climate with a difference of more than 30 °C between the coldest and warmest month. Mean annual temperature increases from north to south and east to west. Mean annual precipitation ranges from just over 300 mm in southeastern Alberta to about 600 mm in the boreal forest and to over 900 mm in the Rocky Mountains.

Tree-ring chronologies

The five tree-ring chronologies, from two species (*Pseudotsuga menziesii* (Mirbel) Franco, *Pinus banksiana* Lamb.) (Fig. 1) in the foothills and boreal forests of Alberta, are part of a larger network spanning the Northwest Territories, Alberta, Montana and Saskatchewan. These moisture-sensitive tree-ring chronologies contain annual and seasonal moisture signals spanning more than 800 years. The wood and tree-ring data were processed in the Tree Ring Laboratory of the University of Regina using standard dendrochronological methods (Stokes and Smiley, 1968; Fritts, 1976; Cook, 1985; Cook and Kairiukstis, 1990). Conservative detrending (negative exponential or a 67% smoothing spline) was used to remove growth trends. The chronologies were cross-dated to detect missing or false rings and verified with COFECHA (Holmes, 1983). They range in length from 147 to 664 years and all of them end in 2003 or later (Table 1).

Table 1
Tree-ring chronologies.

Site	ID	Species	Elev	Lat. (°)	Long. (°)	Period	Years	Radii	EPS < 0.85	SSS < 0.85
Dutch Creek	DCK	*Pseudotsuga menziesii*	1648	49.9	−114.4	1618–2004	387	42	1666	1645
Fighting Lake	FLK	*Pinus banksiana*	516	56.63	−119.62	1860–2006	147	34	1919	1871
Highway 88	H88	*Pinus banksiana*	Na	57.24	−115.22	1856–2007	152	32	1873	1861
West Sharples Creek	WSC	*Pseudotsuga menziesii*	1575	49.9	−114.1	1525–2004	480	62	1589	1582
Wildcat Hills	WCH	*Pseudotsuga menziesii*	1351	51.3	−114.7	1341–2004	664	40	1379	1351

Groundwater data

Aquifers, geologic units with the capacity to store and transmit water at reasonable rates for well water supply (Fetter, 1994), are of two types in the Prairie Provinces. Bedrock aquifers are in sediments that range in age from Ordovician to Tertiary. Quaternary aquifers between the bedrock and ground surface are classified as buried valley, intertill and surficial aquifers (Maathuis and Thorleifson, 2000).

Groundwater information was obtained from Alberta Environment as hourly, daily and monthly measurements for over 500 wells. However, only two well records had sufficient length and continuity. Barons 615E (well 117) and Devon #2 (well 159) (Fig. 1) were the only wells exceeding 30 years of monthly records and with less than 20% missing data. Missing values were estimated using correlations with nearby water level records and median values were used when correlation was not possible, mostly at the beginning of the record. Mean annual water levels were calculated from median monthly data. Well 117 is located in the Horseshoe Canyon aquifer, a bedrock aquifer, at a depth of 19.8 m. Well 159 is in a surficial aquifer at a depth of 7.6 m depth. The aquifer composition is sandstone and sand for the bedrock and surficial aquifers respectively. Table 2 summarizes the information for the studied groundwater wells.

One important assumption of linear regression modeling is the normality of the predictands. A normality test showed that most of the mean annual groundwater levels were not normally distributed. Widely used transformations in hydrological time series were not effective with the groundwater levels hence the complex Johnson transformation was used to produce time series that passed a second test for normality.

Tree-growth groundwater relationships

An exploratory analysis based on simple bi-variate correlation between mean annual groundwater levels and the five standard tree-ring chronologies showed strong relationships between water levels and tree growth. The standard chronologies correlated better with water levels than residual chronologies because groundwater data is significantly autocorrelated. Most of the tree-ring chronologies are from open stands of pine and fir where ecological affects are much less of a growth factor than in closed canopy forests. The highest correlation was between water levels at well 117 and the West Sharples Creek chronology ($r = 0.72$, $p < 0.01$). Well 117 in southern Alberta correlated negatively with the chronologies in north central Alberta. Groundwater levels at well 159 correlate positively with all the chronologies; the highest correlation is with chronology Highway 88 ($r = 0.44$, $p < 0.05$).

