Examining the impacts of climate change and human activities on groundwater recharge in Canada using historical data

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ABSTRACT
Groundwater often plays a major role in social and economic development and in human and ecosystem health. However, little is known about the potential impacts of climate change on this resource in Canada. This paper focuses on trend statistical analysis of historical series of baseflow and groundwater levels. Results show that most groundwater level series have significant trends, whereas most baseflow series have not. Mixed trends are often observed across Canada although some regions can have marked trends for a given variable, period, and series length.

RÉSUMÉ
L'eau souterraine joue souvent un rôle majeur dans le développement socio-économique et dans la santé publique et des écosystèmes. Cependant, les impacts potentiels des changements climatiques sur cette ressource sont assez peu connus au Canada. Ce compte-rendu s'intéresse à l'analyse statistique de tendances de séries historiques de débits de base et de niveaux d'eau dans les puits. Les résultats montrent que la majorité des séries de niveaux d'eau ont des tendances significatives, contrairement à celles des débits de base. Les deux types de tendances (à la hausse et à la baisse) sont souvent observés à travers le Canada, mais certaines régions montrent des tendances marquées pour une variable, une période et une longueur de série données.

1 INTRODUCTION

Groundwater is an important component of the hydrological cycle that responds to climate change. Modifications in hydro-climatic conditions may affect both mean values of the hydrological cycle parameters and the magnitude and frequency of extreme climatic events (flood, droughts, heat waves, storms, etc.), thereby impacting groundwater recharge through runoff, evapotranspiration, and snow accumulation.

Due to increasing concerns of the last decades related to the impact of greenhouse gases and their effect on the environment, numerous studies have attempted to identify trends on meteorological and hydrological data such as temperature, precipitation, and streamflow. Canadian streamflow series were studied by Zhang et al. (2001), Burn and Hag Elnur (2002), Yue et al. (2003), and Ehsanzadeh and Adamowski (2007), whereas precipitation and temperature series were investigated by Zhang et al. (2000). Other studies of trends in Canadian streams focusing on specific regions are also presented in Zhang et al. (2001) and in Burn and Hag Elnur (2002). Burn and Hag Elnur (2002) underlined the importance of studying a large number of hydrologic variables to study climate change, since the latter is expected to affect various parameters in different ways.

All above-cited studies used the Mann-Kendall non-parametric test to detect trends and a procedure to eliminate serial correlation effects using a positive lag-one autoregressive process AR(1) as a filter (called pre-whitening). Indeed, serial correlation leads to the rejection of the null hypothesis of no trend while there might not really be a trend. Using simulation experiments, Yue et al. (2002) found that the commonly used pre-whitening process resulted in a reduction of the magnitude of the existing trend, leading to potentially inaccurate assessments of the trend significance. They developed the trend-free pre-whitening (TFPW) procedure that most studies have been using since. Yue et al. (2003) and Burn and Hag Elnur (2002) have also added a bootstrap procedure to assess the field significance of trends observed in the network. Canadian studies focusing on streamflow have all used RHBN (Reference Hydrometric Basin Network) stations, which is a network of streamflow and surface water level stations across Canada for pristine or stable hydrological conditions, with more than 20 years of good quality record (Zhang et al., 2001).

Zhang et al. (2000) found, using historical data of the last 50 years, that the Canadian climate was generally getting wetter and warmer. Annual precipitation showed a change from -10% to 35%, with the strongest increases occurring in the northern regions of the country; significant decreasing trends in winter precipitation and in the proportion of spring precipitation falling as snow were identified in southwestern regions. However, they found no evidence of changes in the frequency of extreme rain events, but significant trends have been detected for extreme temperatures.

Zhang et al. (2001) found that annual mean streamflow generally decreased during the studied periods (1967-, 1957- and 1947-1996), with significant decreases detected in the southern part of the country. Monthly mean streamflow for most months also decreased, with the greatest decreases occurring in August and September. March and April showed significant increased flow, likely due to earlier snow melt. However, as noted in Yue et al. (2003), this study did not use the TFPW method, therefore probably underestimating the trends across the country.

