Temporal trends in groundwater levels from Saskatchewan, Canada

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Groundwater resources play a key role in supplying water for domestic, industrial, agricultural, and ecological functions on the North American prairies [1]. Prior to the construction of small and large reservoirs, groundwater was often the dominant, if not only, source of water for human activities – particularly during the overwinter periods. In some areas, especially the High Plains aquifer in the central United States, large rates of groundwater abstraction over the past century have led to rapid and substantial declines in regional groundwater tables [2]. On the Canadian prairie provinces of Alberta, Saskatchewan, and Manitoba, there have not been similar reports of large reductions in available groundwater resources. Indeed, very few studies available in the open scientific literature have examined broad-scale trends in groundwater levels from these locations.

As part of a graduate level thesis, Perez-Valdivia [3] considered a network of 33 groundwater wells in Alberta, Saskatchewan, and Manitoba with available time series records, and which were unaffected by pumping. The author found that groundwater levels in north-central areas of the Canadian prairies either exhibit no temporal trends or have decreasing trends, whereas increasing groundwater level time trends are evident in southern regions. The general spatial distribution of the various trends was correlated with changes in evaporation over the respective periods of record. In the current work, we investigate potential temporal trends in groundwater levels in the Canadian province of Saskatchewan over the past several decades. The monitoring network of wells employed includes both relatively undisturbed and heavily anthropogenically impacted aquifers.

In Saskatchewan, there are about 2,650 groundwater abstraction licenses with a total annual allocation of 145,600,000 m^3 (145,600 dam^3) [4]. The Saskatchewan Research Council (SRC) has operated an observation well network since 1964, with most wells being constructed between 1964 and 1970. Wells established during this period were intended to monitor natural groundwater levels and variability in aquifers not subject to anthropogenic influences such as production and artificial recharge. Beginning in 1988, the Saskatchewan Watershed Authority (SWA) started to also monitor wells influenced by human activities. At present, the observation network has 72 active wells, of which 54 are monitored by the SRC and 18 by the SWA. Wells are equipped with automatic water level recorders or dataloggers that allow continuous monitoring of groundwater levels [5].

Monthly median and daily average water level measurements were obtained for the SWA observation well network. The data has been corrected to manual measurements and barometric pressure. Median monthly and daily average data was calculated from hourly recordings using the digital water level recorders. Where gaps existed in the dataset for median monthly values, linear interpolations were used to estimate missing levels. Average annual groundwater levels at each site were taken as the average of all median monthly groundwater levels for the respective years. Only years with complete median monthly groundwater levels (measured and/or interpolated) were used in the analyses.

Details on the 54 groundwater monitoring stations under study are provided in Table 1. Locations of the stations are shown in Figure 1. Average groundwater type (major ion signature) and quality (as total dissolved solids [TDS]) is also given for each station. Four of the stations did not have groundwater quality data available. Among the remaining 50 stations, the groundwater type varies from calcium-bicarbonate (n=12), calcium-sulfate (n=4), calcium/magnesium-bicarbonate (n=6), calcium/magnesium-sulfate (n=7), magnesium-bicarbonate-sulfate (n=1), magnesium/calcium-sulfate (n=1), sodium-bicarbonate (n=6), sodium-bicarbonate-sulfate (n=1), sodium-chloride (n=2), sodium-sulfate (n=8), to sodium-sulfate/chloride (n=2).

Average TDS values in the groundwater range from 240 mg/L (Beauval [calcium-bicarbonate]) to 8300 mg/L (Fife Lake 002 [sodium-sulfate]). Average TDS concentrations (±std. dev.) in each groundwater type range are as follows (error bar not provided where n=1; values in mg/L): calcium-bicarbonate, 467±155; calcium-sulfate, 2710±962; calcium/magnesium-bicarbonate, 898±314; calcium/magnesium-sulfate, 2508±795; magnesium-bicarbonate-sulfate, 1320; magnesium/calcium-sulfate, 3260; sodium-bicarbonate, 1330±563; sodium-bicarbonate-sulfate, 1100; sodium-chloride, 3058±1517; sodium-sulfate, 4092±2242; and sodium-sulfate/chloride, 3683±2705. As expected based on mineral solubility considerations, generally higher TDS values are found in predominantly sodium and/or chloride/sulfate groundwater types.

Time series plots of average annual groundwater levels at each monitoring well over the available hydrogeological record are provided in Figure 2. A number of stations exhibit clear trending reversals and/or stabilizations over their available record lengths that preclude a meaningful linear regression analysis or other statistical trend tests. Armley displays a smooth, continuous decline until 1992, after which levels have continuously (and smoothly) increased to near its original value. Baildon 60 underwent a significant increase in levels between 1981 and about 1997 (which followed a decline between 1975 and 1980), after which levels again appear to be slightly declining. Both Conquest No. 504 and Coronach had sharp declines in levels during the 1980s, but appear to have stabilized and slightly increased over the past 20 years. Estevan No. 1/2 and Outram had stabilized levels prior to a sharp pumping induced drop-and-recovery period that began in the late-1980s [6; 7], with the recovery occurring up to the present. Vanscoy has a similar pattern, except with the drop-and-recovery period occurring in the middle to late 2000s. Levels at Goodale Farm 009 declined linearly from 1975 to 2003/2004, but increased sharply and linearly (and recovered all prior losses) over the past 6-7 years. Instow appears to have generally stablized over the past decade, following a steep decline between 1985 and 1989 and a slower and smaller decline during the 1990s.

Lilac displays a sharp increase during the 1980s and 1990s, followed by stable levels during the 1990s and a sharp decline-and-reverse trend during the 2000s. Meadow Lake had a slight decline during the 1990s, a sharp decline between 2000 and 2004, with apparently stable levels after this time. Similarly, Melfort saw an increase between the late-1960s and mid-1970s, followed by a continuous (but variable) decline up to 2004, after which levels rose rapidly to equal the maximum that existed during the mid-1970s. Nokomis appears to have had increasing levels from the late-1960s to mid-1970s, with a subsequent decline until the mid-1980s, followed by increasing levels back to the mid-1970s maxima at present. Levels at Saskatoon increased between the late-1960s and the mid-1970s, then stabilized until the mid-2000s, and have sharply increased over the past five years. Simpson 13-04, Simpson 16-05, and Swanson appear to have experienced declining levels from 1970 to 1990, after which levels appear to be increasing to levels at present near or above previous maxima.

