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Assessment of Mean Aerial Precipitation Estimation Methods on Natural Watersheds under Varying Geographic and Topographic Terrains across Canada

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ABSTRACT: Estimation of Mean Aerial Precipitation (MAP) is a key component in hydrologic studies. The precipitation amounts at raingauges are used to estimate MAP. Modern estimation techniques of MAP have shifted toward computer technology and satellite imagery. These methods although provide high levels of accuracy of MAP yet traditional techniques because of their simplicity and reliability are still popular. Comparative studies have examined these methods on artificial watersheds involving square boundaries. This paper focuses on assessing the efficacies of these methods through applications on natural watersheds located across various topographic terrains of Canada. Four different methods of estimating MAP are examined and evaluated in natural watersheds from three different topographic terrains. These methods gave comparable results of MAP in any region of interest. These comparable results also reinforce previous claims that no one method is superior to others in the estimation of MAP. Some methods are more preferable than others in certain topographic terrains because they can easily incorporate topographical effects on the occurrence and distribution of precipitation. Computer based MAP methods have proven helpful in faster execution with increased accuracy compared to some traditional methods.

INTRODUCTION

Precipitation being a key component in any hydrologic study, it is measured at various raingauges throughout the area of interest. The precipitation amounts at these gauges are used to estimate Mean Aerial Precipitation (MAP) for the period of interest. An increased level of accuracy depends on among other factors: (a) spatial distribution of raingauges to ensure equal representation of the watershed such that weighting coefficients are approximately equal for all raingauges within the watershed, (b) an awareness of the effect of elevation on various methods and its implications on the final results, and (c) the skill level of the analyst and his/her knowledge of precipitation characteristics and influences based on various topographical considerations. Some methods are more complex and time intensive than others requiring sound judgment and understanding.

Modern techniques of estimating MAP have shifted toward the use of computer technology and satellite imagery. Although these methods provide improved accuracy of precipitation amounts, older techniques still enjoy wide acceptance among the practicing engineers and planners because of their reasonable and reliable accuracy and inherent simplicity. The relative accuracy and efficacy of some of these methods have been reported by Whitmore (1961), Singh and Birsoy (1976), and Singh and Chowdhury (1986) among others. Some of these methods and techniques have been tested for practical considerations based on the assumption of square boundaries of natural watersheds. The focus of this paper is two folds: (a) to provide methods and techniques to delineate watershed boundary within the realm of digital technology, and (b) to test the range of applicability of some of these commonly used methods on natural watersheds located in various topographic terrains across in Canada.

PRELIMINARIES OF THE ESTIMATION OF MEAN AERIAL PRECIPITATION

There exists many methods since early 1980 to quantify the Mean Aerial Precipitation (MAP) over natural watersheds such as Unweighted mean, Grouped area aspect weighted mean, Thiessen Polygon method, Individual area altitude weighted mean, Triangular area weighted mean, Myers method, Isohyetal method, Trend Surface analysis, Reciprocal Distance squared method, Two-Axis method, Modified polygon method, Finite Element Method, and Analysis of Variance. In 1986, Singh and Chowdhury examined all these methods while other researchers compared only a few of these methods for different topographic areas. Since then many advances in estimation of MAP have been reported based on radar and GIS applications.

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However, this paper assesses the efficacy of those methods that are commonly used in natural watersheds by practicing water resources planners and engineers. Thus, four methods of estimation of MAP on three different watersheds across main topographic terrains in Canada have been applied. For each of the watersheds, it was critical to ensure that the boundary was verified by more than one method and thus watershed boundary was delineated using the Streets and Trips method and AutoCAD based Procedure. For each of the three watersheds a published boundary was obtained. As expected, some of these boundaries were found to represent only a portion of a bigger watershed and thus modified areas (size reductions) had to be used to allow for verification.

Some researchers have used square boundaries to represent watersheds in various regions around the world. Although, such a representation of watersheds is technically sound but lacks the rigor of natural watersheds. Artificial representations are not actual representations of natural watersheds. Additionally, a significant difficulty arises when attempting to establish a watershed boundary involving enough rain-gauges to provide adequate accuracy in estimation of MAP. It is noted that arranging and verifying sufficient amount of information on precipitation records to find a common overlapping period of observations presents a challenge in itself for natural watersheds. Four well accepted and yet simple to use methods have been used to demonstrate their applicability within the realm of digital information. Each one of these methods is briefly described below.

Arithmetic Average Method

This method is applied to raingauges that fall within the boundary of the watershed being analyzed (Wilm *et al.*, 1939). Equal weights are given to the measurements at all stations. The mathematical formulation is simply to calculate the mean of a sample: $\sum x/n$, where "x" represents the precipitation at a raingauge and "n" represents the total number of raingauges. This method is optimally useful for situation where raingauges are uniformly distributed within watersheds involving relatively flat topography.

Thiessen Polygon Method

In this method, precipitation within each polygon is considered to be same as the recorded at the raingauge lying within the polygon (Thiessen, 1911). Polygons are constructed as the intersection of perpendicular bisectors of the lines joining a raingauge station to the nearest surrounding raingauge stations. The area of each polygon is directly proportional to the weight (area of the polygon/total area of the watershed) to be assigned to the raingauge station. Alternately, the precipitation of the each raingauge station enclosed within the polygon is multiplied by the areas of their corresponding polygons. The sum of the precipitation area for all raingauges is the divided by the total area of the watershed to obtain the mean (also known as equivalent uniform depth) precipitation depth over the entire watershed. This method is best utilized where orographic effects are not present (e.g., mountainous regions) and raingauges are not spaced uniformly.

Isohyetal Method

Points of equal rainfall depths are adjoined by lines called isohyets (Reed and Kincer, 1917). The isohyets are drawn by interpolation between any two gauges. In interpolating the location of isohyets, it is implicitly assumed that the rainfall between two adjoining raingauges either increases or decreases uniformly. The mean value between any two isohyets is considered as average precipitation between those two isohyets. The average precipitation over the entire watershed is calculated as the sum of the mean precipitation the watershed area contained by any two adjoining isohyets divided by the total area of the watershed. This method is suitable for watersheds located in hilly terrain where orographic effects play a significant role in the spatial distribution of precipitation.

Two Axis Method

This method is a combination of the Thiessen polygon and Isohyetal methods. Initially a line is drawn from the outlet to the farthest point in the watershed. At the midpoint of this line a perpendicular bisector line (also called as the minor axis) is drawn until it meets the boundaries of the watershed. To the minor axis is a perpendicular bisector line (also called as the major axis) to the boundaries of the watershed (Step in Figure 1). A line is then drawn from the rain gauge station to the farthest point on the minor axis. Another line is drawn from the station to the farthest point on the major axis. This procedure is repeated for all rain gauge stations (Step 2 in Figure 1). An acute angle is measured between the two lines that connect to the farthest terminal of the minor and major axes.

The weight of the rain gauge station is the ratio of the station's angle to the sum of all station angles; $W_i = A_i / \sum A_i$, where W_i is the weight of the rain gauge station, A_i is the measure angle for the rain gauge station. The assigned weights of all rain gauge stations must sum up to 1 for the accuracy of validation. The average precipitation over the watershed is the sum of product of each weight of a rain gauge multiplied by the corresponding precipitation for the rain gauge. Alternately, it can be expressed $\sum w_i * p_i = P_a$, where P_a is the average precipitation over the entire watershed area with w_i and p_i respectively represents the weight and unit of precipitation for the i^{th} rain gauge station.