To test the basic assumption that both groundwater and tree growth are responding to precipitation, correlations of homogenized monthly precipitation, from the closest weather station, with standard chronologies and with groundwater levels were computed (Fig. 2). The Wild Cat Hills chronology has a significant correlation with spring, summer, and annual precipitation but mostly from the previous year. The Dutch Creek and West Sharples chronologies have significant correlation with winter, spring, summer, and annual precipitation from the growth year and with autumn, summer, and annual precipitation from the previous year. The northern chronologies, Fighting Lake and Highway 88 show significant correlation only with spring, summer, and annual precipitation from the previous year.

Correlations were calculated for groundwater levels at well 117 and well 159 with precipitation at Calgary and Edmonton respectively since the homogenized precipitation record at Lethbridge ends in 1989. Groundwater levels at well 117 show significant correlation with spring and annual precipitation from the previous season at Calgary. A significant correlation between groundwater levels at well 159 and annual precipitation from the previous year was detected at Edmonton. These results suggest that both, tree growth and groundwater levels at the selected sites respond to precipitation with similar timing supporting the use of tree growth as a historical predictor of groundwater levels. In addition, the groundwater and tree-ring records have similar significant first-order autocorrelation.

Reconstruction of groundwater levels

Step-wise multiple linear regression models were used to reconstruct water levels at the two wells. The models satisfied the linear regression assumptions of linearity. To reduce the chance of overfitting, the pool of predictors was formed from the most significant chronologies in terms of correlation with the predictands. The reduction of error (RE) statistic expresses the cross validation skill of the model. Positive values of RE indicate that the model has some skill for reconstructing groundwater levels.

Post-reconstruction analyses

In order to identify periods of anomalous reconstructed water levels, simple percentiles were computed for the two reconstructions and plotted as a “bar code” which allows us to visualize periods of consecutive years with low and high water levels. Regime shifts (Rodionov, 2004), significant changes in mean groundwater levels, were detected based on a statistical test where data are processed in time sequence and the hypothesis of a regime shift or discontinuity is tested for each new observation (Rodionov, 2004). We set the cutoff parameter at 10 years in order to detect

Table 2
Groundwater wells.

Well	ID	Depth (m)	Aquifer	Lithology	Installation date	Lat. (°)	Long. (°)	Elev. (m)	Years
Barons 615E	Well 117	19.80	Horseshoe Canyon	Sandstone	6/22/1971	49.99	−113.08	964	36
Devon #2 (North)	Well 159	7.62	Surficial	Sand	5/13/1965	53.38	−113.69	693	42

