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Applicability of using ArcMap to spatially calculate and display monthly evapotranspiration rates

An investigation using government climate data

in British Columbia, Canada

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ABSTRACT

Evapotranspiration (ET) is the sum of the evaporation of water from the Earth's surface and the total transpiration from plants. Spatially calculating ET is necessary because it is a major component in quantifying a water budget, and maps provide the spatial ability to display the distribution. Geographic information systems (GIS) are a powerful and capable tool which can spatially process and integrate equations in order to quantify ET rates. Probable ET equation types that best fit with ArcMap software were investigated, and the methodology of España *et al.* was evaluated in terms of usefulness and ease of replication, while beneficial areas for future expansion were also commented on. Interpolation of some weather and other variables, as well as the use of the raster calculator in ArcMap was the basis of the project methodology. Temperature based ET equations were selected as the best equation category, and then specifically the Blaney-Criddle, Thornthwaite, and Hargreaves equations were used to calculate potential evapotranspiration (PET) rates in British Columbia (BC), Canada.

The methodology of España *et al* provided a relatively easy way to spatially display algebraic evapotranspiration equations. The results were compared to values of sixteen reference stations, which had been computed by the Penman-Monteith equation. PET values that were interpolated were not as accurate as hoped, however the Hargreaves and Blaney-Criddle methods produced better results than the Thornthwaite method, which resulted in underestimates. Nonetheless, the PET distribution pattern was displayed, and of use to show the areas of highest and lowest rates of PET. In order to produce more accurate values, regional or crop coefficients could be applied to calculate actual evapotranspiration (AET), but time constraints placed on the project restricted the trial of this.

Keywords: Evapotranspiration (ET), British Columbia (BC), GIS, ArcMap

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1. INTRODUCTION

1.1 BACKGROUND

Evapotranspiration (ET) is the sum of the evaporation of water from the Earth's surface and the total transpiration from plants. It is a significant environmental process, which connects the climatic, hydrological and ecological systems, while it is also a vital part in planning for city and provincial water consumption to ensure that available water is used economically (Chuanyan, Zhongren & Zhaodong, 2004). The main drivers of ET have been determined as available energy (net radiation) and precipitation, and ET becomes problematic when the annual amount of available energy largely exceeds the actual amount of energy needed to evaporate the annual precipitation (Arora, 2002). Therefore, quantifying ET is of significant importance in arid and semi-arid climates, where the available energy is high and the precipitation amounts low (Krishnan, Meyers, Scott, Kennedy, & Heuer, 2012; Portoghese, Uricchio, & Vurro, 2005; Chuanyan, *et al.*, 2004; Shevenell, 1999). Another aspect of consideration is how climate change continually alters energy and precipitation patterns, making quantifying the water balance an issue of increasing importance (Roth, Slatton & Cohen, 2007). Evapotranspiration may be the most ideal process to examine in order to determine exactly how the energy and precipitation rates are potentially shifting.

Geographic information systems (GIS) are an efficient processing tool capable of comparing ET rates through maps, so that different regions can be displayed and compared simultaneously. Modeling ET equations with GIS is advantageous, as detailed maps can be manipulated, or different ET calculation methods can be compared and evaluated (Naoum & Tsanis, 2003). Spatially calculating ET enables a higher level of insight into water distribution patterns which could aid in the preparation of risk management. An example of which could be determining regions at risk for drought, and possibly forest fire would allow for proper regional planning or fire control. An efficient yet simple methodology of displaying ET rates in conjunction with GIS without strong a technology background should be available to professionals in the field of resources management, planning, consulting and research. As with the methods of calculating ET, there are numerous ways to implement these equations in GIS, depending on the type of research question being asked. The calculation methods range from extremely code-dependent to being reliant on remote sensing, and from being general to exceptionally site specific. For an arid location in the state of Nevada, USA, Shevenell (1999) was successful in using ARC/INFO 6.1.1 and the GRID raster modelling package to use a Digital Elevation Model (DEM) to insert elevation values into a linear regression equation, and then modify that equation for aspect by completing a slope calculation within that software. Other ways that these calculations have been implemented in GIS is by breaking them into pieces which correspond to different input layers, and then combining these layers for the final result (España, Alcalá, Vallejos, & Pulido-Bosch, 2011; Chenini & Mammou, 2010; Portoghese, *et al.*, 2005; Naoum & Tsanis, 2003; Ray & Dadhwal, 2001).

1.2 Research Focus

Fresh water is a necessity to all of Earth's ecosystems and with the shifting of weather patterns coupled with increasing pollution rates, it is important that water be used economically. The hydrological cycle is constantly being evaluated. Quantifying water distribution from precipitation events to evaporation back into the atmosphere is a complex process that considers many variables. Next to precipitation itself, evapotranspiration accounts for the largest portion of the hydrological cycle, and the amount of water available for runoff largely depends on this factor (Chuanyan et *al*., 2004; Diodatoa, Ceccarelli, & Bellocchi, 2010). Evapotranspiration is often underestimated, especially in the hot summer months (April to September in the N. Hemisphere), when water consumption may be limited and forest fire hazard is high. Predicting and calculating evapotranspiration is especially vital in agricultural areas in order to properly manage water consumption (Ray & Dadhwal, 2001; Naoum and Tsanis, 2003). GIS have the capability of spatially displaying evapotranspiration rates and its use for integrating environmental variables only continues to increase (eg Portoghese, *et al.*, 2005; España *et al.,* 2011). Adaptions of GIS for these purposes would aid in water resource planning and allow for historical comparison of ET levels determine if the climate is shifting in one direction or another.

This project is centered on the ability of the ArcGIS software to both calculate and display the results of evapotranspiration (ET) equations. Previous research by España *et al.* (2011) evaluated and developed an add-on (ArcE) for ArcGIS software that enabled ET to be easily calculated, requiring only an input map to calculate ET with one tool from the ArcToolbox. The focus of this research is to test how applicable that methodology would be without the ArcE function, as it is not yet available. There are many ET equations throughout scientific literature, and another aspect of this research is to compare and contrast the outcome of each equation against each other, and comment on the ET patterns among various regions in British Columbia (BC), which was the chosen study area of this project. Specific ET equations calculate better in different climates, and while it is possible to apply crop coefficients and calibration values, this research is only looking at reference evapotranspiration (ET_0) equation forms due to the time allotment for this project. ET_0 or potential evapotranspiration (PET) can be defined as the "maximum evapotranspiration rate from a surface, assuming adequate moisture at all times" (Shevenell, 1999). ET_0 is the basis of the formulas that are used to calculate the actual evapotranspiration (AET) rate in a certain area (Allen, Pereira, Raes, & Smith, 1998). The methodology to calculate AET is the same as for ET_0; the only difference being that a coefficient or calibration value is being used in areas of similar climates. This means that the methodology applies to ET equations in general, even though the equations used are specifically to determine ET_0.

1.3 SUMMARY OF RESEARCH AIMS AND OBJECTIVES

This project will use interpolation to spatially calculate ET over the entire area of the province of BC, Canada. It will test the methodology of España, *et al.* (2011) in which interpolation of equation-specific and weather variables were utilized, to display ET rates, without the proposed ArcE add-on as it is not yet available for ArcGIS software. This project aims to assess the feasibility of this method for other water resource professionals, in order to replicate and also to determine the best ET equations to use in conjunction with limited data and ESRI's ArcMap software. In order to evaluate how the equations calculate ET in BC, a sample will be selected and tested against reference values calculated by the complex Penman-Monteith methodology. The maps produced will also be commented upon, and any ET patterns will be discussed. Such produced maps will be useful in reports of both scientists and regional or city planners, and also on government websites such as those displaying climate and weather data. To clarify and summarize, the specific objectives of this project are:

(1) investigate the best types of evapotranspiration equations to be used in conjunction with GIS software for the purpose of spatially calculating and displaying monthly evapotranspiration amounts;

(2) examine if the previous methodology of España *et al*. (2011) is feasible for use in calculating ET with ArcMap;

(3) comment on the distribution of ET over the province of BC, and describe the differences in display of ET patterns among the equations used; and,

(4) compare and evaluate the calculated ET values from the tested equations through statistical analysis.

Doing so will benefit the scientific community, as such analyses have not been completed for the specific study area of BC, Canada. The findings of this GIS study will be beneficial to government organizations in BC such as transportation, environment, fisheries, and agriculture, as well as private consulting firms within those study areas. Processing data with software such as ArcMap adds an additional level of organization to resource planning, as evapotranspiration can be easier displayed and understood, and the data can be handled more efficiently.

2. REVIEW OF EVAPOTRANSPIRATION CALCULATION METHODS

2.1 CHOICE OF EVAPOTRANSPIRATION EQUATION TYPE

ET may be calculated through various methods, depending on whether PET or AET is to be determined. The use of these methods depends on a number of factors such as data availability, and site specific climate conditions. In order to calculate actual evapotranspiration (AET), the potential evapotranspiration (PET) first needs to be determined (Allen *et al.,* 1998). PET rates provide a general estimate of ET as the calculation is un-calibrated, however if a precise calculation is required calibration of the equation to the study site will return more accurate results. The Penman-Monteith method determines ET using aerodynamic and energy-balance variables and has been recommended as the standard method to calculate ET (Allen *et al.,* 1998; Gocica & Trajkovic, 2010; Gavilán, Berengena, & Allen, 2007). This method however, is complex and requires data that is hard to obtain, therefore, other equations were researched for this project. To aid in selecting an appropriate method of calculating ET, the equations may be broken into categories such as Xu and Singh (2002) did, by organizing the equations into groups as temperature, radiation, mass-transfer, water budget, or combination-based methods. Nevertheless this organization is of less importance than the consideration of site conditions and data availability (Shevenell, 1999; Xu & Singh, 2001). The previous literature review revealed temperature based equations as best when data availability is limited; thus, they were the category selected for this project.

2.2 TEMPERATURE BASED EVAPOTRANSPIRATION METHODS

Temperature-based equations are those only requiring temperature as the input variable (Xu & Singh, 2001). These equations are useful for remote areas lacking complete weather stations as temperature data are the most commonly recorded meteorological data. Temperature based ET methods are generally derived from air temperature, a humidity term, day length, and various constants which make the equations more site specific, due to the range of recording standards and variability of the meteorological data in different climates (Xu & Singh, 2002). Some common types of these equations as summarized by Xu and Singh (2001) were developed by Thornthwaite (1948), Linacre (1977), Blaney and Criddle (1950), Hargreaves (1975), Kharrufa (1985), Hamon (1961), and Romenko (1961). These methods may be calculated for different time steps, the most precise of which is the daily level, yet this poses an issue as daily data are not commonly available for many weather stations. Various equations have been developed for use in specific climates, which, when site calibrated, are particularly accurate (Xu & Singh, 2001; Xu & Sing, 2002; Ray & Dadhwal, 2001). As the focus of this project is to apply ET equations to a study site encompassing many different climates, the chosen methods were selected through a literature review. The Blaney-Criddle method has been proven accurate at the monthly time-step (Ray & Dadhwal, 2001;

Papageorgiou, Latinopoulos, & Mallios, 2005), whereas the Hargreaves (1994) model was stated to be the better choice if weather data are irregular (España *et al.,* 2011). Based on these findings, and with specific attention paid to data availability, the three methods selected for use were the Thornthwaite (1948), Blaney-Criddle (1950), and Hargreaves (1994) method.

2.2.1 BLANEY-CRIDDLE (1950) METHOD

The Blaney-Criddle is a temperature based method that may be used to estimate PET at a monthly scale. The only input variables required are temperature values, and fraction of sunlight values, which are available from meteorological tables. Table 1 is an example of one table of variables used in this project, which displays the mean daylight hours for different latitudes for the 15th of the month. The values were converted from per day to per month in order to fit this specific equation. The Blaney-Criddle (1950) equation used is as follows:

$$ET_p = p(0.46T_a + 8) \qquad \text{Eqn. (1)}$$

Where p is the monthly fraction of annual hours of daylight and T_a is the mean monthly temperature (˚C). Results from Xu and Singh (2001), show this equation performed best using both the original and modified constants in comparison to six other temperature-based ET equations, for it yielded the least error when the mean differences between the equations and pan evaporation estimates were compared.