SELECTION OF WATERSHEDS AND PRECIPITATION RECORDS

The process of obtaining computational procedures for relevant data of representative watersheds containing sufficient number of raingauges for assessing the estimation methods of MAP was to ensure that precipitation periods for each of the raingauge within a watershed had sufficient common overlapping periods of precipitation and contained minimal missing records. Another consideration for the selection of watersheds was to ensure that for each watershed had some published information such as to independently conduct checks/verifications of the delineated boundary and also the results of numerous analyses.

Two main sources of data were utilized. The precipitation data was obtained from Canadian Daily Climate Data (CDCD) of the Environment Canada Website http://www.climate.weatheroffice.ec.gc.ca/prods_servs/cdcd_iso_e.html. The relevant precipitation data sets for the year 2002 were obtained for the eastern half and western half of Canada respectively in the form as 2002–EAST CD and the 2002–WEST CD. The topographic and digital maps employed in various analyses were obtained from Natural Resources Canada. Detailed information on a variety of data compiled for various analyses is described by Smaglinskie and Pereira (2006).

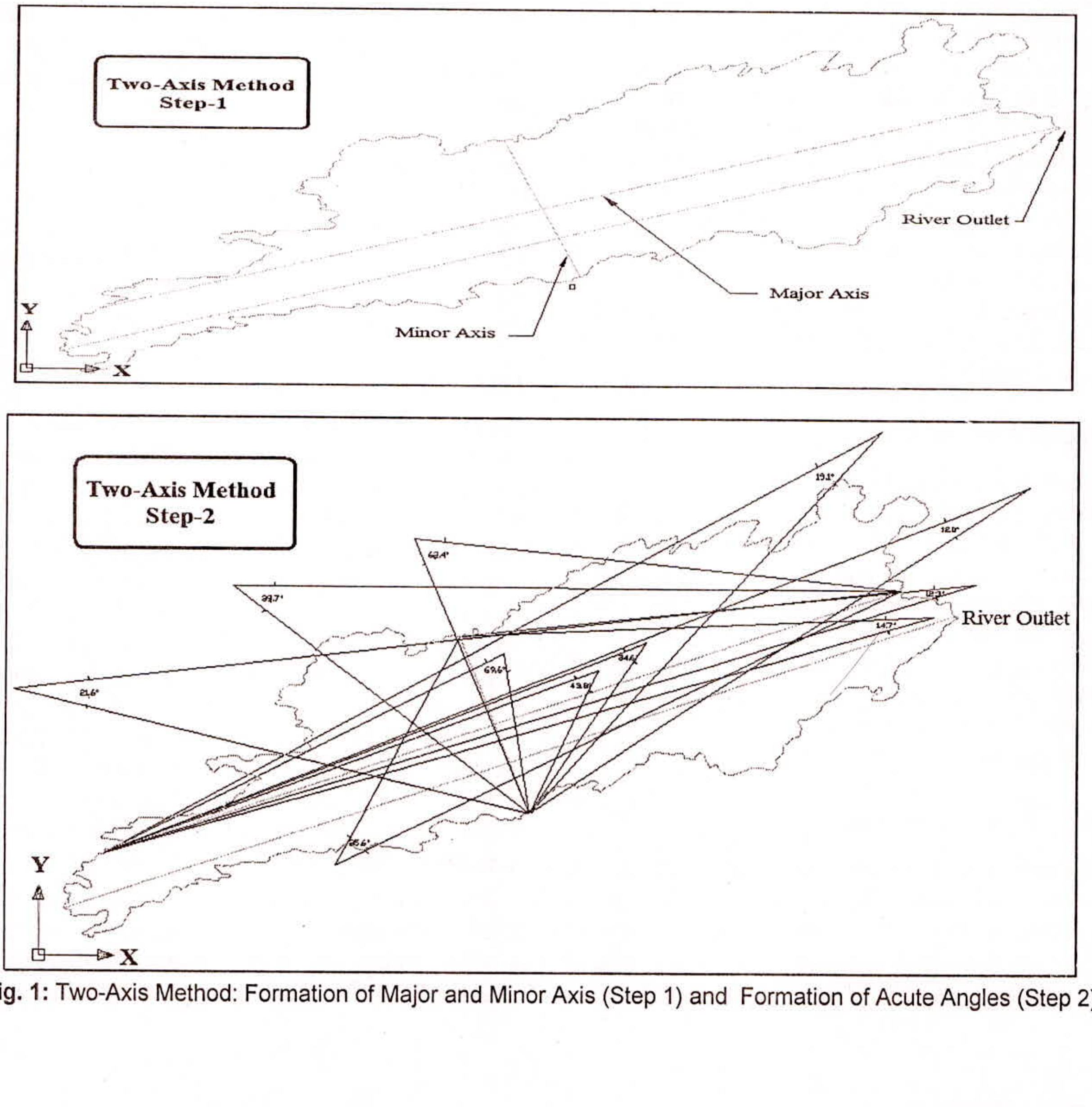

Fig. 1: Two-Axis Method: Formation of Major and Minor Axis (Step 1) and Formation of Acute Angles (Step 2)

Based on preliminary analysis of numerous watersheds along with relevant precipitation records across Canada, three separate watersheds representative of major types of topographic terrains were selected across Canada. The watershed of Banff National Park was chosen because of its predominant mountainous terrain. The Swift Current Creek watershed located in Saskatchewan of the Prairie Region of Canada was chosen because it is predominantly governed by the flat terrain. The Badger Watershed located in central Newfoundland was chosen because of it is significantly dominated by the rolling hill terrain. The topographical features of each watershed along with selected maps and precipitation records are briefly presented below.

Banff National Park Watershed

The watershed is located in the Canadian Rockies of western Alberta as shown in Figure 2. It forms part of the Bow River Basin and consists of mountainous terrain with elevations ranging from 1600 m to 3500 m. The area of the watershed is 4000 km^2 and notable communities within the watershed boundaries are Banff and Lake Louise. The Banff National Park watershed represents roughly the same area as 1 and 2 in the figure below.

Reference Topographic Maps and Precipitation Records

The reference maps used for watershed delineation were NTS maps 82J, 82K, 82N, and 82O obtained from Natural Resources Canada. For this watershed, a summary of relevant precipitation stations is provided in Table 1. The overlapping period of precipitation record for each station was from 1998–2003. There were numerous other stations not considered in this analysis because they had numerous missing records. The most overlapping period was chosen to be July, August, and September for the year 2001 (Table 2). Three months, as well as one storm from each month were analyzed for comparative analysis.

Swift Current Creek Watershed

This watershed is located in south-western Saskatchewan as shown in Figure 3. It forms part of the Saskatchewan River Basin and is the largest tributary to the South Saskatchewan River. Located in this watershed are the communities of Swift Current, Shaunavon and many other small towns. The watershed has flat topographic features with elevations from 580 m to 1160 m and has an approximate area of 5500 km^2. Embedded in this figure are snap shots to provide general representation of the topographical features of the watershed.

Reference Topographic Maps and Precipitation Records

The reference maps used for watershed delineation were NTS map numbers 72G, 72J, 72K and 72F obtained from Natural Resources Canada. For this watershed, a summary of relevant precipitation stations is provided in Table 3. The overlapping periods of precipitation record for each station was from 1973 to 1975. These three years contain the most overlapping data for the precipitation stations located in the watershed (Table 4). Three months, as well as one storm from each month were analyzed for comparative analysis.

