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Possible Relationship between BFI and Physiographic/Physical Characteristics of Watersheds

Ramesh P. Rudra, Professor

School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1, rrudra@uoguelph.ca

S. Imran Ahmed, Post Doctorate Fellow

School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1, sahmed@uoguelph.ca

M. Khayer, Graduate Student

School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1, mkhayer@uoguelph.ca

R. Sharma, Graduate Student

School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1. sharmar@uoguelph.ca

B. Gharabaghi, Assistant Professor

School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1. bgharaba@uoguelph.ca

P.K. Goel, Senior Surface Water Scientist, Environmental Monitoring and Reporting Branch, MOE, Ontario, Pradeep.Goel@ontario.ca

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ABSTRACT

The slow (base flow) and the quick (surface runoff and tile flow) responses of the stream flow are key components that characterize the watershed for its physiographic and geological features. The overall objective of this study is to separate baseflow from streamflow and its relationship to physiographic characteristics of the watershed. A computer program was developed to quantify the amount of base flow index (BFI, base flow/stream flow) using six methods for 161 watersheds in Ontario. The results showed the annual average BFI for 115 southern watersheds computed by digital filter, UKIH, and base sliding methods were 0.39, 0.63, and 0.72 respectively. For 46 northern watersheds, the BFI by digital filter, UKIH, and base sliding methods were 0.55, 0.86, and 0.89, respectively. Out of 115 southern Ontario watersheds, 30 could be designated as slow response and 9 as rapid response watersheds. For 46 watersheds in northern Ontario, all the watersheds could be classified as slow response watersheds. Overall, the seasonal BFI computed was highest during winter months followed by spring, summer, and fall. The results also indicated that physiographic/physical characteristics of watersheds have profound effect on BFI such as soil, drainage class, tile, and landuse. However, analysis also showed no effect of the area of watershed and slope class on the BFI. The results of this study is a step forward for developing nutrient management and source water protection strategies for specific watersheds.

Keywords. slow response, quick response, streamflow, baseflow separation,

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INTRODUCTION

There is a need of understanding of general hydrology to develop effective techniques for managing surface and subsurface runoff in Ontario. Nonetheless, little is known about the dynamic changes in surface water runoff, infiltration, subsurface drainage flow, and influence of physiological/physical characteristics of the soil on surface and subsurface hydrology in Ontario. The mean annual streamflow distribution throughout Ontario shows these flows have significant seasonal pattern. Most of the surface runoff from agricultural lands of the Great Lake Basin occurs during the late winter and early spring period by snowmelt, rain on snowmelt, and freezing or thawing conditions. The summer and fall seasons have the lowest flows in streams in southern Ontario and northern part receives lowest flows during winter.

The physiographic and geological features of the watershed significantly affect the slow (base flow) and the rapid (surface runoff and tile flow) responses to the stream flow. Also, these components vary seasonally due to the change in climatic conditions of the watershed. A baseflow separation study was conducted by Neff et al. (2005) to estimate the baseflow for watersheds tributary to Great Lakes basin in Canada and USA. The aim of the study was to develop regression models for ungaged watersheds by calculating baseflow indices (the long-term ratio of baseflow to total streamflow) for 959 gages with six different separation methods: the fixed base, sliding-interval, and local minimum HYSEP methods (Sloto and Crouse, 1996), PART (Rutledge, 1998), BFLOW (Arnold and Allen, 1999), and UKIH (Piggott et al., 2005). Two regression models were developed by using the data from 959 selected gages in both Canada and USA. The Geology (G) Model was used to correlate baseflow index to the surficial geology and the Geology-Surface Water (G-SW) Model was used to correlate baseflow index to the proportion of surface water within the watersheds.

Long-term average base flow indices (BFI) were estimated using these regression models for all areas in the Great Lakes Basin, Ottawa, and the upper St. Lawrence River Basins. The results showed that in many cases G-SW Model estimated baseflow higher than G Model, particularly in areas with many surface-water features that store water and gradually drain. It was also mentioned in the study that the accuracy of models' results were influenced due to the uncertainty of separation method, and constraining the surficial geology to five classes. Both models consider landscape attributes within a given watershed to estimate baseflow at the downstream end of the watershed. However, this method fails to convey the spatially variable nature of baseflow.

Eckhardt (2008) conducted another study to examine baseflow indices for 65 US and Canadian catchments with seven different baseflow separation methods (HYSEP1, HYSEP2, HYSEP3, PART, BFLOW, UKIH, and Eckhardt). To perform the study 65 randomly selected USGS gages out of 959 gages of Neff et al. (2005) study report were used. The study claims that the results of the Eckhardt method appear to be hydrologically more reasonable than those of the other algorithms. Furthermore, Eckhardt algorithm can be applied to hydrographs of any length. Three HYSEP methods local minima, fixed interval and sliding interval, PART and UKIH methods baseflow indices were directly taken from Neff et al. (2005). BFLOW results were recalculated for one filter instead of three filters. The study concluded that for local

minima, fixed interval, sliding interval, UKIH, and PART methods baseflow hydrographs are produced by joining the points with straight lines, which is an unrealistic baseflow progression. However, in digital filter and Eckhardt methods baseflow hydrographs appear to be more realistic with extensively smooth time series of baseflow, and the results of these two methods were found to be similar.

Lacey et al. (1998) conducted a study to examine the influence of geology, vegetation cover, and catchment properties, including topographic and climatic indices, on the baseflow index for 114 catchments (0.05 to 192 km² in area) in Victoria, Australia. Two geological parameters, bedrock type and formation of soil over the bedrock, control the baseflow to stream in these catchments. Combining the geological parameter and indigenous vegetation community of the catchment, all 114 catchments were divided into 12 vegetation-geology groups. Catchment properties examined were drainage index, slope index, and flat area ratio. The study found that baseflow index has strong relationship with geology-vegetation groups, there is either no or very weak relationship to climatic parameter within a geology-vegetation group, and it is independent of drainage index, slope index, and flat area ratio. It also appears that there is no effect of catchment size on baseflow index for catchment areas up to 100 km², and baseflow index changes beyond this range for same geology-vegetation group and catchment properties. However, it was concluded that this finding is inconclusive, as it requires further investigation with more detailed data.

Nathan and McMahon (1990) analyzed daily streamflow data for 186 watersheds in southeastern Australia to evaluate automated techniques for baseflow separation and recession analysis. Two baseflow separation techniques, digital filter method and UKIH smooth minima method, were used for this analysis. In addition, to analyze the performance of recession analysis techniques, two commonly used techniques, the correlation method and the matching strip method, were used. The study showed a relation between digital filter and UKIH method with a linear correlation coefficient of 0.94 (slope 1.06, and intercept 0.02). Recession behavior analysis by matching strip method was found more realistic than the correlation method. Also, recession constant 0.925 derived by matching strip method was found the best approximation of the parameter used in digital filter method. One of the important contributions of the study was to propose a widely accepted and commonly used recession constant 0.925 for digital filter method. It was also found that digital filter method is better suited with low flow condition than UKIH method and is strongly correlated with other low flow indicator. They also concluded that due to the complexities of catchment processes it is not possible to compute the baseflow accurately.

Aksoy et al. (2008) applied the original UKIH smooth minima method for the European part of Turkey, the Thrace region. This method was originally developed for baseflow separation in perennial streams and adopted for intermittent streams. In original UKIH method baseflow exceeded streamflow in some cases but adopted UKIH method eliminated that problem. Adopted UKIH method was first applied for intermittent flow, and then applied for whole time series of streamflow. This method proposed a drainage area based block size/time window of 5 days with a data filtering parameter 0.9; however, it also suggested that the block size and parameter could be adjusted according to the need of local situation. Results of adopted UKIH method was

compared with digital filter method and they found a good agreement between them. There was little variation in average BFI between UKIH method and digital filter method with minor variability in standard deviation. It was also observed that Adopted UKIH method produced higher baseflow sequences.

Mazvimavi et al. (2004) conducted a study to relate watershed physical characteristics and hydrological parameters with the baseflow for 52 watersheds in Zimbabwe. UKIH smooth minima method was used to separate baseflow. Effect of mean annual precipitation, mean annual evapotranspiration, slope, drainage density, basin area, proportion of basin under different lithological types, and proportion of basin with different land cover on BFI was examined by using linear regression model and artificial neural networks. The results of this study revealed that baseflow index was positively related to mean annual precipitation ($r = 0.71$), basin slope ($r = 0.76$), and drainage density ($r = 0.29$), and negatively related to mean annual evapotranspiration ($r = -0.74$) and proportion of a basin with agriculture, grasslands, and wooded grasslands ($r = -0.53$). Also, differences in lithology did not significantly affect BFI. The investigation also revealed the contribution of delayed interflow and groundwater flow to river flows mainly depends upon climatic (mean annual precipitation and evapotranspiration) and topographical (basin slope and drainage density) variables within a basin. Linear regression and artificial neural networks were both suitable for predicting BFI values. The predicted BFI was used to derive flow duration curves for 52 basins.

The literature review shows that the effect of physiographic/physical characteristics on base flow varies differently and is environment specific. Also, there are various methods to calculate the separation of baseflow from streamflow; therefore, it is important to evaluate different methods for baseflow separation and the effect of physiographic features on hydrology (base flow, surface runoff, and tile flow) in various regions of Ontario.

Objectives

The overall focus of this study is to describe various components of seasonal hydrology in Ontario landscapes (stream flow, surface runoff, base flow, and tile flow) and their relationships with the physiographic characteristics of the watershed, including soil characteristics, depth to an impermeable layer, topography, land use and watershed area. The specific objectives are:

- To evaluate the six different baseflow separation methods for application in Ontario conditions,
- To evaluate the influence of physiographic landscape pattern, formation, and soil properties on baseflow,
- To separate annual and seasonal baseflow for understanding seasonal variability, and
- To identify the slow response (base flow) and rapid response (surface runoff) watersheds for nutrient management and source water protection.

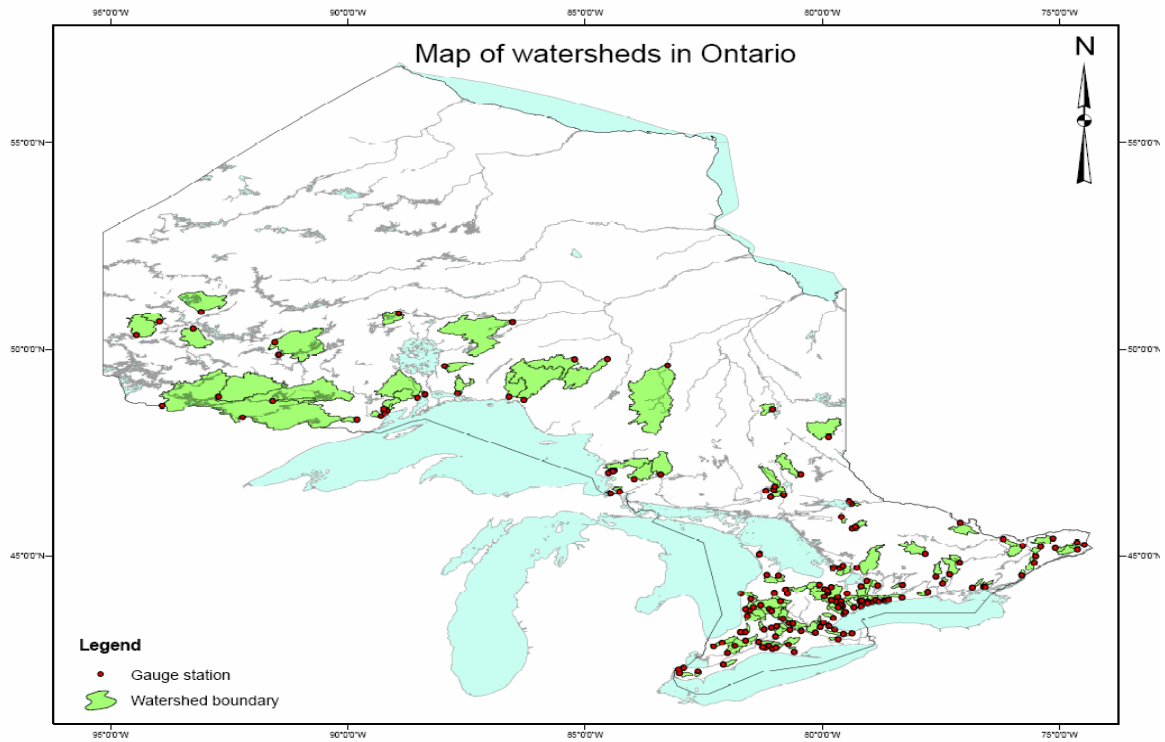


Fig. 1. Map of studied watersheds of Ontario.

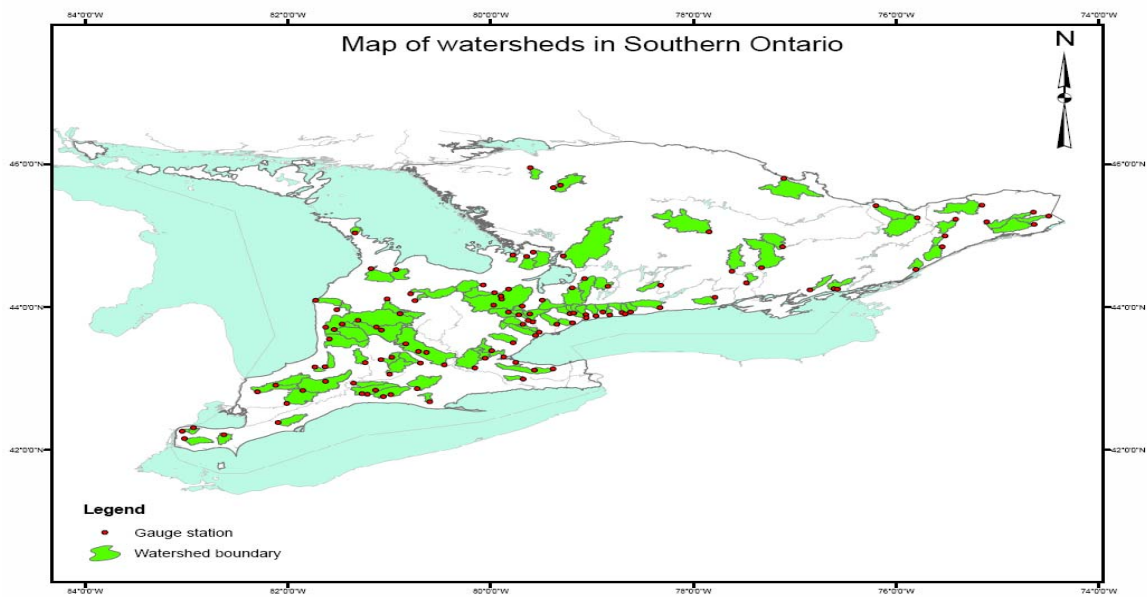


Fig. 2. Map indicating watershed boundary and gauge station for southern Ontario.