Table 1 – Mean daylight hours for different latitudes for the 15th of the month (Allen *et al.,* 1998)

Northern Hemisphere												Lat.
Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	deg.
0.0	6.6	11.0	15.6	21.3	24.0	24.0	17.6	12.8	8.3	2.3	0.0	70
2.1	7.3	11.1	15.3	19.7	24.0	22.3	17.0	12.7	8.7	4.1	0.0	68
3.9	7.8	11.2	14.9	18.7	22.0	20.3	16.4	12.7	9.0	5.2	1.9	66
5.0	8.2	11.2	14.7	17.9	20.3	19.2	16.0	12.6	9.3	6.0	3.7	64
5.7	8.5	11.3	14.4	17.3	19.2	18.4	15.7	12.6	9.5	6.6	4.8	62
6.4	8.8	11.4	14.2	16.8	18.4	17.7	15.3	12.5	9.7	7.1	5.6	60
6.9	9.1	11.4	14.1	16.4	17.8	17.2	15.1	12.5	9.9	7.5	6.2	58
7.3	9.3	11.5	13.9	16.0	17.3	16.8	14.8	12.4	10.1	7.9	6.7	56
7.7	9.5	11.5	13.8	15.7	16.8	16.4	14.6	12.4	10.2	8.2	7.1	54
8.0	9.7	11.5	13.6	15.4	16.5	16.0	14.4	12.4	10.3	8.5	7.5	52
8.3	9.8	11.6	13.5	15.2	16.1	15.7	14.3	12.3	10.4	8.7	7.9	50
8.6	10.0	11.6	13.4	15.0	15.8	15.5	14.1	12.3	10.6	9.0	8.2	48
8.8	10.1	11.6	13.3	14.8	15.5	15.2	14.0	12.3	10.7	9.2	8.5	46
9.1	10.3	11.6	13.2	14.6	15.3	15.0	13.8	12.3	10.7	9.4	8.7	44
9.3	10.4	11.7	13.2	14.4	15.0	14.8	13.7	12.3	10.8	9.6	9.0	42
9.5	10.5	11.7	13.1	14.2	14.8	14.6	13.6	12.2	10.9	9.7	9.2	40
9.6	10.6	11.7	13.0	14.1	14.6	14.4	13.5	12.2	11.0	9.9	9.4	38
9.8	10.7	11.7	12.9	13.9	14.4	14.2	13.4	12.2	11.1	10.1	9.6	36
10.0	10.8	11.8	12.9	13.8	14.3	14.1	13.3	12.2	11.1	10.2	9.7	34
10.1	10.9	11.8	12.8	13.6	14.1	13.9	13.2	12.2	11.2	10.3	9.9	32
10.3	11.0	11.8	12.7	13.5	13.9	13.8	13.1	12.2	11.3	10.5	10.1	30
10.4	11.0	11.8	12.7	13.4	13.8	13.6	13.0	12.2	11.3	10.6	10.2	28
10.5	11.1	11.8	12.6	13.3	13.6	13.5	12.9	12.1	11.4	10.7	10.4	26
10.7	11.2	11.8	12.6	13.2	13.5	13.3	12.8	12.1	11.4	10.8	10.5	24
10.8	11.3	11.9	12.5	13.1	13.3	13.2	12.8	12.1	11.5	10.9	10.7	22
10.9	11.3	11.9	12.5	12.9	13.2	13.1	12.7	12.1	11.5	11.0	10.8	20
11.0	11.4	11.9	12.4	12.8	13.1	13.0	12.6	12.1	11.6	11.1	10.9	18
11.1	11.5	11.9	12.4	12.7	12.9	12.9	12.5	12.1	11.6	11.2	11.1	16
11.3	11.6	11.9	12.3	12.6	12.8	12.8	12.5	12.1	11.7	11.3	11.2	14
11.4	11.6	11.9	12.3	12.6	12.7	12.6	12.4	12.1	11.7	11.4	11.3	12
11.5	11.7	11.9	12.2	12.5	12.6	12.5	12.3	12.1	11.8	11.5	11.4	10
11.6	11.7	11.9	12.2	12.4	12.5	12.4	12.3	12.0	11.8	11.6	11.5	8
11.7	11.8	12.0	12.1	12.3	12.3	12.3	12.2	12.0	11.9	11.7	11.7	6
11.8	11.9	12.0	12.1	12.2	12.2	12.2	12.1	12.0	11.9	11.8	11.8	4
11.9	11.9	12.0	12.0	12.1	12.1	12.1	12.1	12.0	12.0	11.9	11.9	2
12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	0

2.2.2 THORNTHWAITE (1948) METHOD

The Thornthwaite (1948) method used was as summarized by Lu, Sun, McNulty, and Amatya (2005) and is as follows:

$$ET_p = 16L_d\left[\frac{10T_a}{I}\right]^{\alpha} \qquad \text{Eqn. (2)}$$

Here ET_p represents potential evapotranspiration (mm/month), L_d is day length (hrs), T_a is the mean monthly air temperature (℃), I is the annual heat index, and α is computed from Equation 5. The monthly i values are computed as seen in Equation 3, which then produce the annual value of the heat index (I), by summing the 12 monthly i values, seen below in Equation 4.

$$i = (\frac{T_a}{5})^{1.514} \qquad \text{Eqn. (3)}$$

$$I = \sum_{j=1}^{12} i_j \qquad \text{Eqn. (4)}$$

In which I is the annual heat index, i is the monthly heat index for the month j (which is zero when the mean monthly temperature is 0 °C or less), and T_a is the mean monthly air temperature (°C). The calculation for α is as follows:

$$\boldsymbol{\alpha = (6.75 * 10^{-7}) I^3 - (7.71 * 10^{-5}) I^2 + (1.79 * 10^{-2}) I + 0.492} \quad \text{Eqn. (5)}$$

This equation was evaluated by Xu and Singh (2001) and was determined to be accurate in calculating ET rates when the equation was calibrated. However, when un-calibrated, it tended to produce an underestimation in comparison to pan evaporation values.

2.2.3 HARGREAVES (1994) METHOD

Hargreaves (1994) method is shown below:

$$E_P = 0.0023 t^{0.5} A(T + 17.8) \qquad \text{Eqn (6)}$$

Where t is the monthly range of air temperature (˚C), A is the monthly extraterrestrial radiation (mm) (see appendix F) and T is the mean monthly air temperature. There are many variants of this equation, and an examination of scientific literature revealed it to be one of the better, if not the best temperature-based ET equation (e.g. Xu & Singh, 2001; Xu & Singh, 2002; Chuanyan *et al.,* 2004; Hargreaves, & Allen, 2003). The best performance of this model was found to be best in semi-arid or arid areas, whereas under estimation proved problematic when it was applied in a humid or sub-humid setting (Xu & Singh, 2002).

3. Materials and Methodology

3.1 Study area

The selected study area for this project is British Columbia, the westernmost province in Canada (Figure 1). The province borders the Pacific Ocean and covers a large surface area of approximately 950,000 km^2, the population density is approximately 4.4 people per km^2 (McGillivray, 2005). The population is about 4.5 million, yet the distribution is uneven with 60% of the population located in the southwestern corner of the province (Government of British Columbia, 2012). There are multiple climate types within B.C ranging from humid coastal climates, to semi-arid grasslands, to cool mountainous climates due to the complexity of its geography. This presents an issue firstly with irregular water distribution, and secondly with trying to quantify the amount of it lost to evapotranspiration as the climate zones are constantly changing. Depending upon the region, there are different water management concerns regarding agriculture, drought, hydroelectric dams, and the provision of municipal drinking water. Planning for all these issues would benefit from displaying water balance terms, specifically evapotranspiration, to better evaluate each area's specific situation.

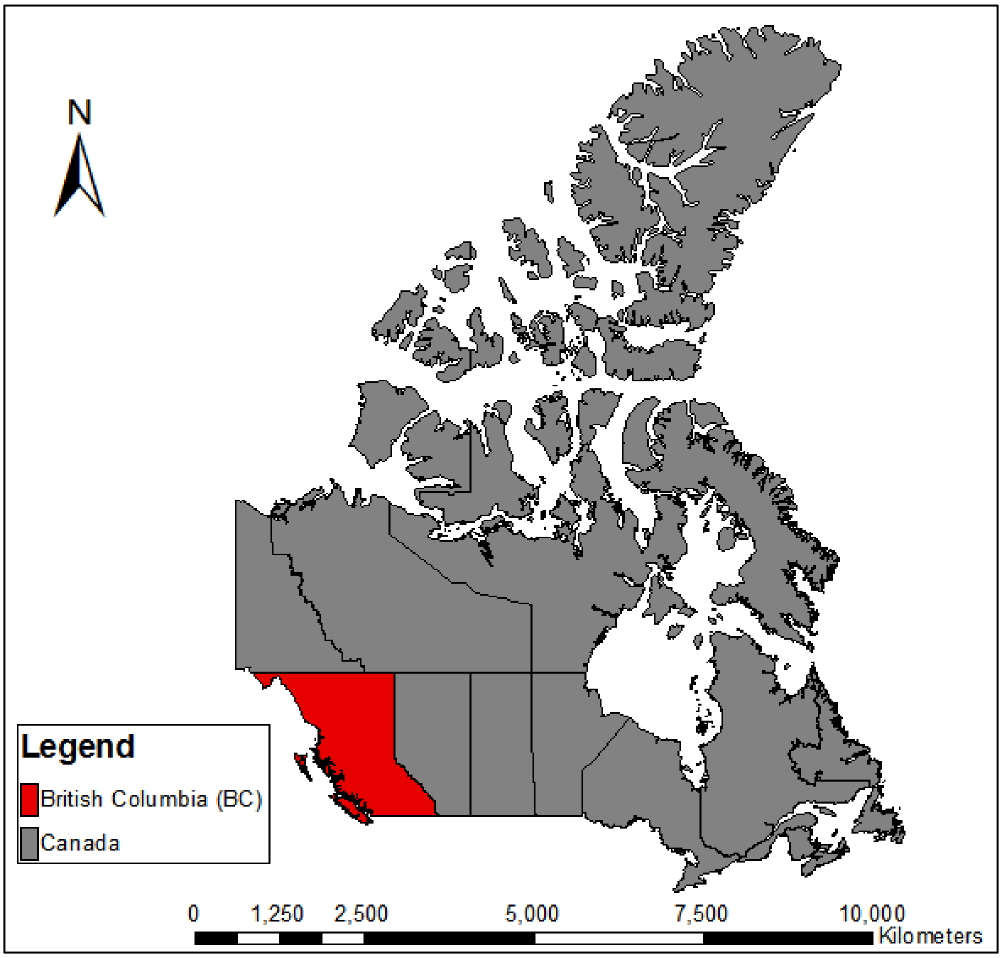

Figure 1 – Location of project study area, British Columbia, Canada

3.2 MATERIALS AND SOFTWARE USED

The materials used for this project include climatic data for the year of 2006, derived from Environment Canada (2012), as well as a vector shapefile of B.C. taken from the Canadian GeoBase (2011) website, which were both analyzed using ESRI's ArcMap version 9.2 software. The equations for evapotranspiration (ET) were replicated from the specific scientific articles previously mentioned in section 2.2. Tables showing required meteorological variables (Table 1) were also obtained from Allen *et al.* (1998) and used in conjunction with weather variables obtained from Environment Canada (2012) to calculate ET rates. Minitab 16 Statistical Software was also used to run a statistical analysis of the calculated ET values against the reference Penman-Monteith values from Farmwest (2012).

3.3 PRE-PROCESSING DATA

Pre-processing the weather data was tedious due to the fact that this study was based on algebraic equations with numerous meteorological variables, and large amounts of data had to be obtained, processed and organized into an Excel spreadsheet. This included first compiling data for stations in BC, as well as the bordering stations in the surrounding provinces/territories (Alberta and Yukon) to ensure a more accurate interpolation. The station name, latitude and longitude coordinates, yearly mean precipitation, yearly mean temperature, and monthly mean temperature and precipitation values from 2006 were copied into an Excel document. These data were then organized along with other calculated variables for each specific ET equation. A portion of the final table can be seen below (Table 2).