Burn and Hag Elnur (2002) studied the statistical trend, magnitude and, for some locations, relationship to meteorological data (temperature and precipitation) of 248 stations using 18 variables (such as annual and monthly means, annual daily maximum, number of ice days, as well as date of spring freshet). Hydrologic variables with particularly strong trends were: date that ice conditions end (earlier), the months of March (increasing trend), April (increasing trend), and June (decreasing trend).

Yue et al. (2003) used 30-, 40-, and 50-year series of streamflow to study trends for mean, maximum and minimum annual data. They generally found more decreasing trends. However, the field significance evaluation of trends did not show evidence of statistical significant changes for any of the three studied parameters at the 5% level.

Using data from 57 stations, Ehsanzadeh and Adamowski (2007) showed that rivers above the 60˚N latitude had an increasing significant trend in minimum annual flows. Significant decreasing trends seemed to dominate the Atlantic provinces and southern British Columbia. No significant trend was found in the Prairies and eastern Ontario.

In order to investigate the potential impacts of climate change and human activities on aquifer recharge, historical records of groundwater levels and baseflow (estimated from streamflow using six graphical methods of hydrograph separation) were used. This paper describes the methodology used to create the database and to analyze the series, and presents observed trends and their field significance.

2 METHODOLOGY

2.1 Database creation

Aquifer recharge is defined in a broad sense as the quantity of water circulating vertically through the unsaturated zone and reaching the water table, therefore representing a contribution to aquifer renewal. In this study, recharge was not estimated directly, but trends were sought in time series of variables typically used to estimate recharge, i.e. baseflows and groundwater levels. Trend estimates are not affected by the transformation of these surrogate data into recharge since, for a given site, the same parameters, such as the specific yield or the catchment area, apply. Valuable information can therefore be obtained from these data.

River baseflows represent an estimate of the aquifer contribution to the river. They are typically estimated from hydrograph separation, based on the assumption that streamflow can be roughly divided into two components: the baseflow (subsurface flow) and the surface flow (mainly representing the runoff). Because of the slow velocity of groundwater, baseflow plays a small role during a storm event, but plays a critical role in the absence of rain and during low-flow periods. Baseflow is therefore an indirect way of estimating recharge, but it has the advantage of being regional. Indeed, streamflow variables tend to reflect a spatially integrated hydrologic response of the entire catchment (Burn and Hag Elnur, 2002). In addition, long records for streamflow are available.

Results from six graphical methods of hydrograph separation were available for this study: BFLOW, HYSEP1 to 3, PART and UKIH. They are individually discussed and referenced in Neff et al. (2005); none of these methods were considered worse or better than the others. Neff et al. (2005) found considerable differences in baseflows obtained with the six methods. This was also observed in the current study. However, an assessment of the performance of each hydrograph separation method is not possible because the actual baseflow at each time step is unknown. In order to reduce the baseflow estimation variance, a multimodel combination technique was used to produce a single time series from the six available ones (Shamseldin et al. 1997). Multimodel combination generally leads to better or similar performance than any available single model (Ajami et al. 2006). The simple model average (SMA) technique was selected here because it is the only quite successful technique that does not resort to a calibration: the same weight is attributed to all time series. This approach thus implies that the initial time series are equally probable. In the current study, the SMA combines either five or six of the available methods. Indeed, the UKIH method sometimes does not allow a baseflow estimation due to the way turning points are calculated.

This study also relies on streamflow data from RHBN hydrometric stations. The RHBN network is made up of a total of 211 continuous streamflow stations across Canada (Burn and Hag Elnur, 2002). There are coverage gaps in some regions of the country and there is no RHBN station north of the 70˚ latitude (Zhang et al., 2001). There are also data gaps for most of the stations, mainly during winter, while freezing conditions occur. Due to series length, ending year (2005 in this study), and important gaps, not all stations could be used (see below). Still, the retained stations cover many of Canada’s major hydrologic regions. Streamflow data were retrieved from the HYDAT database published by the Water Survey of Canada. Data for the province of Quebec were obtained from the provincial Department of Environment (MDDEP). British Columbia has by far the largest number of stations. Provinces of Atlantic Canada also have a quite good concentration of stations.

