Water Yield and Streamflow Trend Analysis for Alberta Watersheds

by Stefan W. Kienzle, University of Lethbridge

Introduction and Brief Background on Water Resources in Alberta

Alberta is a province with a very diverse climate. The consequence is that some watersheds capture large amounts of water for downstream users, while other watersheds capture almost no water. When we add to Alberta's natural diversity of water availability the population distribution, where most Albertans live in the southern third of the province, and water intensive industries, such as irrigated agriculture in the prairies or the oil sands industry around Fort McMurray, the question arises if there is enough water for every user. When we further add the uncertainties that are associated with climate change, it is clear that an inventory of current water resources is the first step towards prudent water resources management.

The sustainability and wealth of Alberta is closely linked to the quantity and quality of its water resources. Five water users - the water requirements by the aquatic habitat, as well as domestic, industrial, agricultural, and recreational demands – rely on sustainable water resources.

Climate change impacts in Alberta are not evenly distributed. The higher the air temperature, the more water is evaporated and less water runs off as streamflow. The largest temperature increases have been observed in the northern parts of the province (Schindler and Donahue, 2006). Median predicted temperature changes across Alberta, relative to the 1961-1990 climate normals, range from approximately 1°C during 2010-2039, to 2-4°C during 2040-2069, to 4-6°C during 2070-2099 (Sauchyn et al., 2008). The largest temperature increases are forecast to occur in Alberta's north-east, while the south-west will exhibit the smallest air temperature increases. Summer temperatures have been fairly unaffected over the 20th century, whereas winter and spring temperatures, especially minimum temperatures, have increased (Akinremi et al., 1999; Cayan et al., 2001).

The question remains as to what extent future changes in precipitation patterns and magnitudes will counteract additional future evapotranspirational losses? The observed declining streamflow in several prairie rivers, such as the Bow, Oldman and Milk, is partly due to reduced winter snowfall in the second half if the 20th century (Akinremi et al., 1999). During warmer winters, more precipitation falls as rain, which shortens the snowfall season, lessens the time for snowfall to accumulate (Cutforth et al., 1999; Leung et al., 2004; Lapp et al., 2005; Mote et al., 2005; Regonda et al., 2005; Knowles et al., 2006), and reduces the spring freshet. This will also result in an earlier spring melt runoff, and, in non-glaciated watersheds, a subsequent longer streamflow recession time during the remainder of the year. For many rivers, this will result in a lowering of late summer and fall streamflows. This put additional stress to the aquatic ecosystem as well as all water users who want to withdraw water from a river.

Along the continental divide, many glaciers contribute significant amounts of melt water to rivers, especially under climate warming conditions. For example, glaciers within the Cline River watershed, the main headwaters of the North Saskatchewan River watershed, contributed an average of 8% of the mean annual streamflow (1961-1990), with a maximum streamflow contribution of 29% (Nemeth et al., 2010). As the Cline River watershed produces approximately 40% of the streamflow that flows through Edmonton, glacier melt contributes an average of 3.2% and as much as 11.6% of the North Saskatchewan River flow at Edmonton. The IPCC Fourth Assessment Report (IPCC, 2007) has provided clear evidence that there is increased runoff and earlier spring peak discharge in many glacier and snow-fed rivers as a result of climate change. This increased runoff from glacier melt can only be short term, because the shrinking glacier area and declining glacier volume will eventually limit the amount of melt water produced, even if climate changes sustain greater melt per unit area (Moore & Demuth 2001). In general, basins with significant, but rapidly declining, glacier cover have exhibited a strong decreasing trend in glacier melt contributions (Demuth & Pietroniro, 2003), to the extent that many glaciers have already passed the period of maximum glacier melt volumes. Due to the timing of glacier melt, which on the eastern slopes of the Alberta Rocky Mountains peaks in July, August and September, declining glacier melt contributions to streamflow will result in a decline in summer and fall streamflows.

According to IPCC (2007), the combined consequences of increased future air temperatures and precipitation amounts (mainly lower in the southern parts, mainly higher in the west-central and northern parts) will result in a decline of streamflow in southern Alberta and an increase in streamflow in northern Alberta during the next 100 years (Sauchyn et al., 2008). Global Climate Models (GCMs) have a spatial resolution of approximately 200 by 200 km to 400 by 400 kms, or coarser. Because of this low spatial resolution it is uncertain where the transition between watersheds with increasing or decreasing streamflow will occur. Using the observed records of streamflow, a number of recent studies investigated the detection and projection of streamflow trends in Alberta and western Canada (i.e. Rood et al., 2005; Schindler and Donahue, 2006; Rood et al., 2008). The conclusion of this latter research is that the Prairie region in southern Alberta is expected to face serious water resources stresses due to global warming.