Table 2- Example portion of final table containing all necessary PET calculation variables

Station	Latitude	Longitude	TAJAN	TAFEB	TAMARCH	TAAPRIL	TAMAY	TAJUNE
100 Mile House	51.646944	-121.3025	-2	-5.1	-0.1	5.9	10.2	14.1
Abbotsford A	49.025278	-122.36	6.2	4.6	6.9	9.9	13.6	16.3
Aggasiz CDA	49.243056	-121.760278	6	4.7	7.3	10.3	14.5	17.6
Alberni Robertson Creek	49.337222	-124.981944	3.7	2.2	4.6	8.6	13.2	17.1
Atlin	59.566667	-133.7	-13.4	-10.5	-9.5	1.5	5.8	11.2
Babine Lake Pinkut Creek	54.446389	-125.459722	-1.6	-7.6	-2.2	4.6	8.5	14.1
Barkerville	53.069167	-121.514722	-4.5	-7.9	-4.5	2.1	6.9	11.2
Blue River A	52.128889	-119.289444	-0.4	-5	0.4	6.4	10.7	15.5
Bonilla Island	53.492778	-130.637778	6.1	4.7	4.9	7.2	9.9	12.3
Burnaby Simon Fraser U	49.278333	-122.917778	4.2	3.4	5.4	8.9	12.8	15.9
Campbell River A	49.951944	-125.273056	4.1	2	4.3	8.3	12.3	16
Castlecar A	49.296389	-117.6325	1.4	-1.1	3.9	9.5	13.8	17.9
Castlegar BCHPA Dam	49.343333	-117.774444	2.3	0.2	4.6	9.8	14	18.2
Chatham Point	50.333333	-125.433333	5.7	3.6	5.5	8.8	12.6	15
Comox A	49.716667	-124.9	5.4	3	5.4	8.9	12.8	16.3
Cowichan Lake Forestry	48.824444	-124.133333	4.7	3.3	5	8.3	12.3	16.1
Cranbrook A	49.612222	-115.781944	-0.8	-4.3	1.4	7.1	12	16.5
Creston	49.096944	-116.517778	1.8	-0.1	4.4	9.4	13.7	17.7
Darfield	51.297222	-120.1825	1	-1.7	3.7	9.3	13.3	17.8
Dease Lake	58.428333	-130.010556	-15.2	-13.5	-8.8	1.2	5.7	11.3
Duncan Lake Dam	50.238611	-116.971389	1.5	-2	2.8	8.1	12.4	16.6
Egg Island	51.247222	-127.835278	5.6	4.2	5.5	7.9	10.2	12.3
Estevan Point	49.383333	-126.550833	6.7	5.3	5.6	8.4	11.2	14.1
Fauquier	49.871944	-118.0675	1.9	-0.7	3	8.3	12.2	16.9
Fernie	49.488889	-115.072222	1	-4.8	0.4	6.4	11.2	15
Fording River Cominco	50.148611	-114.855	-4.3	-10.1	-4.8	2.8	7.2	11.7
Fort Nelson A	58.836389	-122.597222	-19.4	-12.4	-11	4.8	9.7	16.3
Fort St James	54.455278	-124.285556	-2.7	-7.5	-3.9	4.7	10.4	14.2

3.4 INTERPOLATION AND APPLICATION OF ET EQUATIONS

The station names were added to ArcMap, and from their latitude and longitude coordinates (see Figure 2), the rest of the data could then be interpolated within the station location points' attribute table. Firstly, the monthly average temperatures for the year 2006 had to be interpolated to cover the entire area within the B.C. provincial boundary. The Inverse Distance Weighted (IDW) interpolation function was utilized to interpolate each month, with the end result being twelve separate maps of the mean temperatures throughout the entire province of B.C. This same methodology was employed to interpolate all of the equation specific variables including: monthly fraction of annual hours of daylight (p), the Thornthwaite (1948) i, I^3, I^2, I, and $\boldsymbol{\alpha}$ values, as well as the monthly range of air temperature in (°C), and the monthly extraterrestrial radiation (A). Once completed, the chosen ET equations (Blaney-Criddle, 1950; Thornthwaite, 1948; Hargreaves, 1994) were then applied. This resulted in twelve monthly PET maps for each equation, with values over the whole area of BC. For later comparison, Penman-Monteith values from Farmwest (2012) for sixteen of the weather stations were also interpolated following the same methodology as the previous equation specific variables, in order to provide a reference for how the other equations performed.

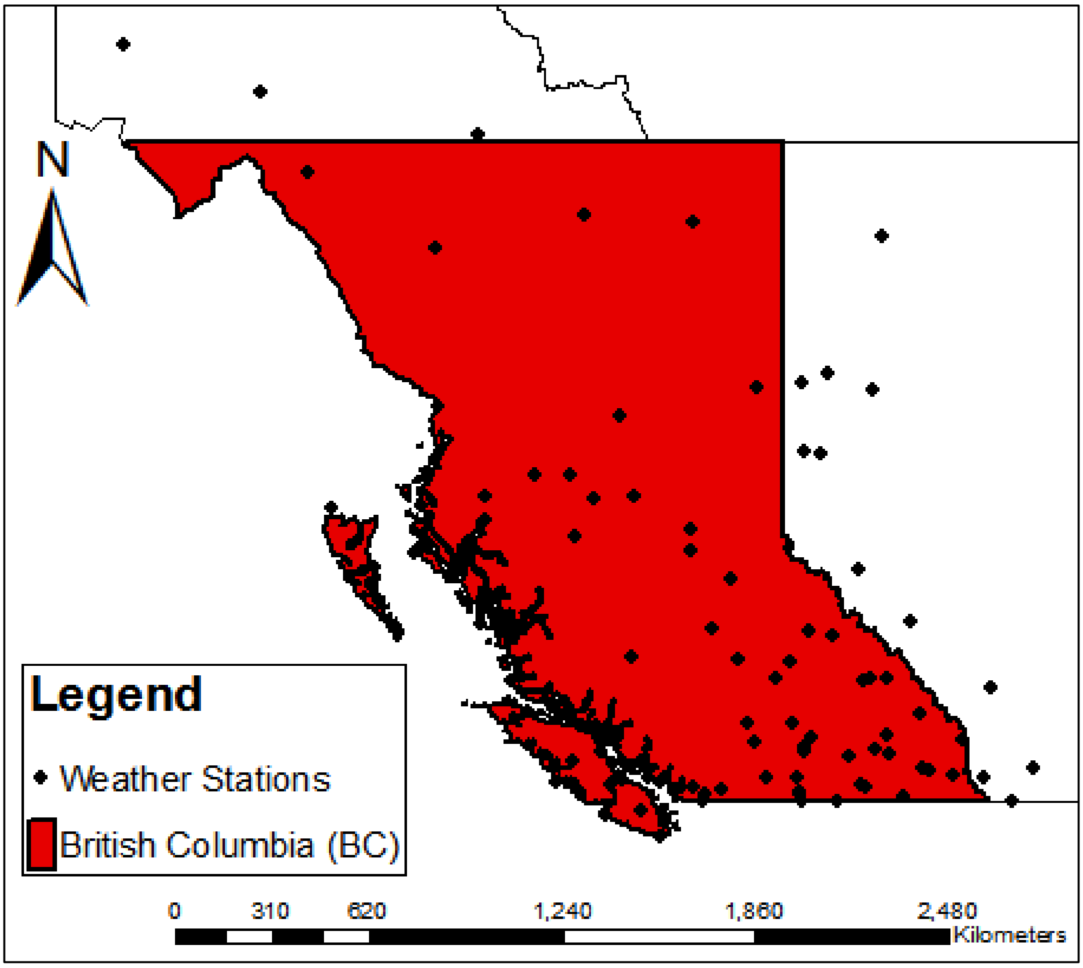

Figure 2- Distribution of weather stations used in the project

3.5 ANALYSIS OF ET VALUES

In order to compare how each equation performed, a statistical analysis was run on the reference ET values from Farmwest (2012) and the calculated ET values from the Blaney-Criddle (1950), Thornthwaite (1948), and Hargreaves (1994) equations performed in ArcMap. A Kolmogorov-Smirnov test of normality was run on the combined ET values for May-September and every equation except the Thornthwaite (1948) were considered normal; thus a Wilcoxon Signed Rank non-parametric test was used. Descriptive statistics were also calculated in order to summarize the calculated values of each equation.

4. RESULTS

4.1 ET EQUATIONS USE WITH ARCMAP

The results of the evapotranspiration equation literature review revealed that temperature-based equations were the best to use for this specific study, due to the fact it that it was interpolation based and multiple weather station points were needed. The available data recorded amongst the chosen weather stations were not congruent, and as the temperature based methods required the least amount of input data yet still produced desirable results, the Blaney-Criddle (1950), Thornthwaite (1948), and Hargreaves (1994) methods were selected. In regards to their use with ArcMap, the Hargreaves (1994) and Blaney-Criddle (1950) methods required significantly less time to run due to involving fewer calculations. The Thornthwaite (1948) method required many variables within the equation to first be calculated (see equations 3, 4 & 5) before the calculation as a whole could be run (see equation 2) and ET values produced.

4.2 DISTRIBUTION PATTERNS OF ET IN BC

4.2.1 COMPARISON AMONGST EQUATIONS

All three ET equations appeared to show similar distribution patterns. While all twelve months of the year were calculated, only the summer months (April-September) were examined in detail, as that is when evapotranspiration rates are highest and of the most concern. The overall distribution from high to low ET was comparable amongst the three equations; however the specific values did in fact differ. Overall the Thornthwaite (1948) method produced the smallest ET rates, as well as the smallest range in ET values, and the Hargreaves (1994) method produced the largest values and consequently largest range of ET values. Due to the fact that temperature-based equations were used, the ET distribution also appeared to be correlated with temperature distribution. Of the three equations, the Blaney-Criddle (1950) ET distribution was the most accurate yet also appeared to be most closely correlated to temperature distribution patterns (Figure 3). The Hargreaves (1994) ET distribution looked least closely related to temperature distribution, while the Thornthwaite (1948) distribution appeared to be somewhat in between these two patterns.