Groundwater levels from provincial monitoring wells represent direct data for the estimation of aquifer recharge. However, these data are very local (contrarily to baseflow) and series are typically short. The total number of wells used for this study is modest, due again to series gaps and especially length, but also to pumping. There are 138 series available with 30 years and 53 series with 40 years. None has a 50-year record (the maximum being

47 years). Most wells are distributed over three provinces: Saskatchewan, Alberta, and British Columbia. No provincial well was monitored for 30 years or more without major gaps (10 years or more) for Ontario (ON), Quebec (QC), New Brunswick, Newfoundland and Labrador. Therefore, only wells from six provinces were used: British Columbia (BC), Alberta (AB), Saskatchewan (SK), Manitoba (MB), Nova Scotia (NS), and Prince Edward Island (PEI). All these provinces have a long history of groundwater use.

For this study, annual and seasonal values for mean, minimum and daily maximum were used. Since an annual extreme minimum river flow may not contain information on the sequence of low flows (Ehsanzadeh and Adamowski, 2007) and may be the result of the malfunctioning of an apparatus (due to ice conditions in the winter for example), it is common to resort to average values over a seven-day period (Hodgkins et al., 2007; Ehsanzadeh and Adamowski, 2007). The seven-day low-flow variable corresponds to the lowest mean flow in a year for seven consecutive days; this parameter was used to represent minimum values.

Baseflow data gaps were filled on a daily basis. The selected procedure was tested simulating gaps in 25 50-year baseflow time series exempt of missing data. More specifically, data from three and five months, consecutive or not, were removed from the gap-free time series. Indeed, most missing data are found during winter months (December through February), but some stations, usually in higher latitude, have many missing data from November to March. Results showed that the final data (after the application of the TFPW procedure) and trends were usually closer to the initial complete series when gaps were filled. To fill the gaps, an arithmetic mean of the 10 years prior and 10 years after the given missing date was used, and a minimum of eight data out of 20 was required. “Filled” data could not be used to fill other gaps. An interpolation between several stations in the same area could not be considered since selected RHBN stations are typically too distant from each other. Data gaps were filled on a monthly basis for groundwater levels, data being much more scarce and less variable than baseflow data.

It is not clear from the literature if previous studies used incomplete series or “filled” series and how they did it, and what was their threshold to reject a year. However, Burn and Hag Elnur (2002) mention that no more than five years during the study period (28, 38, 48, and 58-year series) could be missing, whereas Burn et al. (2004) used a threshold of four years for each studied period (25, 30, 35 and 40 years). In addition, it is never mentioned how many data were used to estimate annual and monthly means. In this study, when baseflow stations did not have at least 350 days for a year or more (4% of data) after the gap filling procedure, they were discarded for annual values, but were usually kept for seasonal values (spring, summer and fall, since the vast majority of missing data occur during winter). This was done to avoid the possibility of including significantly biased annual or seasonal values into the series (e.g. an annual value based on only nine months).

2.2 Site significance

Like the other Canadian-wide studies cited in the introduction, this study used the Mann-Kendall non-parametric test, along with the TFPW procedure (developed by Yue et al., 2002). The pre-procedure and test itself are abundantly described in the literature (e.g. Yue et al., 2002; 2003; Burn and Hag Elnur, 2002) and are therefore not presented herein. The Mann-Kendall test is a rank-based procedure, resistant to the influence of extremes, and applicable to skewed variables (no assumption of normality is required) and to series with missing data (Lins and Slack, 1999). It can be used to detect trends that are monotonic, but not necessarily linear (McBean and Motiee, 2006). A site significance level of 10% was used in the current study.

2.3 Field significance

Field significance allows the determination of the percentage of tests that are expected to show a trend (at a given significance level) purely by chance. If sites were independent and infinite, a binomial distribution could be used. But since we have to deal with a finite number of stations and site correlation, the same properties that were taken into account in the time series must also be quantitatively accounted for to find the required percentage of stations for a given confidence level (Livezey and Chen, 1982).