For the 37 remaining stations, statistical analyses of average annual groundwater levels were conducted using the nonparametric Mann-Kendall test for the linear trend and the nonparametric Sen's method for the magnitude of the trend [8-10]. Details and linear trends (where significant at $p<0.05$) are provided in Table 2. Fifteen stations have no significant trends, 16 have significantly increasing trends (Baildon 59, Bangor A, Bangor B, Bruno, Conquest No. 500, Conquest No. 502, Conquest No. 503, Crater

Lake, Garden Head, Regina 530, Riceton, Shaunavon, Stenen, Tyner, Unity, Warman No. 2), and six stations have significantly decreasing groundwater level trends (Atton's Lake, Fife Lake 002, Hague, Hearts Hill, Smokey Burns A, and Verlo). The suitability of applying linear trend analyses for many of these stations is unknown given the large variability in the underlying dataset. A spatial map of the trendings, including those estimated visually by non-statistical methods as discussed above, is shown in Figure 3. There appear to be no spatial clusterings of trend directions. Regions with co-existing increasing, decreasing, or no observable trends in groundwater levels are located throughout the province.

The time trends at Estevan No. 1/2 and Outram also allow for statistical trend analyses of the pre-pumping and post-pumping recovery periods (Figure 4). The recovery periods for both wells can be adequately fit using a logistic function with three parameters of the general form $y(x)=a/(1+((x-1993)/c)^{b})$, where a, b, and c are constants, y(x) is the groundwater level in masl for year x, and x is the year:

Estevan: $y(x)=568.68/(1+((x-1993)/1.411\times10^{-6})^{-0.202})$; r=0.995
Outram: $y(x)=564.93/(1+((x-1993)/1.112\times10^{-3})^{-0.394})$; r=0.956

At both stations, a decline in groundwater levels existed between the start of the hydrological records (1966 at Estevan 1/2, and 1967 at Outram) and the initiation of pumping in 1988, which can be well-described using a linear function of the general form y(x)=a+bx, where a and b are constants, y(x) is the groundwater level in masl for year x, and x is the year:

Estevan: $y(x)=636.88-0.0395x$; r=-0.864; $p<0.05$
Outram: $y(x)=595.10-0.0205x$; r=-0.655; $p<0.05$

If the pre-pumping linear decline is extrapolated, it intersects with the projected recovery curve in the year 2055 at Estevan 1/2 and in the year 2038 at Outram. The projected recovery curves at both sites reach the corresponding groundwater levels at the start of the available hydrogeological records in the years 2120 and 2100, respectively. Extension of the projected recovery curves to an infinite length yields estimated groundwater levels of 568.68 and 564.93 masl at Estevan 1/2 and Outram that are 14 and 16 meters above the respective start-of-record levels of 554.98 and 558.89 (for comparison, ground surfaces at the two stations are 577.82 and 577.65 masl, respectively). The recovery period at the Vanscoy station is too short (n=4) for a similar analysis.

We note that although groundwater levels at the Estevan No. 1/2, Outram, and Vanscoy stations are considered increasing due to their recent temporal trends, all three stations have current groundwater levels below their pre-disturbance values. As noted previously, other stations also have recent trends (or absence of trends) and/or absolute groundwater levels that potentially conflict with prior trends and/or historical levels at each location. Thus, while some stations have recently increasing trends, the current levels may still be below the historical average, and vice versa. Overall, the large majority of areally distributed stations throughout Saskatchewan with increasing groundwater level time trends suggests that this hydrogeological resource is growing in quantity and is not under current threat from depletion.

Acknowledgements

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Figure 1. Locations and names of the groundwater monitoring stations under study in the province of Saskatchewan, Canada.