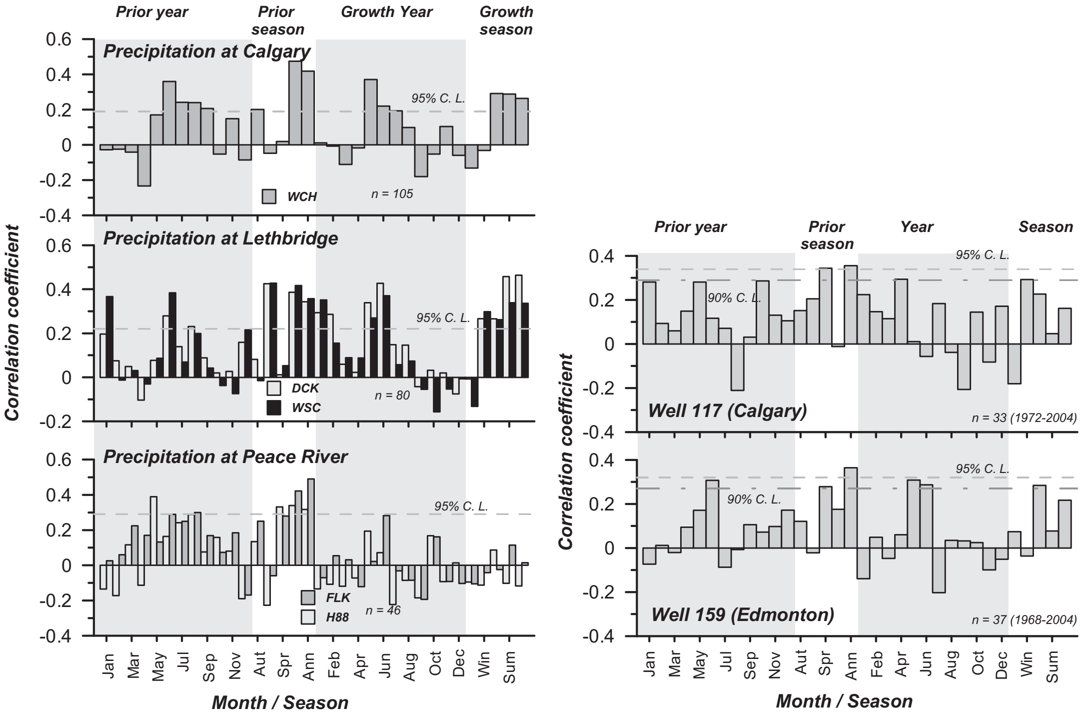

Fig. 2. (Left) Correlation between groundwater levels and monthly, seasonal, and annual precipitation. (Right) Correlation between groundwater levels and monthly and seasonal precipitation.

changes in mean water levels driven by high frequency events and used a 95% level of significance.

Continuous wavelet analysis (CWT; Torrence and Compo, 1998; Grinsted et al., 2004) was used to identify the main oscillatory modes of variability in groundwater levels. The CWT locates the signal in time and identifies the frequency or period of the dominant oscillation modes (Torrence and Compo, 1998; Jevrejeva et al., 2003). Among all the wavelet families, Morlet wavelet ($w_0 = 6$) was chosen and applied to groundwater levels since it provides a good balance between time and frequency domains and is recommended when the purpose is to extract signals (Grinsted et al., 2004). The statistical significance was assessed against a red noise background at 95%.

The multi-taper method (MTM; Ghil et al., 2002) of spectral analysis was used to identify the exact frequency and significance of the dominant oscillation modes in groundwater levels previously identified by wavelet analysis. MTM is non-parametric. It uses a series of tapers that reduce the variance of spectral estimates which is an advantage over other spectral window methods (Percival and Walden, 1993). We applied the SSA-MTM toolkit (Ghil et al., 2002), with robust background estimation, to reconstructed groundwater levels.

Results and discussion

Using tree-ring chronologies as predictors of groundwater levels, regression models were built for two groundwater wells in Alberta. The models expand annual water level records for well 117 by more than 300 years. The length of the reconstructions was limited by the shortest chronology in the model. All the models have a positive skill of cross-validation indicated by the large positive reduction of error. Explained variance (adjusted R^2) ranges from 47% to 71%.

The models capture most of the inter-annual variability following a similar path as the observations. In general, these two models are estimating well both low and high groundwater levels. The regression model for well 117 follows the same pattern as the observed water levels, although beginning in the 1980s the curves are out of phase with groundwater lagging the tree rings and the model underestimating water levels in late 80s and 90s. Well 159 levels are overestimated at the beginning and have less inter-annual variability than the tree rings from the late 70s until late 80s.

The 387-year reconstruction for well 117 shows periods of persistent low and high water levels (Fig. 3a). Major lows are centered on 1698, 1720, 1859, 1920, 1944, and 1985. Major highs are centered on 1775, 1825, 1910, and 1975. From smoothed (15-year weighted) reconstructed time series, the period centered on 1859 represents the lowest water levels for the longest period. Other severe low water level intervals are centered on 1969, 1720, and 1985. During the last 250 years, a clear inter-decadal variability is evident in the reconstruction. Table 3 lists water levels below the 10th percentile. There are five periods of five or more consecutive years in which water level are in the lower 30th percent. This table also shows the 15 single years with the lowest water levels; 5 years were in the last 20 years.