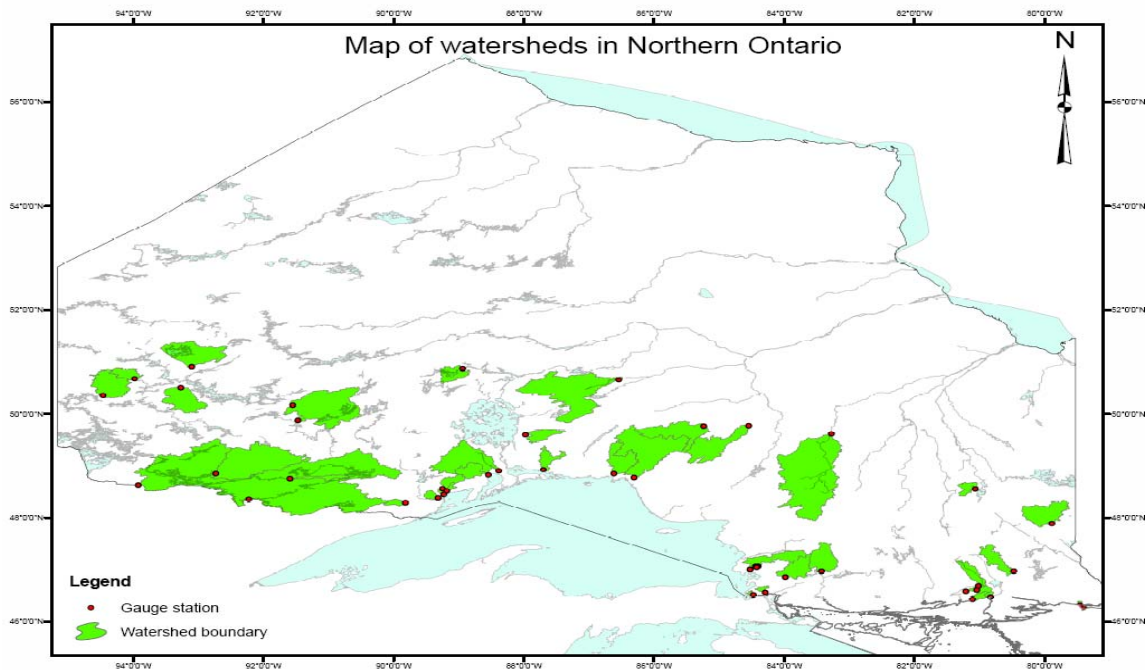


Fig. 3. Map indicating watershed boundary and gauge station for northern Ontario.

MATERIALS and METHODS

The study was conducted for the watersheds in Ontario (Fig. 1). The province was divided into southern Ontario (Fig. 2) and northern Ontario (Fig. 3). At the first step for this study for understanding seasonal variability in responses of streamflow, it was decided to get knowledge of flows from various conservation authorities in Ontario of their respective watersheds. The limited responses and feedback from conservation authorities indicated that very limited analysis has been done for understanding seasonal variability of stream flow.

At the second step, criteria were silhouetted for selection of watersheds with peculiar characteristics and spatial distribution. The physiography (Chapman and Putman, 1984), conservation authority boundary, HYDAT gauging locations, rainfall distribution, snow distribution, surficial geology, and average annual runoff GIS layers were prepared for Ontario.

At the third step, the procedures for analyzing stream flow were reviewed in the literature. The six commonly used procedures; digital filtration technique (Nathan and McMohan, 1990), PART (Rutledge, 1998), UKIH (Piggott et al., 2005), and local minima (Sloto, 1991), base sliding and base fixed methods (Pettyjohn and Henning, 1979) were selected for initial investigation and comparison. All the six methods were applied to the selected watersheds and then the streamflow responses were correlated to the features of the watershed. These six methods are described in detail in the following section.

Digital filter method

The recursive digital filter method is the most common and the simplest one to separate baseflow from the daily streamflow records (Nathan and McMahon, 1990). This method is used for signal analysis and processing to separate high frequency (direct runoff) signal from low frequency (baseflow) signal. The following equation is used for digital filter method:

$$f_k = \alpha f_{k-1} + \frac{(1 + \alpha)}{2} (y_k - y_{k-1})$$

where,

f_k = the filtered quick response at the k_{th} sampling instant;

y_k = the original streamflow;

α = the filter parameter (0.925)

$y_k - f_k$ = the filtered base flow.

PART method

The PART computer program is a hydrograph-separation technique to estimate base flow from the streamflow record. It is widely used to compute base flow in the eastern United States (Holtschlag, 1997; Nelms et al., 1997; Bachman et al., 1998). The PART program computes base flow from the stream-flow hydrograph by first identifying days of negligible surface runoff and assigning base flow equal to streamflow on those days; the program then interpolates between those days. PART locates periods of negligible surface runoff after a storm by identifying the days meeting a requirement of antecedent-recession length greater than "N" (time in days after which surface runoff ceases) and rate of recession less than 0.1 log cycle per day, and uses linear interpolation to connect across periods which do not meet those tests.

UKIH method

UKIH method is based on the identification and interpolation of turning points within an input time series of streamflow, and is used for daily average data. The turning points indicate the days and corresponding values of streamflow where the observed flow is assumed to be entirely baseflow. To calculate the turning points, the streamflow data are partitioned into a sequence of five-day segments and the minimum values of streamflow within each segment, an x and y pair where x_i is the day on which the minimum value of flow of y_i occurred, are selected and defined to candidate turning points. Each candidate turning point is then compared to the minima for the previous and subsequent segments. Turning points are examined using the condition $0.9y_i \leq \min(y_{i-1}, y_{i+1})$. The temporal variation of baseflow is estimated by piecewise linear interpolation bracketed by successive pairs of turning points.

Local minima method

Local minima method searches the hydrograph for the minimum streamflow during an interval $2N$ days. The width of the interval $2N$ used for hydrograph separation is the

nearest odd integer (between 3 and 11) to twice the value of N. The value of N is the approximate duration of surface runoff from Linsley et al. (1982):

$$N = (A)^{0.2}$$

Where, N is the time after which surface runoff ceases, days; and A is the watershed area, square miles.

The local-minimum method checks each day to determine if it is the lowest discharge in one-half the interval minus 1 day [0.5(2N-1) days] before and after the day being considered. If it is, then it is local minimum and is connected by straight lines to adjacent local minimums. Base flow for days between local minimums is estimated by linear interpolation.

Base sliding method

Base sliding method also searches the hydrograph for the minimum streamflow during an interval 2N days. The width of the interval 2N used for hydrograph separation is the nearest odd integer (between 3 and 11 days) to twice the value of N. N is the approximate duration of surface runoff and is related to the watershed area by the following equation developed by Linsley et al. (1982):

$$N = (A)^{0.2}$$

Where, N is the time after which surface runoff ceases, days; and A is the watershed area, square miles. The base sliding version centers the interval 2N on the day of interest. Base flow for that day is assigned the minimum streamflow within the interval; then the interval is moved forward 1 day, and the process is repeated.

Base fixed method

Base fixed method searches the hydrograph for the minimum streamflow during an interval of 2N days like local minima and base sliding methods. The width of the interval 2N used for hydrograph separation is the nearest odd integer (between 3 and 11) to twice the value of N. The value of N is the approximate duration of surface runoff from Linsley et al. (1982):

$$N = (A)^{0.2}$$

Where, N is the time after which surface runoff ceases, in days; and A is the watershed area, in square miles. The base-fixed method assigns the lowest discharge to all days in the interval 2N, starting with the first day of streamflow record; then the analysis is moved forward 2N days, and the process is repeated.

For this study, N equal to 5 days was used for all six methods. All the methods were evaluated and compared with each other for better understanding of the results from them and their relationship with each other.

Linear regression analysis

The results from these methods were analyzed by linear regression models to evaluate the difference among the methods for BFI.

Runoff coefficient

For all the watersheds under study, the runoff coefficients (RC) were calculated to check the effect of base flow in runoff amount. The data needed to calculate RC were stream flow ($\text{m}^3 \text{s}^{-1}$), area of the watershed (m^2), precipitation (mm), and BFI value of the watershed. The first step in the conversion and computation of RC was to convert the stream flow ($\text{m}^3 \text{s}^{-1}$) into runoff (mm) to have same unit as precipitation (mm), and then compute the runoff coefficient as the ratio of runoff to precipitation.

Data acquisition

Streamflow data Environment Canada's HYDAT database website has about 1000 gauge stations in Ontario with historical streamflow data. From this historical data archives, 556 gauge stations were randomly selected and their data were downloaded. Out of 556 stations, 125 stations have no data or discontinuous data in every year. Remaining 431 stations were then sorted based on two criteria: flow data, and water level data. In 431 stations, 360 stations were found with flow data and 71 stations were found with water level data. The 360 stations with flow data were further screened based on regulated flow regime and non-regulated flow regime. Non-regulated flow regime category contains 208 gauging stations and regulated flow regime has 152 gauging stations.

For this baseflow separation study, a minimum of 10 or more years of flow data for non-regulated gauging stations was considered to be adequate to get realistic base flow response. Therefore, out of 208 non-regulated gauging stations with ten or more years flow data only 161 gauging stations met the required criterion. The remaining 47 stations had less than 10 years of flow data or unusual flow data (according to OFAT). The 161 selected gauging stations were divided into southern (southern, central, and eastern) and northern stations. A total of 115 stations were classified as southern stations and 46 as northern stations.

Baseflow separation model is only executable for continuous streamflow time series. If there is any missing data for a single day, the baseflow program will not execute. In historical time series of 161 gauging stations, so many stations had missing data for few days to few months and few years. To overcome this issue, missing data were assumed for previous days, months, or years' data as required. Data were available both in database format and in EXCEL CSV format.

Physiographic data Digital format of physiographic data of southern Ontario was abstracted from the University of Guelph Data Resource Centre (DRC) website, provided by the Ontario Ministry of Agriculture and Rural Affairs (OMAFRA). Only the southern Ontario physiography was available from that source but no physiographic data or sources were available for northern Ontario. Southern Ontario physiographic data were available in detail for 5 major physiographic regions and 55 minor physiographic regions. From the description of 5 major physiographic regions, illustrated in "The Physiography of Southern Ontario, by Chapman and Putman (1984)" a digital

map of 5 major physiographic regions was prepared by using ARC GIS 9.2 software. The selected 115 watersheds for southern, central, and eastern Ontario were clipped with this physiographic map to extract the information of physiographic unit for each watershed.

Soil type and drainage class data Digital format of soil map was abstracted from University of Guelph Data Resource Centre (DRC) website provided by the Ontario Ministry of Agriculture and Rural Affairs (OMFRA). Out of 50 counties in Ontario, 43 counties are located in southern, central and eastern Ontario. The data resource centre provided detailed soil maps of 34 counties which are located in south western, south central, and south eastern Ontario. Soil maps of remaining 9 counties were obtained from Canadian Soil Information System (CANSIS) website. The soil maps of these 9 counties were not that much detailed like other 34 county maps, but it provided some data of hydrologic soil group and drainage class. The two sources did not provide soil maps for northern Ontario; therefore, it was not possible to analyze the northern watersheds based on soil group and drainage class. The selected 115 watersheds were clipped with this soil map to extract the soil group and drainage class information.

Slope data The source of slope data was ESRI Canada Soils (2005). The slope classes are divided as: less than 4%, 4 - 9%, 10 - 15%, 16 - 30%, and more than 30%. To calculate the slope, a GIS boundary was used to clip the watersheds, then “area weighted average” was computed to get the slope class value for the watershed. The data are available for whole Ontario; however, the limitations of data are that the slope classes are too crude.

Land use data The slope data was collected from ESRI Canada Soils (2005). The data were divided into mixed Forest, shrubland, unvegetated surface, marshland, grassland, fen, deciduous forest, coniferous forest, bog, agricultural crops, wetland, and water. The GIS boundary was used to clip the watersheds to reclassify as agriculture, forest, water, wetland, and others. Also, the data were available for the whole province.

Bedrock data The only source of bedrock data available was from Atlas Canada. These data were able to provide an estimate of an average value for a watershed. To calculate the average bedrock depth for the watershed, first geo-referenced the digitized bedrock map to compute bedrock elevations for each watershed, and then surface elevations were computed using DEM (elevation data). Finally, bedrock elevation was subtracted from surface elevation to get “bedrock depth”. It is important to mention that no reliable source available for whole Ontario for bedrock depth. For example, Borehole information available from OMAFRA/bedrock geology and physiography of Ontario does not contain depth of shallow bedrock information. Therefore, crude information from digital map was used in this research.

RESULTS and DISCUSSION

Comparison of baseflow separation methods

Six baseflow separation methods, digital filter, PART, UKIH, Local minima, base sliding, and base fixed, were used to separate baseflow from streamflow records for 161 subwatersheds (115 in southern, central, and eastern regions and 46 in the northern

region) in Ontario. Baseflow separation time series for these sub watersheds varied from 10 to 90 years of streamflow data obtained from Environment Canada's HYDAT records (HYDAT, 2005). As a first step to examine the algorithm of the separation methods, daily baseflow and daily streamflow hydrographs for one-year period were plotted for five randomly selected watersheds (02EC002, 02GA010, 02GA018, 02HC025, and 02KD002).

In all five watersheds' hydrographs, it was found that peak streamflow occurs in spring followed by summer or winter. Each separation method produces different amount of baseflow. A representative example of streamflow/baseflow hydrograph analysis is shown in Figs. 4-10. It was found that digital filter and PART method generate lowest amount of baseflow (Figs. 4-5). While base sliding method and base fixed method produce highest amount of base flow (Figs. 9-10). Both UKIH and local minima methods produce moderate amount of baseflow in between lowest and highest BFIs. It is evident from hydrographs that baseflow amount in each method increases under the flashy peaks, but every method responds differently to these flashy peaks.

Overall, all six separation methods respond to long duration and high magnitude flashy peaks, and the lowest amount of baseflow is generated by digital filter method and the highest amount of baseflow by base sliding method. Under short duration and low magnitude flashy peaks digital filter baseflow does not change, but PART method shows little increase in baseflow while all other methods generate significantly high amount of baseflow (Figs. 7-10).

