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The Use of the Recession Index as an Indicator for Streamflow Recovery After a Multi-Year Drought

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Abstract. A procedure is proposed that enables the estimation of natural baseflow in a gauged watershed through analyses of recession curves and stream hydrographs. The analysis results in a surrogate for the recovery level of a watershed after a prolonged drought and allows the medium term prediction of runoff behaviour for water resources management.

The method has been applied for the Upper Battle River Watershed in the northern Prairies of Alberta, Canada. Results show that baseflow is extremely low after a multi-year drought (2001 to 2003). The recession index indicates that one year after the climatological end of the drought the integrated watershed storage that usually sustains the baseflow is abnormally low, with associated negative impacts on available water resources. This paper describes the derivation, classification and application of a watershed specific recession index. Results show that the described procedure is relatively simple, reliable and efficient.

Key words: streamflow, hydrograph, recession curve, watershed, drought, master recession curve, prediction

1. Introduction

Our society as well as our aquatic ecosystems depend profoundly on river flows, and changes in the river regime will cause concern to all water managers. The recent 2001 to 2003 drought experienced in the interior of North America, particularly in the northern Great Plains, has put water resources under significant pressure, particularly in southern Alberta, Canada. Droughts are expected to increase in frequency, severity and spatial extent due to increased evapotranspiration as a result of climate change (McBean, 2004). Gleick (1999) states that droughts are an increasing threat to water resources in many other parts of the world.

One of the watersheds hardest hit by the recent drought is the upper Battle River watershed (UBRW) in the northern prairies, located in central Alberta, Canada, south-east of the provincial capital, Edmonton. Water managers in the region question when the UBRW will recover to normal conditions, and whether normal winter and summer precipitation in the coming years will result in a recovery of streamflow levels. Most drought research is focussed on the droughts themselves, their frequency, extent and effects, but not on drought recovery. One approach to estimating the severity of a drought is based on stochastical analysis of time series of streamflow records. For example, Tarboton (1995) examined the sustained drought occurrences in southwestern USA, based on tree-ring reconstructed streamflow and subsequent risk analysis. Zelenhasic (2002) introduced a procedure to derive the n-year streamflow drought, based on the distribution of the largest streamflow drought deficit and on the composite hydrograph recession curve.

Recession analysis is a well-known tool in hydrological analysis. According to Tallaksen (1995), a key problem in recession analysis is the highly variable recession behaviour of individual river segments. She further states that the recession rate is a function of both short-term and seasonal influences, which makes the definition of a characteristic recession difficult. Vogel and Kroll (1992) report from their study in central western Massachusetts that low-flow statistics are highly correlated with the product of watershed area, average watershed slope, and the baseflow recession constant. They further state that the baseflow recession constant can be used as a surrogate for both watershed hydraulic conductivity and drainable soil porosity. Nathan and McMahon (1990) evaluated techniques for base-flow and recession analyses, and Chapman (1999) compared algorithms for streamflow recession and noted that the linear storage model can be used as a very good approximation in most cases. Mishra *et al.* (2002) assessed the low-flow characteristics for the Blue Nile River, using a conceptual non-linear storage outflow model. The principle is based on the estimates of the amount of recession flow, which is derived from recorded flow recessions.

The hydrological response of a watershed depends on many physiographical and climatic factors. They include the inputs into the system in the form of rainfall and snow and their temporal and spatial distribution over the watershed (Singh, 1997). Precipitation-runoff relationships are known to be highly non-linear in nature, and estimations of rainfall and snow accumulations for the entire watershed are difficult, particularly in larger watersheds. The main factor why the precipitation-runoff relationship is non-linear is the fact that antecedent soil moisture conditions govern the extent to which a watershed can absorb and store water (Montgomery, 2002). In order to estimate antecedent moisture conditions, the existing soil and groundwater storage must be understood (Troch, 1993; Wittenberg and Sivapalan, 1999) in order to estimate the storage and release properties of the soil and geology of the watershed in question.

Another approach is to view a watershed's hydrological response as the integration of all precipitation-runoff processes. Investigators such as Nathan and McMahon (1990) or Lacey and Grayson (1998) predicted the baseflow index, which is the ratio of groundwater volume over total discharge volume, and examined the relationship between landscape characteristics and observed hydrological response, particularly under low-flow conditions.

This paper introduces a novel application of the recession index, which represents the residence time or turn-over time of the groundwater (Wittenberg, 1999).

The recession index characterizes the integrated watershed response during the dry summer season and is used as a surrogate for overall watershed storage conditions. An argument is made that the recession index can be used to predict the expected streamflow responses in the coming months.