Groundwater level variability at well 159 is dominated by mostly one or two consecutive years with low levels (Fig. 3b). The longest period of consecutive years (5) is centered on 1925. Other periods of low levels are centered on 1932, 1945, and 1970. On the other hand, the reconstruction shows a high level period centered on 1940 between two low periods. Table 4 shows years and periods of water levels in the lowest 10th percentile.

Impacts of three droughts during the last century differ at the wells studied. The 1930s drought had a strong and persistent impact on water levels at well 159 while the impacts at well 117 were of a smaller magnitude. The drought in 1988 has a greater affect at well 117. The periods of low groundwater levels centered on 1715 and 1860 have been recognized as major dry intervals in the Canadian Prairies (Case and MacDonald, 2003; St. George and

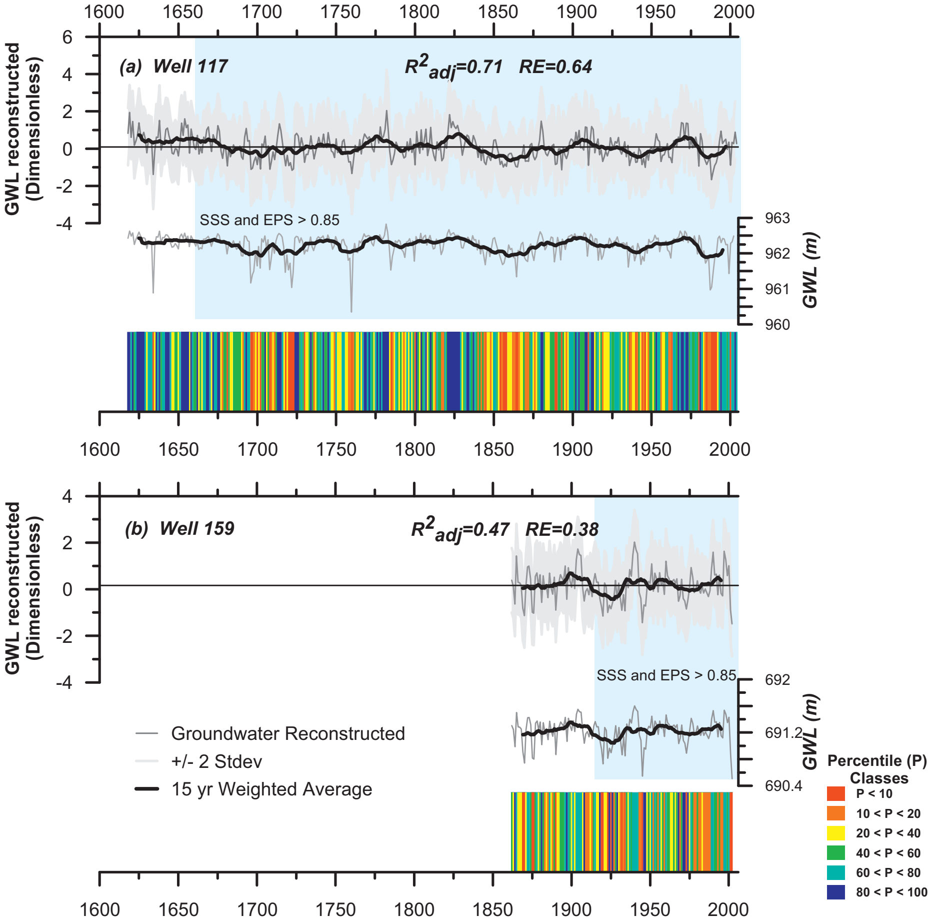

Fig. 3. Groundwater levels reconstructed (top) and bar code (bottom).