Baseflow hydrograph generated by digital filter method appears to be more realistic than any other methods, and its baseflow recession curve follow the exponential decay function associated with storage depletion. Baseflow hydrograph by PART method separates baseflow by equating streamflow to baseflow on the days after a storm meeting a requirement of antecedent-recession length greater than N (5) days and rate of recession less than 0.1 log cycle per day. In UKIH method, local minima method, base sliding method, and base fixed method, 5-day moving time window was used to calculate the baseflow hydrograph for this study; however, filtering and connecting of hydrograph minima for all of these methods vary from each other. It was observed that all of these time-window base methods generate larger amount of baseflow than digital filter method and PART method, whereas base sliding and base fixed methods produce the highest amount of baseflow. In addition, UKIH method and local minima method produce moderate amount of baseflow for all duration and all magnitude of streamflow.

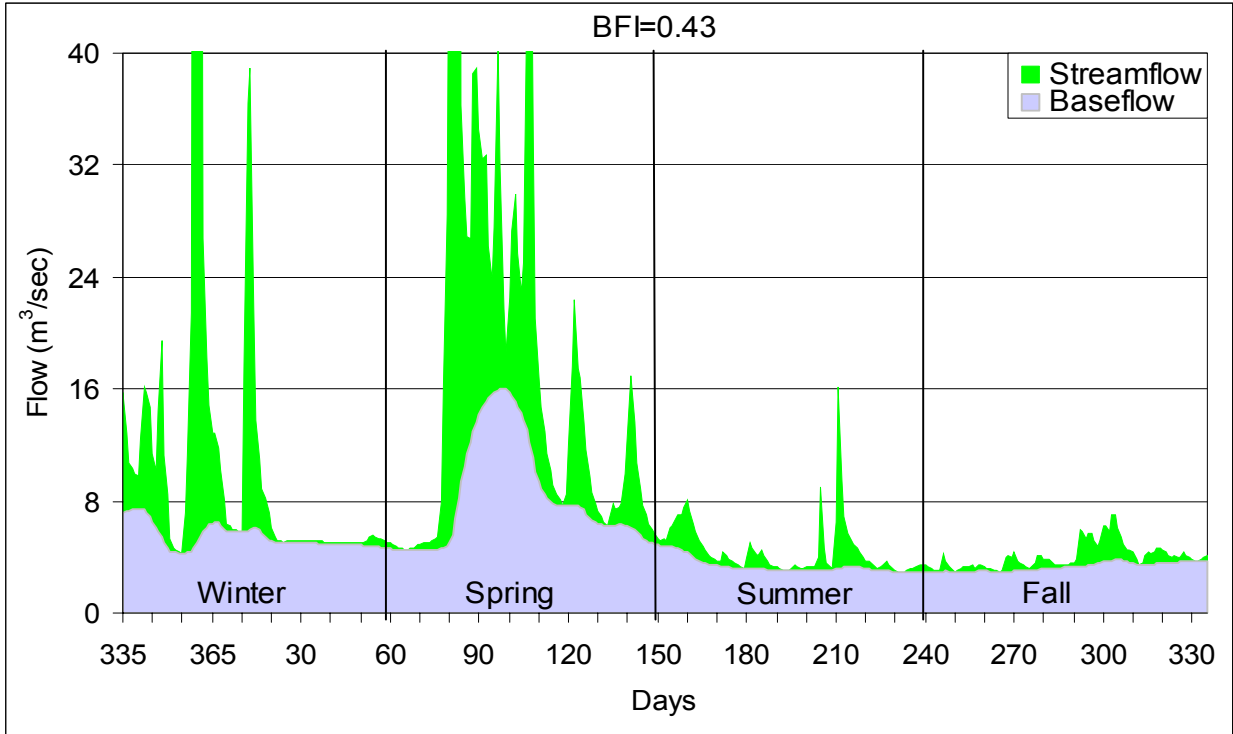


Fig. 4. Stream flow and baseflow hydrographs by Digital filter method for Nith River near Canning for water year 1979-80.

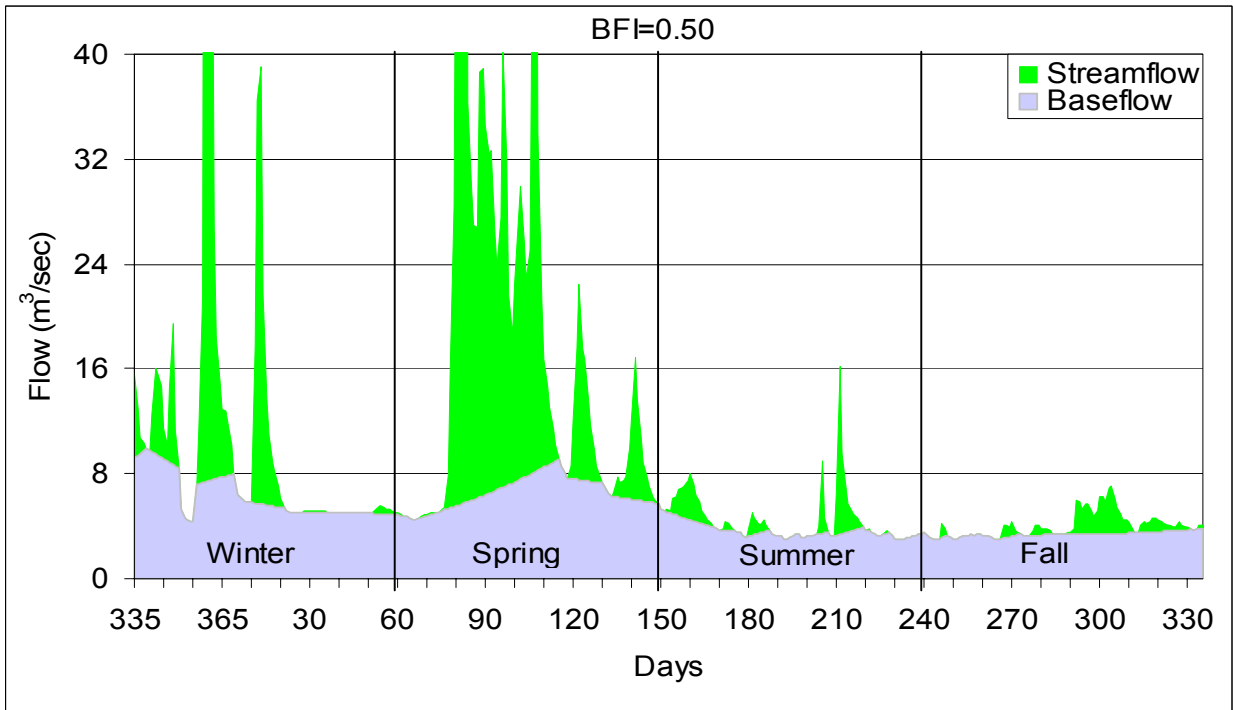


Fig. 5. Stream flow and baseflow hydrographs by PART method for Nith River near Canning for water year 1979-80.

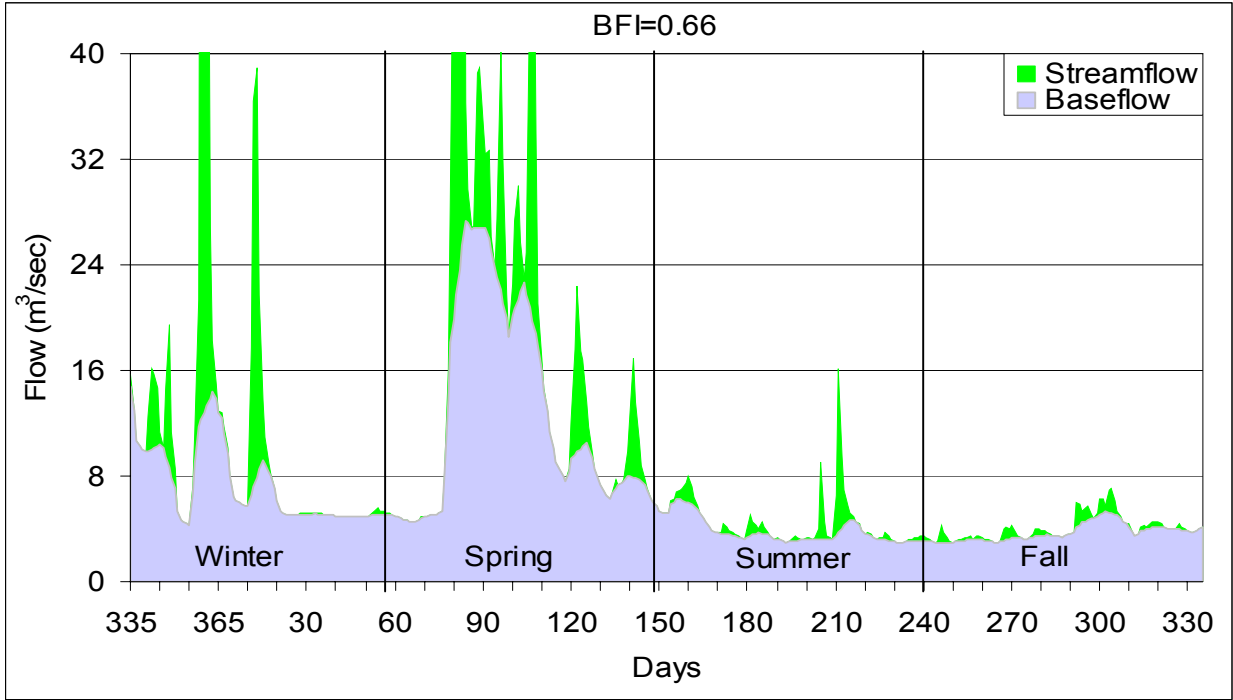


Fig. 6. Stream flow and baseflow hydrographs by UKIH method for Nith River near Canning for water year 1979-80.

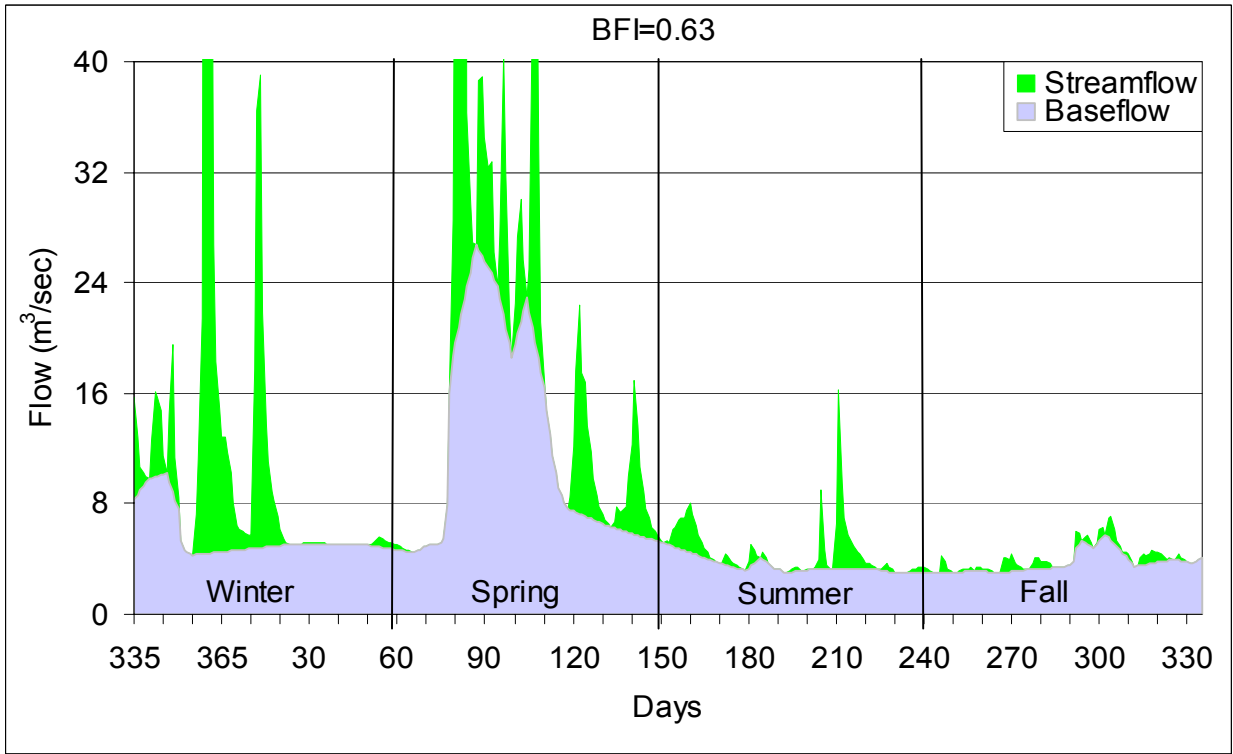


Fig. 7. Stream flow and baseflow hydrographs by Local minima method for Nith River near Canning for water year 1979-80.

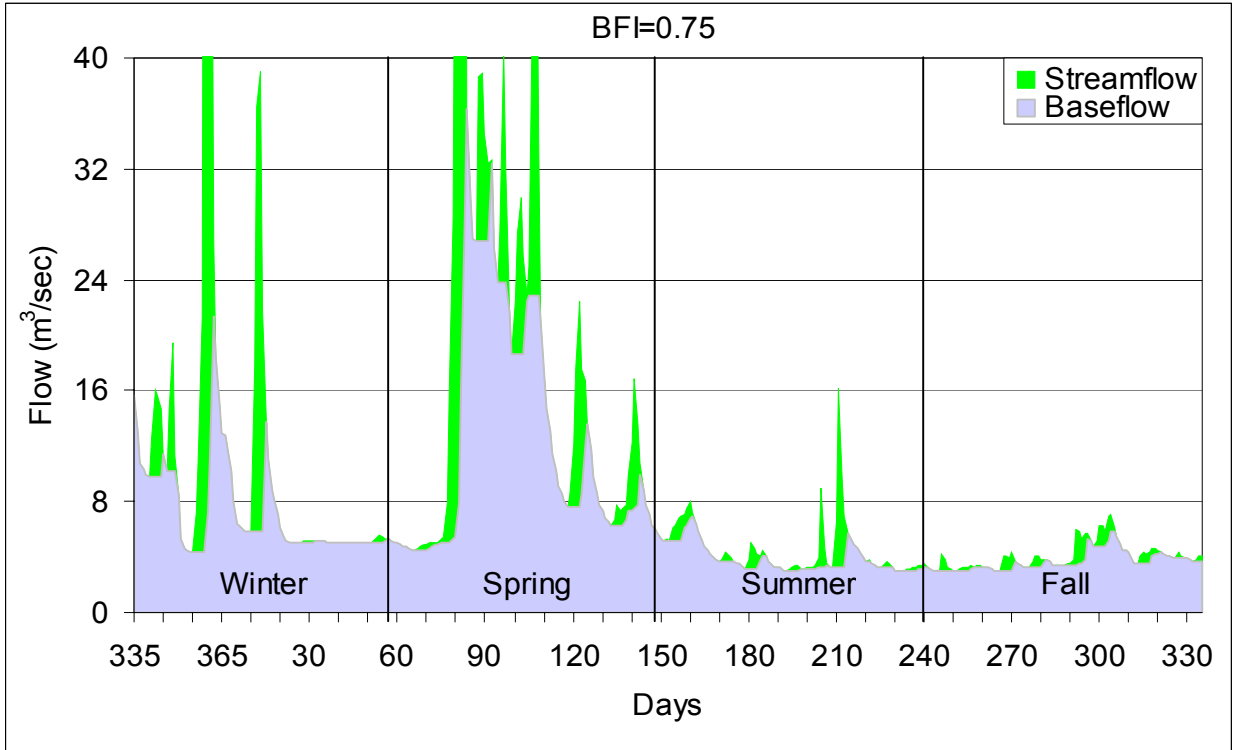


Fig. 8. Stream flow and baseflow hydrographs by Base sliding method for Nith River near Canning for water year 1979-80.