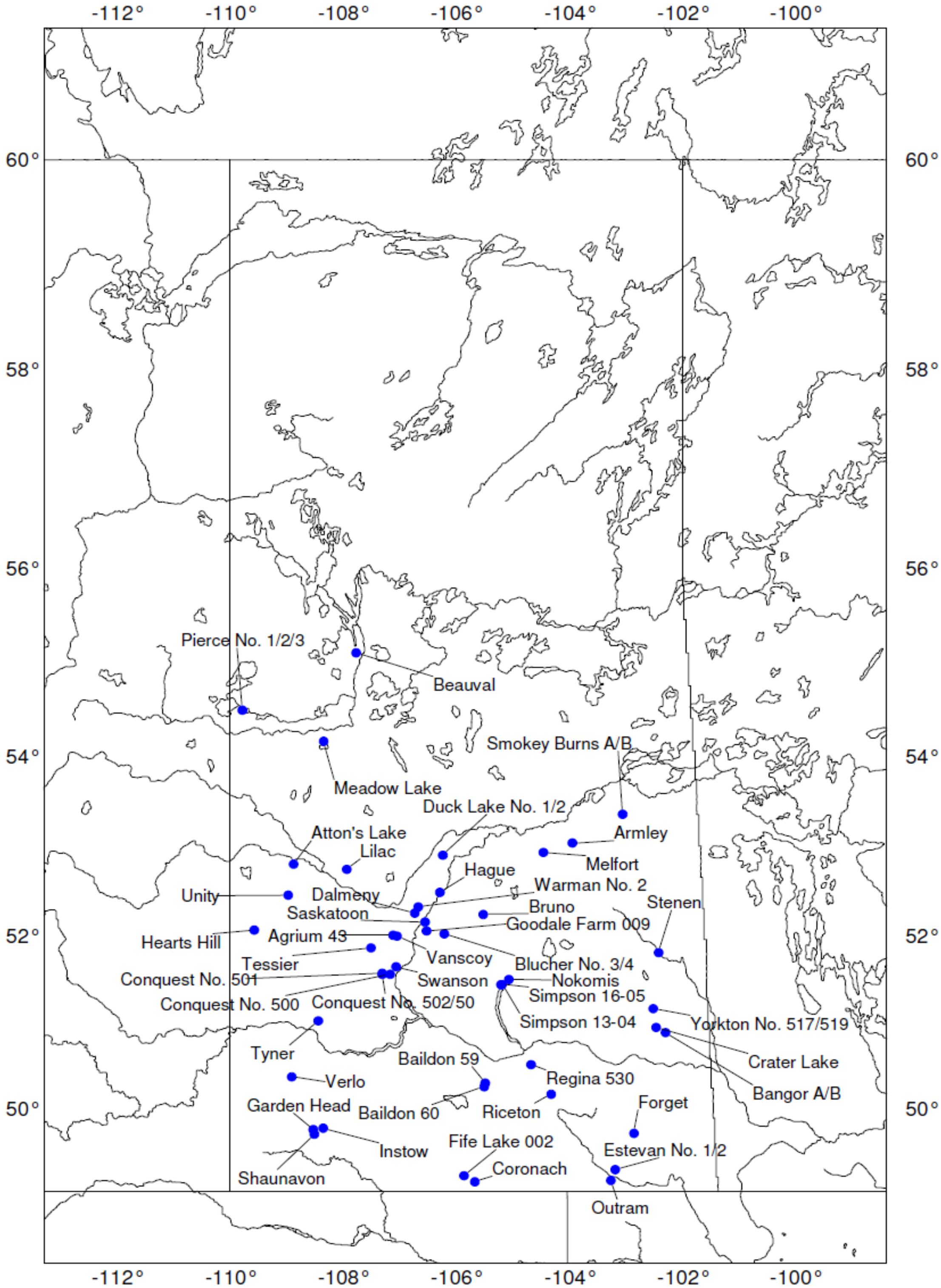
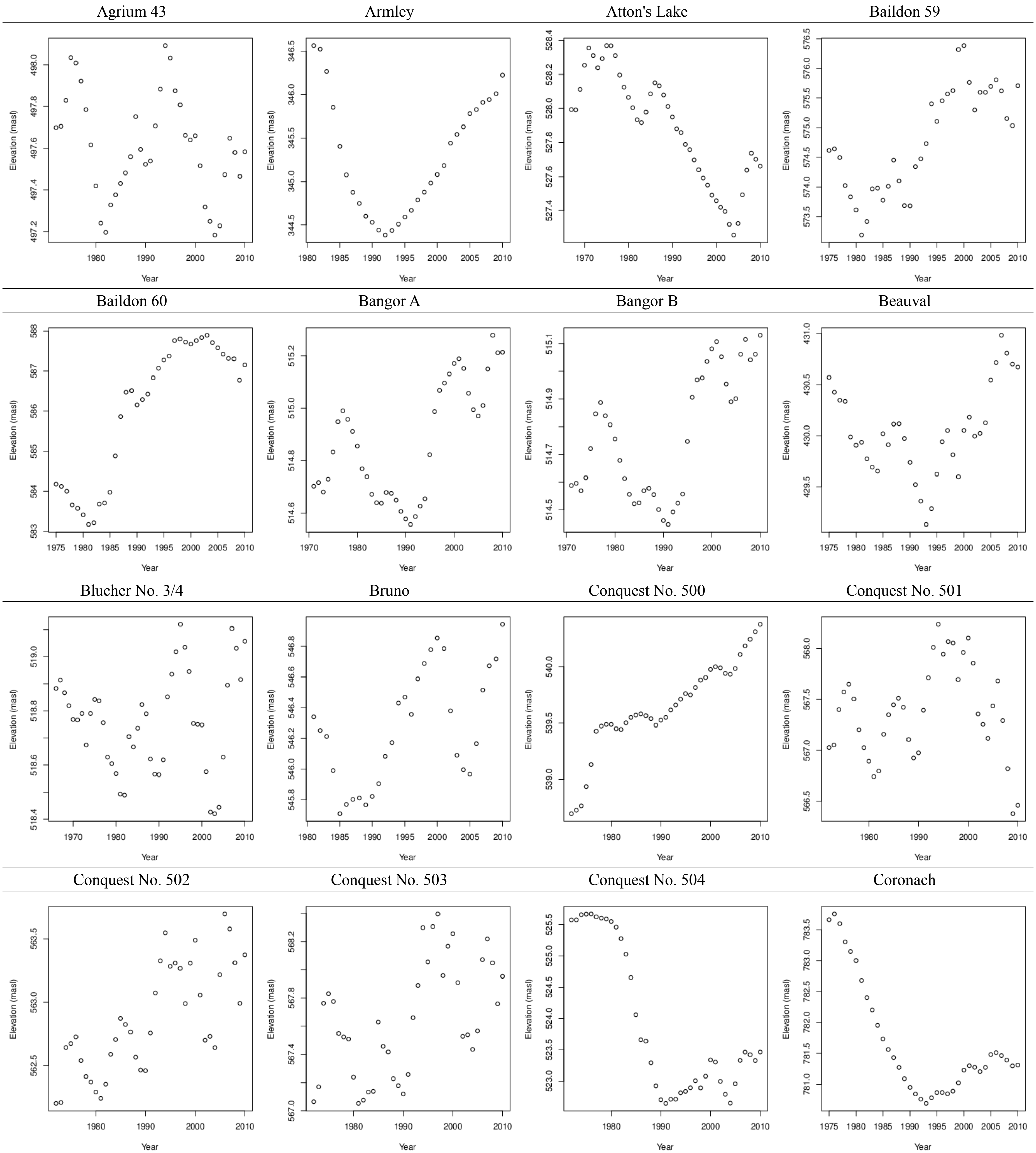


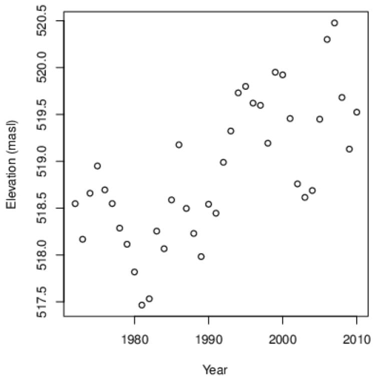
Table 1. Details for the groundwater level monitoring stations under study.