Objectives

As the watershed is the natural hydrological unit within which all hydrological inputs and outputs occur – with the possible exception of groundwater in- and outflows -, the spatial units for the water yield and trend analyses are Alberta watersheds with complete or almost complete streamflow records for the period 1971-2000. The objectives were to compile and analyse these streamflow records for both magnitude and significance levels of possible trends, using the Mann-Kendall non-parametric test. The following variables will be computed:

- water yield in m^3 km^2 $year^{-1}$
- water yield in percent of major watershed
- streamflow trends for
    - annual mean flow
    - annual minimum flow

- annual maximum flow
- winter flow (December, January, February - DJF)
- spring flow (March, April, May - MAM)
- summer flow (June, July, August - JJA)
- fall flow (September, October, November - SON).

The major watersheds considered in this study are (from South to North):

- Milk
- Seven Persons Creek
- Lodge Battle Creek
- Bigstick Lake
- Oldman
- Bow
- Red Deer
- Sounding Creek
- Battle
- North Saskatchewan
- Churchill
- Athabasca
- Peace
- Hay
- Slave

All results will be displayed in Table form, as well as maps to reveal spatial patterns across Alberta.

Methods

As the recorded streamflow time series combines all hydrological processes and reacts to the integrated changes of the hydro-climatological changes within the associated watershed – climate and land cover changes, as well as abstractions (Burn, 1994; Burn and Hag Elnur, 2002; Dėry and Wood, 2005; Regonda et al., 2005; Rood et al., 2005) - the analysis of possible streamflow trends can reveal recent observed changes in watershed behaviour. This is particularly meaningful for those regions which inhibit a historically extremely sparse meteorological monitoring, such as the eastern slopes of the Rocky Mountains, which also produce the largest amounts of streamflow in Alberta. We compiled the streamflow records for Alberta's unregulated rivers from the Water Survey of Canada (HYDAT, http://www.wsc.ec.gc.ca/) database. In addition, a naturalized streamflow database for selected regulated rivers was provided by Alberta Environment for the time period 1912-2001(Seneka, 2004), which included the in-filling of data gaps and the correction of streamflow due to human impacts, e.g. water abstractions and reservoirs.

Water Yield

The water yields for each gauging station could then be related to the watershed within which the water yield was produced. When the watersheds were nested, i.e. where one watershed flows into another one in a cascading pattern, the upstream watershed area and the associated water yield need to be

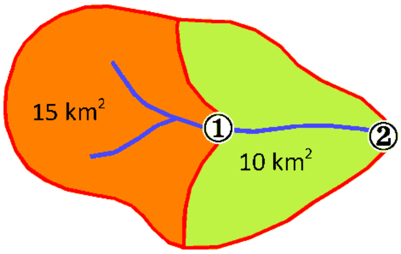

Figure 1: A nested watershed.

subtracted from the watershed under consideration. For example, the watershed associated with Gauging Station 1 (orange in Figure 1) has a nested area of 15 km^2 and a gross area of also 15 km^2 (they are the same, as no further upstream watershed exists). The watershed associated with Gauging Station 2 has a reported gross area of 25 km^2 (green + orange), but a nested area of only 10 km^2 (green). The specific water yield was calculated by dividing the mean annual volume of streamflow produced in a nested watershed (in m^3/year) by the nested watershed area (in km^2).

Trend Analyses

The rank-based non-parametric Mann–Kendall statistical test (Mann, 1945; Kendall, 1975; Helsel and Hirsch, 1992) has been frequently used to qualify the significance of trends in hydro-meteorological time series such as water quality, streamflow, temperature, and precipitation (e.g. Steele et al., 1974; Hirsch et al., 1982; Crawford et al., 1983; Cailas et al., 1986; Hipel et al., 1988; Taylor and Loftis, 1989; McLeod et al., 1991; Chiew and McMahon, 1993; Burn, 1994; Lettenmaier et al., 1994; Gan, 1998; Yulianti and Burn, 1998; Lins and Slack, 1999; Douglas et al., 2000; Zhang et al. 2001; Yue et al., 2002; Rood et al., 2008) . The application of a non-parametric, rank-based trend analysis procedure is particularly advantageous for time series which are not normally distributed and which may include data gaps, such as many streamflow time series.