A bootstrap approach using 1000 Monte Carlo simulations was thus used in this study, following the detailed description presented in Yue et al. (2003). The existing temporal structure present in the original series is not reproduced in the resampled data sets because of the nature of the resampling process, which selects the years to be included at random with replacement. However, cross-correlations of the original data sets are preserved given that all stations use the same resampled year selection. A field significance level of 10% was chosen.

3 RESULTS OF THE TREND ESTIMATION

Results of the trend estimation are presented for time series which are averages of the ones produced by each hydrograph separation methods. Mean values of baseflows and groundwater levels, and minimum and maximum values for baseflow are discussed. Neither minimum nor maximum values were retained for groundwater levels because data are often provided on a monthly basis. Both annual and seasonal results are presented in each section. It is noteworthy that baseflow data from the winter season cannot be considered as reliable as for other seasons, since rivers can be covered by ice and gages can be jammed between ice blocks, therefore biasing data. For this reason, winter minimum values for baseflow were not estimated. On the other hand, water levels in monitoring wells can provide reliable results throughout the year because groundwater usually does not freeze, being typically at 7˚C year round.

Most groundwater level series show significant trends (around 80%), whereas most baseflow series do not (only 2 to 35% show significant trends). Percentages found for baseflows are within the range of those found for streamflow in other studies presented in the Introduction. Both upward and downward significant trends can be observed across Canada for all studied parameters and their location is very variable according to the series length and considered period.

3.1 Mean values

Baseflow

Significant upward trends for annual baseflow can be observed in British Columbia and in Ontario for 30-year series, above the 55˚N latitude for 40-year series, and mainly in the southern part of Ontario for 50-year series (Figure 1). Decreasing trends are mainly present in the eastern part of Canada for 30-year series and distributed across the country below the 55˚N latitude for 40 and 50-year series (except for the southern part of Ontario). Table 1 shows that the percentage of stations showing a downward trend is higher for all series length. The median upward slope values for 30-, 40- and 50-year series are, respectively, 0.29, 0.68, and 0.04 m^3/s. Their downward counterparts are: -0.09, -0.08, and -0.05 m^3/s. This corresponds to a variation of m times the series length, m being the Sen's slope (e.g.: 0.29*30= 8.7 m^3/s over 30 years).

In the spring, most upward trends are located in BC and downward trends in eastern Canada, although some red triangles can be observed on some BC islands. For the summer, decreasing trends are dominant across the country below the 55˚N latitude. In the fall, more downward trends are present in eastern Canada for 30-year series, but very few significant trends are available. Although not very reliable, the winter values show more increasing trends in northern BC, the territories, Ontario, and Quebec, whereas decreasing trends are mainly located in Atlantic Canada. Tables 2 to 5 present percentages of stations with significant trends.

Burn and Hag Elnur (2002) found slightly more downward trends for annual mean flow (15 *vs* 10% for 48-year series and 7 *vs* 6% for 38-year series) in agreement with this study, although the difference found here is larger. They found mainly increasing trends for the spring months, which is not the case here, except for 50-year series, but found more decreasing trends during the summer months, in agreement with this study. Yue et al. (2003) also found more stations having downward trends than upward trends (for 30- and 50-year series), although their number is quite low (12 and 9%).

Groundwater levels

Mixed trends are observed across Canada for annual and seasonal values, except for the Maritimes provinces, where decreasing trends tend to be dominant (see for instance Figure 2). Table 1 reveals that the number of upward trend is slightly higher. This could seem in contradiction with baseflow results. However, most monitoring wells are located in areas where no RHBN stations are available, i.e. in the southern part of the Prairies. Where both kinds of stations are available (i.e. in BC, PEI, and NS), results are in relatively good agreement. Downward trends for 30- and 40-year series have median annual values (magnitude) of -0.034 m and -0.037 m (e.g.: -0.034*30=-1.0 m over 30 years). These declines are therefore modest, but magnitudes over -0.1 m (corresponding to 4 m and more over 40 years) represent 4% of the trend results for 30-year records and 12% for 40-year records. Median upward trends are 0.025 m and 0.025 m respectively.

