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THE RELATIONSHIP BETWEEN WATERSHED PHYSIOGRAPHY, TILE FLOW, AND STREAMFLOW CHARACTERISTICS

R.P. RUDRA[1], S.I. AHMED[1], M. KHAYER[1], W.T. DICKINSON[1], B. HARABAGHI[1]

[1] R.P. RUDRA, Professor, School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1, rrudra@uoguelph.ca.
[1] S.I. AHMED, Post Doctorate Fellow.
[1] M. KHAYER, Graduate Student.
[1] W.T. DICKINSON, Emirates Professor.
[1] B. GHARABAGHI, Associate Professor.

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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 to characterize a 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 a 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 lowest amount of baseflow is generated by digital filter method and the highest by base sliding method. Out of 115 watersheds in southern 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. The analysis of effect of tile drains on base flow showed that tile drainage reduces the amount of baseflow contribution to streamflow. Results also showed that base flow index and runoff coefficient are affected by hydrologic soil group, soil drainage class, and percent of tile drained area. It was also observed that when percentage of heavy textured soil increases, most of the streamflow contribution to the stream is as a rapid flow.

Keywords: Slow response, Rapid response, Streamflow, Baseflow separation.

INTRODUCTION The methods for managing surface and subsurface runoff in Ontario are of great importance for nutrient management and source water protection. The hydrological records show spring season has the highest streamflow, followed by fall and summer, and winter has the lowest flows in Ontario. Physiographic and geological features are other factors which affect the slow (base flow) and the rapid (surface runoff and tile flow) components of the stream flow. Lacey et al. (1998) examined the influence of a set of geology-vegetation groups and topographic and climatic indices on the baseflow index (BFI) for 114 catchments in Australia. The results showed no affect of forest growth stage and catchment size on annual trends for catchments; however, BFI has strong relationship with the geology-vegetation groups, and a weak relationship with the climatic parameters.

Neff et al. (2005) estimated the baseflow for watersheds tributary to Canadian and USA Great Lakes basin to develop regression models for ungaged watersheds using six different separation methods. 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.

Eckhardt (2008) examined baseflow indices for 65 North American catchments, from the 959 gages analyzed by Neff et al. (2005), using seven different baseflow separation methods (HYSEP1, HYSEP2, HYSEP3, PART, BFLOW, UKIH, and Eckhardt) to identify the best method. The results showed that Eckhardt method was hydrologically more plausible than those of the other algorithms. In addition, the baseflow values from BFLOW method provide extensively smooth time series of baseflow similar to the Eckhardt method results.

An Australian study by Nathan and McMahon (1990) for the analyses of daily streamflow data for 186 watersheds for baseflow separation showed a relation between digital filter and UKIH method with a linear correlation coefficient of 0.94 (slope 1.06, and intercept 0.02). This study also helped to accept a constant value of 0.925 for the regression constant used in the 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.

A study in Turkey by Aksoy et al. (2008) applied UKIH smooth minima method for the baseflow separation in perennial streams. This method proposed a drainage area based block size/time window of 5 days with a data filtering parameter 0.9. Results showed an overall good agreement between the UKIH and digital filter method with minor variability in standard deviation. The UKIH smooth minima method was used by Mazvimavi et al. (2004) to separate baseflow using factors such as mean annual precipitation, mean annual evapotranspiration, slope, drainage density, basin area, and proportion of basin with different land cover using linear regression model and artificial neural networks approaches. The results of this study revealed that baseflow index was positively related to mean annual precipitation, basin slope, and drainage density ($r = 0.29$), and negatively related to mean annual evapotranspiration ($r = -0.74$) and wooded grasslands ($r = -0.53$); however, differences in lithology did not significantly affect BFI. The study also revealed that the contribution of interflow and groundwater flow to streams depends upon climatic and topographical characteristics of the basin.

The literature review reveals that the effect of physiographic/physical characteristics on base flow varies spatially and temporally. Also, there are various methods to estimate the baseflow component of streamflow; therefore, it has become important to evaluate methods used for baseflow separation, and also to evaluate the effect of physiographic features on the components of stream flow for better understanding of nutrient management and source water protection.