The period 1971-2000 was chosen for the trend analysis, as it represents the latest available 30-year period for the determination of climate normals, or climate averages, which are used by the World Meteorological Organization (WMO) to represent the average hydro-meteorological behaviour of a region. The period 1961-1990 is used for many climate impacts assessments as the baseline period, which does not yet exhibit a significant climate warming signal. As different time periods would result in different trends, both in significance level and magnitude, there is controversy as to which time period would be the most meaningful for future predictions.

As a detected trend can change by just adding or subtracting a particular year, trend analysis of a system underlying a variety of changes (such as a watershed) can only be representing a selected time slot. This is further complicated by a number of multi-year cycles, such as the Pacific Decadal Oscillation (PDO), which is known to impact southern Alberta, and the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO), which are known to influence the climate in northern Alberta. The PDO has an approximately 60-year cycle, and has recently reversed its direction, which means that we are at the beginning of an approximately 30-year period of higher precipitation. Higher precipitation can, to some extent or entirely, be balanced by higher future temperatures, which result in more water evaporation into the atmosphere. Only detailed hydrological simulations, such as a recently completed study on the upper North Saskatchewan River watershed (Nemeth et al., 2010), can predict future behaviour within the range of output of available global climate change models.

One has to bear in mind that the detection of a statistically significant trend does not necessarily imply a trend of practical significance, and vice versa (Yue et al., 2002). For example, a highly significant negative trend of 0.1% change per year may be negligible for the users in the relevant watershed, but a low significant (e.g. 80% confidence level) negative trend of 2% per year may have large practical implications within 10 or 20 years. Therefore, the magnitudes of possible streamflow trends also need to be reported.

Results and Discussion

Water Yield

A total of 287 watersheds were analyzed for water yield. The water yields vary from negative values in 12 prairie watersheds, where more water enters the watershed than is flowing out (this is possible due to evaporation losses within the watershed), to values of over half a million m^3 per km^2 per year in 21 high altitude Rocky Mountain watersheds (Fig. 2). The water yield can also be expressed in mm, as both precipitation and evaporation are typically expressed in mm. For example, a watershed with 1000 mm annual precipitation, and an annual 40%, i.e. 400mm, water loss due to evaporation, would have a water yield of 600 mm per year.

Table 1: Summary of water yield analysis based on 287 watersheds

Watershed Statistic	Water Yield in m^3 km^{-2} $year^{-1}$	Water Yield in mm	Number of watersheds
Average	137,000	137	-
Minimum	-35,000	-35	-
Maximum	1,084,000	1084	-
Median	64,000	64	-
Low yield	>25,000	>25	83
Medium yield	25,000 – 300,000	25 - 300	164
High yield	>300,000	>300	40