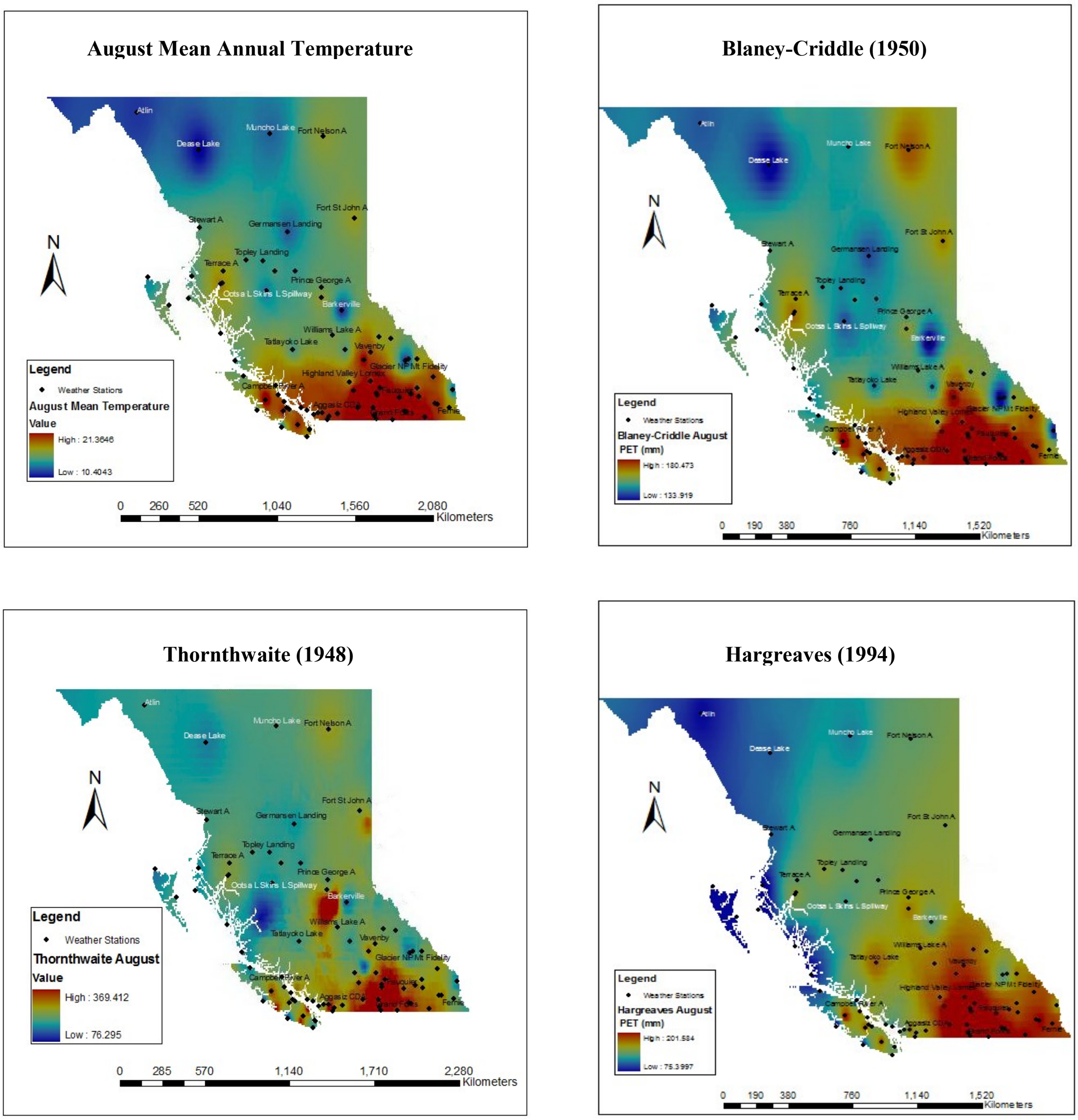

Figure 3- Comparison of PET distributions in BC with mean August temperature

4.2.2 General ET distribution patterns in BC

In general all equations showed the highest areas of ET to be in the southern centre of the province, near the Agassiz CDA-Faquier-Grand Forks area. ET then appeared to decrease at an angle from that SE corner until the NW tip of the province, with a few exceptions. The lowest ET rates are shown in the NW region of BC where the temperatures are not as high, and there is an influence of moisture from the coast.

With regards to how the different equations displayed ET rates as a whole throughout the province, the Hargreaves (1994) equation produced the smoothest results from low to high latitude (Figure 3). The Blaney-Criddle (1950) equation in contrast produced the most localized differences, with a more clustered appearance, whereas the Thornthwaite (1948) equation produced results somewhat in between these two distributions (Figure 3).

4.3 Statistical Analysis of ET equations

The result of the Wilcoxon Signed Rank test showed that three tested equations were statistically different values than the reference Penman-Monteith values. The Thornthwaite (1948) equation produced the smallest range of values (99) while the Hargreaves had the largest range of values (177). As can be seen in Figure 4, the Thornthwaite (1948) equation produced the lowest ET, followed by the Penman-Monteith, Blaney-Criddle (1950) and finally Hargreaves (1994) equation, which produced the largest ET values. The 95% confidence intervals on the mean of the Thornthwaite (1948), Blaney-Criddle (1950), and Hargreaves (1994), equations were (85, 97), (154, 166), (166, 185.5), respectively in comparison to the Penman-Monteith 95% confidence interval of (115.5, 128). The Hargreaves (1994) equation also had the largest standard error (4.47) and deviation (39.94), while the standard error and deviation of the Penman-Monteith, Blaney-Criddle (1950), and Thornthwaite (1948) values ranged from 2.61-3.2 and 23.3-28.6, respectively. The Penman-Monteith and Thornthwaite (1948) equations had slight positive skew (0.2 and 0.68) whereas the Blaney-Criddle (1950) and Hargreaves (1994) equations had a negative skew (-0.16 and -0.14).

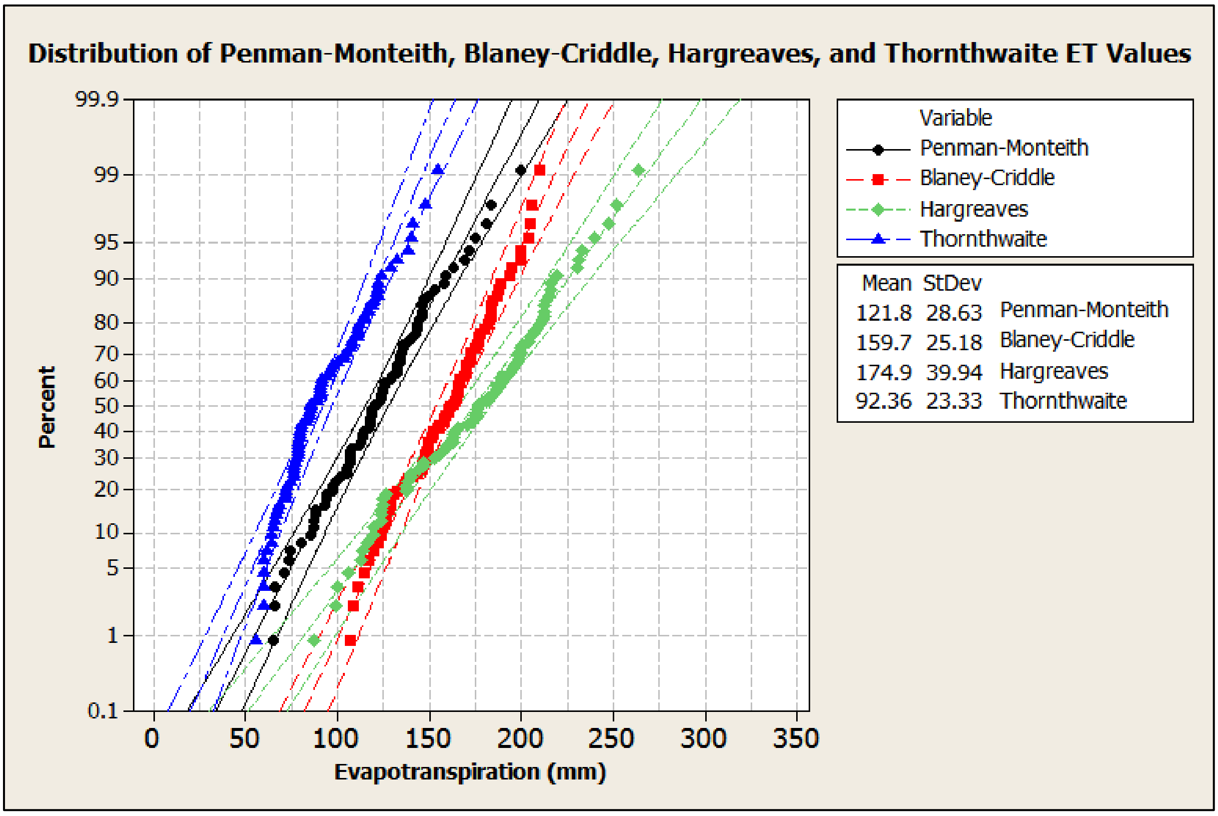

Figure 4- Distribution of Penman-Monteith, Blaney-Criddle, Hargreaves, and Thornthwaite ET values

5. Discussion and Conclusion

5.1 ET distribution in BC

The three ET equations used in conjunction with ArcMap were all temperature based, thus, their distribution patterns are somewhat correlated to the distribution of the temperature values (see Figure 3), nevertheless some differences were observed. The Hargreaves (1994) method produced a smoothed and gradual distribution of ET values, and because of the complex terrain in BC, this method matches the least with the provincial microclimates. The Blaney-Criddle (1950) method ET distribution pattern more accurately depicts the climate zones created by the steep topography, as the radial blue areas on both the East and West side of the province are representative of the mountain ranges that run along the border, which produce colder climates and consequently less ET. These mountain areas do not show up on the Penman-Monteith interpolated maps, but this may be due to the limited data points that they were interpolated from.

5.2 Feasibility of interpolation methodology

The tested methodology of España *et al.* (2011) provided a relatively simple and efficient way to spatially distribute ET rates with the use of ESRI's ArcMap software, yet there was some redundancy. This tediousness is mostly due to the raw data format. If spread sheet data were available, it would have greatly increased initial data pre-processing. The methodology could be replicated without a high level of knowledge of GIS software, but some potential errors must be discussed. While interpolation is a useful way to compute missing data values, it is not a replacement for the actual data if they are available for different interpolation methods can produce different results. This project utilized the IDW method of interpolation as it is generally the method used when it comes to calculating weather related variables, yet other methods could have been utilized and consequently compared to ensure the optimal method was chosen. Naoum and Tsanis (2003) utilized the "distributed" concept in which Spline, IDW, Kriging, and Trend methods were combined in order to reduce interpolation error. That stated, IDW was a good choice for this project due to auto-correlation and because it is an exact interpolation method, and for this reason the IDW interpolation would have derived accurate values.

5.3 Statistical analysis of ET equations

The results from the statistical analysis indicated that all values calculated by the three tested ET methods were different. When the values for all months (May-September) were combined the Thornthwaite (1948) method was the only one without a normal distribution, however when the individual months were examined the Thornthwaite (1948) values were also normal. The four methods did produce an overall similar distribution pattern (Fig 6), yet the Wilcoxon Signed Rank test showed the values were not statistically the same.

This analysis only focused on sixteen weather stations as they were the only ones in which Penman-Monteith ET values were available. Had a larger number of stations been sampled, the results may have been more significant. Moreover, the stations were not randomly selected but based upon data availability, and this could have increased sampling error within the analysis. Another issue concerning accuracy is the large study area of this project as one small weather station point could not fully represent the ET of the surrounding area, due to the variability of ET in microsites near the station.

The actual July ET values can be seen below as calculated by the Penman-Monteith equation in comparison to those derived in this study by the Blaney-Criddle (1950), Hargreaves (1994), and Thornthwaite (1948) methods (Table 3). These values again illustrate the variance amongst the different equations. The underestimation of the Thornthwaite (1948) equation can be noted, especially at the Abbotsford, Comox, and Prince George stations, whereas the overestimation of the Hargreaves (1994) equation can also be observed throughout all the weather stations. The selected equations did not produce overly accurate values of ET. To increase the accuracy, the study area could be reduced and regional or crop coefficients could be applied, however, time constraints of the study restricted the trial of this. Other more detailed equations could also be utilized, such as the Penman-Monteith method if such data variables were widely available, as this type of equation is more suited to smaller study areas.

Table 3- Comparison ET values for the month of July (mm)

Method	Abbotsford	Comox	Oosoyos	Kamloops	Prince George
Penman-Monteith	135	130	200	184	147
Blaney-Criddle	184	182	210	182	185
Hargreaves	212	207	264	214	213
Thornthwaite	92	91	115	101	91

6. Conclusion

6.1 Conclusion

Spatially displaying evapotranspiration rates would aid in water resource planning and also allow historical comparison of maps in order to determine if ET rates are shifting in one direction or another. It would also aid in planning for environmental hazards such as drought, or forest fires, and such maps could aid in risk management strategies for these regions. GIS are powerful tools through which spatially processing and integrating environmental variables continues to increase. The methodology of España *et al.* (2011) provided a relatively simple and efficient way to spatially calculate evapotranspiration rates with use of ESRI's ArcMap software; however, a large amount of data must initially be pre-processed. Temperature-based equations were selected to calculate ET as they work best in general study areas with limited data yet other types of equations may be employed with the same methodology so long as the required data may be obtained.

In terms of the performance of the specific ET equations, none of them produced values statistically comparable to the Penman-Monteith equation, but the Blaney-Criddle (1950) performed better than the Thornthwaite (1948) and Hargreaves (1994) equations, which under and over-estimated ET rates. The overall ET distribution pattern appeared to accurately depict general areas of high and low ET in which areas were at the highest and lowest risk for evapotranspiration, however this is largely due to the equations being dependent on temperature input values. The Blaney-Criddle (1950) method produced the most accurate distribution pattern of the three, in that the two mountain ranges running on either border of the province were shown. The interpolated images of the Penman-Monteith equations did not produce an accurate representation ET throughout the province, yet the specific point values were limited. Therefore, the specific site values were used as a reference for the other three equations for due to the complexity of the equation calibration to the sites was not required.