2. Background

2.1. THE UPPER BATTLE RIVER WATERSHED

Located within the Parkland Natural Region, the UBRW is an important watershed in east-central Alberta. For the purpose of this study, the UBRW is defined as that part of the larger Battle River Watershed that is upstream of Water Survey of Canada stream gauging station 05FC001 near Forestburg (Figure 1). The watershed's water supply is derived entirely from local surface runoff from rain and snow melt, as well as groundwater flows, and outflows from the many connected lakes and wetlands. This watershed is unique in that it is without the benefit of having its headwaters in mountain/foothill regions, where large winter snow accumulations and glacial melt typically generate most of the annual runoff. The eastern portion of the watershed is in a prairie environment where winter precipitation is low (123 cm of snow at Camrose, 1971–2000 normal) relative to the eastern slopes of the Rocky Mountains (over 200 cm of snow, 1971–2000 normal).

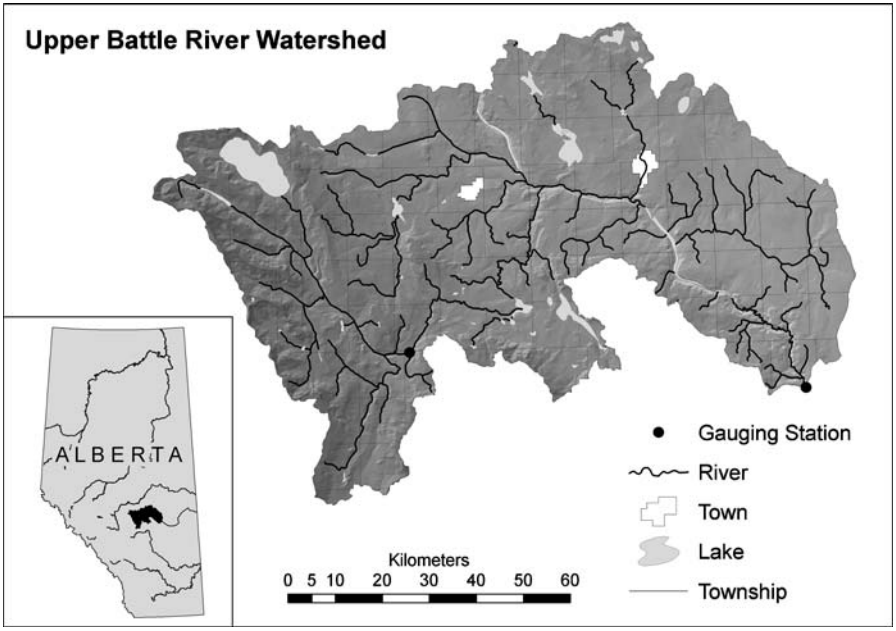

Figure 1. The upper battle river watershed.

The northern prairie region of North America is characterized by undulating terrain with very low regional gradient. The UBRW has a mean slope of about 1.5%. The watershed area of the UBRW is approx. 7,675 km^2 (Figure 1). Typical for a semi-arid climate, the streamflow is highly variable. Based on the streamflow record from 1967 to 2004, the total discharge ranges from a high of 660.7 million m^3 in 1974 to a low of 16.4 million m^3 in 2001, with a median discharge of about 95 million m^3. The seasonal distribution of streamflow can be divided into two distinct periods: the period April to June, which contains the bulk of the snowmelt discharge, and the period July to March, which consists mainly of baseflow and occasional summer precipitation runoff events, which can be significant at times. The median proportion of annual yield discharged during the freshet in April, May and June is 77.5%, but may be as high as 99.2% in years with very low summer rainfall such as 2002, or as low as 23.3% in years with little snowpack and abnormally high summer precipitation such as 1998.

Streamflow data are only recorded from April 01 to October 31, because of ice formation during the remaining five months of the year. Using the streamflow data recorded at Water Survey of Canada station 05FC001, the mean annual runoff depth is about 16 mm. The annual runoff depth includes winter flow estimates for November to March, which is based on flow correlations with the nearest gauging station downstream with a complete 12-month monitoring record. Assuming a mean annual precipitation of approximately 480 mm for the period 1970 to 1999 (Environment Canada, 2004), the annual runoff coefficient is about 3.3% of total annual precipitation, and the July to October period has a runoff coefficient of about 2.3%, with a mean rainfall during this period of 218 mm. The remaining water is lost due to evaporation from the lakes, the soil, wetlands and transpiration by plants.