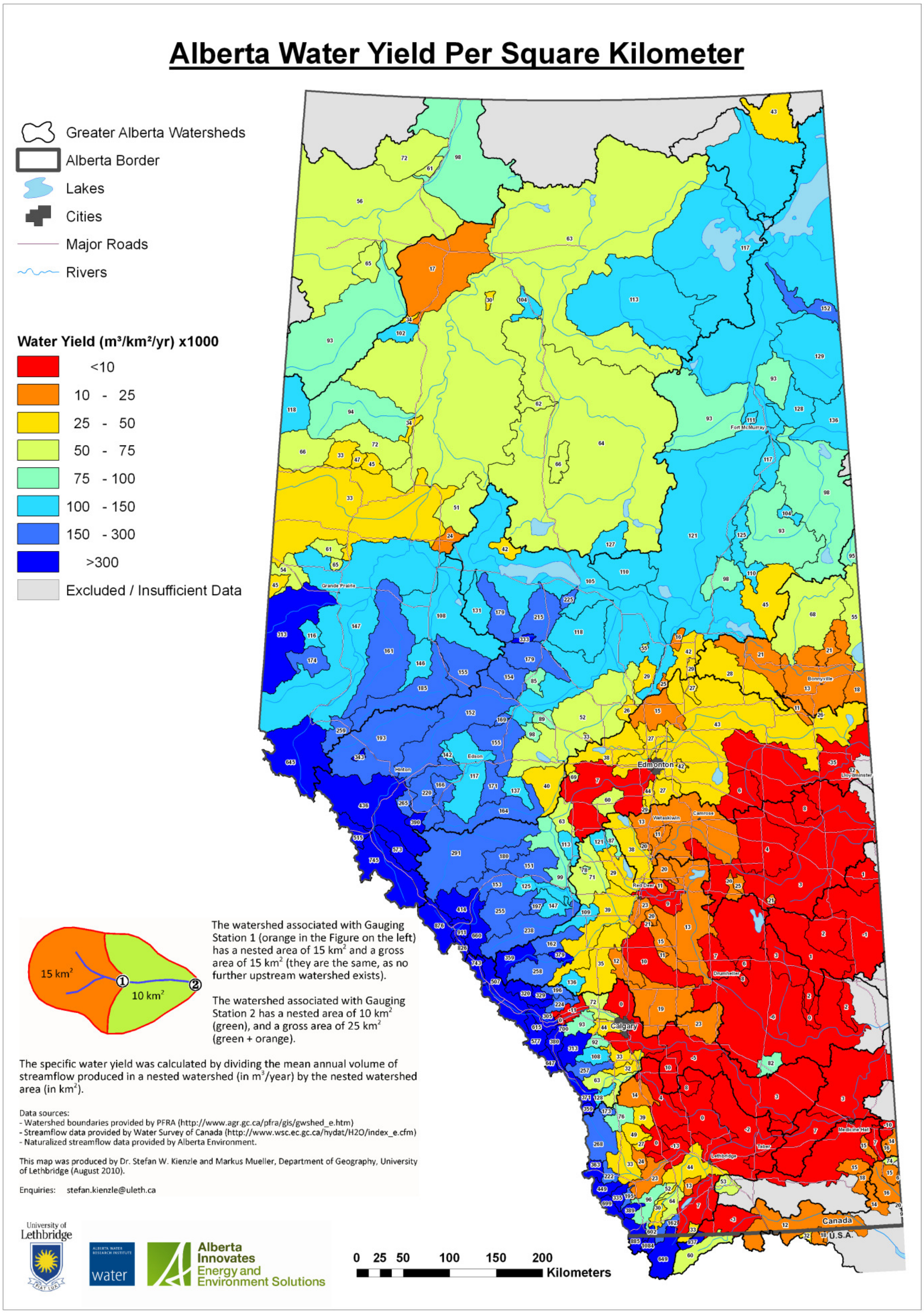

Fig. 2: Water Yield Map for Alberta

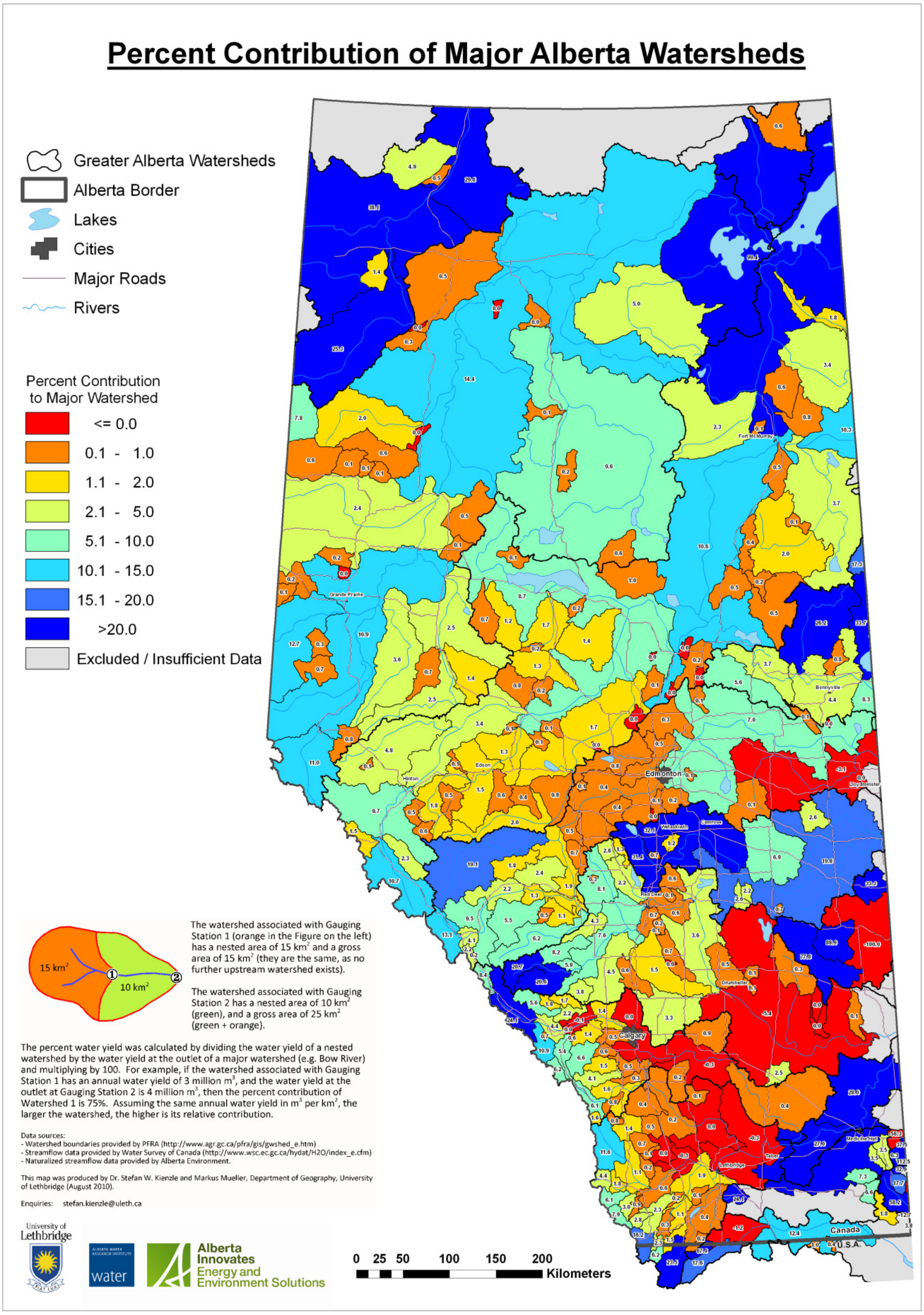

Fig. 3: Percent contribution of sub-watersheds to major Alberta watersheds

The water yield has a distinct spatial distribution, with three major areas (Fig. 1). The highest yields (over 300,000 m^3 km^{-2} $year^{-1}$, dark blue in the map) are produced in the Rocky Mountains. Within the Rocky Mountains, Alberta's south-west corner has the highest yields (also including the St. Mary's watershed, which has its headwaters and highest yields in Montana of 640,000 m^3 km^{-2} $year^{-1}$). These high-yielding watersheds produce, on average, over half a million m^3 km^{-2} $year^{-1}$. The lowest water yields are produced in the prairies, where the combined effects of low annual precipitation and high evaporation losses result in very low (under 25,000 m^3 km^{-2} $year^{-1}$), and occasionally negative, water yields, averaging just under 10,000 m^3 km^{-2} $year^{-1}$. The third region is the in-between region found mainly in central and northern Alberta (as well as between the high-yield and low-yield regions). Here, water yields range from 25,000-300,000 m^3 km^{-2} $year^{-1}$, with an average of just over 100,000 m^3 km^{-2} $year^{-1}$.