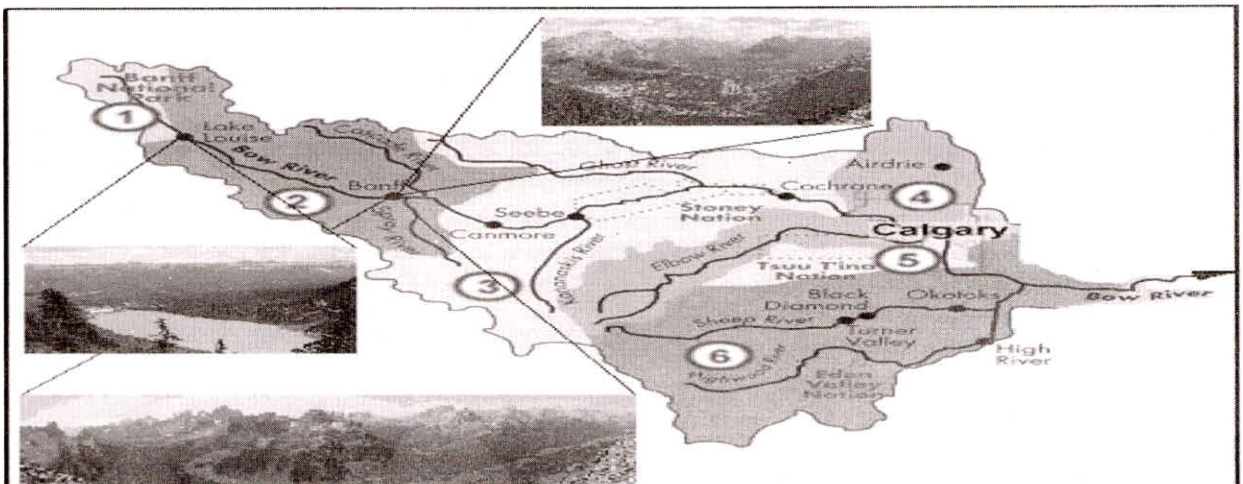

Fig. 2: Banff National Park Watershed is Representative of the Mountainous Terrain

Table 1: Summary of Station Properties for Banff National Park Watershed

Name	*Station #*	*Longitude*	*Latitude*	*Elevation*	*Years*
Bow Summit (AE)	3050PPF	51°42' N	116°28' W	2080 m	1998–2003
Banff CS	3050519	51°12' N	115°33' W	1397 m	1995–2003
Ghost Diversion	3052PP6	51°18' N	115°08' W	1000 m	1998–2003
Kananaskis	3053600	51° 2' N	115° 2' W	1391 m	1939–2003
Kananaskis Pocaterra	3053604	50°42' N	115° 7' W	1631 m	1976–2003
Lake Louise	3053760	51°26' N	116°13' W	1524 m	1915–2003
Skoki	3055976	51°32' N	116° 3' W	2040 m	1998–2003

Table 2: Summary of Precipitation Data for Stations of Banff National Park Watershed

Name	*Year-2001*			*Storm Number*		
	July	*August*	*September*	*1*	*2*	*3*
Bow Summit (AE)	13.2	7.4	10.1	6.6	3.3	2.5
Banff CS	27.6	1.2	24.2	11.6	0.4	1.2
Ghost Diversion	56.1	10.2	13	11.6	0.0	0.0
Kananaskis	53.2	1.6	23.4	25	0.0	0.0
Kananaskis Pocaterra	57.2	3.8	27.8	20	2.7	2.0
Lake Louise	34.1	8.3	24.8	12	3.0	4.6
Skoki	47.6	11	19.6	19.8	0.0	6.6

Note: Precipitation numerical entries in this table have unit of millimeters (mm).

Table 3: Summary of Station Properties for Swift Current Creek Watershed

Name	*Station #*	*Longitude*	*Latitude*	*Elevation*	*Years*
Gull Lake	4023053	50°16'N	108°33' W	762 m	1971–1977
Gull Lake CDA EPF	4023060	49°57'N	108°28' W	907 m	1956–1991
Herbert	4023210	50°26'N	107°13' W	701 m	1973–1985
Instow	4023520	49°43'N	108°17' W	903 m	1950–1976
Klintonel	4024080	49°41'N	108°55' W	1074 m	1910–1994
Neidpath	4025485	50°13'N	107° 6' W	777 m	1973–1985
Rush Lake	4027000	50°24'N	107°24' W	712 m	1952–1975
Shamrock	4027440	50°11'N	106°34' W	710 m	1945–1996
Shaunavon	4027480	49°39'N	108°24' W	917 m	1915–1979
Shaunavon 2	4027485	49°39'N	108°25' W	914 m	1971–2003
Shaunavon 3	4027486	49°54'N	108°25' W	892 m	1971–2003
Swift Current A	4028040	50°18'N	107°41' W	818 m	1938–2003
Swift Current CDA	4028060	50°16'N	107°44' W	825 m	1959–2003

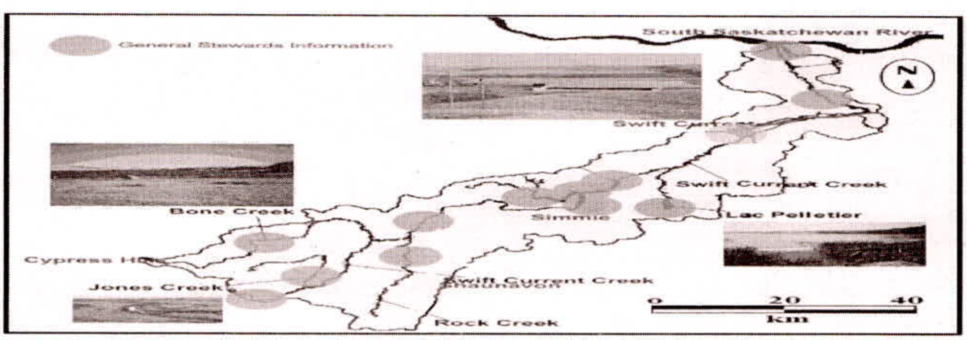

Fig. 3: Swift Current Creek Watershed a tributary of the South Saskatchewan River

Table 4: Summary of Precipitation Data for Stations of Swift Creek Watershed

Name	*Annual Precipitation*			*Year-1974*			*Storm Number*		
	1973	*1974*	*1975*	*May*	*June*	*July*	*1*	*2*	*3*
Gull Lake	226	Misg	Misg	89	26.6	53.7	4.6	5.6	5.1
Gull Lake CDA EPF	248.5	452.7	456.7	132.3	27	64.7	7.6	1.1	0.5
Herbert	Misg	464	446.7	83.1	34.2	52.8	0.0	0.0	0.0
Instow	253.2	435.3	572.6	113.8	22.2	60.9	11.7	3.3	0.0
Klintonel	445.4	571.7	801.3	110.8	45.9	65.3	12.7	17.8	3.6
Neidpath	Misg	459.9	423.5	142.7	4	30	0.0	0.3	0.0
Rush Lake	245.9	438	Misg	86.5	31.8	39.4	0.0	0.0	0.0
Shamrock	388	444	450.8	102.2	8.4	30	0.3	0.0	0.0
Shaunavon	282.4	476.9	540.4	126.4	20.1	45	1.8	4.4	0.0
Shaunavon 2	265.8	455.1	525.4	98.1	51.6	69.7	8.9	3.8	0.3
Shaunavon 3	190.6	387.5	416.5	89.5	23	57.5	5.1	2.1	0.0
Swift Current A	279.2	473.4	446.3	100.4	20.1	45	2.3	0.5	0.0
Swift Current CDA	258.4	415.1	397.7	84.9	21.2	44.5	2.0	0.5	0.0

Note: Where Misg denotes missing record. Precipitation numerical entries in this table have unit of millimeters (mm).