Objectives The overall objective of this study is to evaluate the impact of tile drainage on the components of stream flow in various physiographic regions in Ontario. The specific objectives are to evaluate the baseflow separation methods for application in Ontario conditions; to analyze the distribution pattern of baseflow from each method; to describe linkage between base flow with the physiographic and physical characteristics of the watershed and the effect of tile drainage on baseflow.

MATERIALS and METHODS The studied watersheds in Ontario were divided into southern Ontario and northern Ontario. The criteria for the study 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 the province.

The commonly used procedures for separation of stream flow were reviewed. The methods [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. The results from these methods were analyzed by linear regression models to evaluate the difference among them for baseflow estimation. The runoff coefficients (RC), the ratio of rapid flow to total precipitation by converting the stream flow (m^3 s^{-1}) into surface runoff depth (mm).

Data acquisition The streamflow data for 556 watersheds were obtained from Environment Canada's HYDAT historical streamflow database. Initial analysis indicated that 125 stations have no data or missing data in every year. Out of 431 remaining stations the data were sorted based on two criteria: flow data and water level data, and 360 stations were found with flow data and 71 stations were found with water level data. These 360 stations were further screened for regulated and non-regulated flow regime. The non-regulated flow regime category contains 208 gauging stations and regulated flow regime has 152 gauging stations.

For this study, a minimum of 10 or more years of flow data for non-regulated gauging stations were considered adequate for realistic analysis. Therefore, out of 208 non-regulated gauging stations only 161 gauging stations met ten or more years of data criterion. The 161 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.

Physiographic data Digital format of physiographic data of southern Ontario were abstracted from the University of Guelph Data Resource Centre (DRC) website, provided by the Ontario Ministry of Agriculture and Rural Affairs (OMAFRA). This source only provided the physiopraphic characteristics for southern Ontario but no physiographic information or sources were available for northern Ontario. Southern Ontario data were available in detail for 5 major physiographic regions and 55 minor physiographic regions. From the description of five major physiographic regions (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 the 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 regions of Ontario. The data provided detailed soil maps of 34 counties that 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. These two sources did not provide soil maps for northern Ontario; therefore, it was not possible to analyze the northern watersheds based on hydrologic soil group and drainage class. The 115 southern watersheds were clipped with the soil map to extract the soil group and drainage class information.

Land use data The land use data were collected from ESRI Canada Soils (2005) for the whole province. The data were divided into mixed forest, shurbland, 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.

RESULTS AND DISCUSSION

Comparison of baseflow separation methods To evaluate the algorithm for baseflow separation methods, daily baseflow and daily streamflow hydrographs for one-year period were plotted for five randomly selected watersheds. In all five watersheds' hydrographs, it was found that the highest magnitude of peak streamflow occurs in spring followed by summer and winter. Each separation method generated different magnitude of baseflow. It was found that digital filter and PART method generate lowest amount of baseflow index (BFI). While base sliding method and base fixed method generated highest value of BFI. The UKIH and local minima methods produce moderate values of BFI in between lowest and highest BFIs. The examination of the stream flow hydrographs indicated that baseflow amount in each method increases under the flashy peaks, but every method responds differently to these flashy peaks. Overall, all six base flow 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.

Comparison of Baseflow Index To compare base flow separation methods the computed BFI by five different methods (PART, UKIH, local minima, base sliding, and base fixed) were plotted against digital filter method ,(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. It indicates that PART method and digital filter method produce similar trend of BFI, 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 showed a linear relationship with digital filter method with a slope of 0.93 and 0.90, intercept of 0.27 and 0.25, and coefficient of determination 0.73 and 0.89, respectively. 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. A 0.89 value of the determination coefficient for local minima indicates that sequence of BFI for all watersheds by local minima method and digital filter method have similar trend with very little scatter. A decrease in determination coefficient to 0.73 for the UKIH 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 the digital filter method show linear relationship with slope 0.72, intercept 0.44, and coefficient of determination 0.65. These two methods produce highest value of BFI and the difference in estimated BFI between these and digital filter methods 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 to further investigate the relationship BFI and physiographic and physical characteristics of the watershed.

Relationship of BFI and watershed physiography Based on the physiography, Ontario has been divided into five physiographic regions (South Eastern low land, Canadian Shield, South Central low land, Niagara Escarpment, and South Western low land,) as shown in Fig. 1. The Niagara Escarpment region was not considered because three watersheds identified in this region did not cover more than 15% of the watershed area.