2.2. RUNOFF PROCESSES

Figure 2 shows the median streamflow for the gauging station at Forestburg. The median behaviour of the watershed shows a distinctive behaviour of a streamflow regime largely dominated by spring snowmelt. The dominating soils in the UBRW have formed from clay-rich glacial tills. These soils have very low permeability when they are frozen, and subsequently the infiltration of snowmelt water into frozen soils is highly restricted (Gray *et al.*, 1985). As a result, a large proportion of snowmelt runoff is generated over frozen ground. A subsequent dominating hydrograph occurs in the spring, followed by a steady exponential recession during summer and early fall, which continues until the spring snowmelt in the following year. The two-peak hydrograph is somewhat unusual. The first peak – around April 20 – was exceeded predominantly in the period 1979 to 2003, while the second peak – around April 29 – was exceeded predominantly in the period 1967 to 1985, which may be an indication of a change in the timing of snowmelt as a result of climate change. The small peaks and troughs during the recession curve stem from

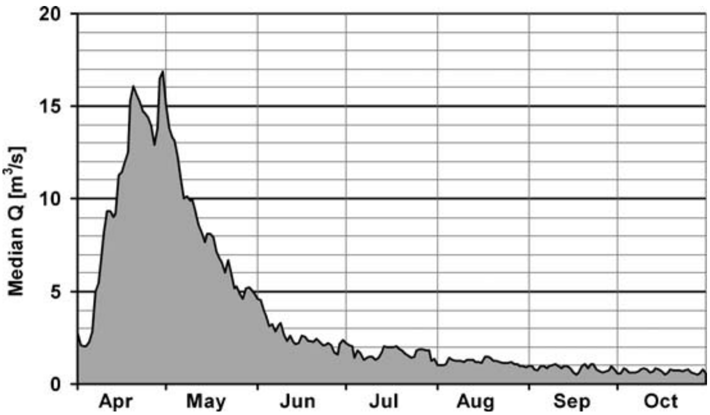

Figure 2. Median streamflow at Water Survey of Canada station 05FC001, showing a distinctive exponential recession after spring snowmelt.

individual runoff events during the observation period. The principal recession is similar from year to year, with the exception of drought years.

Numerous depressions in the undulating terrain trap snowmelt water, resulting in runoff retention and sources for groundwater recharge. Depression storage of flat terrain overlain with clay rich glacial tills was estimated to trap between 40 and 70% of snowmelt within the West Nose Creek watershed north of Calgary, Alberta, about 150 km away from the UBRW (Hayashi *et al.*, 2004). Based on a watershed GIS database available from the Prairie Farm Rehabilitation Administration (Agriculture and Agri-Food Canada, 2003), it is estimated that approximately 50% of the watershed area of the UBRW is within the effective drainage area.

Most of the runoff stored in upland depressions is evaporated or transpired by local plant communities around each wetland (Meyboom, 1966; Van der Kamp and Hayashi, 1998; Hayashi *et al.*, 2004). Upland wetlands, also called sloughs or potholes, likely contribute very modest quantities of water to the regional groundwater system that interacts with the Battle River. After a snowmelt event (Figure 3), the streamflow is maintained, in part, by out-flowing wetlands and lakes connected to the river channels (Byrne, 1989a, b; Stolte and Herrington, 1984). These wetlands drain slowly and, in normal years, provide a stable streamflow source of the Battle River in late summer and fall, sufficient to maintain in-stream reservoir levels needed for municipal water supply as well as for downstream power generation and other users (Figure 3). After a dry year, the wetlands and lakes are relatively shallow, with smaller surface areas, and groundwater levels will have drawn down, subsequently leading to relatively low streamflows. In very dry years, such as 2002, many smaller wetlands and lakes dry out completely.

The seasonal streamflow pattern can be divided into two different components, indicating two distinctly different streamflow sources. The first component of the

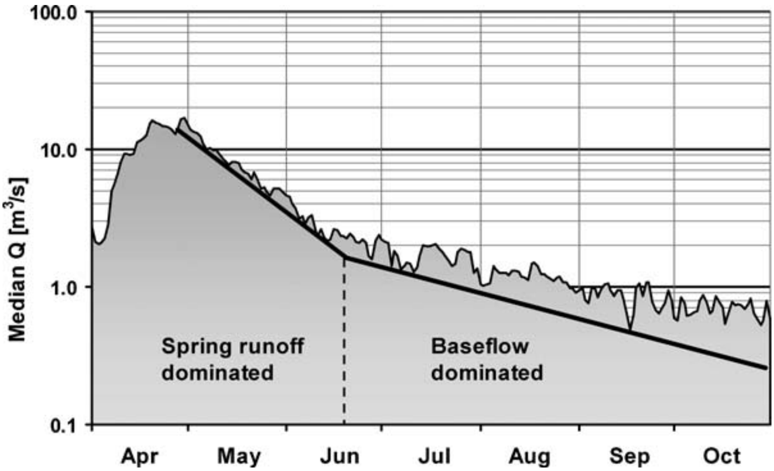

Figure 3. Median streamflow at Water Survey of Canada station 05FC001 as semi-logarithmic graph; the recession lines become linear, and snowmelt and summer components can be distinguished.