ID	Name	Latitude (°N)	Longitude (°W)	Datum (masl)	Depth (m)	Groundwater type	TDS (mg/L)
1	Agrium 43	52.0200	-107.1105	500.229	17.50	calcium/magnesium-bicarbonate	1040
2	Armley	53.0529	-103.9409	364.309	154.83	sodium-chloride	4130
3	Atton's Lake	52.8203	-108.8706	536.448	16.15	calcium-bicarbonate	490
4	Baildon 59	50.3021	-105.4775	583.277	30.42	calcium-bicarbonate	790
5	Baildon 60	50.2585	-105.5004	590.184	13.05	calcium/magnesium-bicarbonate	480
6	Bangor A	50.8928	-102.2966	527.505	39.16	calcium/magnesium-sulfate	1990
7	Bangor B	50.8928	-102.2966	527.630	15.27	calcium-bicarbonate	540
8	Beauval	55.1182	-107.7606	434.340	16.15	calcium-bicarbonate	240
9	Blucher No. 3/4	52.0347	-106.2070	519.983 (1965-1997) 521.061 (1998-present)	79.25 (1965-1997) 50.63 (1998-present)	sodium-sulfate	3680
10	Bruno	52.2529	-105.5153	570.784	180.06	calcium/magnesium-sulfate	2430
11	Conquest No. 500	51.5694	-107.1638	555.202	19.16	calcium-sulfate	2350
12	Conquest No. 501	51.5839	-107.3044	572.625	8.24	calcium-bicarbonate	660
13	Conquest No. 502	51.5694	-107.3044	572.015	19.21	calcium-sulfate	1610
14	Conquest No. 503	51.5694	-107.3044	572.411	7.85	calcium-sulfate	3870
15	Conquest No. 504	51.5694	-107.3044	572.094	82.80	calcium/magnesium-sulfate	3565
16	Coronach	49.1235	-105.6678	801.898	36.88	calcium/magnesium-bicarbonate	1240
17	Crater Lake	50.9523	-102.4626	524.158	11.58	calcium-sulfate	3010
18	Dalmeny	52.2676	-106.7297	515.188	26.52	calcium/magnesium-sulfate	2735
19	Duck Lake No. 1	52.9215	-106.2331	502.920	13.26	calcium-bicarbonate	300
20	Duck Lake No. 2	52.9215	-106.2331	502.920	124.60	sodium-sulfate/chloride	5595
21	Estevan No. 1/2	49.2680	-103.1836	577.819	145.08	sodium-bicarbonate	1680
22	Fife Lake 002	49.1951	-105.8504	810.049	9.94	sodium-sulfate	8300
23	Forget	49.7046	-102.8532	606.552	5.94	calcium-bicarbonate	450
24	Garden Head	49.7494	-108.5231	899.160	22.62	sodium-bicarbonate	1105
25	Goodale Farm 009	52.0638	-106.5155	511.159	10.06	calcium-bicarbonate	410
26	Hague	52.5004	-106.2800	468.609	49.68	sodium-sulfate	3275
27	Hearts Hill	52.0779	-109.5621	688.848	76.81	sodium-bicarbonate	1110
28	Instow	49.7640	-108.3424	922.020	554.94	sodium-bicarbonate	1980
29	Lilac	52.7621	-107.9269	548.640	122.53	calcium/magnesium-bicarbonate	1175
30	Meadow Lake	54.1727	-108.3402	477.317	73.14	sodium-sulfate/chloride	1770
31	Melfort	52.9510	-104.4586	451.104	10.64	calcium/magnesium-sulfate	3435
32	Nokomis	51.5110	-105.0654	516.267 (1967-2008) 516.151 (2008-present)	99.67 (1967-2008) 99.97 (2008-present)	sodium-sulfate	3050
33	Outram	49.1377	-103.2642	577.651	111.25	sodium-bicarbonate	1680
34	Pierce No. 1	54.5074	-109.7722	528.344	111.56	n/a	n/a
35	Pierce No. 2	54.5074	-109.7722	528.498	71.32	n/a	n/a
36	Pierce No. 3	54.5074	-109.7722	528.508	19.80	n/a	n/a
37	Regina 530	50.5207	-104.6754	591.970	38.56	calcium/magnesium-bicarbonate	575
38	Riceton	50.1709	-104.3155	579.120	22.40	sodium-sulfate	6900
39	Saskatoon	52.1656	-106.5394	512.064	27.05	magnesium/calcium-sulfate	3260
40	Shaunavon	49.6911	-108.5006	896.112	15.67	sodium-bicarbonate-sulfate	1100
41	Simpson 13-04	51.4527	-105.1826	496.620	7.22	calcium-bicarbonate	350
42	Simpson 16-05	51.4527	-105.2060	493.776	6.04	calcium-bicarbonate	350
43	Smokey Burns A	53.3729	-103.0497	319.101	37.12	sodium-chloride	1985
44	Smokey Burns B	53.3729	-103.0497	318.903	6.25	magnesium-bicarbonate-sulfate	1320
45	Stenen	51.8165	-102.4201	499.872	14.63	calcium-bicarbonate	485
46	Swanson	51.6562	-107.0551	534.921	9.18	calcium-bicarbonate	540
47	Tessier	51.8743	-107.5041	554.736	26.05	calcium/magnesium-sulfate	1400
48	Tyner	51.0306	-108.4343	591.312	113.69	sodium-sulfate	2820
49	Unity	52.4713	-108.9657	673.608	26.72	calcium/magnesium-bicarbonate	880
50	Vanscoy	52.0056	-107.0391	512.064	88.70	sodium-sulfate	2440
51	Verlo	50.3757	-108.9034	737.616	12.80	sodium-bicarbonate	425
52	Warman No. 2	52.3401	-106.6638	518.160	108.51	sodium-sulfate	2270
53	Yorkton No. 517	51.1733	-102.5094	513.643	40.23	calcium/magnesium-sulfate	2000
54	Yorkton No. 519	51.1733	-102.5094	513.448	6.52	n/a	n/a

Figure 2. Temporal trends in groundwater levels at the 54 monitoring stations under study.