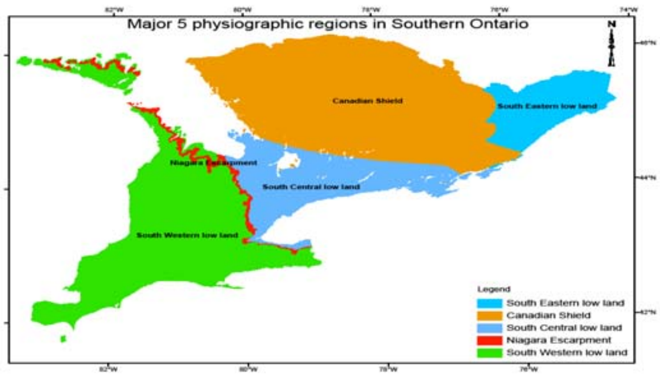

Figure 1. Five major physiographic regions in southern Ontario.

Analysis of annual and seasonal BFI The comparison of annual and seasonal mean BFI for 115 watersheds for four physiographic regions also showed that digital filter gives the lowest and base sliding gives the highest BFI (Table 1). In addition, seasonal analysis also shows that digital filter gives highest value of BFI during summer than the other seasons. However, UKIH and base sliding methods give highest value of BFI during spring and winter season.

Slow and rapid response watersheds Further analysis was conducted to identify the number of watersheds in four physiographic regions based on slow response and rapid response and the results are presented in Table 2. The criterion used was based on the results from the digital filter, the most conservative method for the estimation of BFI. It

Table 1. 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

was assumed that the watershed having 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. The 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 Southwestern low land. The total number of the could be designated as slow response and rapid response watersheds were 30 and 8, respectively out of 115, and none of these watersheds was in Southeastern low land region. The South central low land, south western low land, and Canadian shield regions have 17, 7, and 6 slow response and 0, 5 and 3 rapid response watersheds, respectively. The other watersheds which do not lie in these two categories are identified as moderate response watersheds.

Table 2. List of slow and rapid response watersheds for four physiographic regions.

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

Relationship between BFI and Physiographic Characteristics As described earlier Ontario has divided Ontario into five major physiographic region, (Chapman and Putman (1984), 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). For this analysis 10 (out of 115) watershed with highest BFI and 10 with lowest were used. This analysis indicated that most of the watersheds in the 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

Table 3. Analysis of 21 watersheds having single class physiography for southern Ontario.

Station ID	Major Physio.	Soil (A+B)%	Soil (C+D)%	Bedrock depth (m)	Tile area (%)	Well drain (%)	Poor drain (%)	Digital BFI	RO Coeff. (RC)
02GH011	South Western	5	95	49	32	5	95	0.13	0.33
02HA024	South Western	1	97	9	5	19	79	0.14	0.30
02HA020	South Western	1	95	33	14	20	77	0.16	0.30
02GH002	South Western	5	94	18	76	5	94	0.16	0.33
02GC029	South Western	5	85	64	51	13	79	0.23	0.22
02GD019	South Western	3	92	45	72	12	88	0.25	0.30
02GH004	South Western	13	87	23	0	13	87	0.30	0.33
02GD010	South Western	20	74	58	65	44	51	0.30	0.22
02MC028	South Eastern	66	34	24	8	60	40	0.31	0.33
02MC026	South Eastern	64	36	26	7	59	41	0.33	0.33
02LB017	South Eastern	65	35	0	3	35	65	0.33	0.25
02GD004	South Western	58	38	17	48	52	45	0.35	0.22
02HM009	Canadian Shield	0	94	0	0	0	100	0.36	0.52
02HJ001	South Central	69	4	79	1	68	28	0.38	0.24
02ED017	South Central	77	21	47	0	74	26	0.43	0.18
02FC011	South Western	78	6	0	21	70	27	0.46	0.26
02HC023	South Central	13	78	82	4	87	6	0.56	0.18
02KD002	Canadian Shield	29	5	0	0	29	5	0.58	0.17
02GC021	South Western	68	27	42	6	49	46	0.72	0.19
02GA043	South Western	85	13	28	8	86	11	0.72	0.12

runoff. The physiographic characteristics of 10 watersheds with highest BFI mostly contains moraine, rocky, and sandy soils. In some watersheds, the underlying bedrock is sedimentary limestone. Some of the watersheds have also been overlaid by outwash sand and gravel. Overall, all of these characteristics help in good to very drainage through the soil profile.