3.2 Minimum values of baseflows

Minimum (7-day low-flow) values usually show the highest number of significant trends, as in the study of Yue et al. (2003). Downward trends appear to be a little more present for annual values across the country below the 55˚N latitude, especially for 40- and 50-year series in eastern and western Canada. Several increasing trends can be observed above this latitude in BC and in the territories. Table 1 confirms that the three series length have more decreasing trends.

In the spring, few significant trends are present, but stations above the 55˚N latitude show more increasing trends for 40-year series. For the summer period, considerably more downward trends can be observed: the Atlantic provinces show only decreasing trends and this is also the case for BC for 40- and 50-year series, and for ON and QC for 40-year series. In the fall, downward trends are mainly present in the southern part of BC, ON, QC, and the Atlantic provinces with the exception of PEI, which does not show any significant trend. However, a few increasing trends can be observed near Toronto for the 50-year series.

Yue et al. (2003) found more decreasing trends for annual values over 30-years in agreement with this study, but equal over 40-years and fewer over 50-year. They also observed many increasing trends in the northern part of BC and the territories. However, it is not clear if they used the minimum daily flow or the 7-day low flow. Ehsanzadeh and Adamowski (2007) found significantly higher numbers of downward trends for 40, 60, and 80-year series, with downward trends dominating the Maritimes provinces and southern BC, in agreement with results of this study.

3.3 Maximum values of baseflows

30-year series have very few significant trends and they appear to be mixed for maximum annual values when mapped. However, 40- and 50-year series have a marked dominancy of decreasing trends throughout the country (mainly below the 55˚N latitude). The same is true for the spring and summer seasons. Few significant trends are found in the fall and winter is characterized by more increasing trends, mainly located in the territories and ON. The latter could be the result of milder weather conditions.

In agreement with our results, Burn and Hag Elnur (2002) and Yue et al. (2003) found more streamflow stations having decreasing trends.

3.4 Field significance

A bootstrap technique with preservation of the cross-correlation provided the field significance of upward and