receding hydrograph is relatively steep and associated with the snowmelt during spring. At this time the soil water storage capacity is relatively full, groundwater tables are relatively high and exerting a high pressure head, and lakes and wetlands are at their fullest and drain significant volumes of water into the drainage network of the upper Battle River system. The second, flatter, component is disconnected from the snowmelt events and is associated with a drying of the watershed. During this time the soil moisture store is already quite depleted, groundwater tables are relatively low, and – probably most significantly – lakes and wetlands levels have declined to levels that allow only small volumes of water to drain into the upper Battle River system.

It is this second component that is of significance to water resources managers of the UBRW. With the first and only exception in 2004, all streamflow associated with the first component resulted in sufficient flows which filled all instream reservoirs such as Driedmeat Lake used by the City of Camrose or, further downstream, a reservoir supplying cooling water for a coal power plant.

Surficial deposits in the UBRW are typically less than 20 m thick, except in areas of bedrock lows, where the thickness of surficial deposits can exceed 60 m (Agriculture and Agri-Food Canada, 1999a, b). There are hydraulic connections between one or more major aquifers and the Battle River. These likely include the deltaic/outwash deposits in the Red Willow and Big Knife tributaries, the buried Buffalo Lake Valley, the Paskapoo Sandstone, and local or regional groundwater in the glacial tills. This would mean that during the late summer, fall and winter periods, and in normal to wet years, the Battle River receives a steady groundwater inflow. Water tables are influenced by long-term climate conditions and by the intensity of pumping from numerous water wells used by the rural community. Under drought and/or intensive pumping, the water table in these aquifers declines, and the associated flow from the groundwater into the Battle River decreases. Given conditions of consecutive drought years, such as the period 2001 to 2003, the water table may decline such that water flow between the river and one or more aquifers ceases or perhaps, reverses. In the latter case, the Battle River would be losing water where it is in contact with the aquifer. There is anecdotal evidence that severe groundwater depletion was observed in parts of the UBRW, which is associated with intensive pumping of potable water from the Paskapoo Sandstone by towns and rural residents.

2.3. BASEFLOW RECESSION CHARACTERISTICS

The baseflow recession is the integrated response of all runoff processes in the watershed, and depends on topography, drainage pattern, soils and the geology of the watershed. While the snowmelt event in spring is important for the recharge of the integrated lakes-wetlands-groundwater system, a strong snowmelt event does not necessarily result in a sustained summer flow. The reason is that the overall volume in the combined lakes-wetlands-groundwater system responds only in part to inputs in an individual year, but mainly to the multi-year fluctuations between wetter and drier years and the frequency and duration of summer rainfall events. This is demonstrated in Figure 4, which illustrates that the baseflow recession is interrupted by occasional summer storms, which at times can significantly increase the summer streamflow, fed predominantly by elevated lake levels and an increase in wetland storage. Examples are a multi-week event in July 1974 or a short event

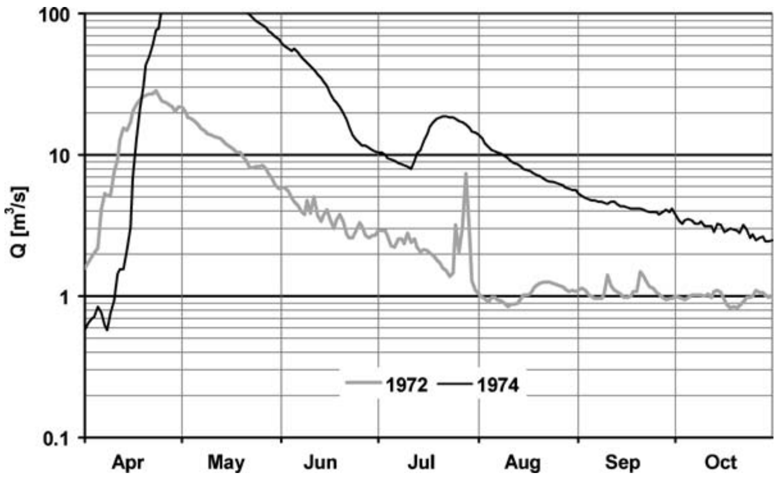

Figure 4. Selected hydrographs with high summer streamflows; they are associated with large lakes-wetlands-groundwater outflows.