The data given in Table 3 show that 21 out of 115 watersheds could be identified as having single physiographic/physical feature. For further analysis to evaluate the effectiveness of these variables in hydrological processes, the data such as soil type and drainage class were pooled. The hydrologic soil groups A and B were combined as one group, and C plus D as the other group. Similarly, drainage classes were also pooled as poorly drained (very poorly, poorly, and imperfectly drained) and well-drained (very well and well drained) soils. The identified 21 watersheds cover 14 minor physiographic regions. The St. Clair clay plain has 4 watersheds, and Haldimand clay plain and Glengarry till plain have two watersheds each.

The analysis indicated no relationship between base flow index/runoff coefficient with the area of the watershed, slope class, and depth of bedrock. This was due to the poor quality of data available for these variables. Some of the data (GIS layer) available on soil class was very crude. The slope class data covered very wide range. The poor quality of available data was also the major reasons that effect of depth of bedrock and slope was not visible in the analysis. However, there is a visible relationship between BFI/RC and soil group, drainage class, and percent of tile area.

Table 4. 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

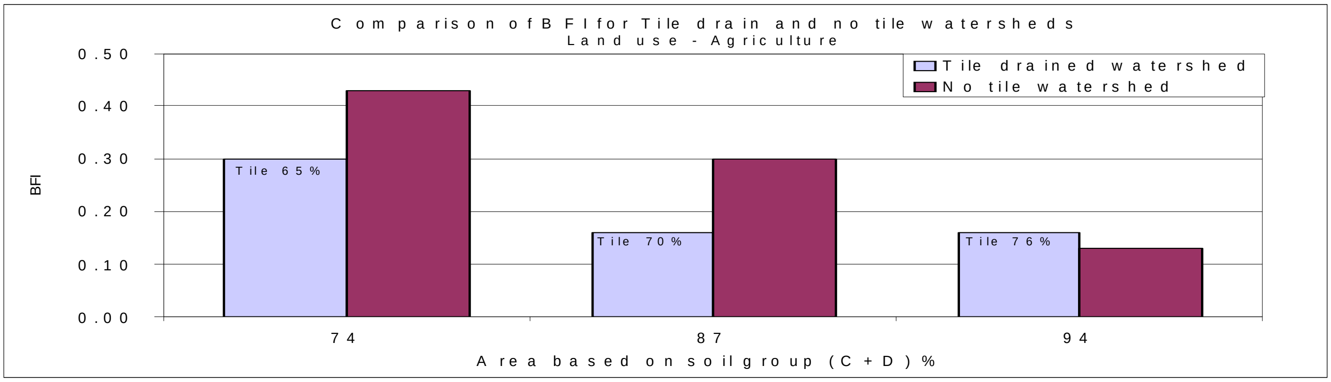

Figure 2. Comparison of BFI for tile and no-tile watersheds for Soil group C and D.

Six watershed having similar soil group (C+D) and similar land use were selected to analyze the effect of tile drainage on base flow. These six watersheds were divided into two categories: three tile drained and three with no-tile drainage, and the results are shown in Fig. 2. The detailed information on the hydrologic soil groups for these watersheds is given in Table 4. These results show that tile drainage results in the reduction the BFIand tile flow either constitute a portion of either interflow or rapid flow. When percentage of heavy (C and D) soil increases, most of the flow 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 are needed to identify the base flow separation method most suitable for dominantly tile-drained watersheds.

Figures 3-4 show the effect of braod categories of land use on BFI for these watersheds. These data suggest a significant difference in BFI values of agriculture and forest watersheds on similar soil. With an increase in the percentage of area occupied by C+D hydrologic soils groups, the difference in BFI became more prominent. However, such effect of land use on BFI is not visible for watersheds dominated by A and B hydrologic soil groups (Figure 4). Therefore, it can be concluded from the analysis that effect of landuse on base flow varies with soil type.