Table 3
Groundwater levels < 30th percentile at well 117 (1618–2003). Bold entries indicate groundwater levels < 10th percentile. Asterisks indicate years during the last two droughts in the Canadian Prairies.

Single year	>2 and <5 years	5 or >5 consecutive years	Lowest GWL (increasing order)
1630	1663–1664–1665	**1696–1700**	**1760**
1634	1687–1688	**1718–1723**	**1634**
1650	1690–1691	1853–1859	**1988***
1681	**1708–1709**	1861–1867	**1722**
1702	1730–1731–1732	1983–1992	**1989***
1706	**1758**–1759–**1760**–1761		**1696**
1711	1763–1764		**1865**
1736	**1785**–1786–1787		**1697**
1748	1792–1793–1797		**2000***
1753	1812–1813		**1718**
1800	1817–1818		**1723**
1840	1830–1831		**1990***
1842	1844–**1845**–1846		**1698**
1883	1848–1849		**1785**
1893	1870–**1871**–**1872**		**1720**
1896	1875–**1876**–1877		
1910	**1889**–1890		
1917	**1919**–1920–1921–1922		
1926	**1936**–1937		
1948	**1940**–1941		
1956	1943–**1944**–1945–**1946**		
1980	1961–1962–1963		
2000			

Nielsen, 2002); water levels at well 117 were the most affected with the strongest and longest impact (Fig. 3a bar code). Previous tree-ring reconstructions of precipitation for Maple Creek, Saskatchewan (Sauchyn and Beaudoin, 1998) and the Red River valley in Manitoba (St. George and Nielsen, 2002) are consistent with the groundwater levels reconstructed at well 117 in Alberta. Low-frequency variation in precipitation and groundwater levels across the southern Prairies are represented by sustained dry conditions in the mid to late 19th century.

Table 4
Groundwater levels < 30th percentile at well 159 (1859–2002). Bold entries indicate groundwater levels < 10th percentile. Starts indicate years during the last two droughts in the Canadian Prairies.

Single year	>2 and <5 years	5 or >5 consecutive years	Lowest GWL (increasing order)
1864	**1869–1870**	**1923**–1927	**2002***
1881	**1875–1876**		**1945**
1885	1918–**1919–1920**		**1920**
1888	1931–**1932**–1933–**1934**		**1870**
1890	1944–**1945**–1946–1947		**1876**
1897	1968–1969		**1923**
1908	1971–1972–**1973**–1974		**1875**
1911	1995–1996		**1934**
1913	**2001–2002**		**1932**
1929			**2001***
1959			**1890**
1987			**1973**
1993			**1925**
			1869
			1919