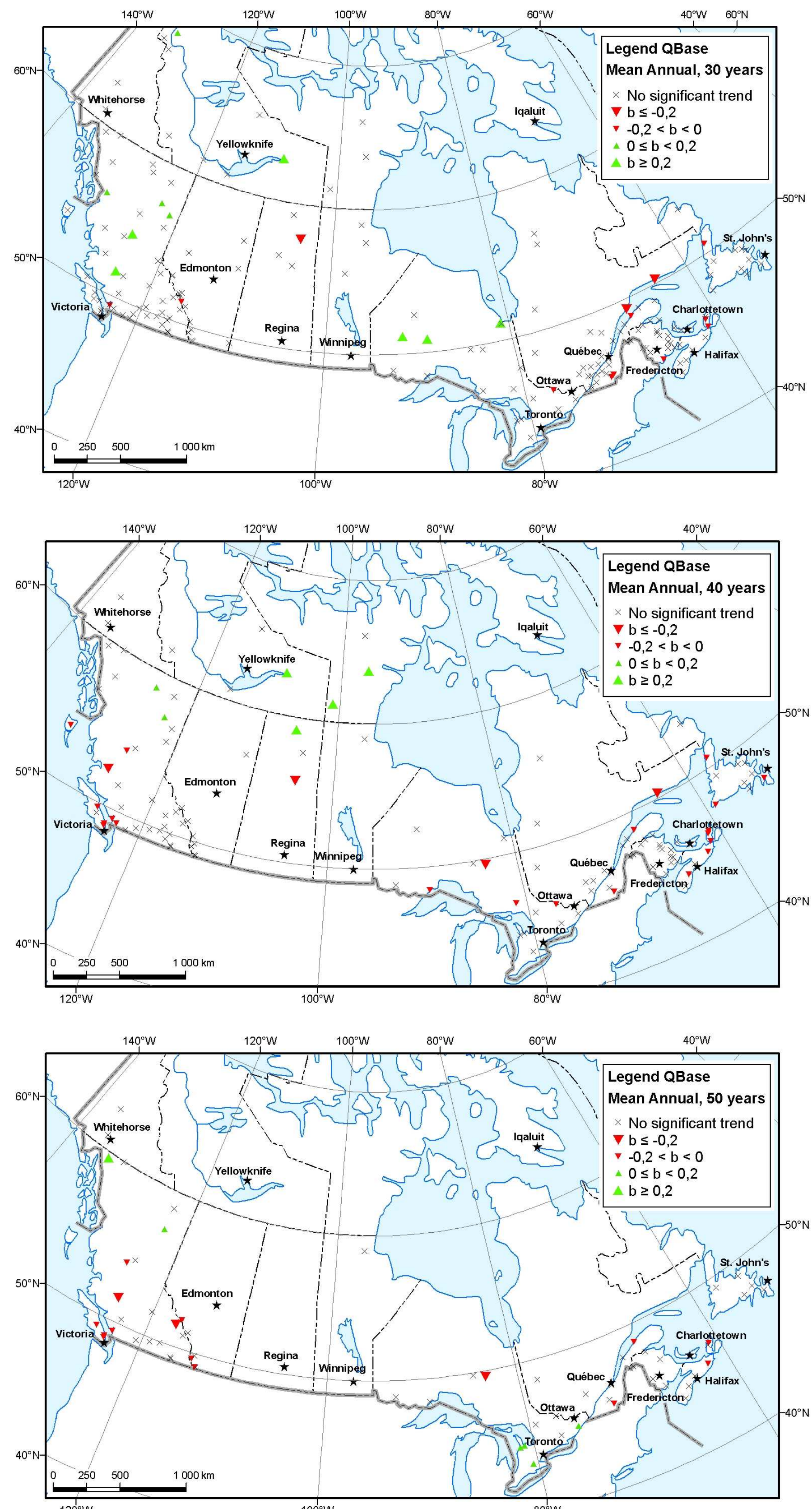

Figure 1 : Trends for annual mean baseflow for 30-, 40-, and 50-year series

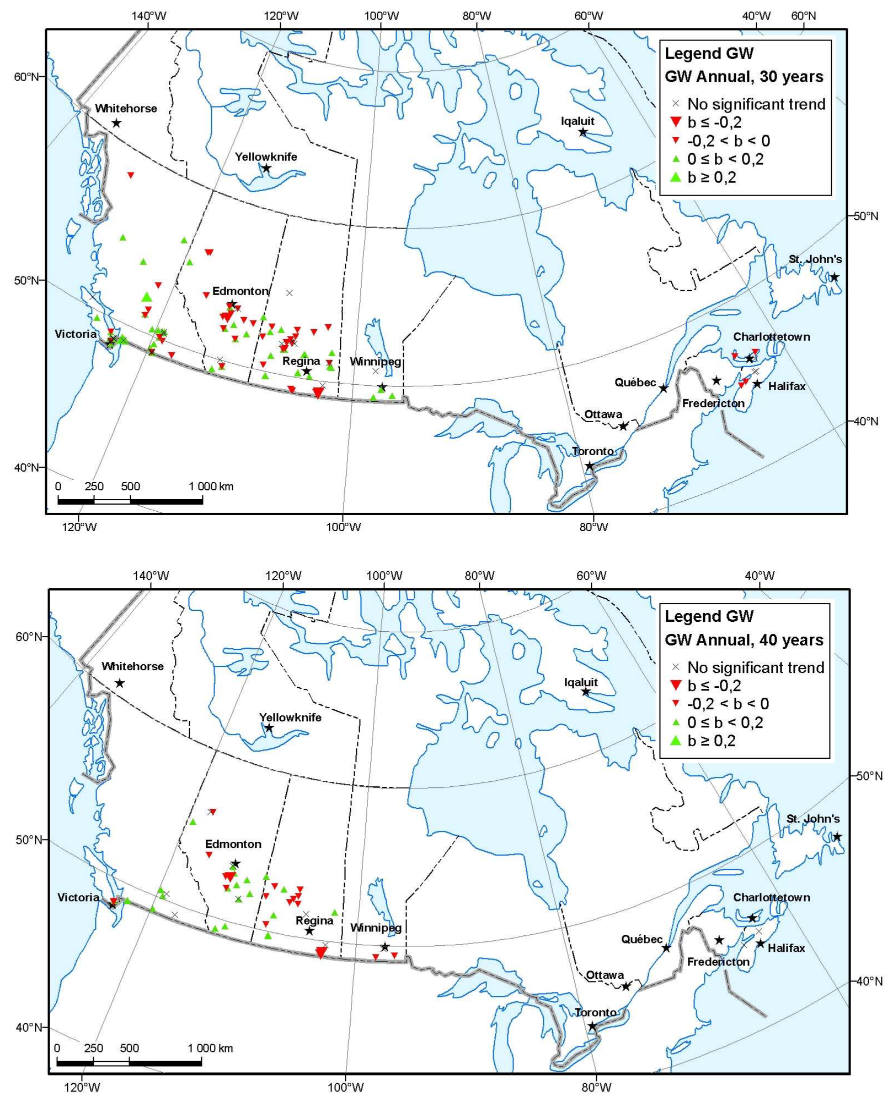

Figure 2 : Trends for annual mean groundwater levels for 30- and 40-year series

Table 1 : Percentages of stations with significant upward and downward trends for annual values

Variable	30 years (1976-2005)			40 years (1966-2005)			50 years (1956-2005)		
	No sites	Up	Down	No sites	Up	Down	No sites	Up	Down
Baseflows									
Minimum	195	12.5%	20.5%	126	11.9%	31.0%	67	19.4%	28.4%
Mean	177	5.6%	7.3%	117	5.1%	20.5%	65	9.2%	23.1%
Maximum	207	5.8%	2.4%	127	1.6%	27.6%	69	1.4%	26.1%
Groundwater levels									
Mean	138	47.1%	34.8%	53	43.4%	37.7%	-	-	-

Table 2 : Percentages of stations with significant upward and downward trends for spring values

Variable	30 years (1976-2005)			40 years (1966-2005)			50 years (1956-2005)		
	No sites	Up	Down	No sites	Up	Down	No sites	Up	Down
Baseflows									
Minimum	195	12.0%	5.0%	126	9.5%	10.3%	67	20.9%	7.5%
Mean	177	5.1%	5.6%	117	6.8%	10.3%	65	13.8%	7.7%
Maximum	207	4.3%	6.3%	127	2.4%	22.0%	69	4.3%	11.6%