A second map (Fig. 3) shows what proportion within each of the major watersheds is produced where. This map is useful for water managers, as it provides insight into which are the most water producing watersheds. The reader must bear in mind that the percentage (colour) is dependent on the size of the watershed. For example, where two neighbouring watersheds have the same water yield per km^2, the larger watershed would have a higher proportion of water contribution. For example, during 1971 - 2000, almost 33% of all water flowing out of the Bow River at the confluence with the Oldman River is produced by two small sub-watersheds upstream of Banff, while another approximately 45% is produced in the other Rocky Mountain and adjacent foothill sub-watersheds. The entire lower half of the Bow River watersheds produces only, on average, 3% of the streamflow.

Streamflow Trends

<u>The influence of the chosen time period on streamflow trends</u>

In order to allow the most detailed analysis possible for Alberta, the trend analysis was based on a 30-year time period (1971-2000). In order to investigate if the 1971-2000 period results in different trends than other time periods, the 1971-2000 trends were compared to trends covering the periods 1912-2001, 1951-1980, 1961-1990, and 1970-2008. Minimum, maximum, mean, and seasonal flow trends were compared. A few stations were chosen for which it is important to know how much the 1971-2000 period trend differs from all other trends, in particular the long-term trends (Table 2).

Table 2: Comparison for trend differences between the 1971-2000 streamflow trends and other time periods.