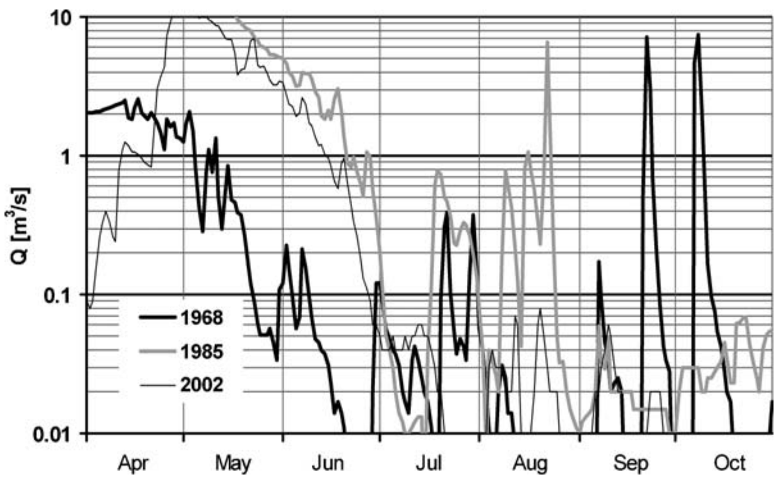

Figure 5. Selected hydrographs with low summer streamflows; they are associated with very small lakes-wetlands-groundwater outflows.

in July 1972. The recession in 1974 shows a non-exponential decay, which is likely due to unusually wet conditions, which would result in faster that usual decay of the lake-wetland system. After winters with little snowfall, the spring snowmelt event is quite weak, followed by below-normal flows during the remainder of the year (Figure 5). Then, summer streamflow can be entirely governed by storm events and subsequent short-lived runoff events.

However, depending on the amount of the combined lakes-wetlands-groundwater volume available for discharge, a decent snowmelt event will not necessarily be able to maintain summer flows. This is evident from the 1968 drought year, followed by a strong snowmelt in 1969, which was not able to sustain flows during the summer season and resulted in extremely low flows during the remainder of 1969 (Figure 6).

3. Methods

In order to evaluate the hydraulic properties of the combined lakes-wetlands-groundwater discharge and the sustainability of baseflow in the Upper Battle River, the analysis of the recession characteristics of the streamflow hydrographs was carried out. Although there are man-made impoundments present in the watershed, these are not regulated and were designed to act like a natural impoundment, where the outflow is a linear function of the storage volume. Regulated streamflows cannot be used for this analysis, except where the regulated outflows from impoundments are known and the streamflow record can be naturalized. While Figures 2 and 3 show the long-term median behaviour of the watershed, it is obvious that the streamflow has many individual fluctuations as a result of rainfall events in various parts of the

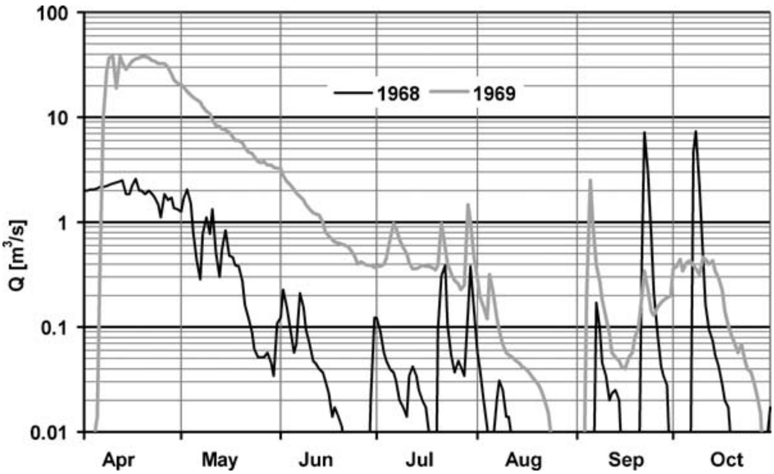

Figure 6. A high snowmelt volume in 1969 resulted in low summer flows due to still exhausted watershed storage from the previous drought year.

watershed (Figures 4 and 5). These runoff events result in individual recessions. The behaviour of those individual recessions is used as an integrating indicator for the overall status of the combined lakes-wetland-groundwater regime.

3.1. RECESSION INDEX

The recession index is a measure of the time required for the groundwater discharge to recede by one log cycle (Rutledge, 1998). It is quantified in days per log cycle, which is the time when streamflow recedes to 10% of streamflow since the beginning of the recession (Figure 7). The calculation of the recession index is a convenient way of describing recession characteristics, because it treats the typically complex groundwater system as a lumped store. It does, therefore, not require any detailed physical watershed and groundwater knowledge and is rather entirely based on daily streamflow records and can be determined for any gauged watershed.