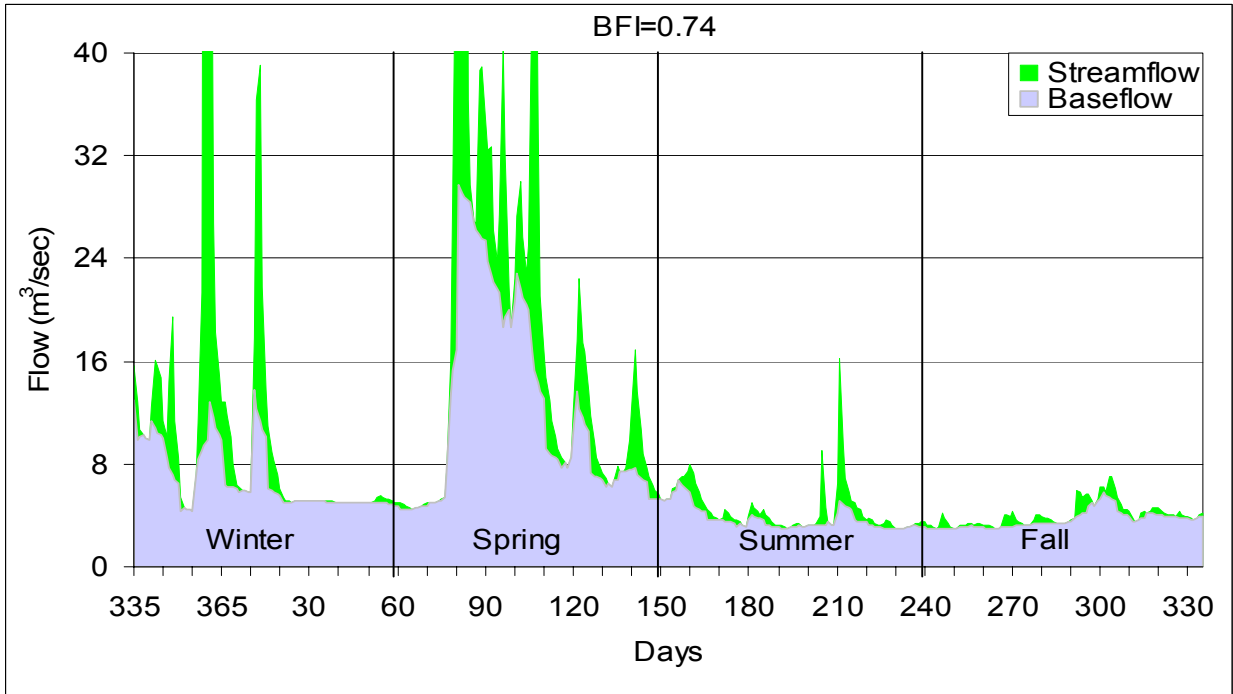


Figure 9. Stream flow and baseflow hydrograph by Base fixed method for Nith River near Canning for water year 1979-80.

Comparison of Baseflow Index

To compare and relate the computed baseflow indices by five different methods (PART, UKIH, local minima, base sliding, and base fixed) were plotted against digital filter method (by considering digital filter as a reference method). The analysis showed that digital filter and PART show a linear relationship with slope 1.16, intercept 0.01, and coefficient of determination 0.90 (Fig. 10). It indicates that PART method and digital filter method produce similar BFI values, however, the difference in BFI increases towards higher BFI. In addition, the intercept of the linear equation is very small (0.01), so it can also be inferred that for low BFI watersheds digital filter method and PART method produce very similar result.

UKIH and local minima methods also have linear relationship with digital filter method having slope 0.93 and 0.90, intercept 0.27 and 0.25, and coefficient of determination 0.73 and 0.89, respectively (Figs. 11-12). These slopes and intercepts show that these two methods produce higher BFI value than the digital filter method. The slopes and intercepts of these two methods are very similar. The coefficient of determination for local minima is 0.89 (Fig. 12) which indicates that sequence of BFI for all watersheds by local minima method and digital filter method have similar trend with very little scatter. The coefficient of determination for UKIH (0.73) gives an indication that UKIH and digital filter methods have similar trend of BFI with larger scatter.

The relationship between the base sliding method and base fixed method with digital filter method show linear relationship with slope 0.72, intercept 0.44, and coefficient of determination 0.65 (Figs. 13-14). These two methods produce higher BFI values than digital filter method and the difference in BFI decreases towards high BFI values.

It is evident from the comparison results that digital filter and PART methods produce lowest BFI values, and base sliding and base fixed methods produce the highest BFI values. UKIH and local minima methods produce moderate BFI values in between the lowest and highest. Therefore, one method from each category, digital filter, UKIH, and base sliding methods were selected for separation of baseflow for 161 watersheds and for developing relationship of baseflow indices with physiographic and physical characteristics of the watershed.

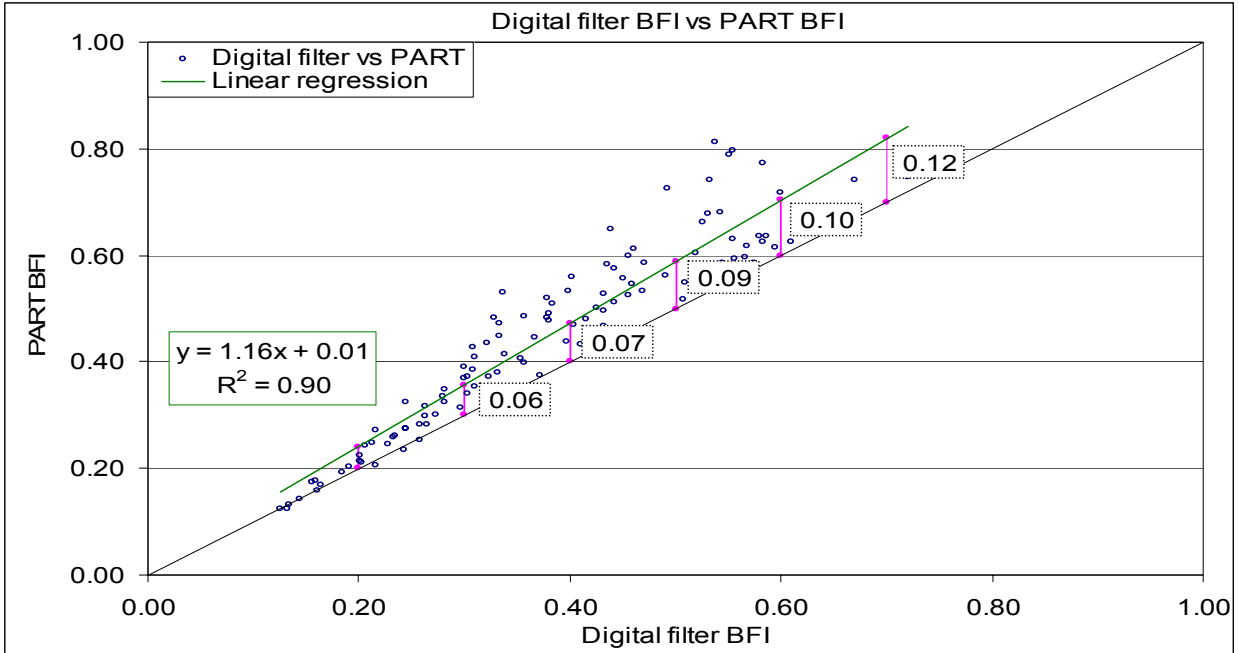


Fig. 10. Digital filter BFI vs PART BFI for 115 Southern Ontario watersheds.

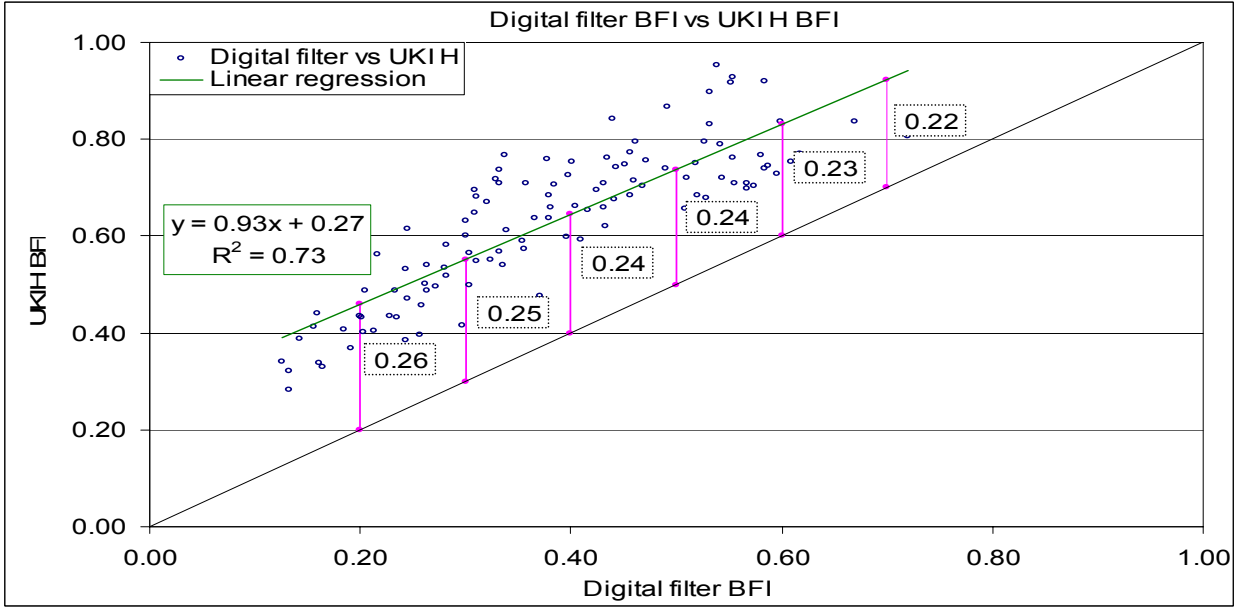


Fig. 11. Digital filter BFI vs UKIH BFI for 115 Southern Ontario watersheds.

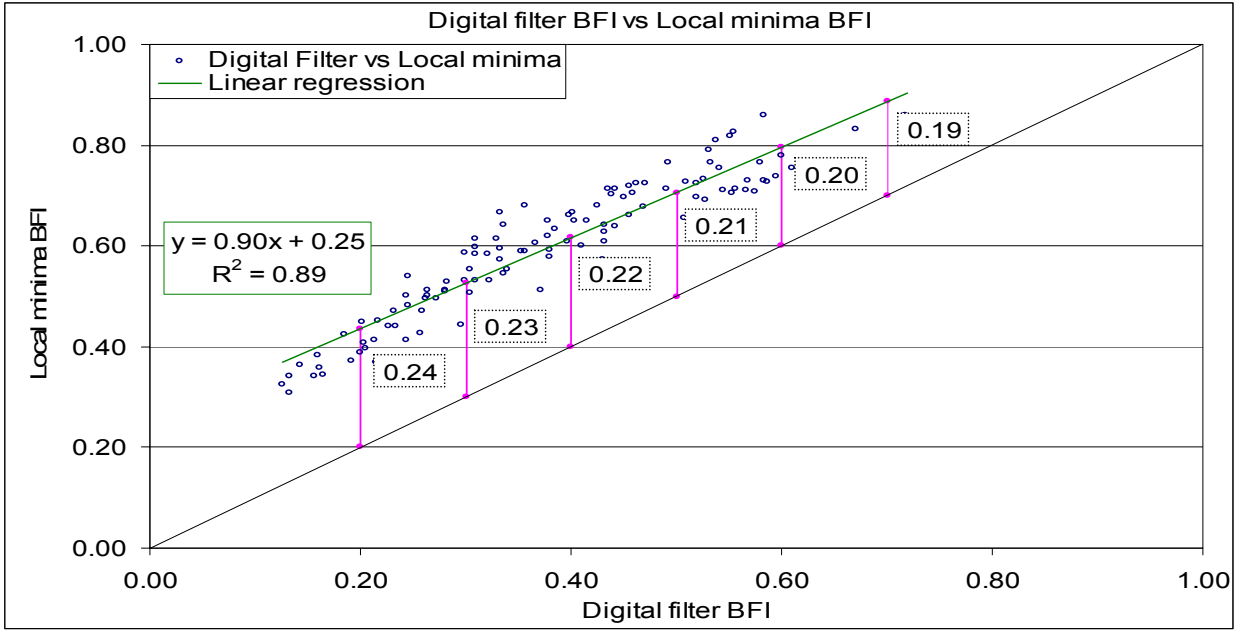


Fig. 12. Digital filter BFI vs Local minima BFI for 115 Southern Ontario watersheds.