Gauging Station	**Compared to the other trend periods, the 1971-2000 period trends were:**
St. Mary River at the International Boundary:	in good agreement with the 1912-2001 trends in both direction and magnitude, and never the strongest or weakest trend.
Oldman River near Lethbridge	the lowest negative trends in maximum, spring and summer

	flows, and the highest positive trend in mean annual flow.
Red Deer River at Drumheller	the lowest negative trends for maximum, mean and summer trends. Only minimum flow showed the most negative trends in 1971-2000.
Bow River at Banff:	the only positive mean annual trend, otherwise never the strongest or weakest trend.
Bow River at Calgary:	generally, in agreement with most other trends, with a tendency to be rather too positive. The further back the other trend periods were in time, the more negative the trends became.
North Saskatchewan River at Edmonton	the least negative for maximum, mean and summer trends
Athabasca River below Fort McMurray	not very different when compared to the 1957-2008 and 1970-2008 trends (no flow data before 1957 were available).

From the trend comparison analysis it can be concluded that the application of the 1971-2000 period for trend analysis does not generally result in extremely negative trends, and rarely results in the highest positive trend. In the contrary, and especially in southern Alberta, the use of the 1971-2000 period results in rather too positive trends, especially when compared to longer time periods. Therefore, using the 1971-2000 trends can be interpreted as resulting in either average or under-estimating trends. Therefore, reported trends are more likely to be more negative than the long-term trends.

<u>1971-2000 Trend Analysis</u>

Out of 102 watersheds for which trend analyses could be carried out, 60 had negative trends in mean annual streamflow. 14 watersheds had a negative streamflow of over 1% per year, which means that after 10 years, over 10% less streamflow would be available if the detected trends were to continue.

Altogether, seven maps were produced that show the trends, however, only the mean annual trend map is included here.

Mean Annual Flow

The mean annual flow is declining in southern Alberta (Oldman, Milk, lower Bow) as well as northern Alberta (lower North Saskatchewan, Athabasca, Peace) and increasing in western-central Alberta (upper Bow, Red Deer, upper North Saskatchewan)(Fig. 4). However, the only watersheds that exhibit highly significant trends are the Athabasca and the Churchill Rivers, both with the strongest negative trends, and the central Peace River.

Minimum Annual Flow

As minimum flows are more sensitive to environmental changes, the trends are stronger in magnitude (both negative and positive trends). The spatial pattern across Alberta is not as clear as the mean annual trends, with many major watersheds having both strong positive and strong negative trends, most of which are also highly significant. Again, the Athabasca and Churchill Rivers stand out as rivers which have strong negative trends.