Crater Lake



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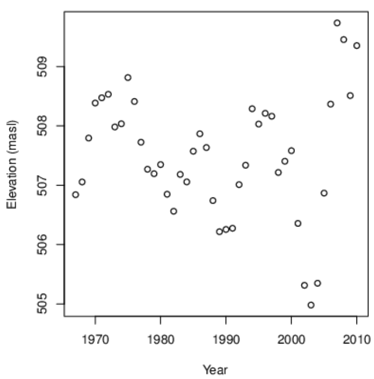

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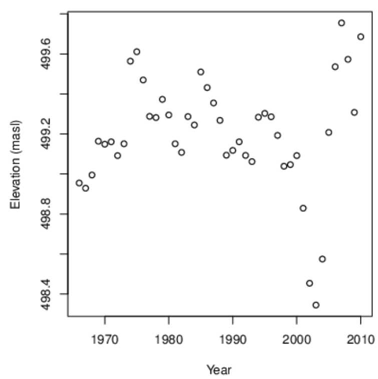

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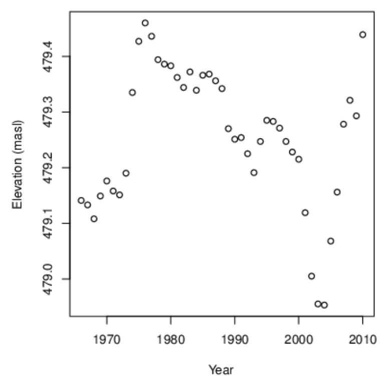
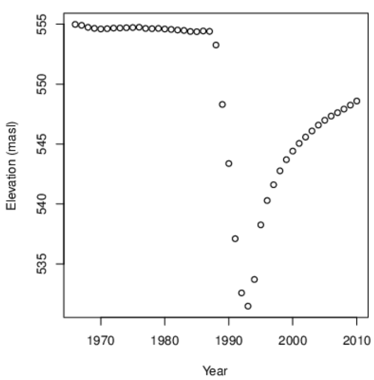
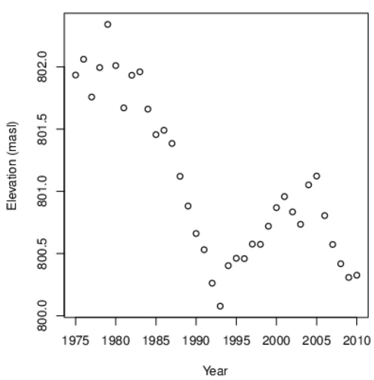


Estevan No. 1/2



Fife Lake 002



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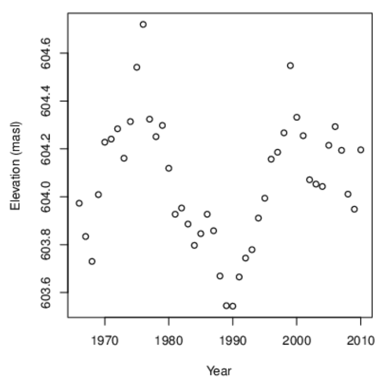

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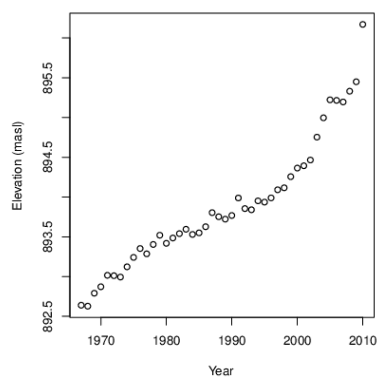

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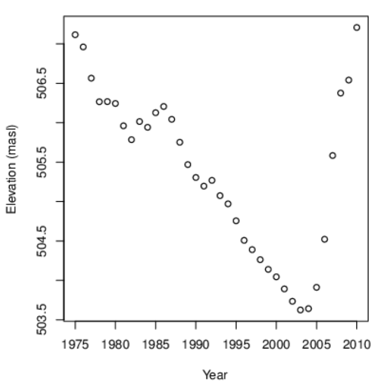
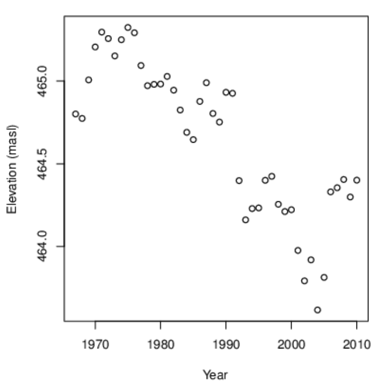


Hague



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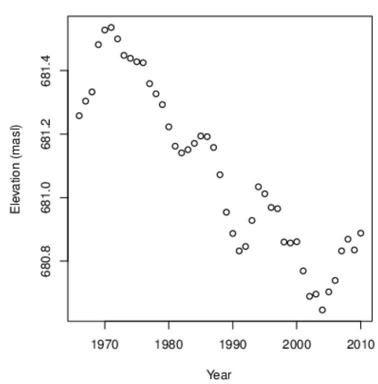
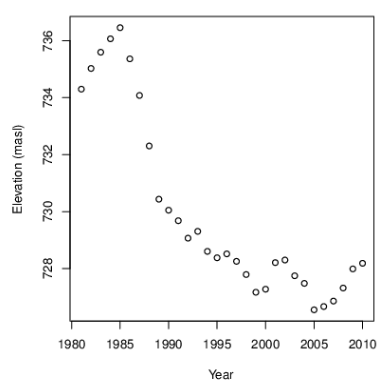


Instow



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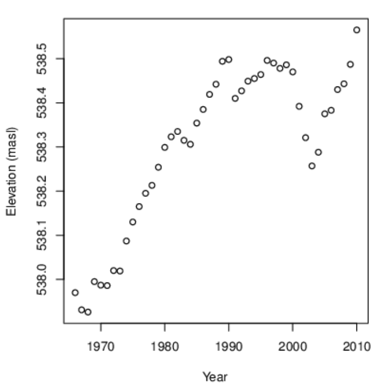
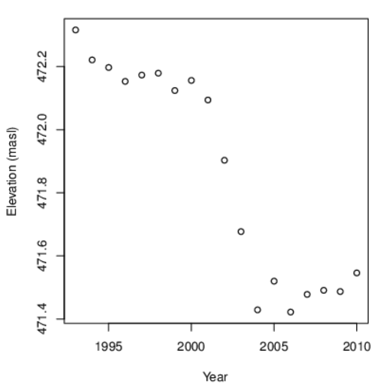
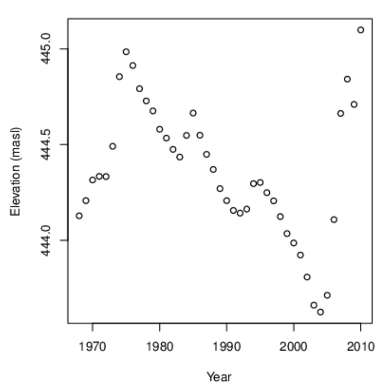