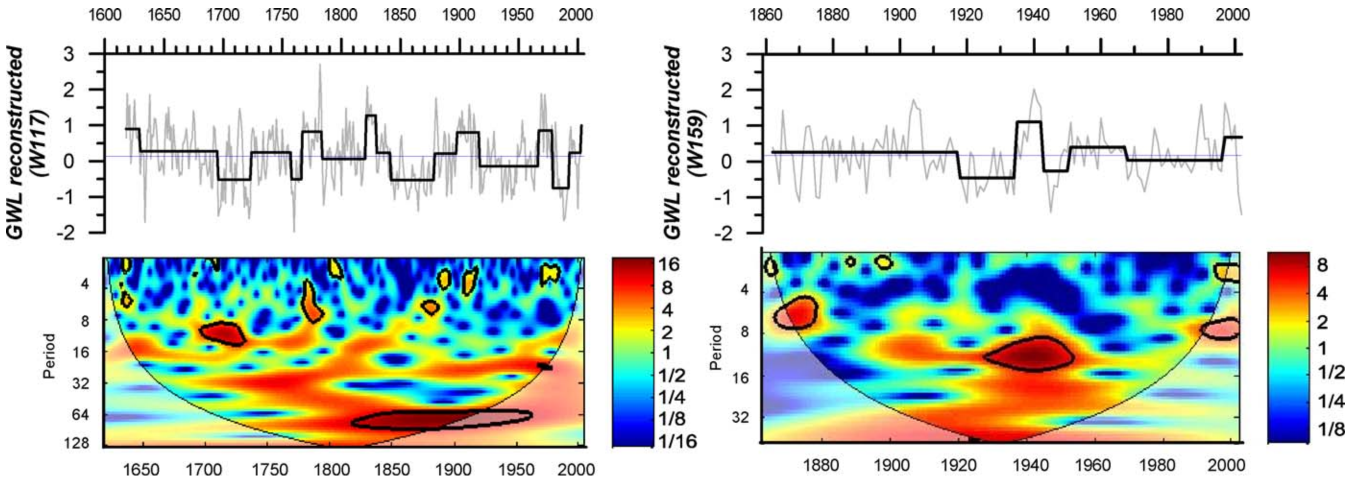

Fig. 4. Top: Groundwater levels reconstructed at wells 117 and 159 (grey line), regime shifts showing significant shifts in mean water levels at $p < 0.05$ (black line) and mean water levels reconstructed (blue line); Bottom: Wavelet power spectrum using Morlet wavelet. The curve delimits the cone of influence within which the effects are important. The black contour line shows the 95% confidence level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Results of the regime shift analysis suggest that there have been constant changes in mean groundwater levels at well 117 (Fig. 3a) which are dominated by short periods of above average water levels. Two major periods with low levels were 36 years starting in 1842 and 35 years starting in 1914. Another relatively long period detected by regime shifts was 1696–1723 with mean water levels lower than 1914–1949. The period centered on 1985 is one of the shortest with below average groundwater levels, however, this period registers the lowest mean in the 386-year reconstruction.

Results of wavelet analysis show significant activity in the 2–4, 4–8, 8–16, and around 64 year bands (Fig. 4b). Most of the activity in the 2–4 year band occurs in the period 1850–2000. Significant activity in the 4–8 and 8–16 year bands occurs in the early and late 1700s. The band around 64 years presents significant activity starting from the first quarter of the 18th century that coincides with the first period of low levels. From the application of the multi-taper method five oscillation modes in groundwater levels were identified with a 95% and above confidence level. These dominant modes are centered at periods of 3.4, 3 and 2 years with a 99% confidence level and at 2.9 and 13.6 year periods with a 95% confidence level (Fig. 5a).

Regime shifts identified fewer changes in mean water levels at well 159 than at well 117. Two major periods of below average water levels are centered on 1930 and 1945 (Fig. 4a). The second period was one of the lowest flow intervals in a reconstruction of the North Saskatchewan River (Case and MacDonald, 2003). These two periods are divided by an unusual period of high levels centered on 1940.

Wavelet analysis shows significant although not powerful activity in the 2–4 year band between 1880 and 1900, more powerful activity in the 4–8 year band around 1870, and in the 8–16 year band centered on 1940 (Fig. 4b). Major variability and positive and negative shifts in groundwater levels from 1930 to 1950 coincide with activity in the 8–16 year band centered on 1940. The MTM analysis of groundwater levels at well 159 revealed five oscillation modes. The modes in the 2–4, 4–8, and 8–16 year bands also were identified by wavelet analysis and are centered at 2.3, 3, and 6.6 years with 99% confidence level and at 4.7 and 11.5 years with 95% confidence (Fig. 5b).

In general, the multi-taper method identified dominant oscillation modes in the ENSO band (2–8 years) for the water levels reconstructed. Inter-decadal modes were identified for water levels at wells 117. The inter-decadal variability seen in observed water levels, and ratified by the results of wavelet analysis, was not considered significant by the multi-taper method. Modes in the 8–16 year bands were detected in the two reconstructed water level records. These results illustrate the lack of stationarity in long hydrologic records. While the observational records might be representative of mean long-term levels, they are too short to capture the shifts in the frequency of hydroclimate variability evident in reconstructions of the paleohydrology but represent a different regime in terms of the nature of variability.