Badger Watershed

This watershed is located in central Newfoundland as shown in Figure 4 and is part of a larger watershed of the Exploit River. Located in this watershed are the communities of Badger and Buchans Junction. The watershed has a rolling terrain with a major increase in elevation from its east to the west side. The elevations vary from sea level to about 600 m and it has an approximate area of 10000 km^2. This watershed is considered to be representative of the rolling terrain. Embedded in Figure 4 are snap shots for a visual perspective of the topography of the watershed.

Reference Topographic Maps and Precipitation Records

The reference maps used for watershed delineation were NTS map numbers 2D, 2E, 12A, 12H, 11O, 11P, and 12B obtained from Natural Resources Canada. For this watershed, a summary of relevant precipitation stations is provided in Table 5. The overlapping periods of precipitation record for each station was from 1989 to 1991. These three years contain the most overlapping data for the precipitation stations located in the watershed (Table 6). Three months, as well as one storm from each month were analyzed for comparative analysis.

Table 5: Summary of Station Properties for the Badger Watershed

Name	*Station #*	*Longitude*	*Latitude*	*Elevation*	*Years*
Buchans	8400698	48°49' N	56°52' W	270 m	1965–2003
Buchans Junction	8400711	48°51' N	56°28' W	161 m	1988–1997
Grand Falls	8402050	48°56' N	55°40' W	60 m	1934–2003
Exploits Dam	8401550	48°46' N	56°36' W	154 m	1956–2003
Burnt Pond	8400812	48°10' N	57°20' W	299 m	1972–1997
Wooddale Bishop's Falls	8404310	49° 2' N	55°33' W	46 m	1974–2003
Point Leamington	8402966	49°20' N	55°24' W	8 m	1982–2003
Robert's Arm	8403093	49°30' N	55°49' W	30 m	1982–1996
Howley	8402415	49°10' N	57° 7' W	94 m	1987–1990
South Brook Pasadena	8403693	49° 1' N	57°37' W	38 m	1985–2003
Gallants	8401642	48°42' N	58°14' W	143 m	1982–2003

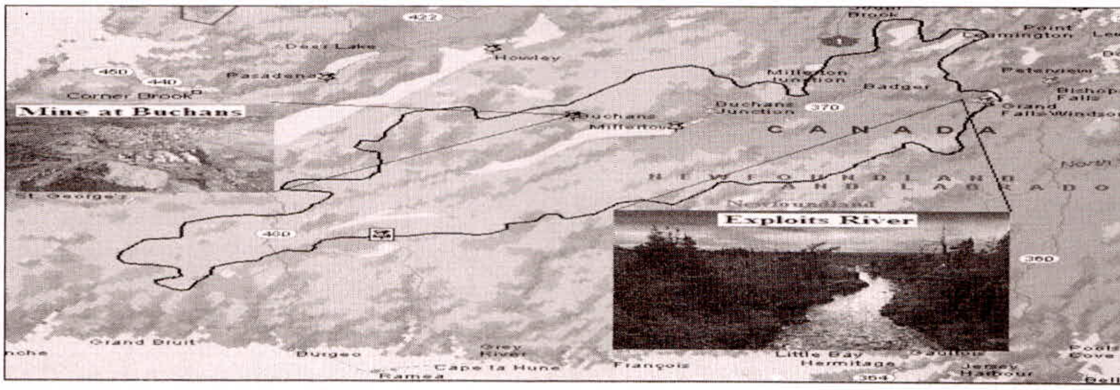

Fig. 4: Badger Watershed a tributary of the Exploits River in Newfoundland

Table 6: Summary of Precipitation Data for the Badger Watershed

Name	*Annual Precipitation*			*Year-1989*			*Storm Number*		
	1989	*1990*	*1991*	*May*	*June*	*July*	*1*	*2*	*3*
Buchans	1191.1	1264.4	1219.5	66.4	52.3	51.8	13.1	7.6	80.6
Buchans Junction	946	1114.8	1155.1	53	46.6	56.4	12.8	6.2	73
Grand Falls	863	987.1	1198.5	49.8	39.4	58.4	12	2.4	64.8
Exploits Dam	916.8	1009.9	1124.6	57.1	47.2	64.2	11.2	6.0	64.2
Burnt Pond	1219.2	1424.8	1369.5	68.6	47.5	65.9	18.1	5.1	67.6
Wooddale Bishop's Falls	900.6	1039	1171.7	71.8	40.8	73.6	14.2	4.4	67.2
Point Leamington	773	923.5	1159	60.5	53	83.5	22.5	6.0	43
Robert's Arm	858.6	1032.7	1111.2	75.2	52.2	58.7	18.2	2.1	38.1
Howley	724	0.0	0.0	55.2	49.2	32.7	11	4.2	56.2
South Brook Pasadena	856.2	1157.4	922.8	54.2	56	41.6	12.6	0.8	57.8
Gallants	1548.4	1768.6	1476.1	100.4	80.4	62	14.6	10	129

Note: Precipitation numerical entries in this table have unit of millimeters (mm).

DELINEATION OF WATERSHED BOUNDARY

The watershed boundary of each of three watersheds was identified and delineated by using easily available software such as (a) Street and Trips method, available from Microsoft and (b) AutoCAD software. Digital maps corresponding to each watershed were obtained from the Natural Resources of Canada. The methods of watershed boundary delineation are briefly described below.

Streets and Trips Method

It is a fairly simplistic method for route planning of trips. Using the draw feature of this package the watershed boundary was traced between rivers by invoking local topographic features from the digital maps. A typical layout of the package is shown in Figure 5(a). In this normal view, there are no defining topographic features. To obtain relevant topographic features one need to change the view through the "View drop down menu" and select "Map Style" and "Topographic" as shown in Figure 5(b). The subtle changes that appear are easily discernable when one compares both of these maps. For accurate location of a raingauge station, this program contains an option which allows the user to view the Longitude and Latitude coordinates of the desired location. A procedural detail on the application of this feature is shown in Figure 5(c). Actuation of this feature allows placement of pins to identify locations of raingauges and their corresponding local names can also be associated to them for ease of operation as shown in Figure 5(d).

While delineating the watershed boundary using this method one need to be cautious about the accuracy because there are very few topographic features that would allow the user to trace the high points even though the maps are to scale. In the Badger and the Banff National Park watersheds, some highpoints are visible and consequently a good representation of watersheds was accomplished. However, it was somewhat difficult to ascertain the high points in case of watersheds located in flat terrain (i.e., the Swift

Current Creek Watershed). Such a lack of detail arises due to the feature less terrain of the Canadian prairies.

AutoCAD Based Procedure

Digital maps of 1:250,000 scales were obtained from Natural Resources Canada to accomplish the delineation of boundary of a specific watershed. These digital maps usually are in "dxf" file format ready for use by AutoCAD. However, to reduce the file size by approximately 50%, each of the digital maps was resaved in the "dwg" format. The digital maps thus obtained contain all layers in "white" format and thus it was necessary to remobilize them for use in the "ByLayer" option of the AutoCAD. To accomplish this operation, first all the objects in the file are selected. The objects tend to turn blue when selected. A pull down menu is used to select the "ByLayer" option. Changing the layers properties allowed the layers to be isolated and formatted. This operation facilitated the layers to be turned "on/off" and also a change in colour of layers or individual lines. This was a time intensive operation that had to be completed for each individual map and understandably requires computational time varying from 15 to 95 minutes. During this operation, at times, one feels as if the computer has frozen, however, a check through the task manager ensures that the file is still being processed.