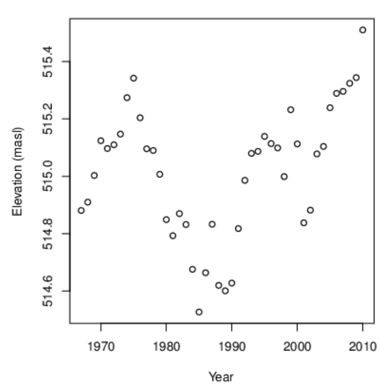
Meadow Lake

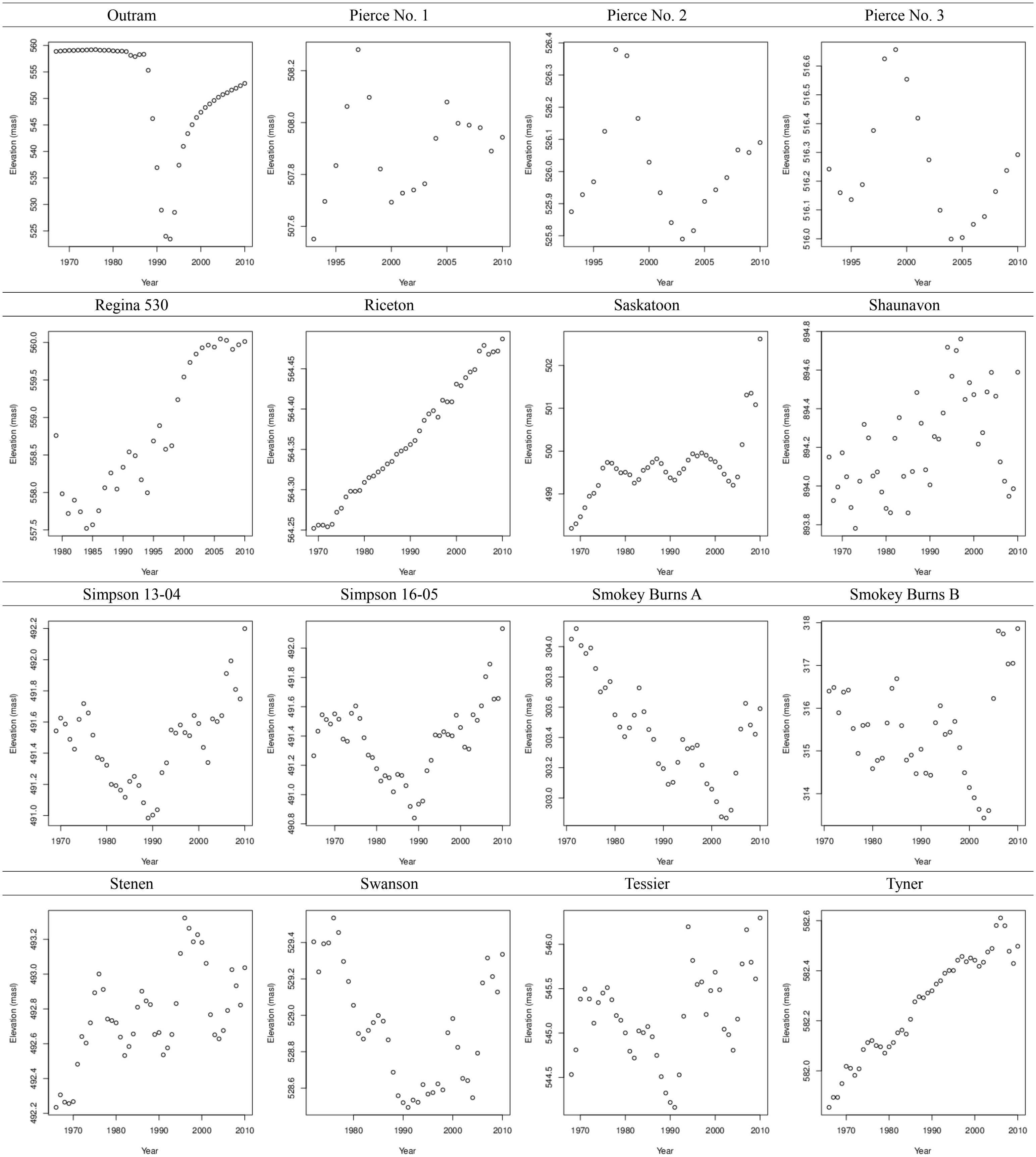


Melfort

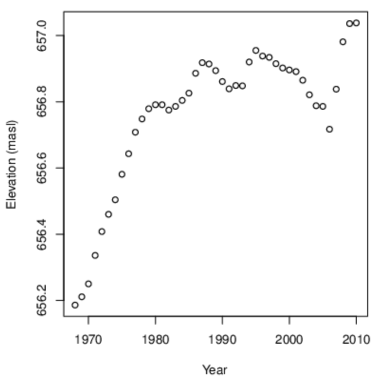


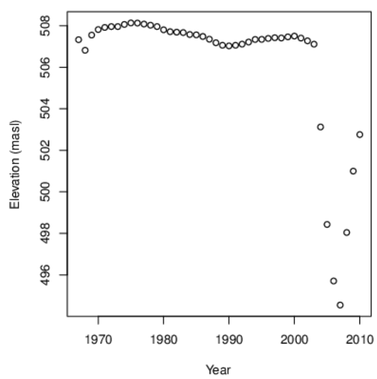
Nokomis

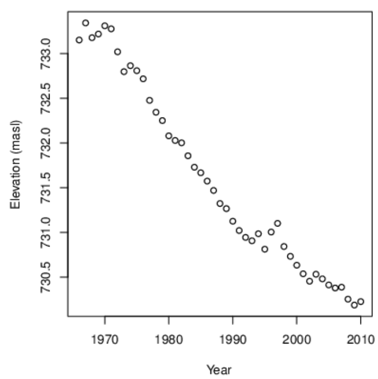


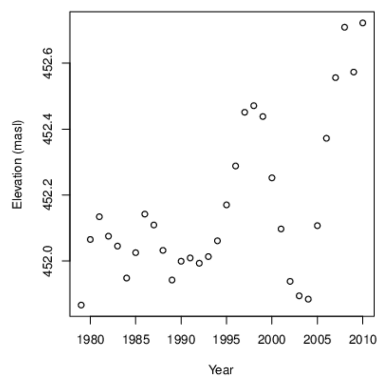

Outram
Pierce No. 1
Pierce No. 2
Pierce No. 3
Regina 530
Riceton
Saskatoon
Shaunavon
Simpson 13-04
Simpson 16-05
Smokey Burns A
Smokey Burns B
Stenen
Swanson
Tessier
Tyner
Elevation (masl)
Year