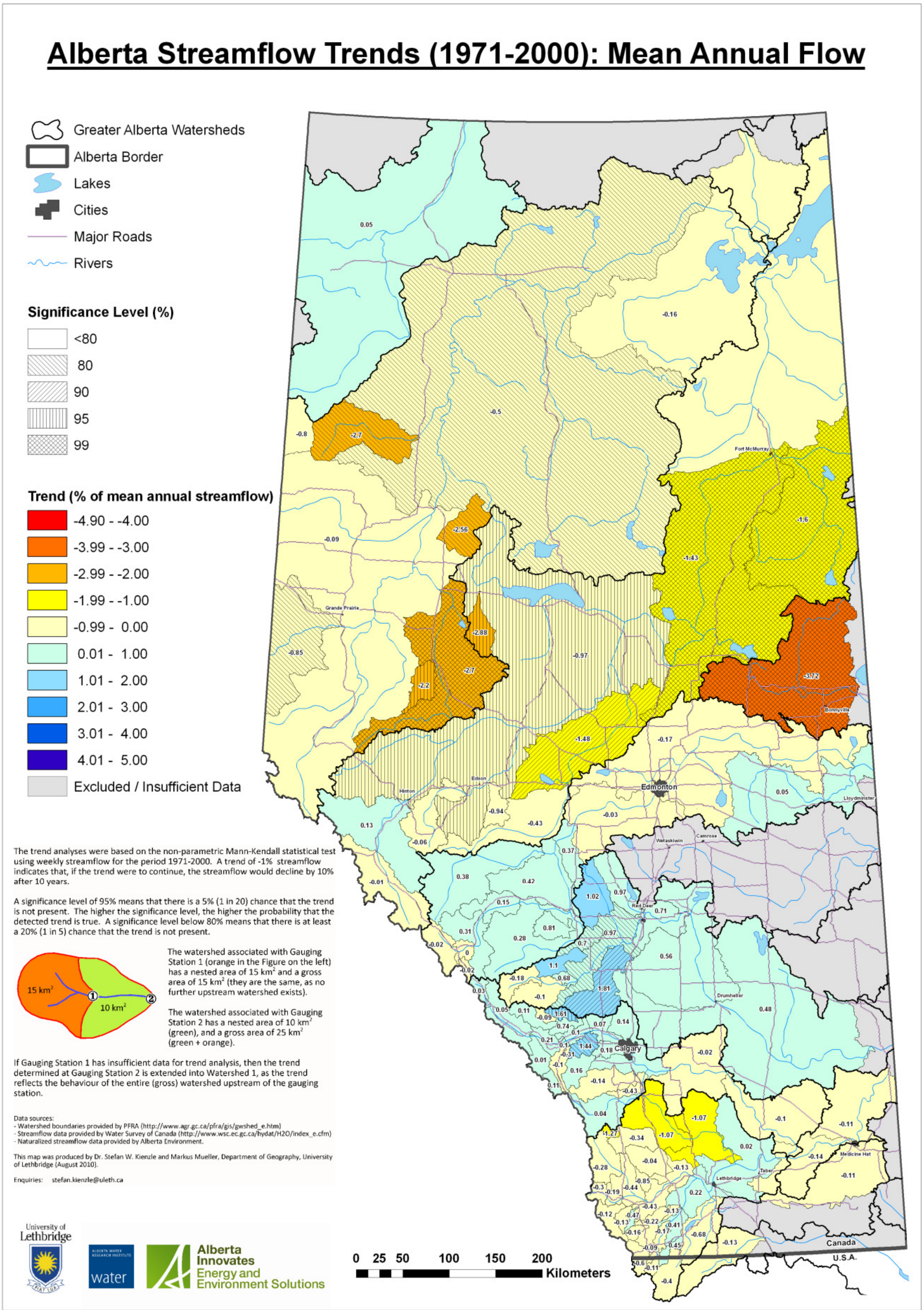

Fig. 4: Mean annual streamflow trends (1971-2000) for Alberta watersheds

Maximum Annual Flow

The spatial pattern of the maximum annual flow is quite similar to the mean annual flow, with the Red Deer River having the strongest increase in maximum flows. However, with the exception of the Peace River and the Churchill River, most maximum annual flow trends are not significant.

Winter Flow

With few exceptions, such as large parts of the Athabasca River and the Churchill River, winter flows are increasing. This can be explained by the recent increase in rainfall during winter, which is not stored, such as snow, and can run off to become streamflow.

Spring Flow

Spring flows are declining in southern Alberta, with the exception of the St. Mary watershed, which contributes about one quarter of the streamflow in the Oldman River watershed. Some headwaters in the Bow, as well as the upper North Saskatchewan River and most of the Peace River show an increase in spring streamflow. The Athabasca River and the Churchill River show a strong decline in spring streamflows.

Summer Flow

The spatial pattern across Alberta of summer flows is quite similar to the mean annual flow. Central Alberta exhibits increasing flows (central Bow, Red Deer, North Saskatchewan, upper Athabasca), while the rest is showing declining trends. Other than in some northern watersheds, most trends have a significance level of under 80%.

Fall Flows

With few exceptions, the fall streamflow trends are quite similar to the summer streamflow trends.

Acknowledgments

This research was funded by the AWRI fund # 43471. Naturalized and void-filled stream flow data were provided by Alberta Environment, with the assistance of Michael Seneka.

References:

Barnett, T.P., Adam, J.C., Lettenmaier, D.P. (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303–309.

Burn, D.H. (1994) Hydrologic effects of climatic change in West Central Canada. J. Hydrol. 160 (1994), pp. 53–70.

Burn, D.H., Hag Elnur, M.A. (2002) Detection of hydrologic trends and variability. Journal of Hydrology 255, 107–122.

Cailas, M.D., Cavadias, G., Gehr, R. (1986) Application of a nonparametric approach for monitoring and detecting trends in water quality data of the St. Lawrence River. Can. Water Poll. Res. J. 21 2 (1986), pp. 153–167.

Chiew, F.H.S., McMahon, T.A. (1993) Detection of trend or change in annual flow of Australian rivers. Int. J. Clim. 13 (1993), pp. 643–653.

Crawford, C.G., Slack, J.R., Hirsch, R.M. (1983) Nonparametric tests for trend in water quality data using the statistical analysis system. Open Report no. 83-550, US Geological Survey, USA.

Cutforth, H.W., McConkey, B.G., Woodvine, R.J., Smith, D.G., Jefferson, P.G., Akinremi, O.O. (1999) Climate change in the semi-arid prairie of south-western Saskatchewan: late winter-early spring. Canadian Journal of Plant Science 79, 343–350.