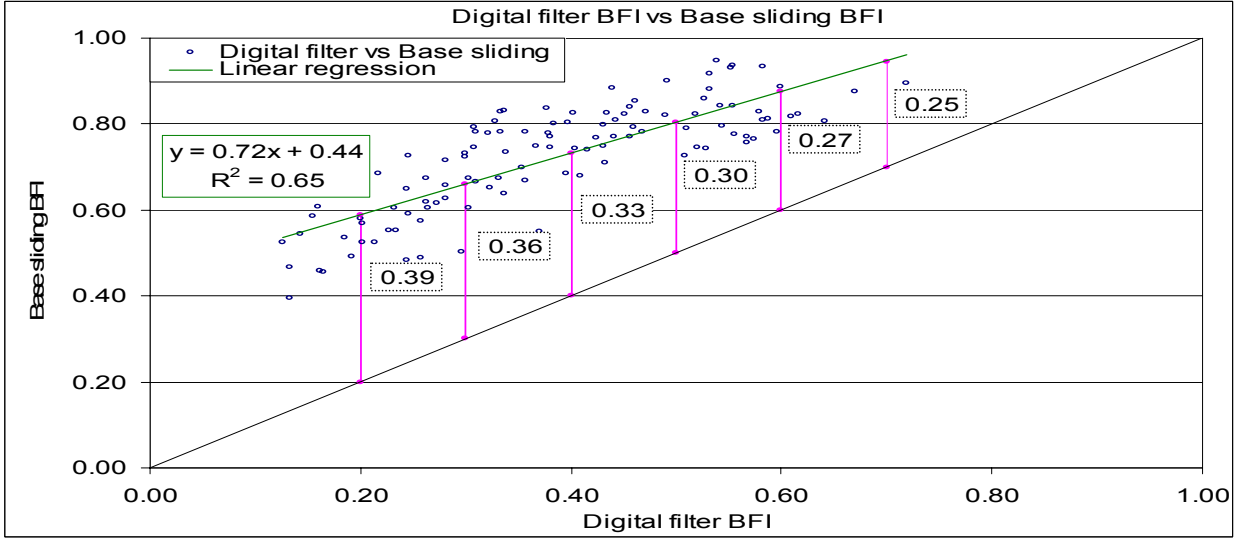


Fig. 13. Digital filter BFI vs Base sliding BFI for 115 Southern Ontario watersheds.

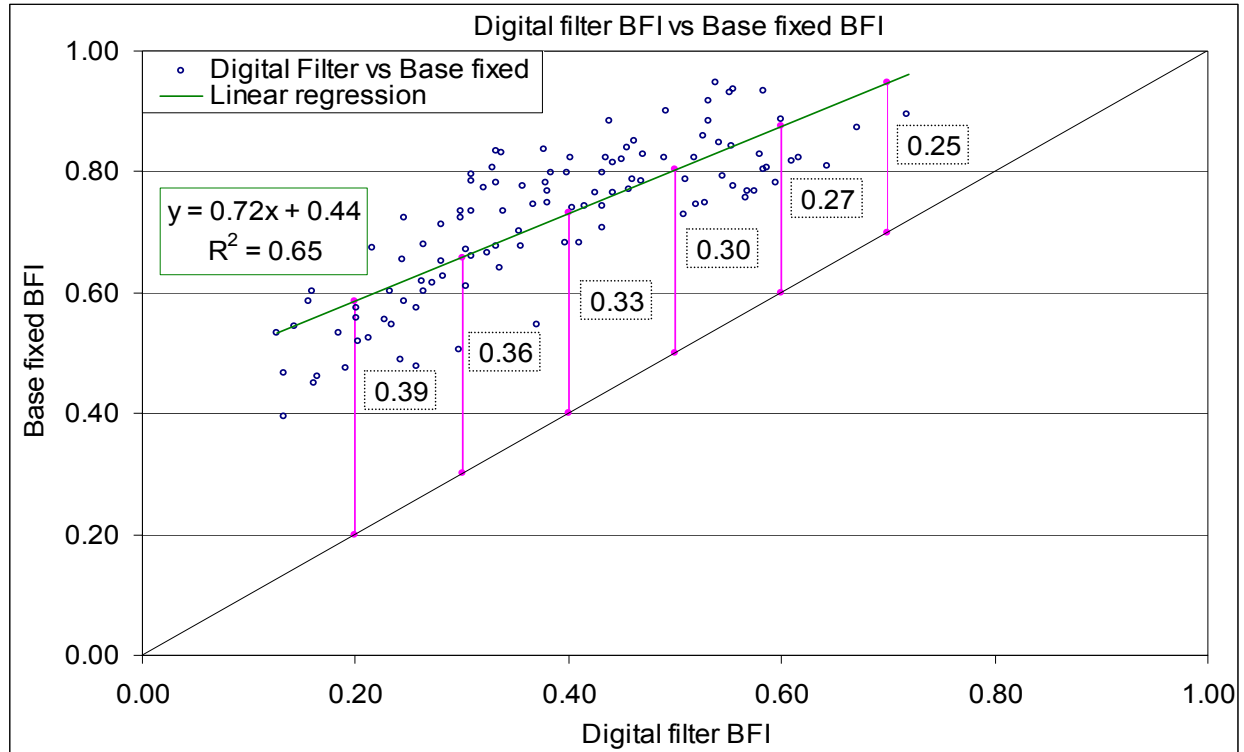


Fig. 14. Digital filter BFI vs Base fixed BFI for 115 Southern Ontario watersheds.

Analysis of frequency distribution for annual BFI

Frequency distribution analyses were conducted to compare the distribution of BFI by three methods (digital filter, UKIH, and base sliding). For this analysis, the BFI values have been divided into ten equal class interval (0 to 1 with an increment of 0.1), and BFI values by all three methods were grouped under each class interval. The frequency distribution graphs are prepared based on the BFI values for 115 watersheds in southern Ontario. The frequency distribution plot for the digital filter and UKIH (Fig. 15) show that BFI estimated by digital filter are clustered between 0.1-0.2 to 0.7-0.8 class intervals and by the UKIH BFIs are grouped between 0.2-0.3 to 0.9-1.0 class intervals with a mean value of 0.39 and 0.72, respectively. There is a difference of 0.24 between the mean values by these two methods. Similarly the BFI estimated by base sliding are clustered toward higher class interval range of 0.3-0.4 to 0.9-1.0 with a difference in mean value of 0.33 when compared with the mean BFI estimated by the digital filter method (Fig. 16). The frequency distribution and difference in mean value indicate that digital filter method produces the lowest BFI, and base sliding method produces the highest BFI. UKIH method produces moderate BFI values in between the lowest and the highest values.

These data also indicate that the digital filter method estimated more than 0.50 value of BFI for 26% of the watersheds (30), UKIH method for 76% of the watersheds (87), and base sliding method for 93% of the watersheds (107) out of 115 watersheds used in the analysis. Examination of these watersheds also indicated that the 30 watersheds identified by digital filter method were common to UKIH and base sliding methods. Therefore, it is very clear that out of 115 southern Ontario watersheds examined, 30

watersheds can be easily designated as slow response watersheds. Similarly, based on this analysis digital filter method identified 85 watershed with BFI less than 0.5, followed by 28 watersheds by UKIH, and 8 by base sliding . Again, 9 identified by base sliding method were common to digital filter and UKIH methods. Therefore, these 9 watersheds can definitely be considered as rapid response.

The frequency distribution analysis was also performed on the BFI for the BFI obtained by three groups of methods for 46 watersheds in northern Ontario. These data show that BFI estimated by digital filter is distributed between 0.3-0.4 to 0.8-0.9 class intervals, UKIH between 0.6-0.7 to 0.9-1.0 class intervals, and base sliding between 0.7-0.8 to 0.9-1.0 class intervals with a mean value of 0.55, 0.86, and 0.89, respectively. Overall, BFI estimated by digital filter is clustered toward lower class interval (Fig. 17) and UKIH and base sliding BFIs are clustered toward upper class interval (Figs. 17-18). The analysis of these data indicated that UKIH and base sliding methods estimated BFI for all the watersheds in northern Ontario more than 0.5 while the digital filter method estimated 50% watershed with BFI more than 0.5 and 50% less than 0.5. These data also indicate that at least 50% (23) watershed can be easily classified as slow response watersheds.

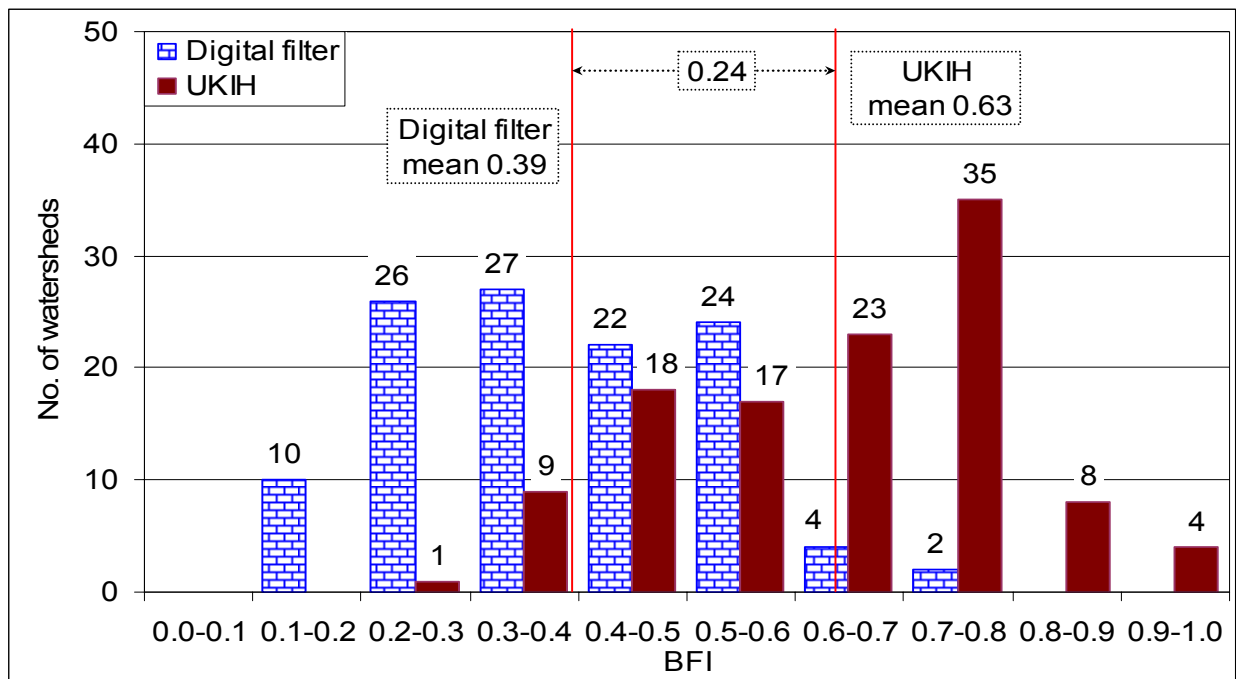


Fig. 15. Frequency distribution of annual BFI using Digital filter and UKIH for 115 watersheds in southern Ontario.

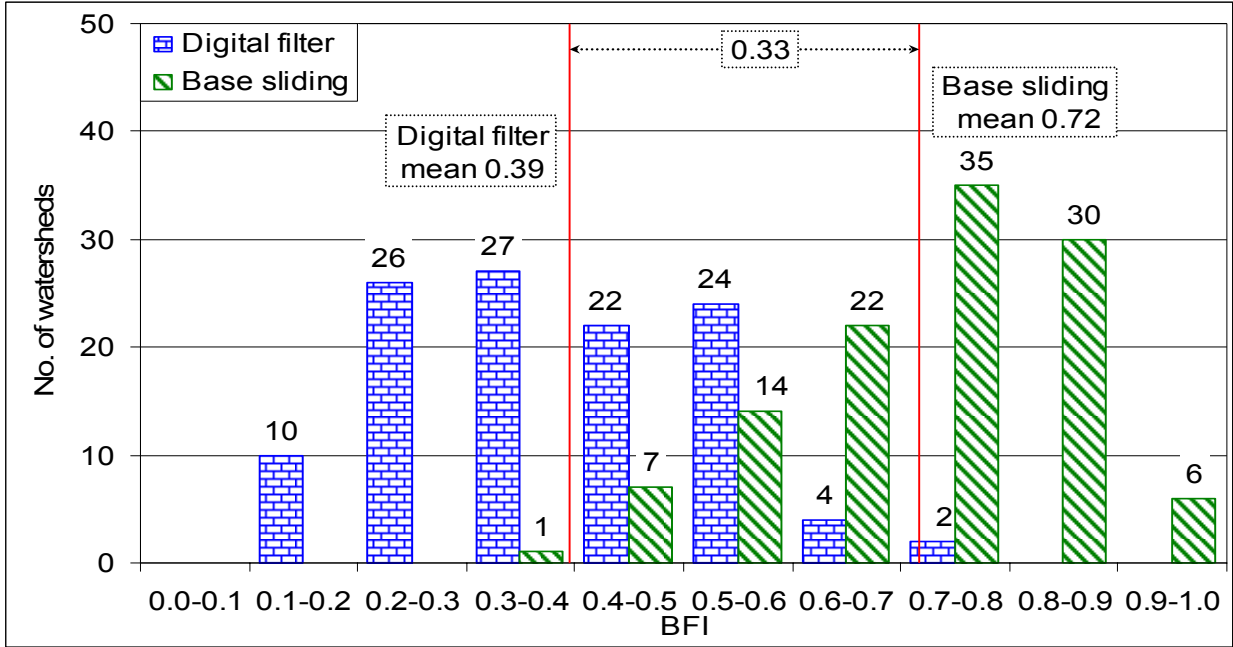


Fig. 16. Frequency distribution of annual BFI using Digital filter and base sliding for 115 watersheds in southern Ontario.

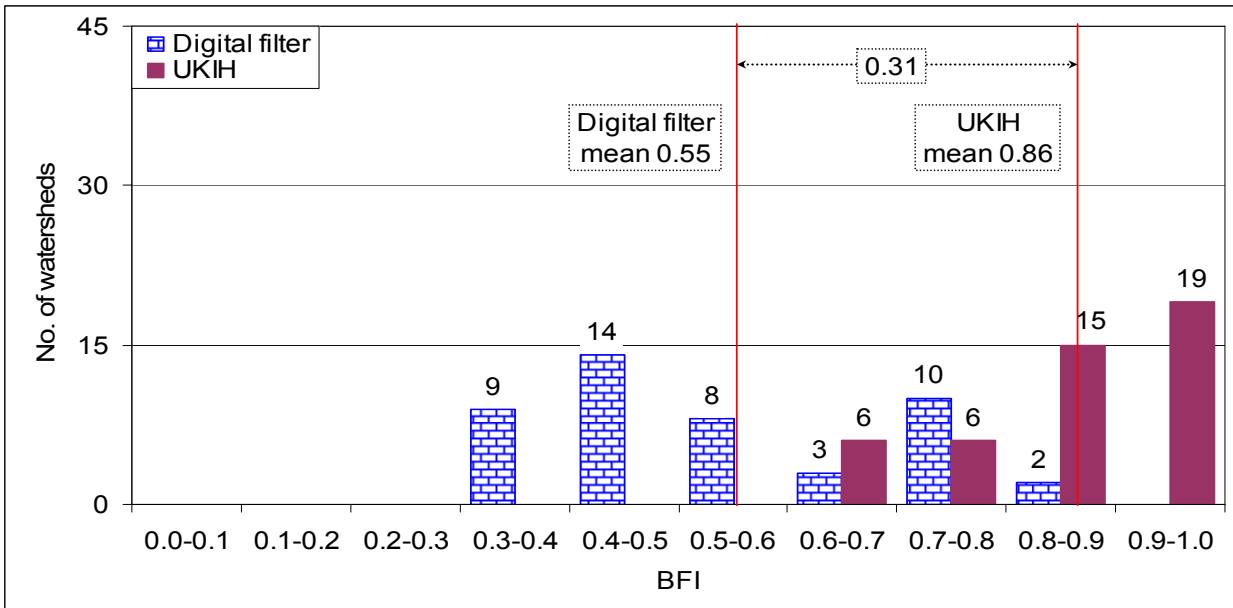


Fig. 17. Frequency distribution of annual BFI using Digital filter and UKIH for 46 watersheds in northern Ontario.