Unity	Vanscoy	Verlo	Warman No. 2

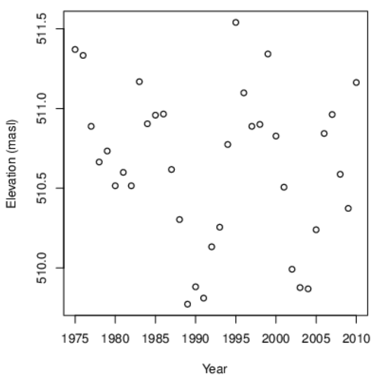








Yorkton No. 517	Yorkton No. 519



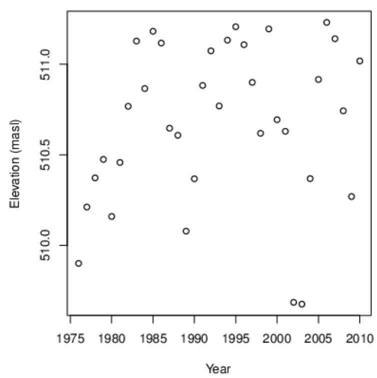


Table 2. Summary of non-parametric Mann-Kendall test statistics for temporal trends in average annual groundwater levels at the monitoring stations under study. Values are in masl/year for Q and masl for B.

				Mann-Kendall trend		Sen's slope estimate					
Station name	First year	Last year	n	Test Z[a]	Significance[b]	Q[c]	$Q_{min,95}$[d]	$Q_{max,95}$[e]	B[f]	$B_{min,95}$[g]	$B_{max,95}$[h]
Agrium 43	1972	2010	39	-1.60	n/s	-0.0065	-0.0132	0.0021	497.750	497.956	497.544
Atton's Lake	1967	2010	44	-6.44	*** (–)	-0.0241	-0.0294	-0.0187	528.459	528.543	528.346
Baildon 59	1975	2010	36	4.64	*** (+)	0.0652	0.0424	0.0850	572.914	573.635	572.343
Bangor A	1971	2010	40	3.13	** (+)	0.0111	0.0057	0.0164	514.633	514.756	514.477
Bangor B	1971	2010	40	3.30	*** (+)	0.0117	0.0065	0.0170	514.512	514.638	514.363
Beauval	1975	2010	36	1.46	n/s	0.0097	-0.0062	0.0269	429.744	430.184	429.321
Blucher No. 3/4	1966	2010	45	-0.05	n/s	-0.0001	-0.0050	0.0054	518.767	518.837	518.674
Bruno	1981	2010	30	3.35	*** (+)	0.0270	0.0126	0.0451	545.447	545.940	544.845
Conquest No. 500	1972	2010	39	7.94	*** (+)	0.0317	0.0267	0.0386	538.815	538.989	538.593
Conquest No. 501	1972	2010	39	0.68	n/s	0.0064	-0.0099	0.0219	567.227	567.641	566.878
Conquest No. 502	1972	2010	39	4.69	*** (+)	0.0288	0.0185	0.0371	562.071	562.378	561.933
Conquest No. 503	1972	2010	39	3.10	** (+)	0.0186	0.0074	0.0281	567.157	567.431	566.899
Crater Lake	1972	2010	39	4.04	*** (+)	0.0447	0.0256	0.0608	517.717	518.299	517.268
Dalmeny	1967	2010	44	-0.37	n/s	-0.0071	-0.0387	0.0232	507.682	508.367	506.993
Duck Lake No. 1	1966	2010	45	0.19	n/s	0.0005	-0.0050	0.0065	499.177	499.339	499.096
Duck Lake No. 2	1966	2010	45	-1.30	n/s	-0.0032	-0.0066	0.0017	479.352	479.451	479.211
Fife Lake 002	1975	2010	36	-4.62	*** (–)	-0.0472	-0.0607	-0.0359	802.438	802.774	802.145
Forget	1966	2010	45	0.13	n/s	0.0006	-0.0065	0.0070	604.030	604.260	603.879
Garden Head	1967	2010	44	9.09	*** (+)	0.0543	0.0484	0.0628	892.589	892.673	892.468
Hague	1967	2010	44	-5.90	*** (–)	-0.0302	-0.0392	-0.0238	465.393	465.546	465.309
Hearts Hill	1966	2010	45	-7.07	*** (–)	-0.0199	-0.0225	-0.0169	681.558	681.620	681.492
Pierce No. 1	1993	2010	18	1.14	n/s	0.0148	-0.0099	0.0249	507.331	508.325	506.956
Pierce No. 2	1993	2010	18	0.15	n/s	0.0012	-0.0182	0.0201	525.931	526.677	525.208
Pierce No. 3	1993	2010	18	-0.83	n/s	-0.0092	-0.0311	0.0141	516.530	517.379	515.732
Regina 530	1979	2010	32	6.05	*** (+)	0.0888	0.0757	0.1058	556.140	556.559	555.666
Riceton	1969	2010	42	9.02	*** (+)	0.0059	0.0057	0.0060	564.219	564.223	564.214
Shaunavon	1967	2010	44	3.11	** (+)	0.0105	0.0039	0.0163	893.970	894.134	893.864
Smokey Burns A	1971	2010	40	-4.91	*** (–)	-0.0262	-0.0328	-0.0163	304.076	304.213	303.825
Smokey Burns B	1971	2010	40	-0.73	n/s	-0.0193	-0.0564	0.0235	315.926	316.560	314.971
Stenen	1966	2010	45	3.81	*** (+)	0.0118	0.0065	0.0180	492.489	492.596	492.315
Tessier	1968	2010	43	1.70	n/s	0.0108	-0.0015	0.0231	544.993	545.217	544.656
Tyner	1966	2010	45	8.52	*** (+)	0.0160	0.0147	0.0172	581.908	581.925	581.871
Unity	1968	2010	43	5.62	*** (+)	0.0107	0.0075	0.0153	656.560	656.648	656.428
Verlo	1966	2010	45	-9.11	*** (–)	-0.0776	-0.0844	-0.0716	733.370	733.510	733.224
Warman No. 2	1979	2010	32	2.68	** (+)	0.0147	0.0049	0.0237	451.735	451.974	451.515
Yorkton No. 517	1975	2010	36	-1.19	n/s	-0.0096	-0.0284	0.0081	510.933	511.485	510.524
Yorkton No. 519	1976	2010	35	1.45	n/s	0.0101	-0.0047	0.0264	510.425	510.858	510.032