Groundwater levels									
Mean	138	43.5%	50.0%	53	39.6%	39.6%	-	-	-

Table 3 : Percentages of stations with significant upward and downward trends for summer values

Variable	30 years (1976-2005)			40 years (1966-2005)			50 years (1956-2005)		
	No sites	Up	Down	No sites	Up	Down	No sites	Up	Down
Baseflows									
Minimum	195	8.5%	21.0%	126	4.0%	27.8%	67	7.5%	22.4%
Mean	177	4.5%	10.7%	117	4.3%	27.4%	65	4.6%	24.6%
Maximum	207	7.2%	10.6%	127	3.9%	32.3%	69	4.3%	34.8%
Groundwater levels									
Mean	138	42.8%	33.3%	53	43.4%	39.6%	-	-	-

Table 4 : Percentages of stations with significant upward and downward trends for fall values

Variable	30 years (1976-2005)			40 years (1966-2005)			50 years (1956-2005)		
	No sites	Up	Down	No sites	Up	Down	No sites	Up	Down
Baseflows									
Minimum	195	10.0%	24.5%	126	6.3%	25.4%	67	10.4%	32.8%
Mean	177	4.5%	6.2%	117	2.6%	4.3%	65	9.2%	6.2%
Maximum	207	9.2%	4.3%	127	3.9%	5.5%	69	7.2%	4.3%
Groundwater levels									
Mean	138	50.7%	28.3%	53	41.5%	35.8%	-	-	-

Table 5 : Percentages of stations with significant upward and downward trends for winter values