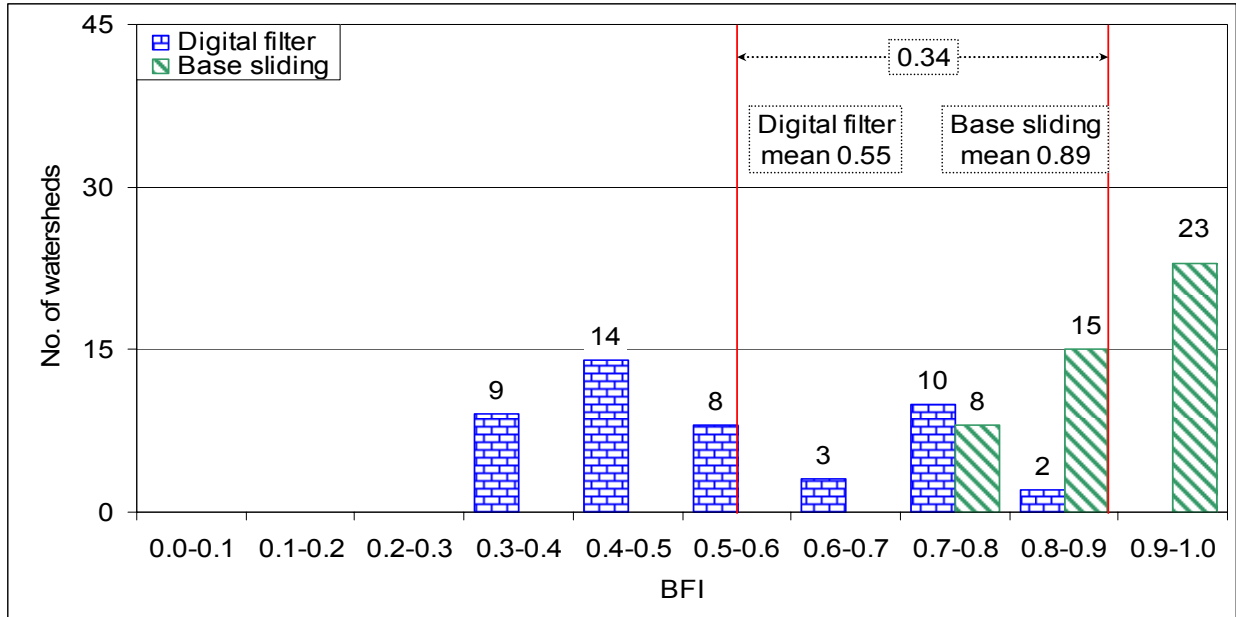


Fig. 18. Frequency distribution of annual BFI using Digital filter and base sliding for 46 watersheds in northern Ontario.

Relationship of BFI and watershed physiography

Based on the physiography, Ontario has been divided into five physiographic regions as shown in Figure 19. Three base flow separation methods (digital filter, UKIH, and base sliding methods) were used to compute BFI for four physiographic regions and the results obtained are presented in Figs. 20-27. The Niagara Escarpment region was not considered because three watersheds identified in this region did not cover more than 15% of the area.

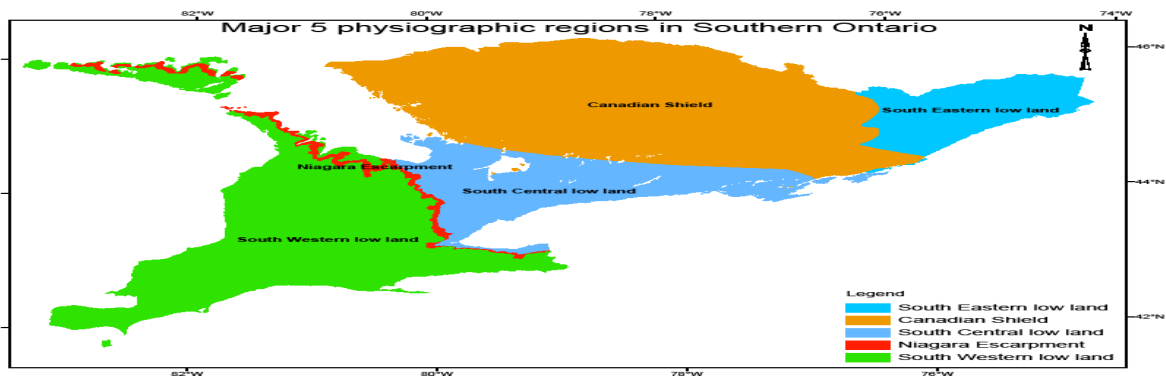


Fig. 19. Five major physiographic regions in southern Ontario.

Frequency distribution of annual BFI (Regional basis)

Figures 20-21 show the frequency distribution of annual BFI with all three methods for all the watersheds (11) for South eastern low land region. The average BFI with digital filter was 0.31 and highest BFI value was found to be less than 0.4. The UKIH method gave an average BFI of 0.68, and range from 0.5 to 0.8. The difference in mean BFI

from these two methods was 0.37 (Fig. 20). The base sliding method estimated average annual BFI of 0.77, and the range was from 0.6 to 0.9. The difference in mean BFI between the digital filter and base sliding was 0.46 (Fig. 21).

The analysis of 13 watersheds for Canadian shield is shown in Figs. 22-23. The analysis of these data indicated annual BFI values of 0.48, 0.82, and 0.87 by digital filter, UKIH, and base sliding methods, respectively. Also, the range for digital filter BFI was 0.3 to 0.6 as compared to 0.6-1.0 by UKIH and base sliding range. The high values of BFI for all the watersheds show that these are dominantly base flow watersheds.

The frequency distribution of BFI for 40 watersheds of South central low land is shown in Figs. 24-25. The annual BFI estimated by digital filter and UKIH methods ranged between 0.2 to 0.6 and 0.3 to 0.8, respectively (Fig. 24), and with a difference in mean of 0.18. The difference between the annual mean BFI estimated by digital filter and base sliding methods was 0.26 (Fig. 25).

Figures 23-24 show the frequency distribution of annual BFI for 56 watersheds in the South western low land region. The analysis showed a wide range of BFI with all three methods. The digital filter estimated an annual BFI ranging between 0.1 to 0.7, and UKIH and base sliding 0.2 to 0.9. The mean differences in annual BFI were 0.24 between digital filter vs. UKIH (Fig. 26) and 0.36 between digit filter and base sliding methods (Fig. 27).

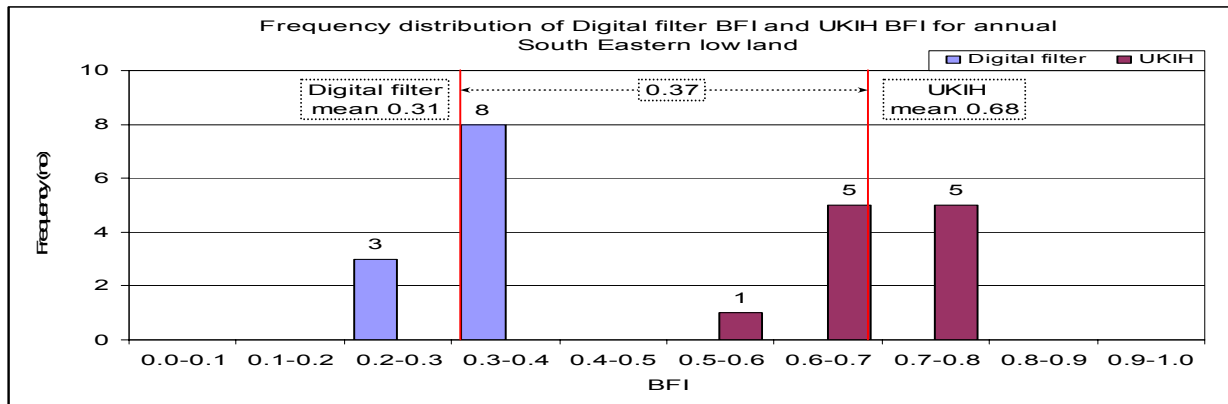


Fig. 20. Frequency distribution of annual BFI using digital filter and UKIH for south eastern low land.

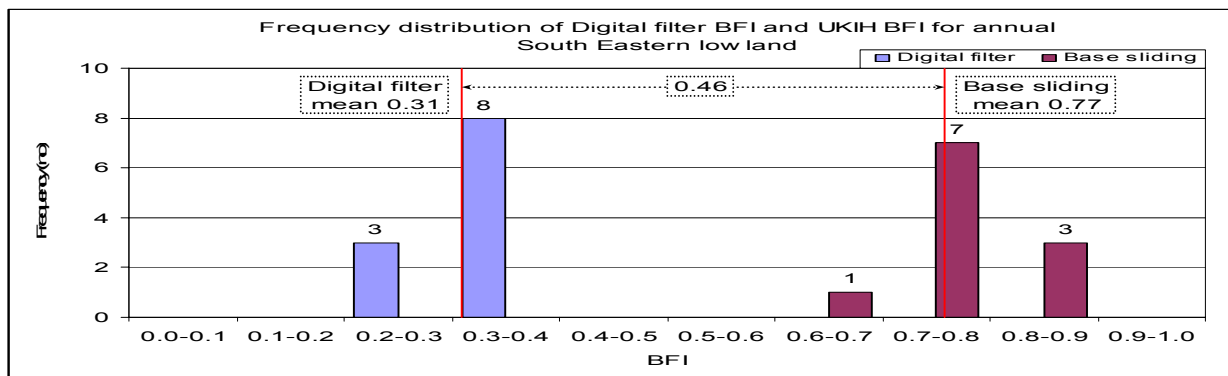


Fig. 21. Frequency distribution of annual BFI using digital filter and base sliding for South eastern low land.

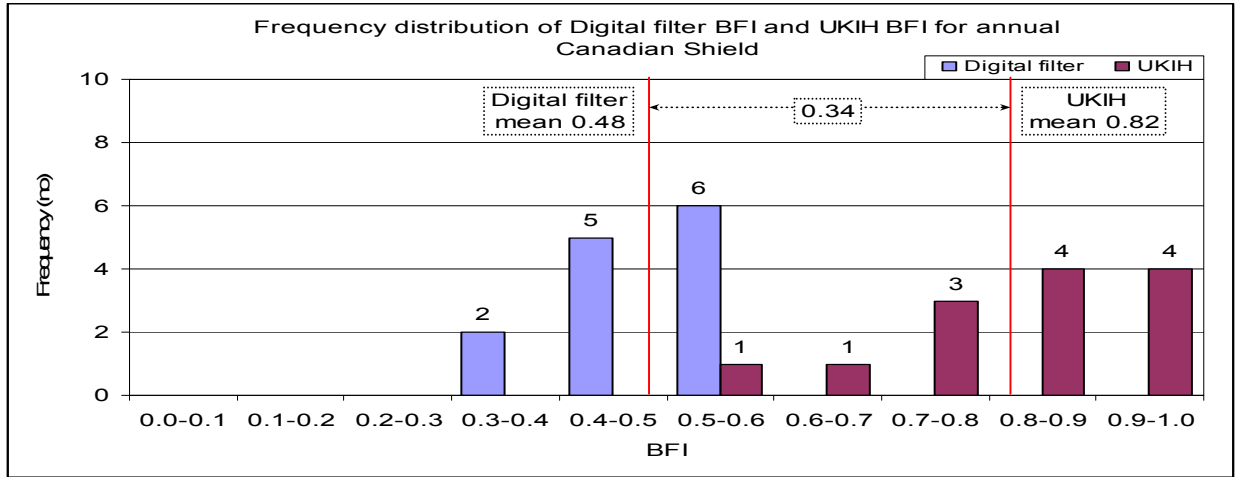


Fig. 22. Frequency distribution of annual BFI using digital filter and UKIH for Canadian shield.

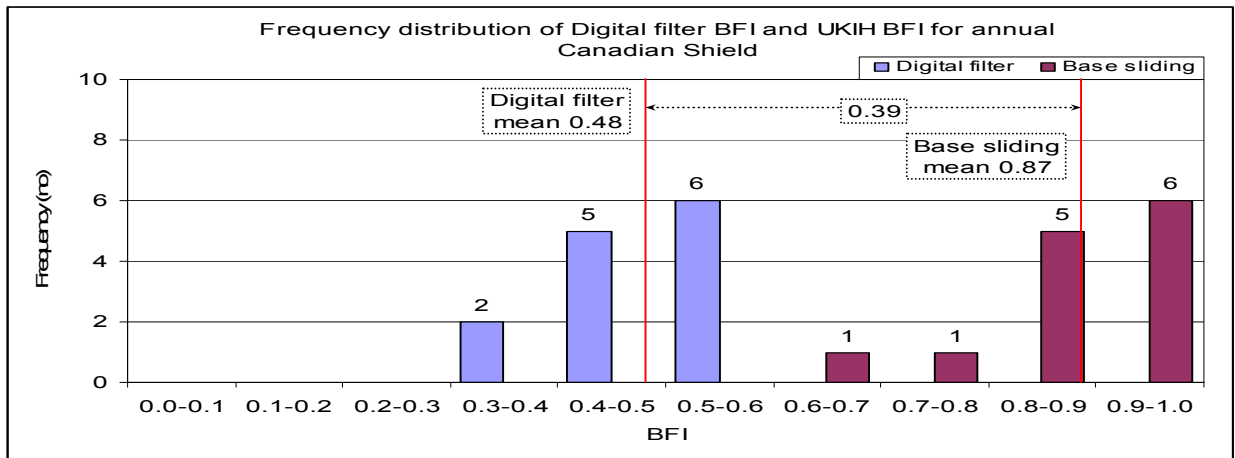


Fig. 23. Frequency distribution of annual BFI using digital filter and base sliding for Canadian shield.