6.2 Future perspectives

This project was centered on the spatial display of ET equations, yet this type of study is applicable for other environmental equations with different data inputs, such as calculating interception loss or stemflow. Moreover a future expansion upon this project could apply crop coefficients to various regions in order to obtain more specific values. Ray and Dadhwal (2001) also show that remote sensing is relevant in ET calculations to categorize different land types and subsequently assign appropriate crop coefficients. This should be considered for future projects looking to display AET, for it is key way to use technology to determine crop coefficients for specific areas. GIS software also have the capabilities to program the element of time to display output shapefiles. If ET is to be calculated, different areas will have different rates of evapotranspiration, and thus linking the areas to a time display could prove useful for the sake of comparing and contrasting regions and ET seasonality. The

Tracking Analyst extension in ArcMap has the capability of this so future studies may want to examine the use of this extension.

Choice of interpolation method is another area that has the potential for extension, as the focus of this study was on the ET equations themselves, not on the specific interpolation methodology. There are numerous ways to interpolate variables and future work should be done to quantify the absolute best method to interpolate climatic variables such as precipitation and temperature. Technology and programming based studies could also further develop on extensions specifically for calculating ET, such as those proposed by Papageorgiou *et al.* (2005) and España *et al.* (2011). These add-ons for ArcGIS enable calculating ET to be completed more efficiently because only simple input and output maps are needed; the calculation function is carried out similarly to the already existing ArcToolbox functions. The development of these extensions are extremely valuable since the user would not need a heavy knowledge of GIS, and variables within these methods could easily be changed or compared to the output of a different ET calculation method. Ultimately, this type of addition would be the ideal outcome as it would provide the most effective way to spatially calculate ET rates.

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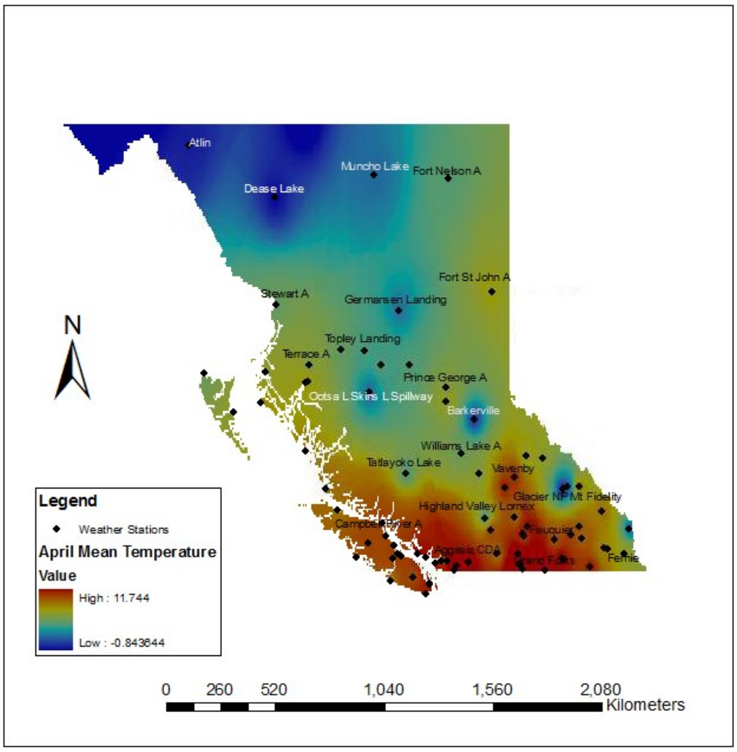
APPENDIX A- MEAN TEMPERATURE DISTRIBUTION IN BC



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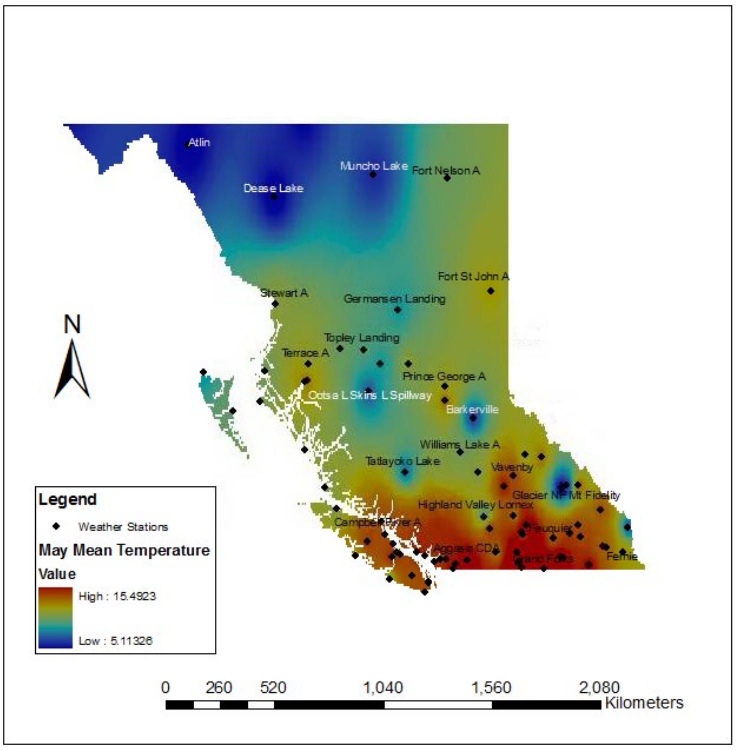

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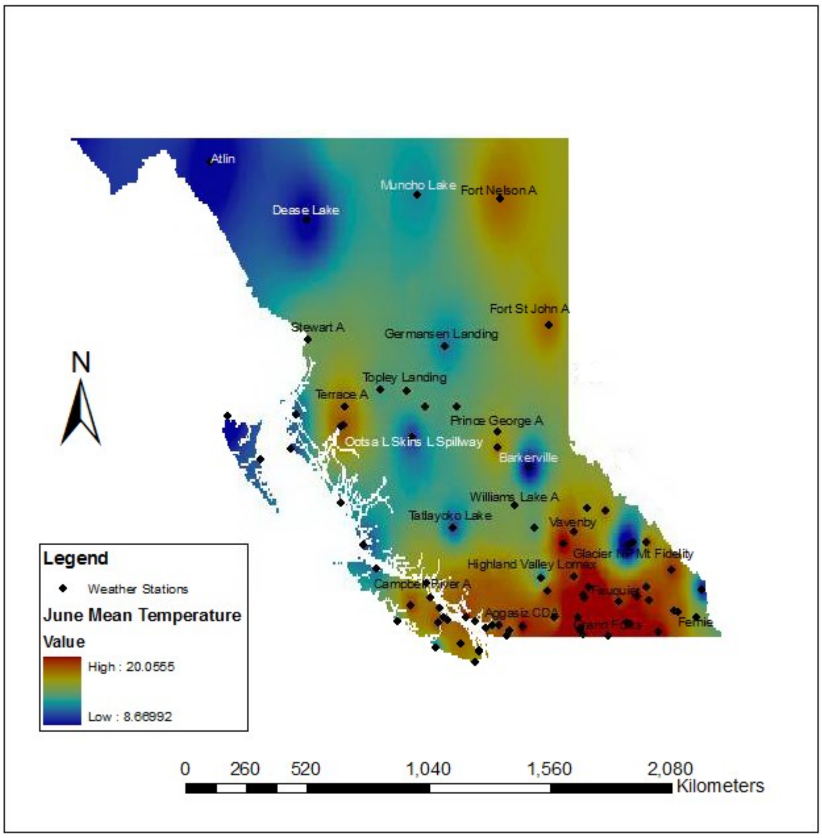
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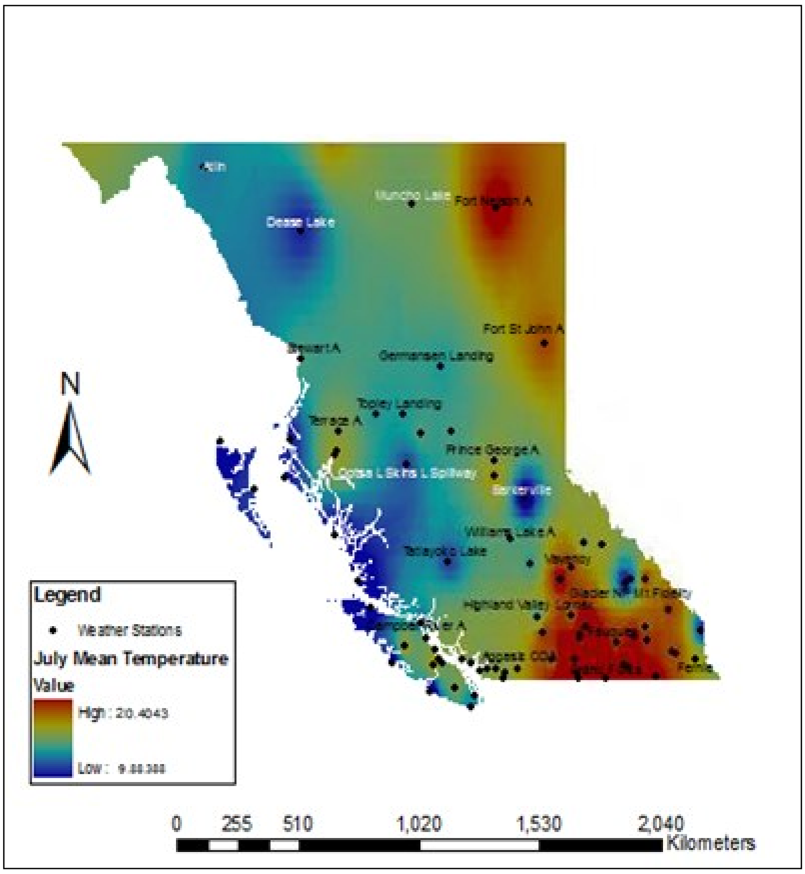
Muncho Lake
Fort Nelson A
Fort St John A
Stewart A
Germansen Landing
Topley Landing
Terrace A
Prince George A
Ootsa L Skins L Spillway
Barkerville
Williams Lake A
Tatlayoko Lake
Vavenby
Glacier NP Mt Fidelity
Highland Valley Lornex
Campbell River A
Agassiz CDA
Fernie
N
Legend
Weather Stations
June Mean Temperature
Value
High : 20.0555
Low : 8.66992
0
260
520
1,040
1,560
2,080
Kilometers

June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Tatlayoko Lake
Glacier NP Mt Fidelity
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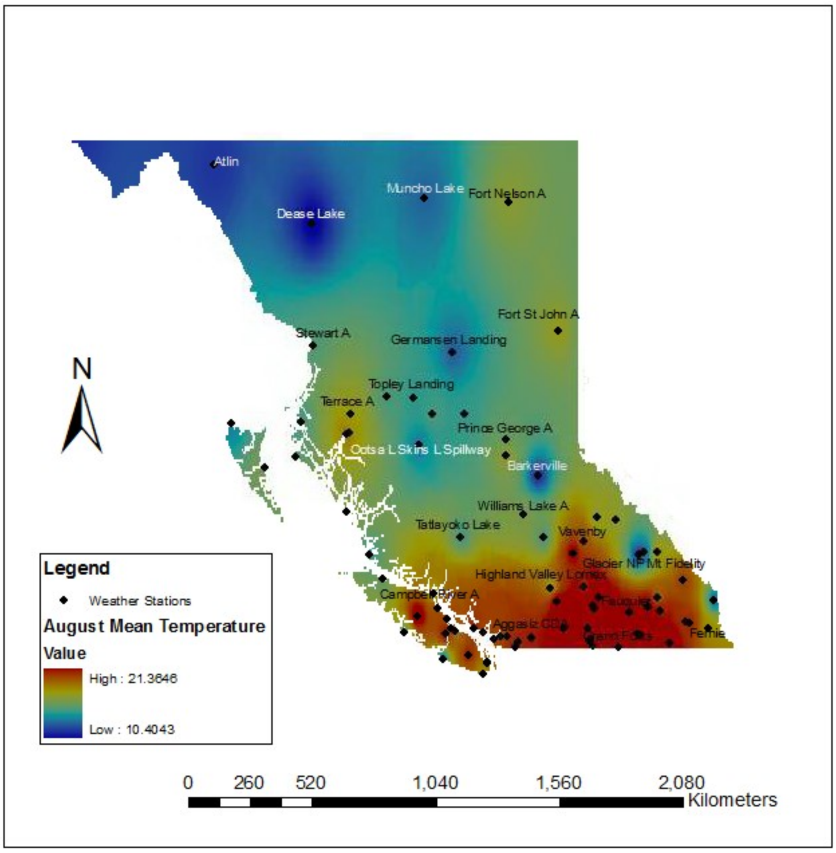
2,040
Kilometers