The connected and interdependent lakes-wetlands-groundwater system can be conceptualized as a single linear reservoir, where the outflow is a linear function of the storage:

$$Q_t = S_t/K \tag{1}$$

where Q_t is the outflow at time t, S is the volume of water in storage in the reservoir at time t, and k is the reservoir storage coefficient, determining the rate of outflow with units in time, e.g. days. The linearity of the conceptional reservoir for the UBRW is confirmed by the linear, or near-linear, decay of individual recessions (Figures 3 and 6). Baseflow can be conceptualized to be the outflow from a single

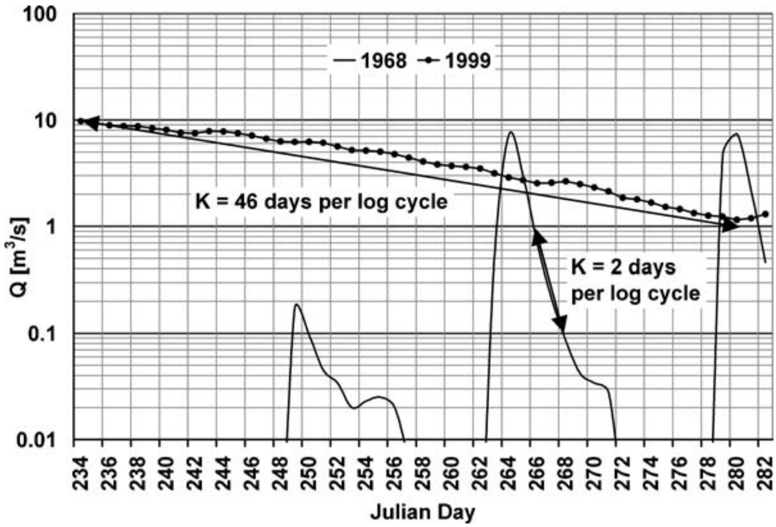

Figure 7. Graphical determination of recession index K for two hydrographs with a long and short recession. Note that one log cycle represents a streamflow reduction of 90%.

linear reservoir:

$$Q_t = Q_0 \cdot \mathrm{EXP}(-t/k) \tag{2}$$

where Q_t is the outflow at time t, Q_0 is the initial outflow and k is the reservoir constant in days. For each hydrograph, the recession index can be calculated as follows:

$$t = k_1 \cdot \mathrm{Log}\, Q + k_2 \tag{3}$$

where t is time in days, $\mathrm{Log}\, Q$ is the logarithm of the streamflow in m^3s^{-1}, and k_1 and k_2 are coefficients that are determined by the linear regression of $\mathrm{Log}\, Q$ versus t (Rutledge and Mesko, 1996). The recession index was calculated using the RECESS program (Rutledge and Mesko, 1996), available free from a USGS Web site. The program scans the streamflow for periods of continuous recession with a selected minimum duration of 5 days. If the streamflow is nearly linear after a log transformation, then it is suitable for further analysis, because the recession is then assumed to be unaffected by other recharging events. For the observation record March 1967 to October 2004, a total of 411 individual recessions were analyzed, of which 194 occurred between July and October.

A complete analysis of all observable recessions of 5 days or longer during the period July to October revealed a mean K value of 35.8 days per log cycle and a median K value of 27.2 days per log cycle. This median value, however, is thought to be biased towards the lower values, because during relatively dry years (example: 1968 in Figure 7) there are more, but shorter recession events than in relatively wet years (example: 1999 in Figure 7), when the recession events are much longer. Therefore, the median value may indicate conditions which are associated with low flow conditions rather than normal conditions.

3.2. MASTER RECESSION CURVE

If one combines a whole series of recession curves by lining them up to form a relatively smooth continuous line, a master recession curve is created. Each watershed has its individual master recession curve, because the master recession curve reflects the overall storage characteristics of the watershed and determines how the combined lakes-wetlands-groundwater system reacts to a snowmelt or rainfall event (Lamb and Beven, 1997). Figure 8 shows the master recession curve for UBRW at Water Survey of Canada station at Forestburg. The recessions are clustered to form two individual master recession curves. This is an indication that there are two different watershed storages, which react distinctively different from one another. Each one can be described by a best-fit linear equation for K as a function of LogQ. The left master recession curve with a gentle slope shows a very strong correlation between time and streamflow of 0.978. 'A' was determined to be 58 days per log cycle.