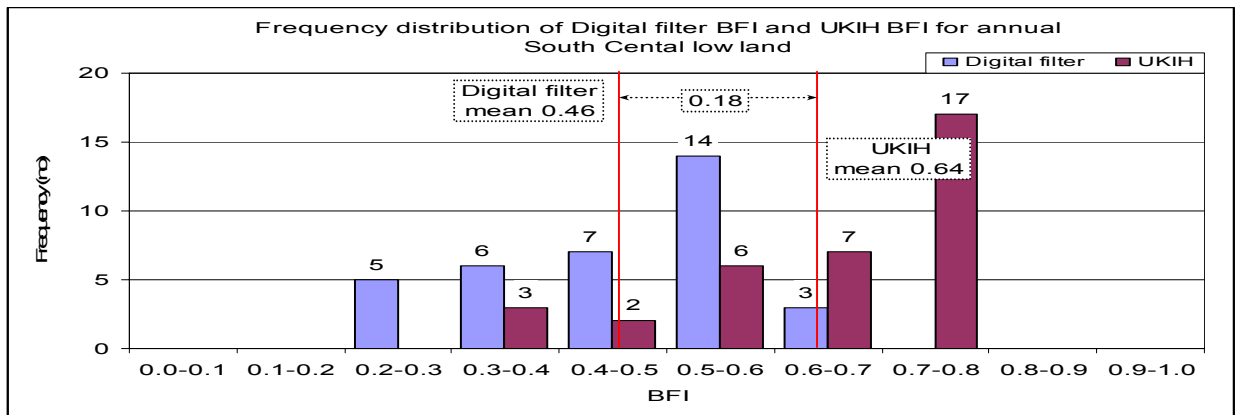


Fig. 24. Frequency distribution of annual BFI using digital filter and UKIH for South central low land region.

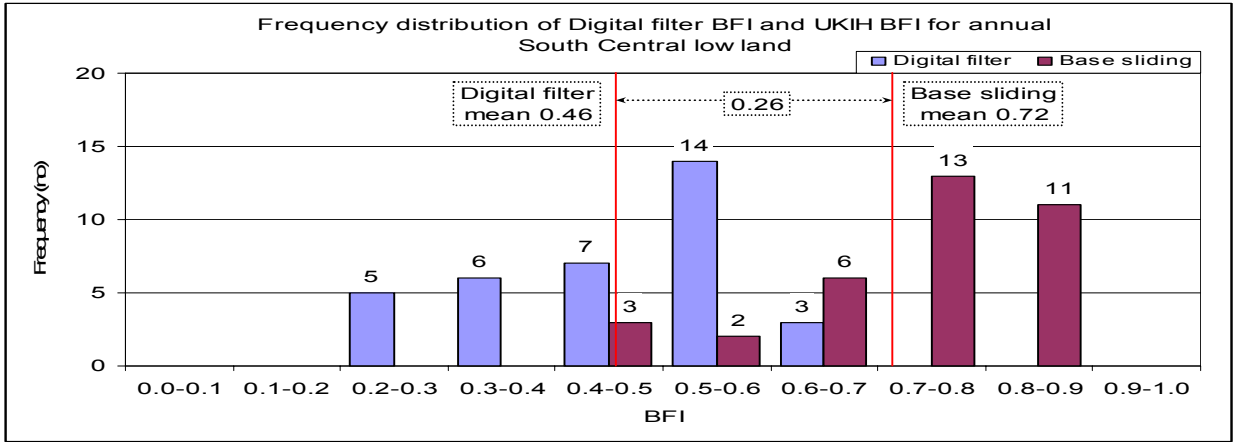


Fig. 25. Frequency distribution of annual BFI using digital filter and base sliding for South central low land region.

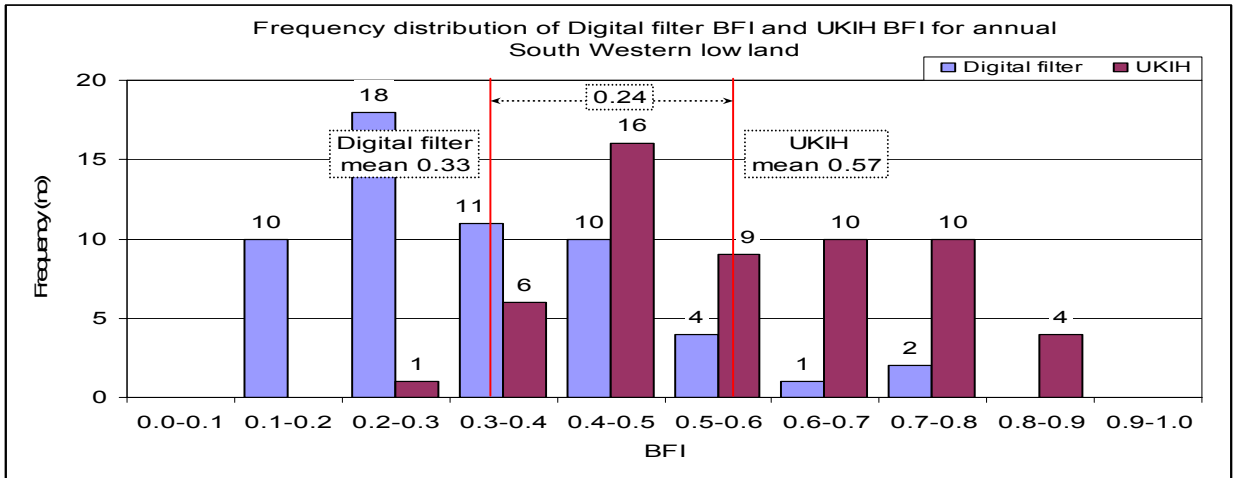


Fig. 26. Frequency distribution of annual BFI using digital filter and UKIH for South western low land region.

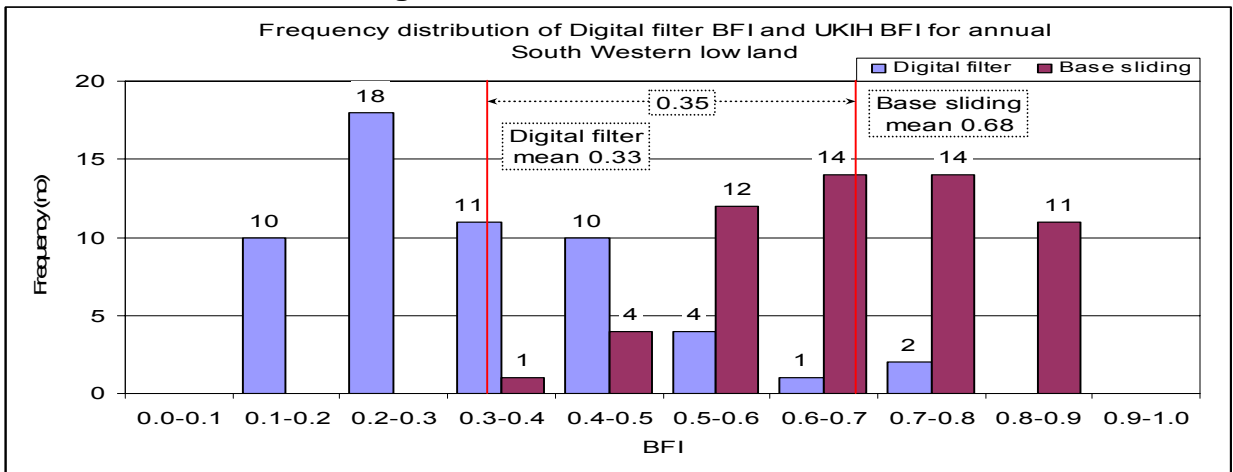


Fig. 27. Frequency distribution of annual BFI using digital filter and base sliding for South western low land region.

This analysis shows that the BFI estimation is method dependent. Therefore, proper attention is needed while comparing the base flow estimated in various studies in the province.

Analysis of annual and seasonal BFI

Tables 1-3 show the average annual and seasonal BFI for four regions (115 watersheds) in southern Ontario with three selected methods. The trends of BFI with all three methods were found to be similar; however, the magnitude varied with the method. The annual BFIs using digital filter for south eastern low land and south western low land regions were found to be similar (0.31 and 0.33, respectively), and this trend was also evident for seasonal BFIs for these regions (Table 1). Analysis of physiographic characteristics of these watersheds shows that both of the regions are predominantly sand or clay plains (Chapman and Putman, 1984).

The annual mean BFIs for Canadian shield and south central low land regions were also found to be similar (0.48 and 0.46, respectively) as shown in Table 1. The Canadian shield area is mostly comprised of granite, igneous, and metamorphic rocks and mostly non agriculture due to shallow, sandy, and acid soils. Therefore, due to the physiographic characteristics (high recharge rate), no farming activities, and barren land, the contribution of base flow to stream flow was the highest among all four regions using all three separation methods (Tables 1-3).

The seasonal BFI analysis for these physiographic regions showed that baseflow contribution estimated by UKIH and base sliding methods was highest during winter months (Dec.-Feb.) followed by spring, summer, and fall when calculated. However, the pattern was slightly different with the digital filter method. The digital filter method also showed high BFI during winter for some regions followed by summer, spring, and fall.

Another analysis was conducted to identify the number of watersheds in these four physiographic regions on the basis of slow response and rapid response and the results are presented in Table 4. The criterion used was based on the results from the digital filter, the most conservative method for the estimation of BFI. It was assumed that the watershed which have less than 0.5 value of BFI would be categorized as rapid response watersheds. Also, the watersheds would be categorized as slow response when the BFI is more than 0.5. This analysis indicated that there is no rapid response watershed in South eastern low land and Canadian shield regions. There were 3 rapid response watersheds in South central low land and 5 in South western low land. The total number of the slow response watersheds were 30 out of 115 , and none of these watersheds were in South eastern low land region. The South central low land, south western low land, and Canadian shield regions have 17, 7, and 6 slow response watersheds, respectively. The other watersheds which do not lie in these two categories are identified as moderate response watersheds.

Table 1. Average annual and seasonal BFI for four physiographic regions by Digital filter method.

<i>Physiographic Region</i>	<i>Annual BFI</i>	<i>Spring BFI</i>	<i>Summer BFI</i>	<i>Fall BFI</i>	<i>Winter BFI</i>
South Eastern low land	0.31	0.31	0.34	0.32	0.36
Canadian Shield	0.48	0.45	0.55	0.46	0.60
South Central low land	0.46	0.42	0.53	0.53	0.46
South Western low land	0.33	0.34	0.37	0.33	0.33

Table 2. Average annual and seasonal BFI for four physiographic regions by UKIH method.

<i>Physiographic Region</i>	<i>Annual BFI</i>	<i>Spring BFI</i>	<i>Summer BFI</i>	<i>Fall BFI</i>	<i>Winter BFI</i>
South Eastern low land	0.68	0.68	0.61	0.63	0.68
Canadian Shield	0.82	0.83	0.82	0.79	0.84
South Central low land	0.64	0.63	0.65	0.68	0.64
South Western low land	0.57	0.59	0.54	0.55	0.55

Table 3. Average annual and seasonal BFI for four physiographic regions by base sliding method.

<i>Physiographic Region</i>	<i>Annual BFI</i>	<i>Spring BFI</i>	<i>Summer BFI</i>	<i>Fall BFI</i>	<i>Winter BFI</i>
South Eastern low land	0.77	0.77	0.74	0.73	0.77
Canadian Shield	0.87	0.87	0.88	0.84	0.89
South Central low land	0.72	0.71	0.71	0.73	0.71
South Western low land	0.68	0.69	0.65	0.65	0.67

Table 4. List of slow and rapid response watersheds for four physiographic regions.

<i>Physiographic Region</i>	<i>Total watersheds</i>	<i>Rapid response</i>	<i>Slow response</i>
South Eastern low land	11	-	-
Canadian Shield	13	-	6
South Central low land	35	3	17
South Western low land	56	5	7
<i>TOTAL</i>	<i>115</i>	<i>8</i>	<i>30</i>

The comparison of annual and seasonal mean BFI for all 115 watersheds for all four physiographic regions also showed that digital filter gives the lowest and base sliding gives the highest BFI (Table 5). In addition, seasonal analysis shows that digital filter

gives highest BFI during summer than the other seasons. However, UKIH and base sliding methods give higher BFI during spring and winter season.

Table 5. Summary of average annual and seasonal BFI by three methods for 115 watersheds in southern Ontario.

Method	Annual BFI	Spring BFI	Summer BFI	Fall BFI	Winter BFI
Digital filter	0.39	0.38	0.43	0.40	0.41
UKIH	0.63	0.64	0.61	0.62	0.62
Base sliding	0.72	0.72	0.70	0.70	0.72

Relationship between BFI and Physiographic Characteristics

As described earlier that Chapman and Putman (1984) have divided Ontario into five major physiographic regions, these regions have been further subdivided into 55 minor physiographic regions. The analysis of the possible relationship between the BFI and the regional physiographic characteristics was done by using the data provided by Chapman and Putman (1984). The analysis is based on the analysis for 10 (out of 115) watershed with highest BFI and 10 with lowest. It was found that most of the watersheds which lie in lowest BFI group are comprised of heavy clay soil and flat slope. The dominant soils with low hydraulic conductivity and relatively flat topography result in slow internal drainage and less movement of rain water to deeper layers. While the base sliding method partitions tile flow as surface runoff.

For the 10 watersheds with highest BFI in southern Ontario, the physiographic characteristics of Moira River watershed, Hasting County, are typical example of most of the watersheds in this category. The physiography of these watersheds mostly contains moraine, rocky, and sandy soils. In some watersheds, the underlying bedrock is sedimentary limestone. Some of the watersheds also have been overlaid by outwash sand and gravel. Overall, all of these characteristics help in good drainage through the soil profile.

Table 6 shows 21 watersheds identified as having single physiographic/physical feature in southern Ontario. Some of the data such as soil type and drainage class were pooled for simplicity and to evaluate the effectiveness of these variables in hydrological processes. The hydrologic soil groups (A,B,C, and D) were combined as A plus B as one group, and C plus D as the other group as show in Table 6. Similarly drainage classes were also pooled as poorly drained and well drained soils. These 21 watersheds cover 14 minor physiographic regions. However, The St. Clair clay plain has 4 watersheds, and Haldimand clay plain and Glengarry till plain have two watersheds each.

The analysis of BFI and runoff coefficient (RC) for these watersheds show that area of the watershed, slope, and depth of bedrock have no effect on BFI or RC based on the data used for slope class and identification of bedrock. As mentioned earlier that the GIS layer for the depth of bedrock was not available from any reliable sources, so it could be due to the poor quality of the data available used in this analysis. Also, some

of the data (GIS layer) available on soil class was very crude. The slope class data were available in the range. The poor quality of available data might be one of the reasons that effect of depth of bedrock and slope was not visible in the analysis. However, BFI and RC both were affected by soil group, drainage class, and percent of tile area.