July



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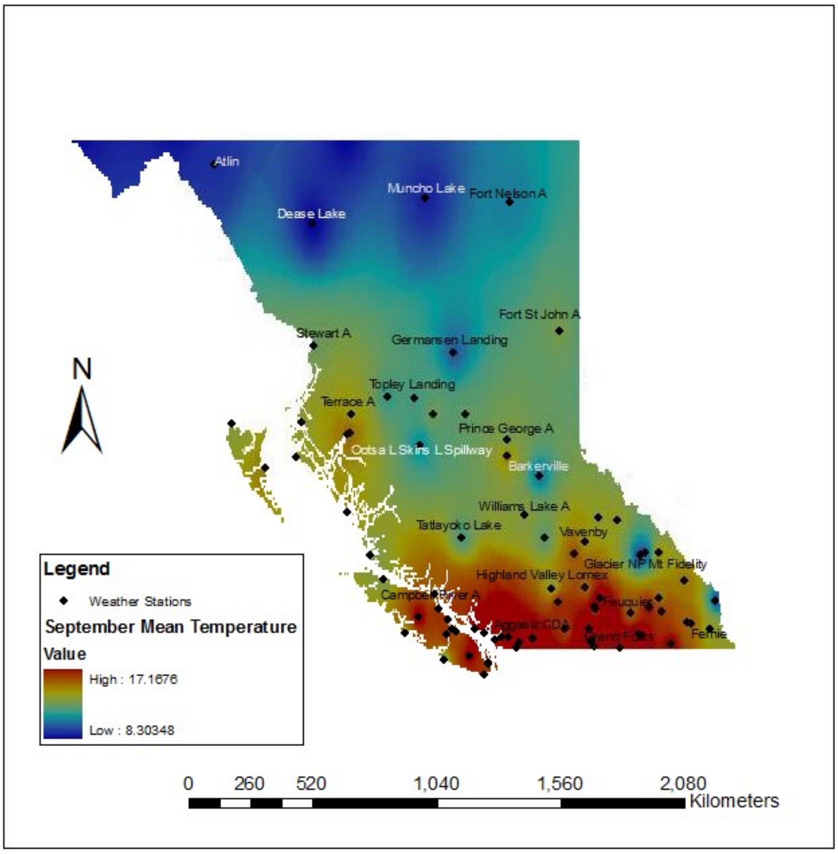
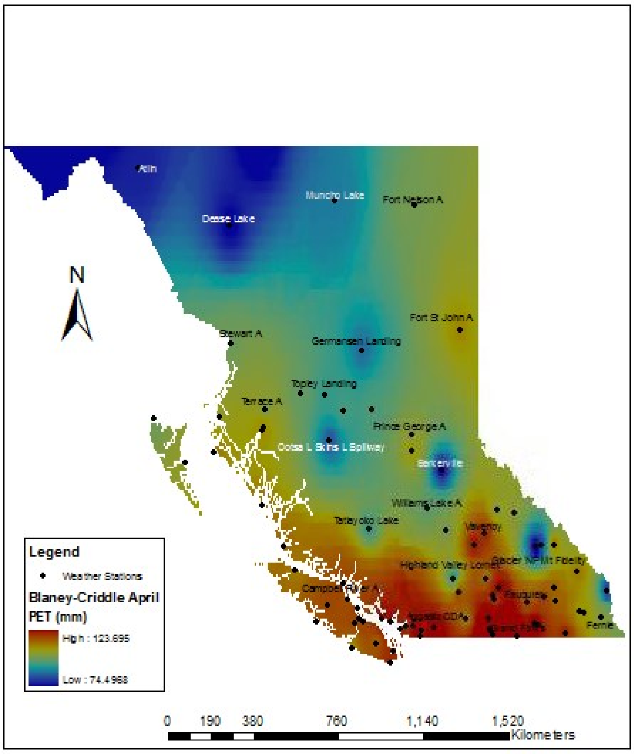


September

APPENDIX B – BLANEY-CRIDDLE (1950) MONTHLY PET DISTRIBUTION IN BC



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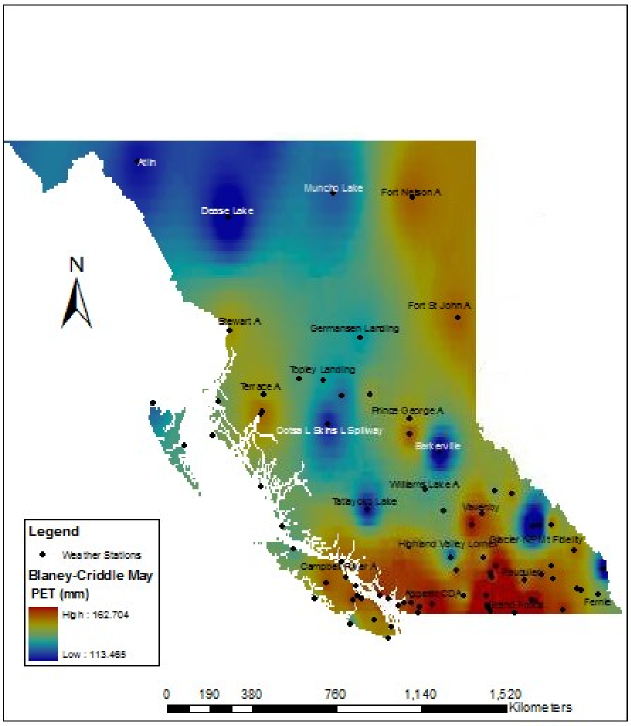

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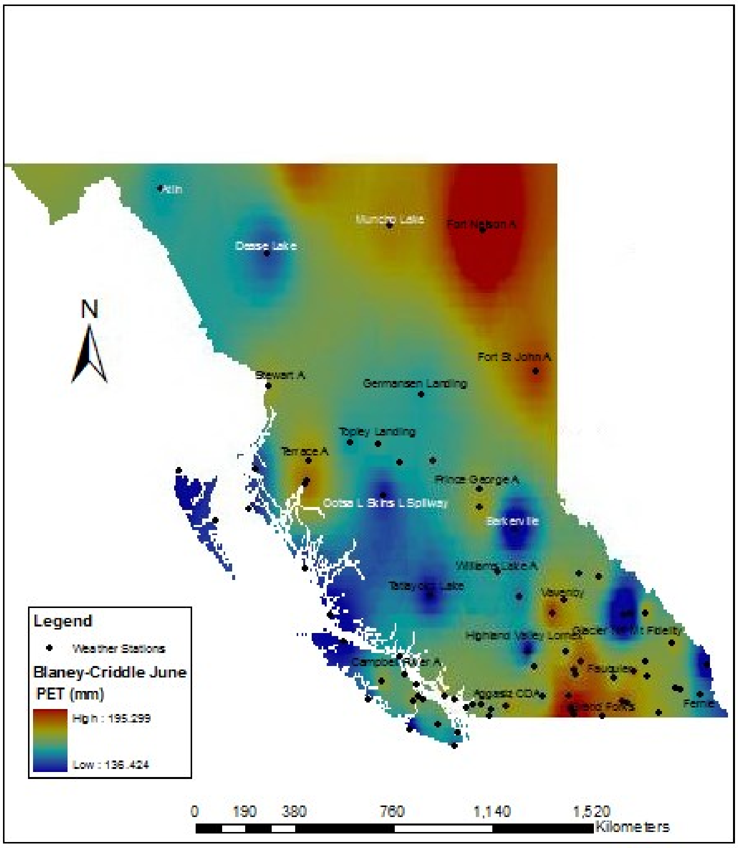
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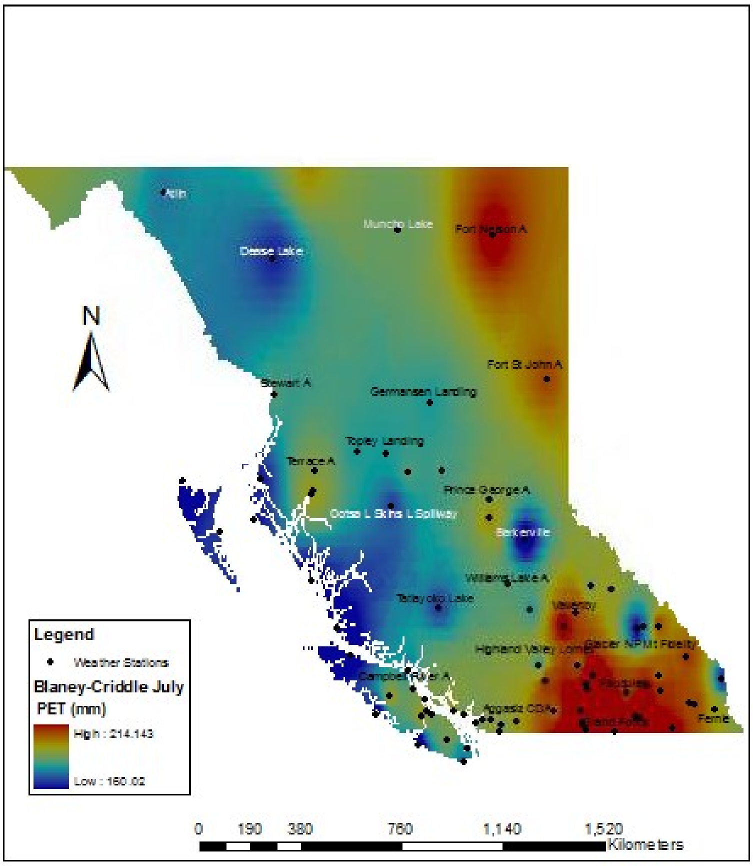
Barkerville
Williams Lake A
Tatlayoko Lake
Vavenby
Highland Valley Lornex
Glacier NP Mt Fidelity
Campbell River A
Fauquier
Agassiz CDA
Grand Forks
Fernie
Legend
Weather Stations
Blaney-Criddle June PET (mm)
High : 195.299
Low : 136.424
0 190 380 760 1,140 1,520
Kilometers

June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Highland Valley Lornex
Glacier NP Mt Fidelity
Campbell River A
Fauquier
Agassiz CDA
Grand Forks
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Legend
Weather Stations
Blaney-Criddle July PET (mm)
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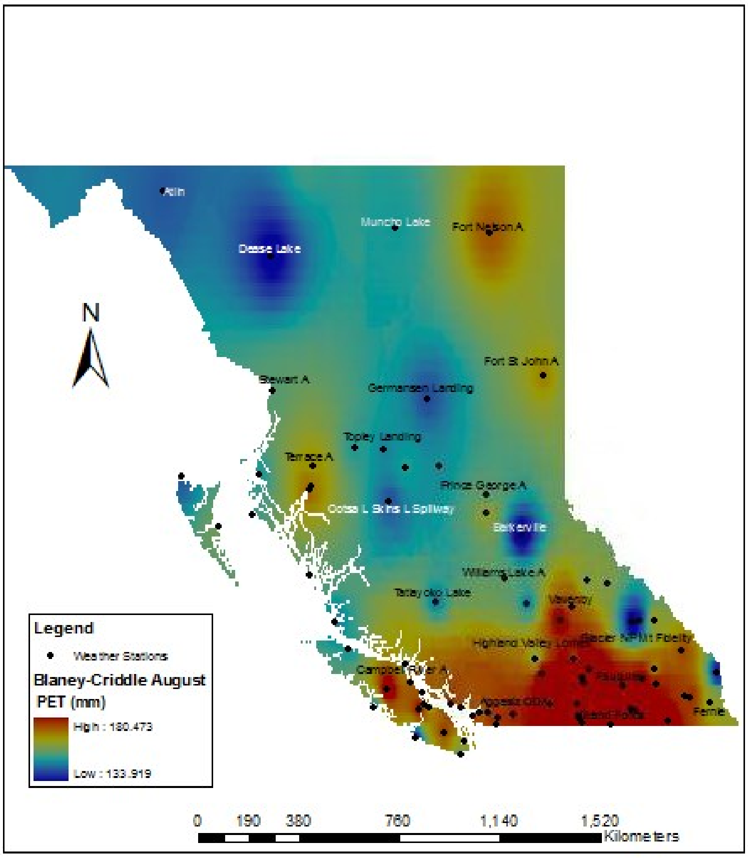
Kilometers