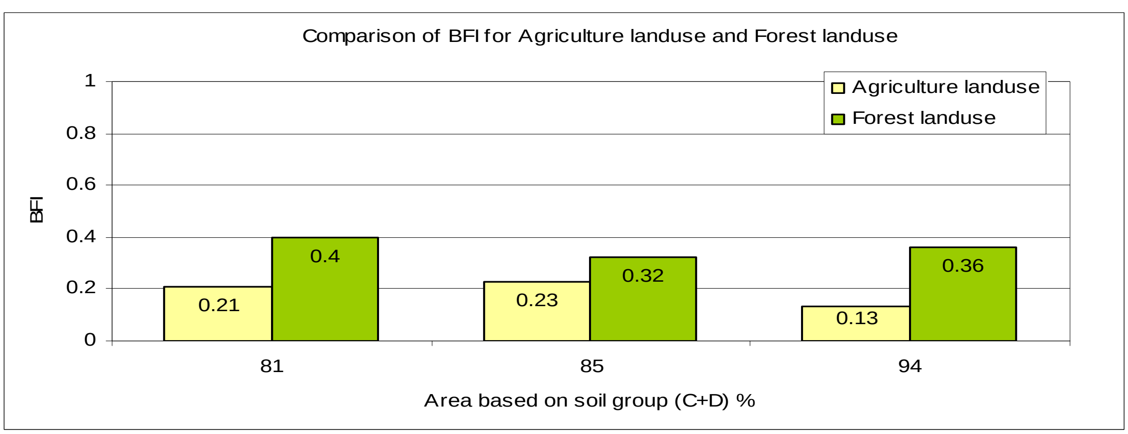

Figure 3. Comparison of BFI for tile and no-tile watersheds for Soil group C and D.

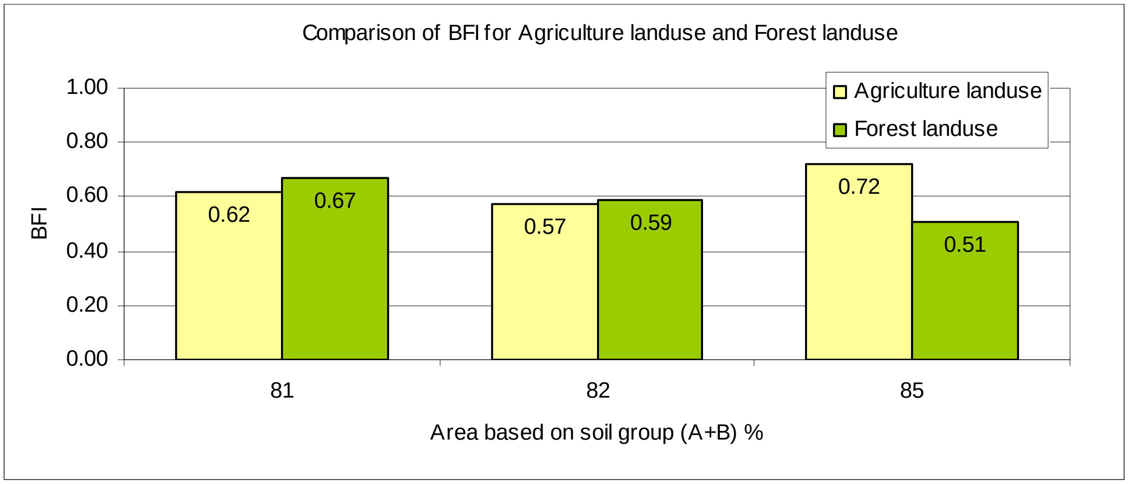

Figure 4. Comparison of BFI for tile and no-tile watersheds for Soil group A and B.

CONCLUSIONS

The pattern of average annual and seasonal base flow index southeastern low land and south western low land regions in Ontario is similar. In any physiographic region, the area of the watershed does not have any impact on the base flow index. The base flow index is strongly influenced by hydrologic soil groups and soil drainage class and tile drainage. The tile drainage results in the decrease of the magnitude of baseflow and the and tile flow becomes a part of rapid response From the 115 watersheds investigated in southern, central and eastern regions of Ontario 30 can be classified as slow response watersheds, 9 as rapid response watersheds, and 66 as medium response watersheds. For the northern region of Ontario, all the 46 watersheds can be classified as slow response watersheds. The magnitude of base flow index is method dependent. The lowest amount of baseflow is generated by digital filter method and the highest by base sliding method.

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