Variable	30 years (1976-2005)			40 years (1966-2005)			50 years (1956-2005)		
	No sites	Up	Down	No sites	Up	Down	No sites	Up	Down
Baseflows									
Minimum	-	-	-	-	-	-	-	-	-
Mean	177	13.6%	7.3%	117	10.3%	7.7%	65	16.9%	12.3%
Maximum	207	10.1%	8.2%	127	8.7%	4.7%	69	30.4%	5.8%
Groundwater levels									
Mean	138	43.5%	32.6%	53	41.5%	39.6%	-	-	-

downward trends over the network for each variable. Only results for annual values are provided in Table 6 due to limited space. Field significance with a value of 10% or less are shown in bold over a yellow background. Tables (for annual and seasonal values) reveal that all groundwater level results are field significant (as the percentage of stations is large, see Tables 1 to 5), whereas only 38% of the baseflow results show field significance. However, downward trends for 40- and 50-year baseflow series appear to be strongly field significant (17/28=71%), especially for annual values and the summer period, and field significance is also manifest for upward and downward trends for minimum values of all series length (15/24=62.5%).

Yue et al. (2003) found field significance at the 10% level for downward trends for minimum and maximum annual values for the 1967-1996 period. Burn and Hag Elnur (2002) concluded that "a greater number of trends are observed than are expected to occur by chance", but numbers are not provided.

Table 6 : Field significance assessment results obtained with the bootstrap test – annual values

Variable	30 years (1976-2005)		40 years (1966-2005)		50 years (1956-2005)	
	Up	Down	Up	Down	Up	Down
Baseflow						
Minimum	**0.05**	**0.01**	**0.07**	**0.00**	**0.02**	**0.00**
Mean	0.31	0.21	0.34	**0.02**	0.14	**0.02**
Maximum	0.36	0.22	0.23	**0.00**	0.28	**0.00**
Groundwater levels						
Mean	**0.00**	**0.00**	**0.00**	**0.00**	-	-

4 DISCUSSION AND CONCLUSION

The Mann-Kendall test was applied with a pre-processing procedure to historical series of baseflow and groundwater levels of 30-, 40, and 50-years. Field significance of both upward and downward trends was assessed using a bootstrap technique. Results show mostly mixed trends across Canada for all variables and results can vary significantly with the record length and type of data used (baseflows or groundwater levels).

These results suggest that there are no major concerns for water decline in Canada, at least at the national scale, although impacts may occur at local scales. However, as underlined by Valeo et al. (2008), statistical tests heavily depend on the series length. It could be added that these tests are also highly dependent on the period covered and the data used. For these reasons, the interpretation and description of the results are not easy.

On average, about 80% of the groundwater level series results show a significant trend, with a slightly larger number of stations showing an increasing trend. However, these series are not well distributed across the country, mainly due to the limited number of wells having long records. Baseflow series, which have a better spatial distribution, have fewer significant trends (between 2 and 35%, the number generally increasing with the series length), and they show more decreasing trends. Most wells are located in areas where very few RHBN stations are available. All groundwater level results show field significance at the 10% level, whereas only minimum values and downward trends for 40- and 50-year series show evidence of field significance for baseflow series.

BC and the Maritimes provinces often appear to behave distinctly from the rest of the country, but this might be due, at least in part, to a larger concentration of stations. Summer values tend to have much more decreasing trends, maybe due to the fact that increasing temperature and evapotranspiration have more impact than in other seasons.

Trend results obtained with baseflow in this study are in general agreement with results from Ehsanzadeh and Adamowski (2007), Yue et al. (2003), and Burn and Hag Elnur (2002). Discrepancies reported in section 3 can be explained in part by 1) the different, although strongly related, studied parameters (streamflow versus baseflow), 2) the type of hydrograph separation methods used to obtain baseflow, and 3) the different periods used by the other studies (different by almost 10 years). It is also believed that part of the explanation can be attributed to the database itself, i.e. if data gaps were filled and how they were filled.

The different direction of trends depends both on direct human impacts (water withdrawal, irrigation, land use changes, etc.) and climate change. RHBN stations and provincial monitoring stations were used to study statistical trends, but these stations could nevertheless be influenced by anthropogenic activities. The study of land use changes and pumping history at each station over the last 50 years was beyond the scope of this paper. Causes of the observed trends will be investigated more in details in the near future.

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