July



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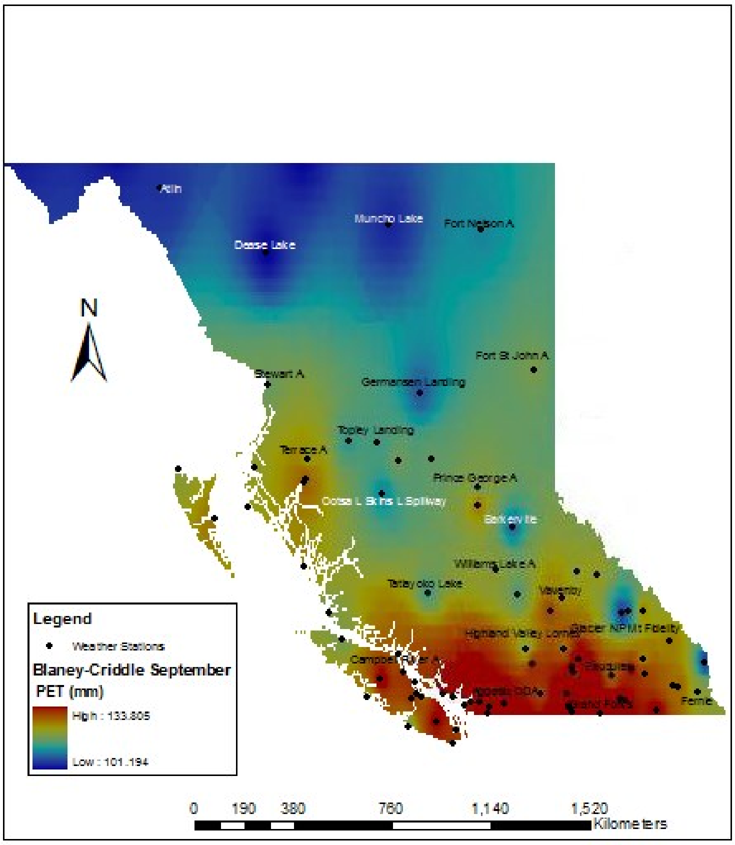
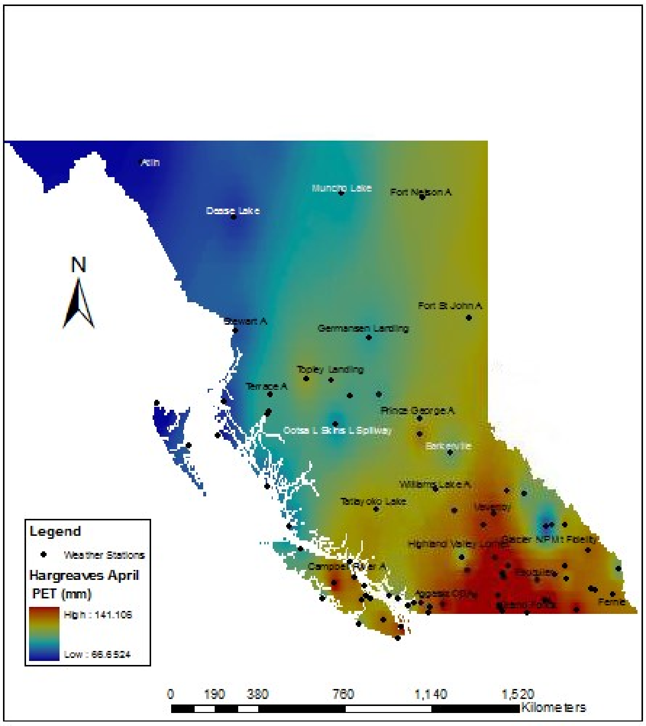


September

APPENDIX C- HARGREAVES (1994) MONTHLY PET DISTRIBUTION IN BC



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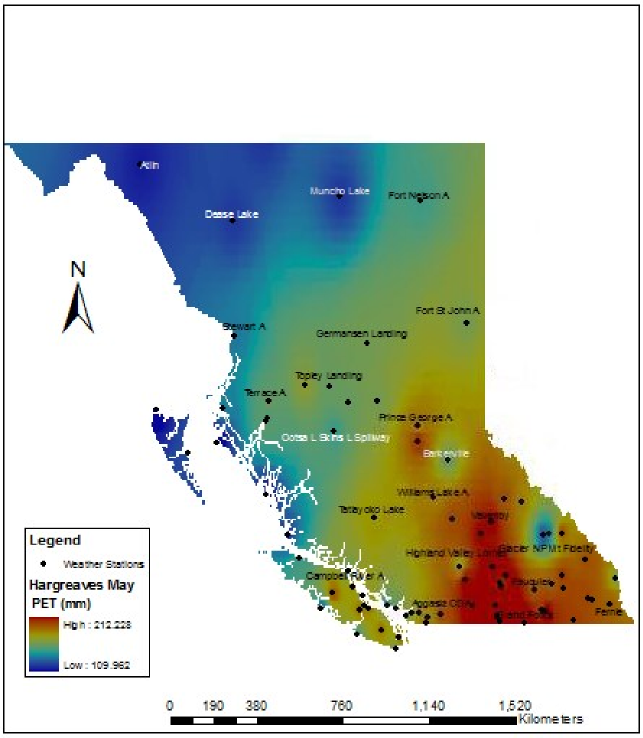

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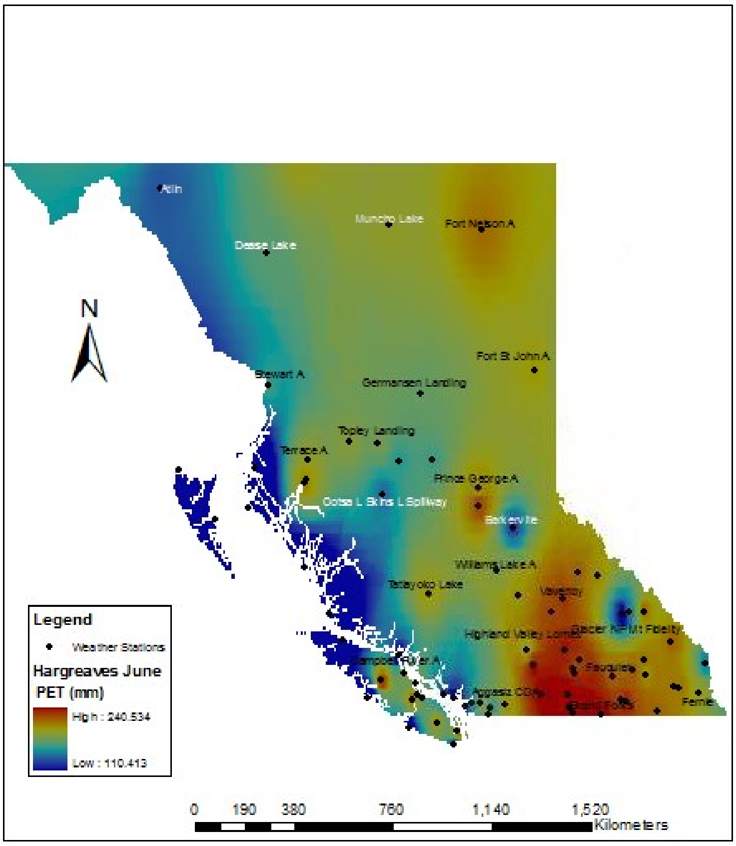
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Barkerville
Williams Lake A
Tatlayoko Lake
Vavenby
Highland Valley Lornex
Glacier NP Mt Fidelity
Campbell River A
Fauquier
Agassiz CDA
Grand Forks
Fernie
Legend
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Hargreaves June PET (mm)
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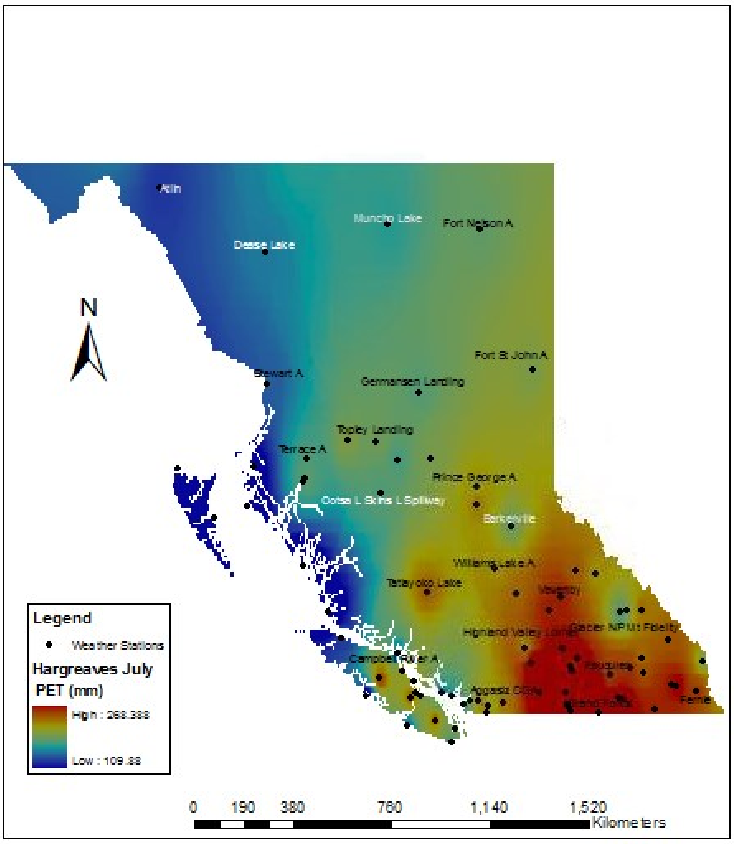
Kilometers