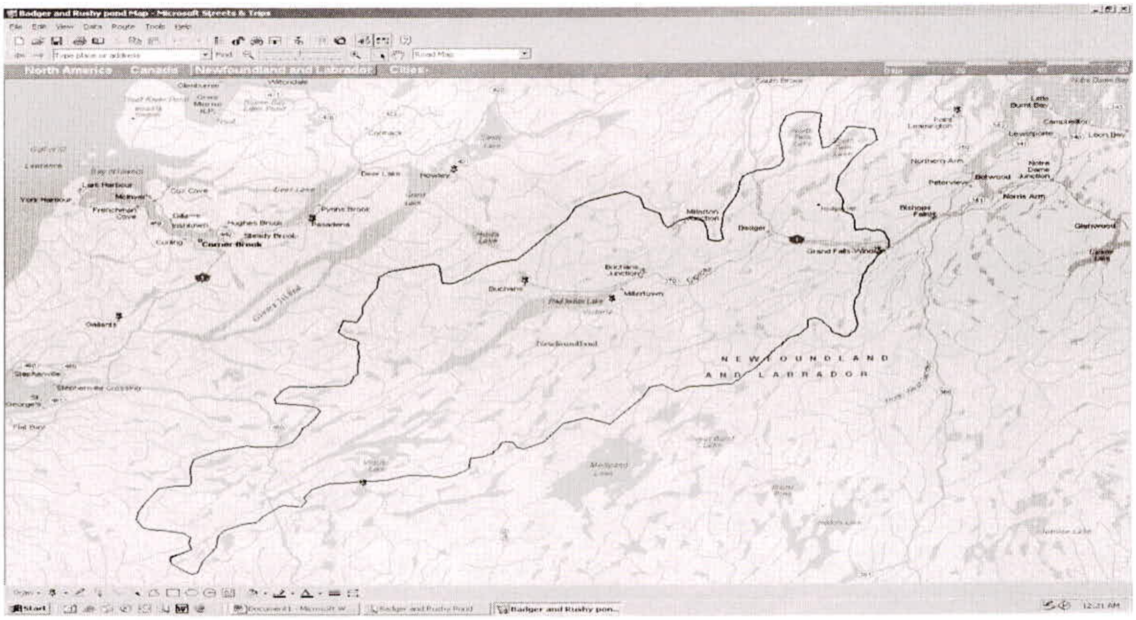

Fig. 5(a): A Typical map of Badger Watershed in the Streets and Trips. (None of the topographic representations are present)