Based on the current knowledge of the UBRW, the following storages and processes can be characterized:

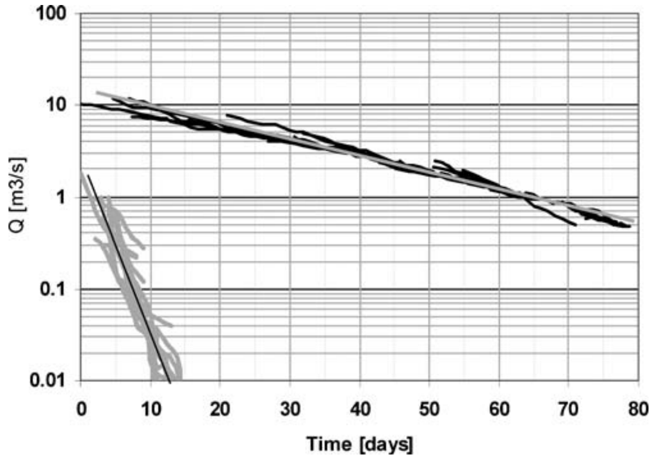

Figure 8. Two master recession curves indicate that two distinctively different outflow sources exist; the grey line with the gentle slope represents recessions for streamflows which are predominantly based on outflows from the lakes-wetlands-groundwater system, while the steep, black line represents recessions which are based entirely on surface runoff from summer rainfall events.

- The gentle master recession curve (grey regression line) is the result of slow outflow from a large storage within the lakes-wetlands-groundwater system. This system is, as was mentioned earlier, following the multi-year behaviour of the watershed based on higher and lower long-term inputs into the system.
- Conversely, the steeper master recession curve (black regression line) shows an exhaustion of the storage capacity within a few days. This suggests a very small storage, which is likely rainfall input from a relatively small, localized portion within the watershed. This is, compared to the potential lakes-wetlands-groundwater storage, small in volume, especially when one considers the large depression storage in the watershed and the fact that only about 50% of the watershed contributes to surface runoff.

3.3. USING K AS AN INDICATOR FOR DROUGHT RECOVERY

If the recession index K is an indicator for the watershed storage available to produce baseflow, then there should be a correlation between the recession index and streamflow. A series of analyses were carried out, and the behaviour during each entire July to October season proved to give the most insight. Individual runoff events can obscure the general behaviour of the watershed, because it is generally not known where an individual hydrograph was generated, and a high intensity rainfall event over a small area may result in the same runoff volume than a less intense rainfall event over a larger area, resulting in distinctively different associated recession curves.

4. Results

Figure 9 shows the time series for median July to October streamflow and recession indices. A pattern is apparent, where years with high streamflow have relatively high K values, and vice versa. Figure 10 shows the dependence of the two variables. The coefficient of determination (r^2) is 0.598.

Based on insight revealed by Figures 8 and 10, one can determine the approximate K value that is associated with certain streamflow conditions (Table I). The following information can be derived from the recession curve analysis:

- Severe historical droughts such as 1968/69 and 1984/85 had median K values of between 4 and 9 days per log cycle for the July to October period. The median K value for 2004 is 8 days per log cycle;
- the median K values for the drought years 1989, 1992, 1994 and 2001 to 2003 range from about 15 to 20 days per log cycle;
- according to Figure 10, a median streamflow for the period July to October of approximately 1.12 m^3s^{-1} is associated with a K value of 55 days per log cycle;
- according to Figure 10, a lower quartile streamflow for the period July to October of approximately 0.35 m^3s^{-1} is associated with a K value of 17 days per log cycle.

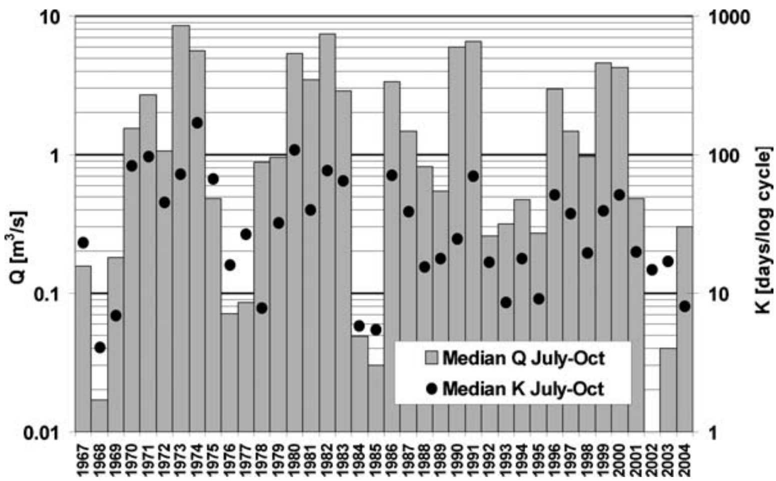

Figure 9. Time series of median streamflow and median recession indices K for July to October; generally, high median streamflow is associated with a high recession index and vice versa.