The results of spectral methods coincide with the results of other studies which have detected an ENSO influence on groundwater and hydrologic variables in Western Canada and the Canadian Prairies. Fleming and Quilty (2006) found a direct effect of El Niño-Southern Oscillation (ENSO) on groundwater levels at four shallow wells in the Fraser Valley, British Columbia. During La Niña years water levels are above average and below average during El Niño

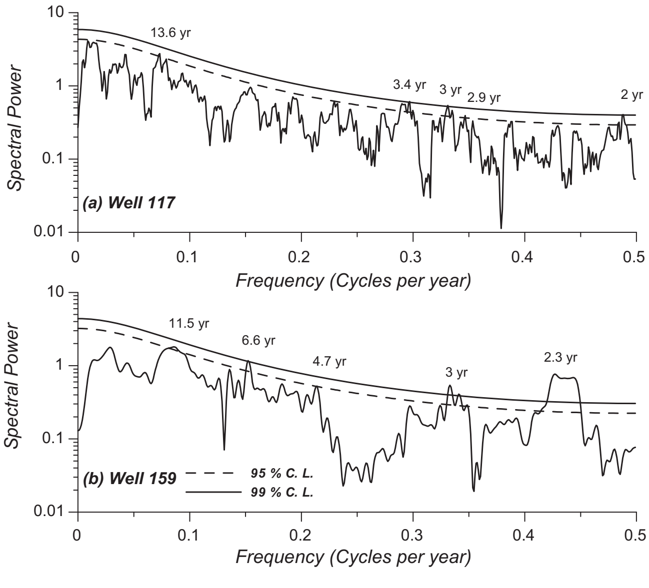

Fig. 5. Multi-taper power spectra of the reconstructed groundwater levels. The solid and dashed lines represent the 95% and 99% confidence levels.

years reflecting variability in winter and spring precipitation that recharges the aquifer systems. Also Coulibaly and Burn (2004) used wavelet analysis to study the variability in annual stream flows in Canada and showed that stream flows are dominated by activity in the 2–3 and 3–6 years bands. Strong correlations between teleconnection patterns (ENSO) and mean annual stream flow were detected for western stream flows. More recently, Gan et al. (2007) applied wavelet analysis to precipitation records at 21 climate stations in southwestern Canada. The results suggest that there is a relation between precipitation and teleconnection 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 increases and decreases of 14 and 20% during El Niño and la Niña phases, respectively.

Conclusion

Moisture-sensitive tree-ring chronologies proved useful for the reconstruction of historical groundwater levels in Alberta making possible the analysis of long-term hydroclimatic variability. Longer periods of low groundwater levels than directly observed were identified in reconstructed water levels. The 1980s is the decade with the lowest water levels at well 117. 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 and 8–16 year bands. Increased inter-annual variability occurred without significant changes in the mean. Activity in the same bands is also observed in groundwater levels at wells 117 and most of the activity in the 2–8 year band is significant after 1850. Generally, changes in mean water levels are caused by the superposition of different oscillation modes acting at the same time.

Historical droughts have had different impacts on groundwater levels at different wells suggesting that groundwater response to climate variability, and the impacts of drought, needs to be studied at the aquifer level. Tree-ring networks capture a regional climate signal including widespread droughts that affect water levels over 100s of kilometers. Thus, even though in occasional years precipitation and groundwater recharge could differ significantly between well sites, in general, a regional pattern of climate variability and change produces a differential response of groundwater systems at various depths and hydrogeologic settings.

Acknowledgements

This research was supported by two projects involving collaboration between Canada and Chile: Institutional Adaptation to Climate Change (SSHRC MCRI) Project, and the Inter-American Institute Collaborative Research Network II-047. Funding also was provided by the Drought Research Initiative and Alberta Geological Survey with thanks to Dr. Garth van der Kamp and Dr. Roger Paulen, respectively. We also thank Alberta Environment for providing the groundwater data and Aslak Grinsted for the Matlab package WTC-R15 used to compute wavelets.

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