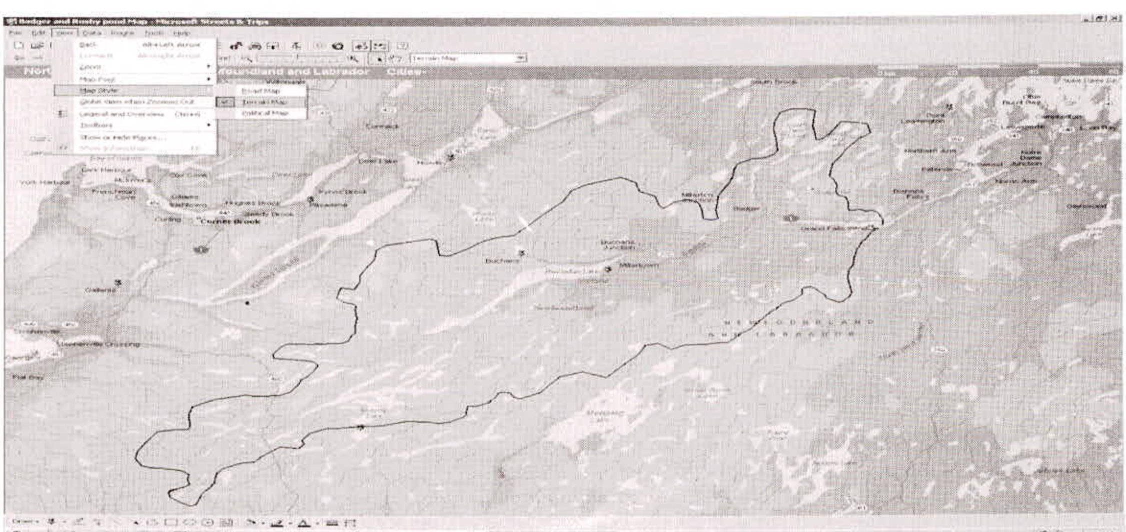

Fig. 5(b): Badger Watershed Showing Topographic Map Style

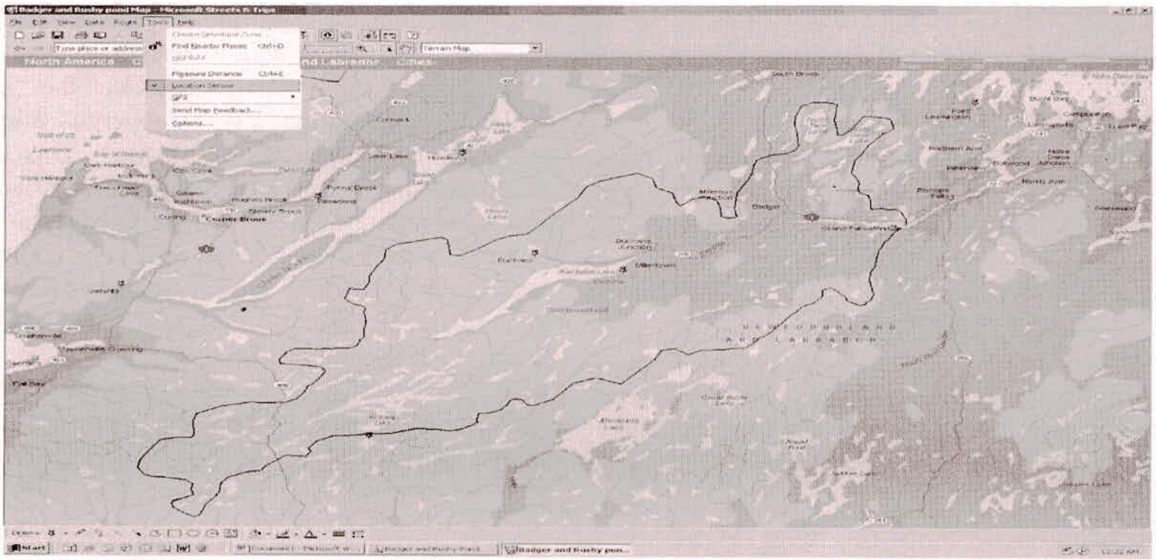

Fig. 5(c): Badger Watershed with Topographic View and Location Sensor

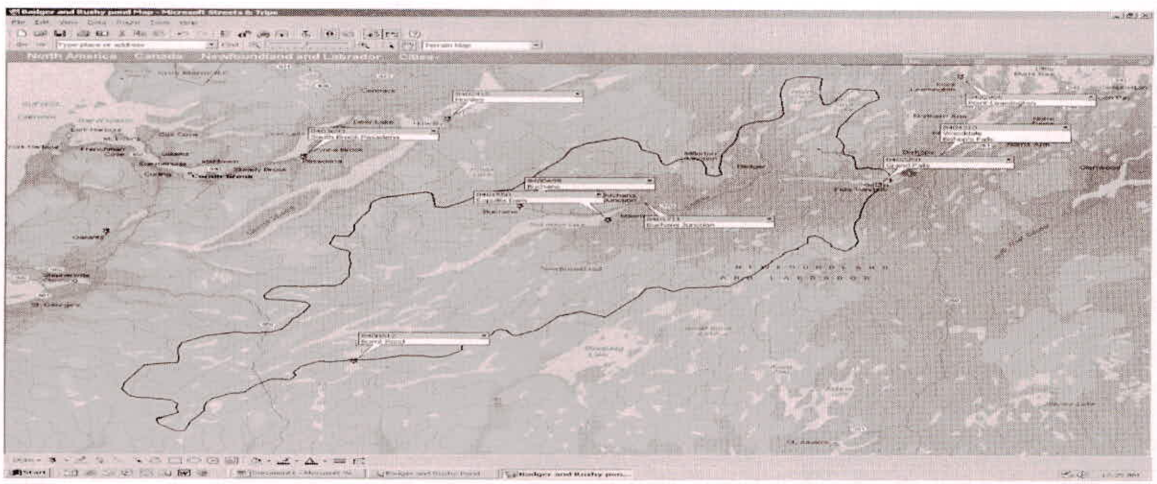

Fig. 5(d): Badger Watershed Showing Pins and Station Names of Raingauges

Once each of the maps was reformatted in to their layers by the "ByLayer" option of the AutoCAD, the respective maps were then stitched together. Additional procedural detail for locating the precipitation raingauges and for obtaining the watershed area are: (a) Tracing a tentative watershed boundary, (b) Delineation of an actual watershed boundary, (c) Inputting the raingauge stations, (d) Stretching the AutoCAD files, and (e) Calculation of the watershed area. These procedures are described by Smaglinskie and Pereira (2006).

Completing the Analysis Using AutoCAD

The remaining procedures used in solving methods of the Polygon, Two-Axis, and Isohyetal are fairly simple to AutoCAD users. The procedures primarily require the use of "polylines" and "splines". A few helpful suggestions are listed below for the ease of computational effort and reduction in computational time.

- For each analysis create and use a new layer.
- Create one layer that just has lines connecting the points to each station. This can later be used for offsetting and other processes.
- When completing the Isohyetal analysis, first use splines to define the isohyets. Trace these isohyets using polylines in a separate layer. It is noted that AutoCAD will not calculate the area if splines are used instead of polylines.
- Individual areas can be calculated once a specific method has been completed.

For brevity, it is stressed that compensatory factors were used instead of the stretching operation. All such factors are presented later.

SUMMARY OF RESULTS OF COMPUTATIONAL METHODS FOR MEAN AERIAL PRECIPITATION

Results of the four methods of computation of Mean Aerial Precipitation (MAP) for three watersheds are summarized in a tabular format separately for each watershed. In these tables, the abbreviations such as "All Stations" implies that all precipitation stations located inside and around the watershed are used. Whereas the abbreviation "TA All" implies that all precipitation stations located inside and around the watershed are used in the Two-Axis method. In addition, the abbreviation "TA in" implies that only stations located inside the watershed are being used in the Two-Axis method.

Banff National Park Watershed

Summary of results for this watershed is given in Tables 7(a), 7(b), 7(c), and 7(d) as follows.

Table 7(a): Results of the Polygon Method for the Banff National Park Watershed

Name	*AutoCAD*			*Planimeter*	
	AutoCAD Area	*Relative Area*	*Area (km^2)*	*Relative Area*	*Area (km^2)*
Bow Summit (AE)	0.0344	0.068	275	0.092	313
Banff CS	0.2415	0.475	1931	0.415	1411
Ghost Diversion	0.0296	0.058	237	0.082	279
Kananaskis	0.0052	0.010	42	0.043	146
Kananaskis Pocaterra	0.027	0.053	216	0.079	270
Lake Louise	0.0819	0.161	655	0.202	686
Skoki	0.0886	0.174	708	0.087	296
Total	0.5082	1.0	4063	1.0	3400

Table 7(b): Results of the Two-Axis Method for the Banff National Park Watershed.

Name	*AutoCAD*				*Planimeter*			
	Stations within Watershed		*All Stations*		*Stations within Watershed*		*All Stations*	
	Angle	*Relative Angle*	*Angle*	*Relative Angle*	*Angle*	*Relative Angle*	*Angle*	*Relative Angle*
Bow Summit (AE)	18	0.119	18	0.106	23	0.131	23	0.116
Banff CS	18	0.119	18	0.106	22.5	0.129	22.5	0.114
Ghost Diversion	16	0.106	16	0.094	21	0.120	21	0.106
Kananaskis	0.000	0.000	10	0.059	0.000	0.000	13	0.066
Kananaskis Pocaterra	0.000	0.000	9	0.053	0.000	0.000	10	0.051
Lake Louise	37	0.245	37	0.218	49.5	0.283	49.5	0.250
Skoki	62	0.411	62	0.365	59	0.337	59	0.298
Total	151	1.0	170	1.0	175	1.0	198	1.0

Table 7(c): Comparison of Results of All Methods Using AutoCAD for the Banff National Park Watershed

Storm	*Mean Aerial Precipitation (mm)*				
	Arithmetic Average Method	*Polygon Method*	*Two-Axis Method*		*Isohyetal Method*
			TA in	*TA All*	
Storm 1	15.2	13.3	14.5	15.4	14.5
Storm 2	1.3	1.0	1.2	1.2	1.5
Storm 3	2.4	2.7	4.3	3.9	3.2
2001 July	38.4	33.3	36.6	38.7	N/A
2001 Aug	6.2	5.0	8.7	8.0	N/A
2001 Sept	20.4	21.9	19.6	20.3	N/A

Table 7(d): Comparison of Results of All Methods Using Planimeter for the Banff National Park Watershed

Storm	Mean Aerial Precipitation (mm)			
	Arithmetic Average Method	Polygon Method	Two-Axis Method	
			TA in	TA All
Storm 1	15.2	13.2	13.7	14.9
Storm 2	1.3	1.3	1.3	1.3
Storm 3	2.4	2.4	4.0	3.6
2001 July	38.4	33.3	35.3	37.4
2001 Aug	6.2	4.9	8.4	7.8
2001 Sept	20.4	21.8	19.6	20.2

Swift Current Creek Watershed

Summary of results for this watershed is given in Tables 8(a), 8(b), 8(c), and 8(d) as follows.

Table 8(a): Results of the Polygon Method for the Swift Current Creek Watershed

Name	AutoCAD			Planimeter	
	AutoCAD Area	Relative Area	Area (km^2)	Relative Area	Area (km^2)
Gull Lake CDA EPF	0.0534	0.07	433	0.07	347
Herbert	0.0628	0.09	510	0.04	215
Instow	0.0398	0.05	323	0.06	300
Klintonel	0.1038	0.14	842	0.10	534
Neidpath	0.0357	0.05	290	0.01	56
Rush Lake	0.0710	0.10	576	0.15	740
Shaunavon 2	0.0682	0.09	553	0.12	590
Shaunavon 3	0.0818	0.11	664	0.15	759
Swift Current A	0.0886	0.12	719	0.08	403
Swift Current CDA	0.1234	0.17	1001	0.22	1143
Total	0.7285	1.0	5912	1.0	5085