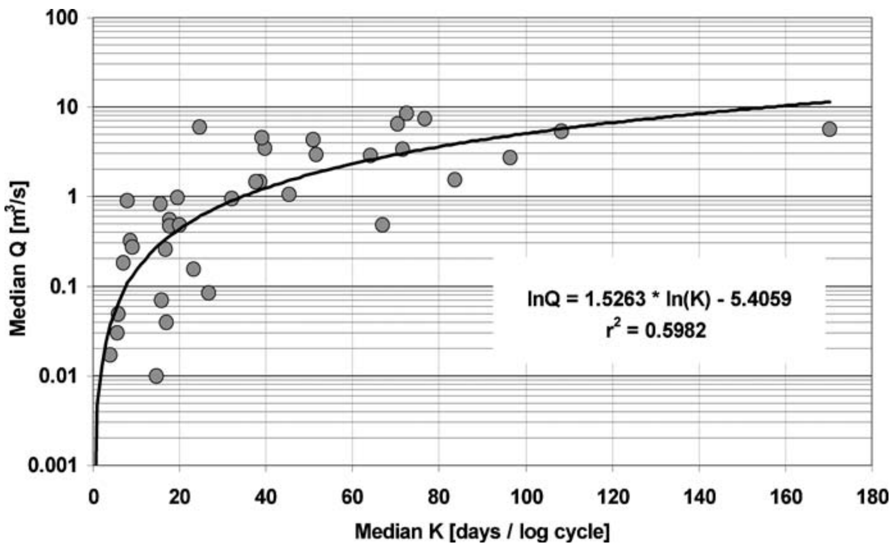

Figure 10. Correlation between the median July to October recession indeces K and median July to October streamflows.

The information displayed in Table I can be used by water resource managers as a guideline to indicate the level of drought recovery the watershed has undergone. It is clear that the K values, expressed in days per log cycle, can only serve as a relatively rough guideline.

Analysis of the 2004 flow record reveals a median K value of 8 days per log cycle, with individual recession curves with K values ranging from 5 to 12 days per

Table I. Categorization of median July to October recession indices as indicators for streamflow condition

Streamflow condition	Recession index in days per log cycle	Comment
Severe low flow occurring and expected to continue	Below 10	Occurred in drought years or just after a multi-year drought: 1968/69, 1978, 1984/85, and 2004; also occurred in non-drought years: 1993,1995
Low flow occurring and expected to continue	10–below 20	Occurred during drought years: 1976 and 2001/02/03; also occurred in non-drought years: 1988/89, 1992, 1994, 1998
Risk of low flow, future flows uncertain	20–25	Alternative A: based on historical drought conditions
Risk of low flow, future flows uncertain	20–30	Alternative B: based on median July to October flow of 0.8 m^3s^{-1}(Figure 10)
No risk of low flow in the near future	Over 30	Median July to October flow of over 0.8 m^3s^{-1} (Figure 10)

log cycle. One runoff event around September 20 had a K value of 10 days per log cycle, and one around October 15 had a K value of 12 days per log cycle. Although this is an improvement relative to a recession speed of 5 to 8 days per log cycle earlier in the summer, these values do not represent a meaningful recovery. It can be concluded that the UBRW has not yet recovered from the 2001 to 2003 drought, and future streamflows will require significant snowmelt events and summer rainfall to improve antecedent watershed conditions in order to create sustainable summer flow conditions to maintain sufficient water levels for the Battle River reservoir.

5. Conclusions

It has been shown that a strong relationship exists between median summer flows (July to October) and the associated median recession index. Therefore, the recession index can be used as an indicator for streamf low recovery. The basis for this is that the integrated lakes-wetlands-groundwater storage of the upper Battle River Watershed reacts in a sustainable or non-sustainable fashion to rainfall inputs, depending on the status of the combined lakes-wetlands-groundwater reservoir storage. The advantage of this method is that once the relationship between streamflow and recession indices is established for a watershed, the individual K values can be determined as soon as a recession is completed, and the median K value is available as soon as the season is over, providing insight into watershed conditions for the near future.

This methodology was applied in a complex semi-arid watershed in central Alberta, Canada. The concept is based on a lumped reservoir and should be applicable to a wide range of geological conditions and climatic settings (Chapman, 1999). This methodology should, therefore, be easily transferrable to other watersheds, as only relatively simple recession and streamflow analyses are required, such as the analysis described here. In order to be applicable to other watersheds, four tests have to be carried out: (a) the streamflow record investigated must be non-regulated flow, (b) the condition of reservoir linearity has to be confirmed, (c) the time period which is snowmelt dominated needs to be determined, so that it can be omitted from the recession index analysis, and (d), there has to be a significant relationship between seasonal streamflow and the recession index.

The benefits of this analysis to water resources managers for seasonal water planning and the implementation of water conservation measures easily outperform the efforts to conduct the initial recession curve analysis.

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