Douglas, E.M., Vogel, R.M., Knoll, C.N. (2000) Trends in flood and low flows in the United States: impact of spatial correlation. J. Hydrol. 240 (2000), pp. 90–105.

Gan, T.Y. (1998) Hydroclimatic trends and possible climatic warming in the Canadian Prairies. Water Resour. Res. 34 (11), pp. 3009–3015.

Hipel, K.W., McLeod A.I. (1994) Time series modelling of water resources and environmental systems. Developments in Water Science Vol. 45, Elsevier, Amsterdam.

Hipel, K.W., McLeod, A.I., Weiler R.R. (1988) Data analysis of water quality time series in Lake Erie. Water Resour. Bull. 24 (3), pp. 533–544.

Hirsch, R.M., Slack J.R., Smith R.A. (1982) Techniques of trend analysis for monthly water quality data. Water Resour. Res. 18 1 (1982), pp. 107–121.

Hirsch R.M., Slack, J.R. (1984) Non-parametric trend test for seasonal data with serial dependence. Water Resour. Res. 20 6 (1984), pp. 727–732.

Kendall, M.G. (1975) Rank Correlation Methods, Griffin, London.

Knowles, N., Dettinger, M.D., Cayan, D.R. (2006) Trends in snowfall versus rainfall in the western United States. Journal of Climate 19, 4545–4559.

Lapp, S., Byrne, J., Townshend, I., Kienzle, S. (2005) Climate warming impacts on snowpack accumulation in an alpine watershed. International Journal of Climatology 25, 521–536.

Lettenmaier, D.P., Wood, E.F., Wallis J.R. (1994) Hydro-climatological trends in the continental United States, 1948–88. J. Clim. 7, pp. 586–607.

Leung, L.R., Qian, Y., Bian, X., Washington, W.M., Han, J., Roads, J.O. (2004) Mid-century ensemble regional climate change scenarios for the Western United States. Climatic Change 62, 75–113.

Lins, H.F., Slack J.R. (1999) Streamflow trends in the United States. Geophys. Res. Lett. 26 2 (1999), pp. 227–230.

Mann, H.B. (1945) Nonparametric tests against trend. Econometrica 13, pp. 245–259.

McLeod, A.I., Hipel K.W., Bodo, B.A. (1991) Trend assessment of water quality time series. Water Resour. Bull. 19, pp. 537–547.

Mote, P.W., Hamlet, A.F., Clark, M.P., Lettenmaier, D.P. (2005) Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society 86, 39–49.

Regonda, S.K., Rajagopalan, B., Clark, M., Pitlick, J. (2005) Seasonal cycle shifts in hydro-climatology over the Western United States. Journal of Climate 18, 372–384.

Rood, S.B., Samuelson, G.M., Weber, J.K., Wyrot, K.A. (2005) Twentieth-century decline in streamflows from the hydrographic apex of North America. Journal of Hydrology 306, 215–233.

Sauchyn, D., Kulshreshtha S. (2008) Prairies. In: From Impacts to Adaptation: Canada in a Changing Climate 2007, edited by D. Lemmen et al., Government of Canada, Ottawa.

Seneka, M. (2004), Trends in historical annual flows for major rivers in Alberta, technical report, Alberta Environment, Edmonton, Canada. (Available at http://environment.gov.ab.ca/info/library/6792.pdf)

Schindler, D.W., Donahue, W.F. (2006) An impending water crisis in Canada's western prairie provinces. Proceedings of the National Academy of Sciences of the United States of America 103, 7210–7216.

Steele, T.D., Gilroy, E.J., Hawkinson, R.O. (1974) Techniques for the assessment of areal and temporal variations in streamflow quality. Open File Report, US Geological Survey, Washington, DC.

Taylor, C.H., Loftis, J.C. (1989) Testing for trend in lake and groundwater quality time series. Water Resour. Bull. 25 (4), pp. 715–726.

Yue, S., Pilon P., Cavadias, G. (2002) Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. Journal of Hydrology, Vol. 259 (1-4), 254-271, doi:10.1016/S0022-1694(01)00594-7

Yulianti, J.S., Burn, D.H. (1998) Investigating links between climatic warming and low streamflow in the Prairies Region of Canada. Can. Water Resour. J. 23 (1), pp. 45–60.

Zhang, X., Harvey, K.D., Hogg W.D., Yuzyk , T.R. (2001) Trends in Canadian streamflow. Water Resour. Res. 37 4 (2001), pp. 987–998.