Table 8(b): Results of the Two-Axis Method for the Swift Current Creek Watershed

Name	AutoCAD				Planimeter			
	Stations within Watershed		All Stations		Stations within Watershed		All Stations	
	Angle	Relative Angle	Angle	Relative Angle	Angle	Relative Angle	Angle	Relative Angle
Gull Lake CDA EPF	45.2	0.238	45.2	0.177	50	0.210	50	0.169
Herbert	11.0	0.058	11.0	0.043	17	0.071	17	0.058
Instow	0.000	0.000	50.1	0.196	0.000	0.000	38	0.129
Klintonel	16.3	0.086	16.3	0.064	27.5	0.116	27.5	0.093
Neidpath	0.000	0.000	14.8	0.058	0.000	0.000	19	0.064
Rush Lake	11.5	0.060	11.5	0.045	19	0.080	19	0.064
Shaunavon 2	35.7	0.188	35.7	0.140	24	0.101	24	0.081
Shaunavon 3	41.0	0.215	41.0	0.161	45	0.189	45	0.153
Swift Current A	14.1	0.074	14.1	0.055	26	0.109	26	0.088
Swift Current CDA	15.5	0.081	15.5	0.061	29.5	0.124	29.5	0.100

Table 8(c): Comparison of Results of All Methods Using AutoCAD for the Swift Current Creek Watershed

Storm	*Mean Aerial Precipitation (mm)*				
	Arithmetic Average Method	*Polygon Method*	*Two-Axis Method*		*Isohyetal Method*
			TA in	*TA All*	
Storm 1	5.0	5.0	6.0	6.8	5.3
Storm 2	2.9	3.5	3.0	2.9	4.0
Storm 3	0.4	0.6	0.5	0.4	0.7
1974 May	104.2	100.1	103.0	107.4	N/A
1974 June	28.1	29.4	32.1	28.5	N/A
1974 July	53.0	53.2	58.8	57.6	N/A

Table 8(d): Comparison of Results of All Methods Using Planimeter for the Swift Current Creek Watershed

Storm	*Mean Aerial Precipitation (mm)*			
	Arithmetic Average Method	*Polygon Method*	*Two-Axis Method*	
			TA in	*TA All*
Storm 1	5.0	5.0	5.4	5.9
Storm 2	2.9	3.0	3.2	3.0
Storm 3	0.4	0.4	0.6	0.4
1974 May	104.2	96.8	101.7	105.9
1974 June	28.1	29.9	30.3	27.6
1974 July	53.0	53.4	56.4	55.3

Badger Watershed

Summary of results for this watershed is given in Tables 9(a), 9(b), 9(c), and 9(d) as follows.

Table 9(a): Results of the Polygon Method for the Badger Watershed

Name	*AutoCAD*			*Planimeter*	
	AutoCAD Area	*Relative Area*	*Area (km^2)*	*Relative Area*	*Area (km^2)*
Buchans	0.2305	0.19	1909	0.22	2119
Buchans Junction	0.3145	0.25	2605	0.17	1616
Grand Falls	0.1647	0.13	1364	0.14	1326
Exploits Dam	0.1507	0.12	1248	0.18	1707
Burnt Pond	0.2849	0.23	2360	0.27	2606
Wooddale Bishop's Falls	0.0024	0.00	20	0.00	30
Point Leamington	0.0000	0.00	0	0.00	46
Robert's Arm	0.0368	0.03	305	0.02	229
Howley	0.0066	0.01	55	0.00	N/A
South Brook Pasadena	0.0317	0.03	263	0.00	N/A
Gallants	0.0190	0.02	157	0.00	N/A
Total	1.2418	1.0	10285	1.0	9678

Table 9(b): Results of the Two-Axis Method for the Badger Watershed

Name	*AutoCAD*				*Planimeter*			
	Stations within Watershed		*All Stations*		*Stations within Watershed*		*All Stations*	
	Angle	*Relative Angle*	*Angle*	*Relative Angle*	*Angle*	*Relative Angle*	*Angle*	*Relative Angle*
Buchans	69.6	0.428	69.6	0.190	56	0.357	56	0.153
Buchans Junction	34.6	0.213	34.6	0.095	38	0.242	38	0.104
Grand Falls	14.7	0.090	14.7	0.040	20	0.127	20	0.055
Exploits Dam	43.8	0.269	43.8	0.120	43	0.274	43	0.117
Burnt Pond	0.000	0.000	35.6	0.097	0.000	0.000	40	0.109
Wooddale Bishop's Falls	0.000	0.000	12.3	0.034	0.000	0.000	17	0.046
Point Leamington	0.000	0.000	12.0	0.033	0.000	0.000	15	0.041
Robert's Arm	0.000	0.000	19.1	0.052	0.000	0.000	18	0.049
Howley	0.000	0.000	62.4	0.171	0.000	0.000	36	0.098
South Brook Pasadena	0.000	0.000	39.7	0.109	0.000	0.000	52	0.142
Gallants	0.000	0.000	21.6	0.059	0.000	0.000	31	0.085

Table 9(c): Comparison of Results of All Methods Using AutoCAD for the Badger Watershed

Storm	*Mean Aerial Precipitation (mm)*				
	Arithmetic Average Method	*Polygon Method*	*Two-Axis Method*		*Isohyetal Method*
			TA in	*TA All*	
Storm 1	14.6	13.9	12.4	13.6	14.5
Storm 2	5.0	5.5	6.4	5.2	5.0
Storm 3	67.4	70.4	73.1	68.3	70.8
1989 May	64.7	60.6	59.5	62.8	N/A
1989 June	51.3	47.9	48.5	51.3	N/A
1989 July	59.0	58.6	56.7	53.7	N/A

Table 9(d): Comparison of Results of All Methods Using Planimeter for the Badger Watershed

Storm	*Mean Aerial Precipitation (mm)*			
	Arithmetic Average Method	*Polygon Method*	*Two-Axis Method*	
			TA in	*TA All*
Storm 1	14.6	14.1	12.4	13.9
Storm 2	5.0	5.6	6.2	5.1
Storm 3	67.4	69.5	72.3	69.8
1989 May	64.7	61.0	58.5	63.7
1989 June	51.3	47.4	47.9	52.0
1989 July	59.0	59.8	57.2	55.8

DISCUSSION OF RESULTS

For each of the watersheds, it was crucial to ensure that the delineated boundary was verified by more than one method. A search for the published information (such as watershed area and the watershed boundary) was undertaken. Some of these boundaries were corresponding to parts of the larger watersheds. For these published boundaries the software Streets and Trips of the Microsoft was used to verify the sourced data. In two of three such cases the boundary established by the software Streets and Trips was able to make a good approximation of the watershed boundary. However, for flat terrain this program was unreliable and a boundary sourced from www.sccws.com was used. For these cases, the watershed boundary was also established using AutoCAD.

Comparative analysis of results is discussed below separately for each watershed. The results of each of the three watersheds are discussed specifically concerning: (a) comparison of the watershed area computed by various methods and the published data obtained from Environment Canada, (b) comparison of estimated results of MAP by the four methods, (c) potential sources of errors in computational procedures, and (d) factors used for stretching the AutoCAD files.

Banff National Park Watershed

For this watershed, there is a lack of published data or availability of information through accredited websites. However, a comparative analysis was conducted for its sub-watershed corresponding to the Bow River Basin. The published area of this sub-watershed is 2200 km^2 which was calculated by the AutoCAD analysis to be 2297 km^2 (with an error of + 4.41%). Due to lack of sufficient precipitation stations, the outlet corresponding to the junction of the Cascade River and the Bow River south of Banff (Figure 2) was chosen as a test sub-watershed. The reason for choosing the outlet at the junction of the two rivers was that this sub-watershed would include at least 5 stations which are considered to be the minimum number of stations for the estimation of MAP. Two additional stations located outside the boundary on the eastern side were included to improve the accuracy in this area which was lacking in precipitation records.