Table 6. Analysis of 21 watersheds having single class physiography for southern Ontario.

Station ID	Major Physio.	Minor physio.	Area (km²)	Soil (A+B)%	Soil (C+D)%	Bedrock depth (m)	slope (%)	Landuse	Tile area (%)	Well drain (%)	Poor drain (%)	Digital BFI	RO Coeff. (RC)
02GH003	South Western	St. Clair clay plains	180	2	95	15	2.0	Ag. (100%)	54	2	95	0.13	0.33
02GH011	South Western	St. Clair clay plains	51	5	95	49	2.4	Ag. (99%)	32	5	95	0.13	0.33
02HA024	South Western	Haldimand clay plain	81	1	97	9	3.9	Ag. (89%)	5	19	79	0.14	0.30
02HA020	South Western	Haldimand clay plain	170	1	95	33	10.9	Ag. (100%)	14	20	77	0.16	0.30
02GH002	South Western	St. Clair clay plains	140	5	94	18	2.0	Ag. (100%)	76	5	94	0.16	0.33
02GC029	South Western	Mount Elgin ridges	140	5	85	64	5.6	Ag. (100%)	51	13	79	0.23	0.22
02GD019	South Western	Stratford till plain	45	3	92	45	2.0	Ag. (100%)	72	12	88	0.25	0.30
02GH004	South Western	St. Clair clay plains	19	13	87	23	8.8	Ag. (81%)	0	13	87	0.30	0.33
02GD010	South Western	Stratford till plain	150	20	74	58	5.5	Ag. (100%)	65	44	51	0.30	0.22
02MC028	South Eastern	Glengarry till plain	84	66	34	24	6.5	Ag. (100%)	8	60	40	0.31	0.33
02MC026	South Eastern	Glengarry till plain	133	64	36	26	6.5	Ag. (100%)	7	59	41	0.33	0.33
02LB017	South Eastern	Edwardsburg sand plain	76	65	35	0	4.0	Ag. (100%)	3	35	65	0.33	0.25
02GD004	South	Oxford till	260	58	38	17	6.5	Ag.	48	52	45	0.35	0.22

	Western	plain						(100%)					
02HM009	Canadian Shield	Napanee plain	6	0	94	0	2.0	Forest (87%)	0	0	100	0.36	0.52
02HJ001	South Central	Peterborough drumlin field	120	69	4	79	6.5	Ag. (100%)	1	68	28	0.38	0.24
02ED017	South Central	Simcoe uplands	58	77	21	47	5.2	Ag. (100%)	0	74	26	0.43	0.18
02FC011	South Western	Teeswater drumlin field	150	78	6	0	7.6	Ag. (83%)	21	70	27	0.46	0.26
02HC023	South Central	Oak Ridges moraine	65	13	78	82	10.4	Ag. (65%)	4	87	6	0.56	0.18
02KD002	Canadian Shield	Algonquin highlands	846	29	5	0	8.1	Forest (100%)	0	29	5	0.58	0.17
02GC021	South Western	Norfolk sand plain	78	68	27	42	2.0	Ag. (100%)	6	49	46	0.72	0.19
02GA043	South Western	Waterloo hills	13	85	13	28	2.0	Ag. (100%)	8	86	11	0.72	0.12

Table 7. Detail for soils for the six watersheds used to evaluate the tile effect on base flow.

Station ID	% Tile area	Digital BFI	Soil A (%)	Soil B (%)	Soil C (%)	Soil D (%)	Undefined (%)	(A+B) %	(C+D) %
02GH002	76	0.16	5		13	81	1	5	94
02HA022	0	0.13	1	1	64	30	4	2	94
02FF004	70	0.16	5	3	46	41	5	8	87
02GH004	0	0.30	13		1	86		13	87
02GD010	65	0.30	1	20	70	3	6	20	74
02HC029	0	0.43	8	9	71	3	8	17	74

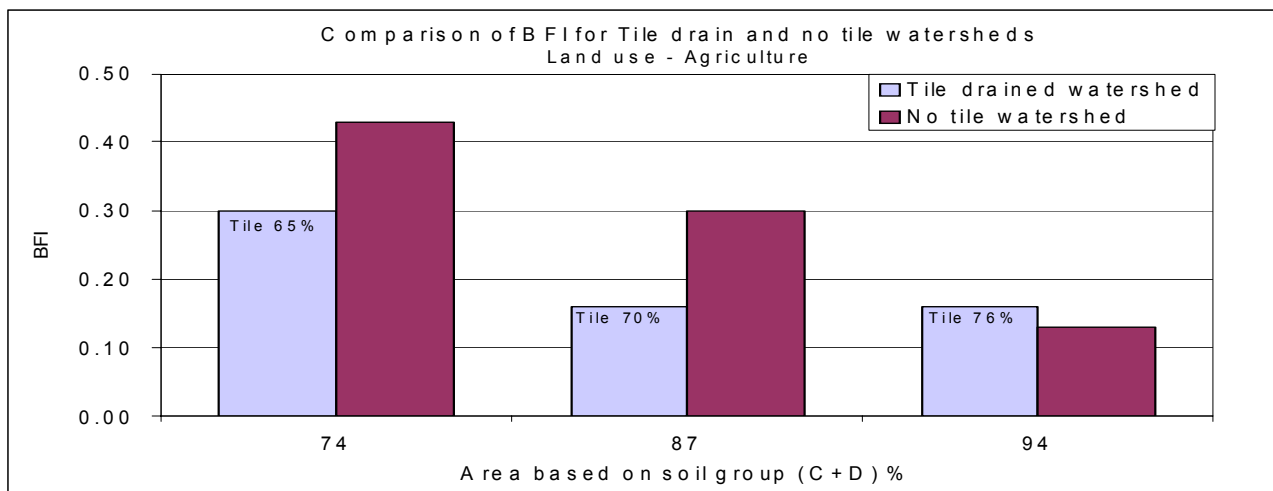


Fig. 28. Comparison of BFI for tile and no-tile watersheds for Soil group C and D.

To further analyze the effect of tile drains on base flow six watersheds were selected, three tiled and three with no-tile drainage, having similar soil group (C+D) and similar landuse and the results are shown in Figure 28. Table 7 shows the detail of soils for these watersheds. These results show that tile drainage reduces the amount of baseflow and tile flow contributes to streamflow as either interflow or rapid flow in the hydrology of a watershed. It was also observed that when percentage of heavy soil increases, most of the streamflow contribution to the stream is in the form of surface runoff and tile flow. More research and analysis of the data compiled in this study is needed to identify the base flow separation method most suitable for dominantly tile drained watersheds.

To evaluate the effect of landuse on baseflow, the soil and limited landuse data were used for these watersheds. Figures 29-30 show the effect of landuse on BFI for these watersheds. Figure 29 illustrates that there is a significant difference in BFI values of agriculture and forest watersheds on similar soil. Also, as the percentage of C+D soils area increased, the difference in BFI became more prominent. However, effect of landuse on BFI was not much different on light soils (A+B) as shown in Fig. 30.

Therefore, it can be concluded from this analysis that effect of landuse varies with soil type in a watershed.

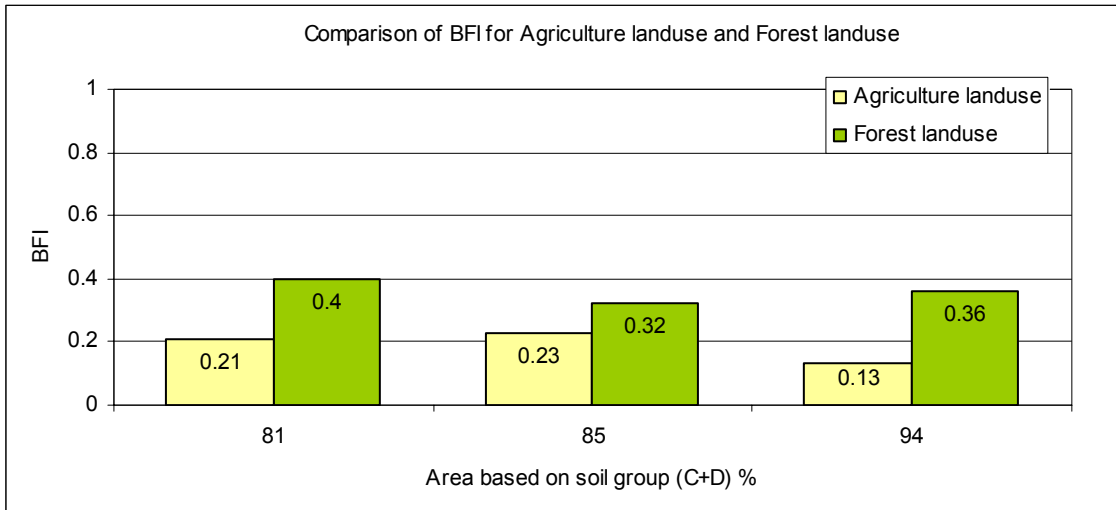


Fig. 29. Comparison of BFI for tile and no-tile watersheds for Soil group C and D.

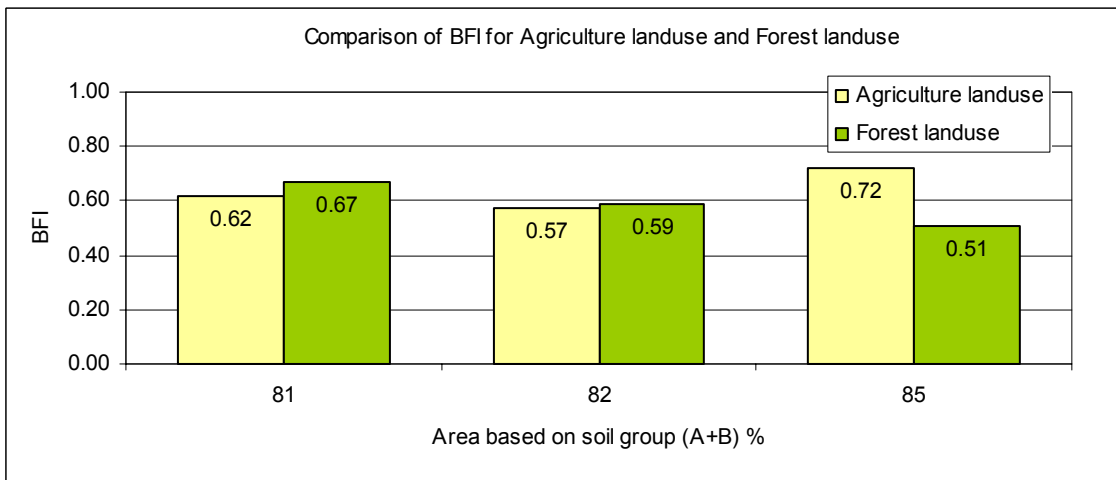


Fig. 30. Comparison of BFI for tile and no-tile watersheds for Soil group A and B.

CONCLUSIONS and RECOMMENDATIONS

The results were related to the physiography/physical characteristics of the watershed. The conclusions of the study are:

- The lowest amount of baseflow is generated by digital filter method and the highest by base sliding method. Baseflow hydrograph generated by digital filter method appears to be more realistic than any other methods.
- The average annual and seasonal BFI for four regions (115 watersheds) in southern Ontario were found to be similar for south eastern low land and south western low

land regions (0.31 and 0.33, respectively), and this trend was also evident for seasonal BFIs for these regions. Analyses of physiographic characteristics of these watersheds show that both regions are predominantly sand or clay plains.

- The seasonal BFI analysis for four physiographic regions showed that baseflow contribution was highest during winter months followed by spring, summer, and fall when calculated by the UKIH and base sliding methods. However, digital filter showed highest BFI values during summer, followed by spring and fall for BFI for these physiographic regions.
- Classification of slow and rapid response watersheds on annual basis showed that out of 115 watersheds in southern (southern, central and eastern) Ontario 30 can be classified as slow response watersheds, 9 as rapid response watersheds, and 66 as medium response watersheds. For the 46 watersheds in northern Ontario, all the watersheds can be classified as slow response watersheds. Also, the identification of watersheds as slow and rapid response lead to suitability of base flow separation method for a specific area. For example, base sliding method can be effectively used for northern Ontario as those watersheds are dominantly base flow watersheds.
- The analysis to divide the number of watersheds on the basis of slow response and rapid response showed that there is no rapid response watershed in South eastern low land and Canadian shield regions, and there are only 3 rapid response watersheds in south central low land and 5 in South western low land. The South central low land, South western low land, and Canadian shield regions have 17, 7, and 6 slow response watersheds, respectively. The other watersheds which do not lie in these two categories are named as moderate response watersheds. More research is needed to further classify the medium response watershed for source protection and nutrient management.
- Analysis of subdivision of five major physiographic regions into 55 minor physiographic regions, according to their characteristics, showed that most of the watersheds in the lowest BFI group are comprised of heavy clay soil and low slope. These characteristics of soil and topography result in low hydraulic conductivity and slow movement of rain water to deeper layer in the soil profile. For the highest BFI watersheds, it was found that the physiography of these watersheds is mostly dominated by moraine and sandy soil. In some watersheds, the underlying bedrock is sedimentary limestone. Also, some of the watersheds have been overlaid by outwash sand and gravel.
- The analysis of watersheds having single physiographic feature showed that the BFI and runoff coefficient (RC) were not affected by the area of the watershed. Due to lack of detailed data on slope class and depth of bedrock, the significant effect of these factors on BFI or RC was not visible. However, BFI and RC both were affected by hydrologic soil group, soil drainage class, and percent of tile drained area. Since most of these watersheds are agricultural watersheds and due to lack of detailed land use data, it was difficult to determine the significance of land use on base flow.
- The analysis of effect of tile drains on base flow showed that tile drainage reduces

the amount of baseflow and tile flow contributes to streamflow as either interflow or rapid flow in the hydrology of a watershed. It was also observed that when percentage of heavy soil increases, most of the streamflow contribution to the stream is in the form of surface runoff and tile flow.

- The results of this study have shown significant relationship between BFI hydrologic soil group, tile drainage, and soil drainage classes. The results from this study would lead to better nutrient management practices in Ontario.
- This intensive study has also highlighted many important gaps such as further similar research and availability of quality data. There was very limited sources and availability of data on tile drainage, slope class, bedrock depth. For northern Ontario, scarcity of physiographic data put this research on abrupt hold in terms of physiographic analysis for those watersheds. Since most of the watersheds are baseflow watersheds, efforts and plans should be developed to prepare database for northern part of the province.

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