[a] The absolute value of the test statistic (Z) is compared to the standard normal cumulative distribution to define if there is a trend or not at the selected level α of significance. A positive (negative) value of Z indicates an upward (downward) trend. [b] The smallest significance level α with which the test shows that the null hypothesis of no trend should be rejected. n/s=not significant. *=significant at α=0.05. **=significant at α=0.01. ***=significant at α=0.001. [c] The Sen's estimate for the true slope of the linear trend. [d] The lower limit of the 95% confidence interval of Q (α= 0.05). [e] The upper limit of the 95% confidence interval of Q (α= 0.05). [f] Estimate of the constant B in the equation f(Year)=Q×(Year-First Year)+B for a linear trend. [g] Estimate of the constant $B_{min,95}$ in the equation f(Year)=$Q_{min,95}$*(Year-First Year)+$B_{min,95}$ for 95% confidence level of a linear trend. [h] Estimate of the constant $B_{max,95}$ in the equation f(Year)=$Q_{max,95}$*(Year-First Year)+$B_{max,95}$ for 95% confidence level of a linear trend.

Figure 3. Map of groundwater level monitoring stations with decreasing (red circles) or increasing (green circles) temporal trends, or no temporal trends (blue circles), as well as cities and towns throughout the region.

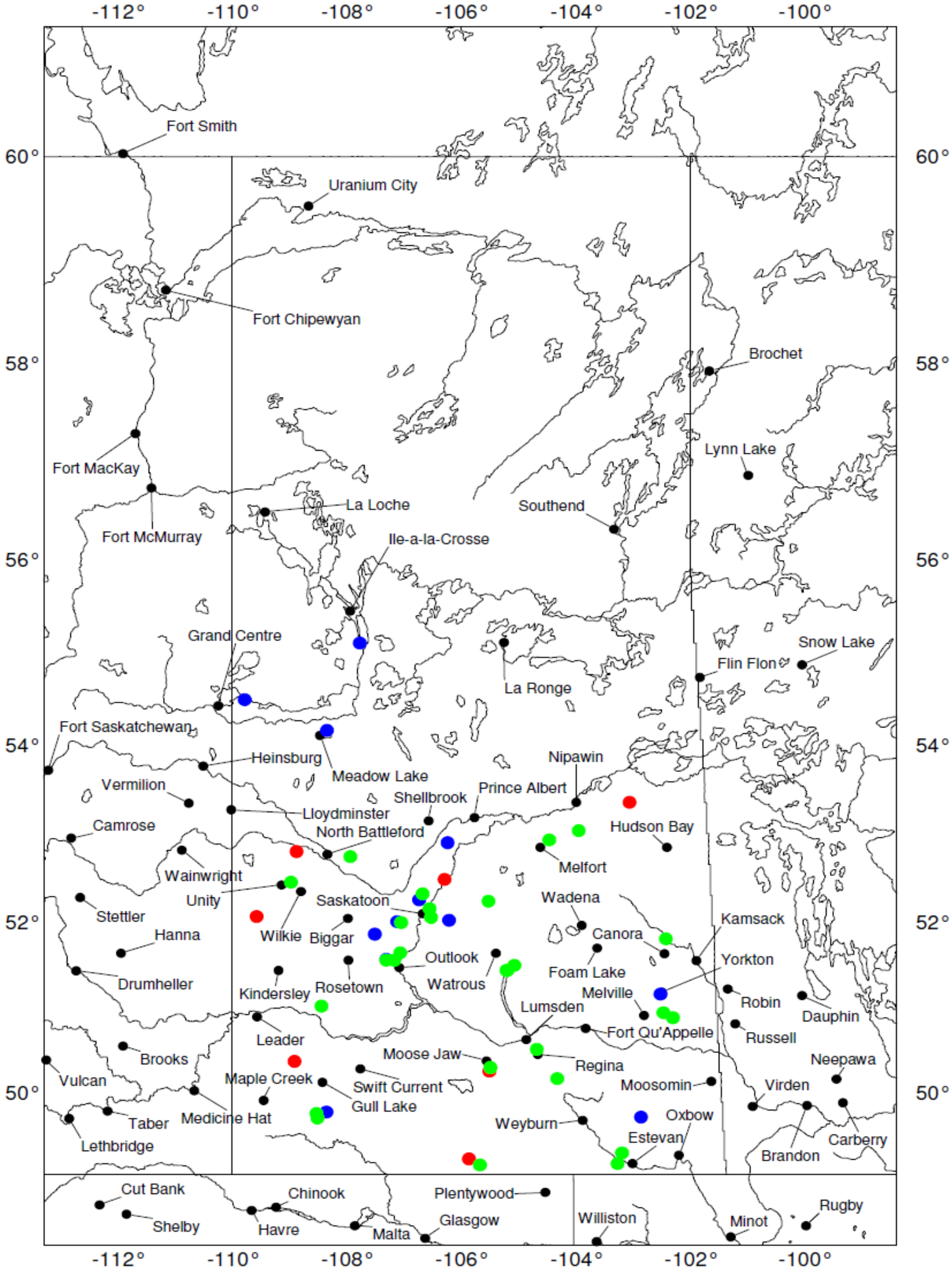


Figure 4. Statistical analysis of pre-pumping and post-pumping recovery period average annual groundwater levels at the Estevan 1/2 and Outram monitoring stations.