The four different methods of estimating MAP were applied to the watershed for comparative results. The arithmetic average method was used for its simplicity and for reliable results. The Thiessen polygon method is not considered for use on this watershed due to the influence of orographic effects arising from the presence of mountains. The Two-Axis method was considered using both cases of stations (TA in or TA All). That is the stations only inside the watershed and all the inside and outside stations were considered for comparative analysis. Subjective judgment was used in developing isohyets especially for the placement of isohyets near or on the watershed boundary because there were limited numbers of reliable raingauges within reasonable distance from the boundary.

Three monthly and three storm events were chosen as shown in Table 2. Calculation of MAP by the four different methods is shown in Table 7(c). The four methods (arithmetic average, polygon, isohyetal, and Two-Axis) produced comparable results. The polygon method on average yielded lower estimates than the other three methods. This is partly due to the influence of orographic effects in mountainous regions. Also, the calculations of the areas in the Thiessen polygons are based on the assumption of polygon are lying in a flat terrain. Since the polygons are located over top of high mountainous terrain, the area does not consider any elevation factors. Such a situation can severely misrepresent the actual area of the polygon leading to inaccuracies in final results.

The Isohyetal method involves a fair degree of judgment in the interpolation of isohyets between any two nearby raingauges. Therefore some inaccuracies in areas of isohyets are expected. The lack of raingauges located outside the watershed boundary at shorter distances made the delineation of the isohyets conditioned to the boundary areas. This method is widely accepted as the most favorable method for its ability to describe spatial distributional characteristics of precipitation at high elevation areas.

Two analyses were completed using the Two-Axis method (Table 7(d)). In one analysis, only the raingauges located inside the watershed were considered in the calculation of MAP. The results were similar to those of the isohyetal method. In the other analysis, all raingauges including those located outside the watershed boundary were considered. The results between the two analyses differed by less than 10% proving that weighting of the raingauges is heavier when only the gauges inside the watershed are considered. All the four methods produced fairly accurate results considering the complex topographical area.

Since the AutoCAD files were originally prepared in Latitude and Longitude coordinate system, the calculated areas were not actual areas. The drawings were stretched by a factor of 72 in the x-axis and 111 in the y-axis. The scale factor was based on the distance in km of 1° on the NTS maps of 1:250,000 scale. As a result of this stretching, there was some elongation of the watershed boundary in the y-axis. Likewise, sub-watershed areas within the boundary were established and compared against the published results in the Surface Water Data Reference Index of Environment Canada. The sub-watershed area of the Bow River near Banff had a drainage area of 2200 km^2 in the surface water data reference index. It was calculated to be 2297 km^2 in AutoCAD resulting in a 4% difference from the published area. Given the complexity of the situation and based on the results, it is reasonable to conclude that errors involved in stretching of the drawings were within tolerance limits.

Swift Current Creek Watershed

A map of the watershed obtained from the Swift Current Creek website was planimetered to obtain an average area of 5107 km^2. However, the watershed area using AutoCAD was obtained to be 5912 km^2 with a difference of 13.6% between both computational procedures. The area of this watershed reported by the Surface Water Data Reference Index (Station No. 05HD037) is 3910 km^2. This is substantially lower then the area calculated by the planimeter and AutoCAD methods. To explain this discrepancy, a small sub-watershed corresponding to the Station No.05HD003 for which published area is 39.9 km^2 was selected. However, the area obtained using AutoCAD resulted in 44.8 km^2 with a difference of 12.3%. This difference is approximately similar to the earlier difference of 13.6% obtained for the entire Swift Current Creek watershed.

Three monthly and three storm events were chosen as shown in Table 4 for analysis. Three methods of estimation of MAP were completed using the planimeter method for this watershed. For the polygon method the polygons that were produced have a range of areas associated with each station. The only station that picks up a substantially greater proportion of the watershed area is the Swift Current CDA Station (1143 km^2). Other than this station the polygons relatively well divide the watershed.

The Two-Axis method of analysis was performed for two cases (Table 8(d)). Case one involves only the precipitation stations inside the watershed and in case two consider stations inside and outside but in close proximity of the watershed boundary. The isohyetal procedure was not completed for the planimeter method. However, should it has been conducted then it would have produced similar results to the AutoCAD representation because of predominant presence of the flat terrain.

Each of these methods was completed using AutoCAD for the storm events (Table 8(c)). The factors used to stretch the map for this watershed are 73.125 times in the x-axis and 111 times in the y-axis. The polygon method was completed using AutoCAD and planimeter methods. The results of the isohyetal method by AutoCAD are summarized in Table 8(c) and by the planimeter are given in Table 8(d). There are no significant differences in results of both tables. In such flat terrain watersheds simple arithmetic average method is sufficient provided precipitation stations are approximately equally spaced.

Badger Watershed

A map of the watershed was traced using Streets and Trips method. A comparison of this watershed boundary with that obtained from the Hydrotechnical Study of the Badger and Rushy Pond Areas was found to be reasonably similar. The area of the watershed defined using the Streets and Trips method was planimetered to be 9678 km^2 (Table 9(a)). The area of the watershed using the AutoCAD was found to be 10285 km^2 (Table 9(b)). There exists a difference of 5.9%. Some of this difference in area is attributed to the fact that AutoCAD picks up all high points and the boundary defined using the Streets and Trips method is much more subjective. However, the area for this watershed obtained from the Surface Water Data Reference Index (Station No. 02YO005) is 8640 km^2. This is somewhat lower (~16–11%) then the area calculated by both earlier methods. An assessment of the source of this difference attributed to some discrepancy associated with the exact location of Station No. 02YO005 at the outlet.

Three monthly and three storm events chosen for analysis are given in Table 6. Three methods of estimation of MAP were completed using the planimeter method for this watershed (Table 9(d)). For the polygon method, polygons that were produced have a range of areas associated with each station. The only station that picks up a substantially greater proportion of the watershed area is at Bunt Pond (2606 km^2). Other stations could not be sourced in this area as this area is relatively uninhabited portion of central Newfoundland. Other than this one station, the polygons fairly divide the watershed.

The Two-Axis method of analysis was performed for two cases. Case one involves only the precipitation stations inside the watershed and in case two consider stations inside and outside but in close proximity of the watershed boundary. The results of these analyses can be found in Table 9(d). The isohyetal procedure was not completed for the planimeter method. It is expected to be similar to the AutoCAD representation.

Each of the methods of analysis has been completed using AutoCAD for the storm events. The factors used to stretch the map for this watershed are 74.625 times in the x- axis and 111 times in the y-axis. The areas of the polygon method are given in Table 9(a). The results for the Two-Axis method are similar to the planimeter method.

The results of the isohyetal method by AutoCAD are summarized in Table 9(c) and by the planimeter are given in Table 9(d). There are no significant differences in results of both tables.

CONCLUSIONS

This paper is the first to analyze and compare some methods of estimation of MAP on natural watershed across different terrain and different hydrological regimes across Canada. For ease of computations, earlier investigators have used square watersheds to represent natural watersheds in various regions around the world. Such a representation is not an exact representation of an actual watershed. A significant difficulty arises when attempting to establish a watershed boundary involving sufficient number of raingauges to provide adequate accuracy of estimation of MAP. Four different methods of estimating MAP have been compared in three topographic regions. Similar results were produced by the four methods in different regions of interest. These results reinforce previous claims that no one method is superior to the other. Some methods are more preferable than others in certain topographical regions because of altitudinal factors on the occurrence and distribution of precipitation. Computer technology has been very helpful in the execution, for example, watershed boundary and estimation MAP at a relatively faster pace with enhanced accuracy compared to some traditional methods.

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