June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Barkerville
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Vavenby
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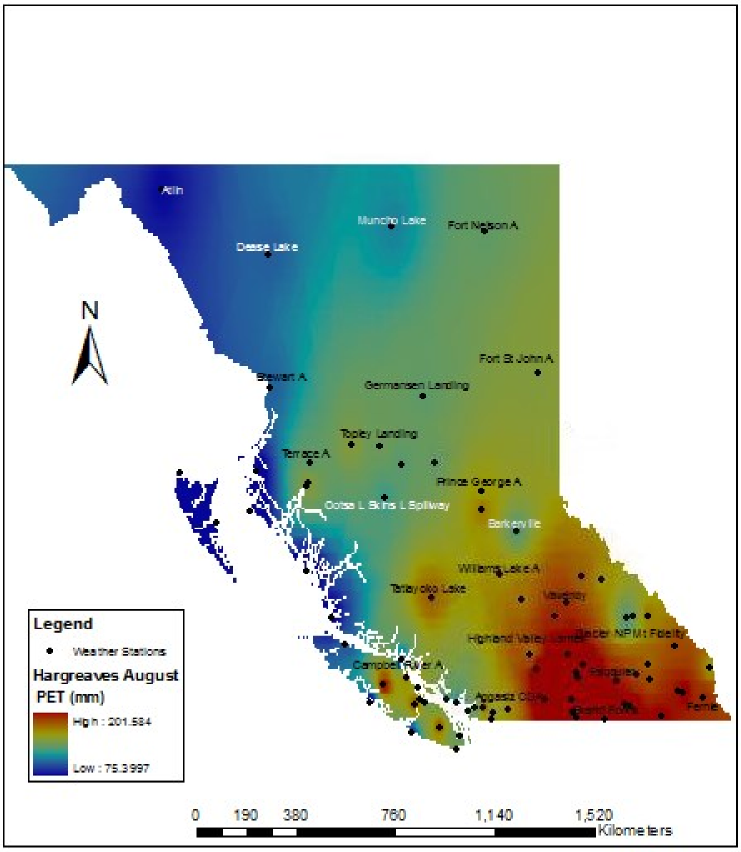
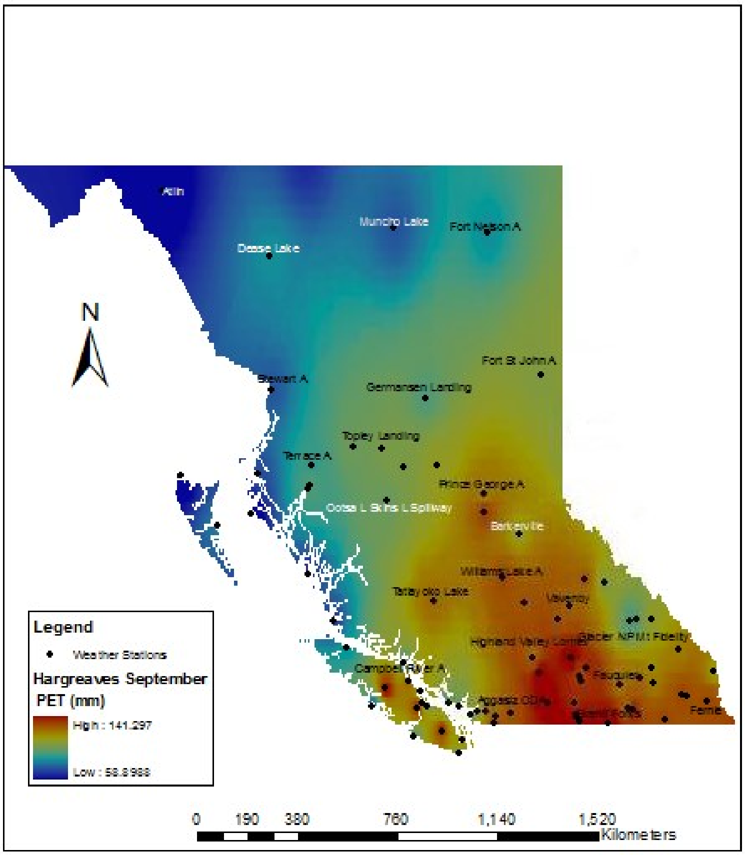
Glacier NP Mt Fidelity
Campbell River A
Fauquier
Agassiz CDA
Grand Forks
Fernie
Legend
Weather Stations
Hargreaves July PET (mm)
High : 268.388
Low : 109.88
0 190 380 760 1,140 1,520
Kilometers

July

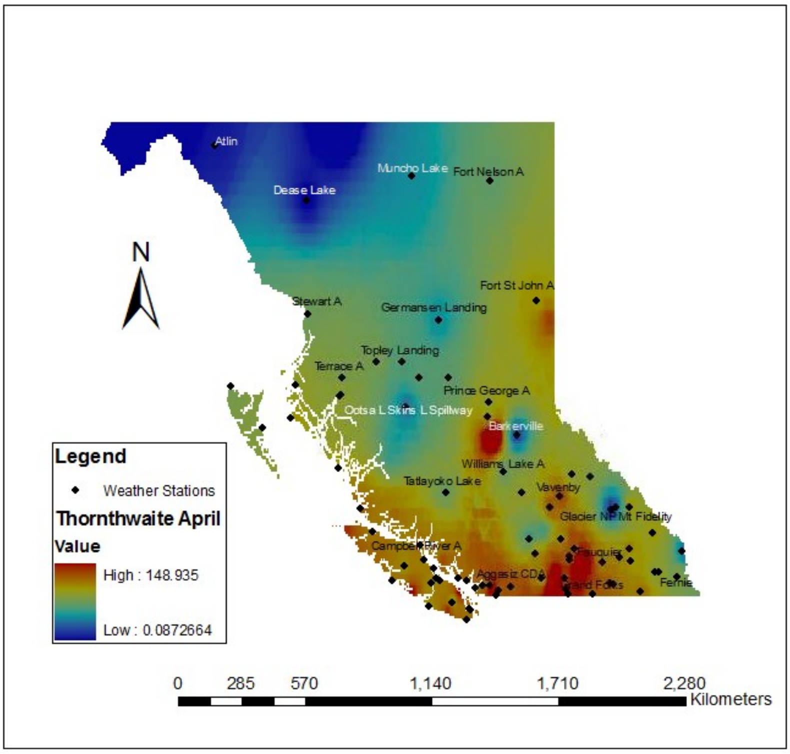


August

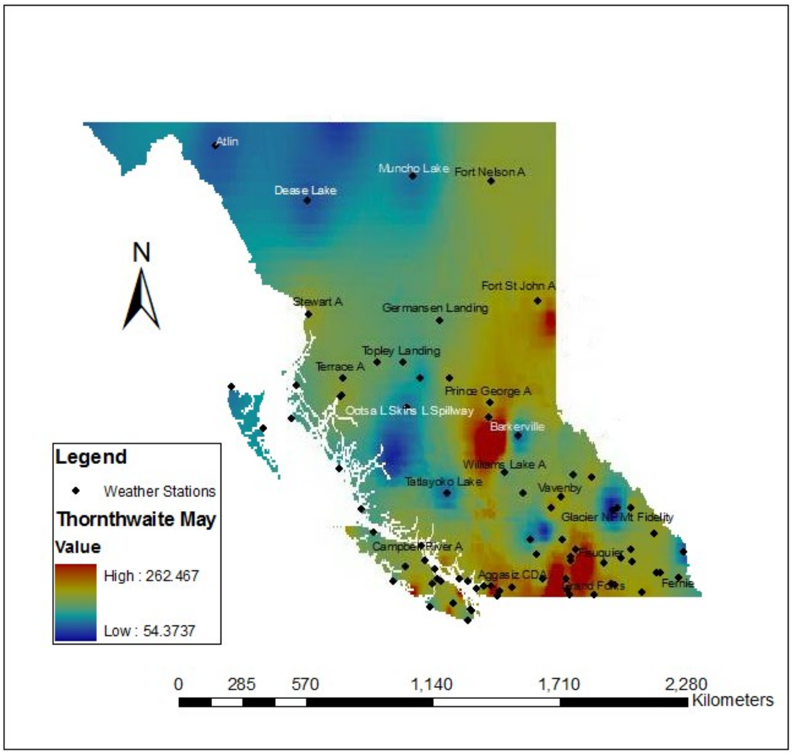


September

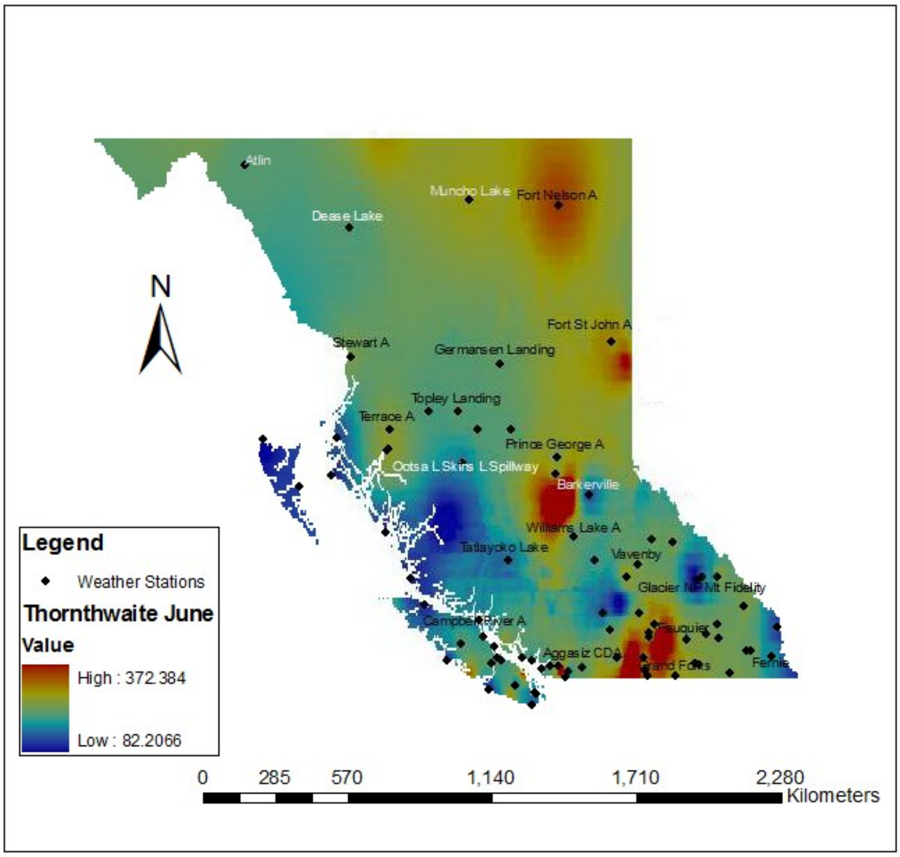
APPENDIX D- THORNTHWAITE (1948) MONTHLY PET DISTRIBUTION IN BC

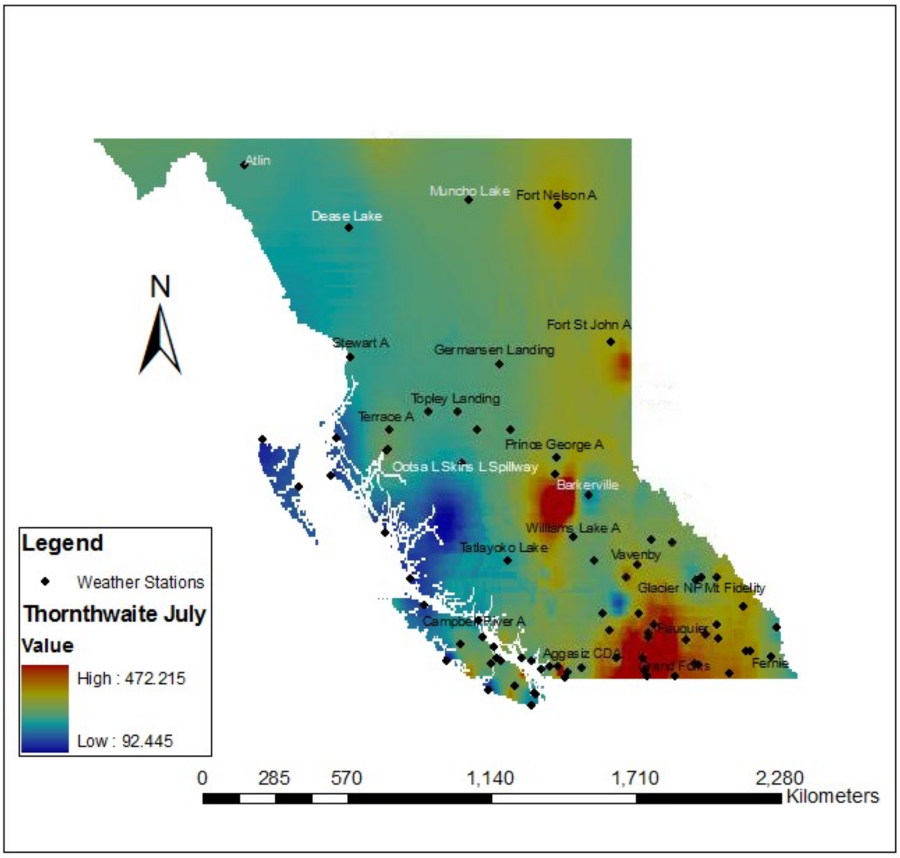


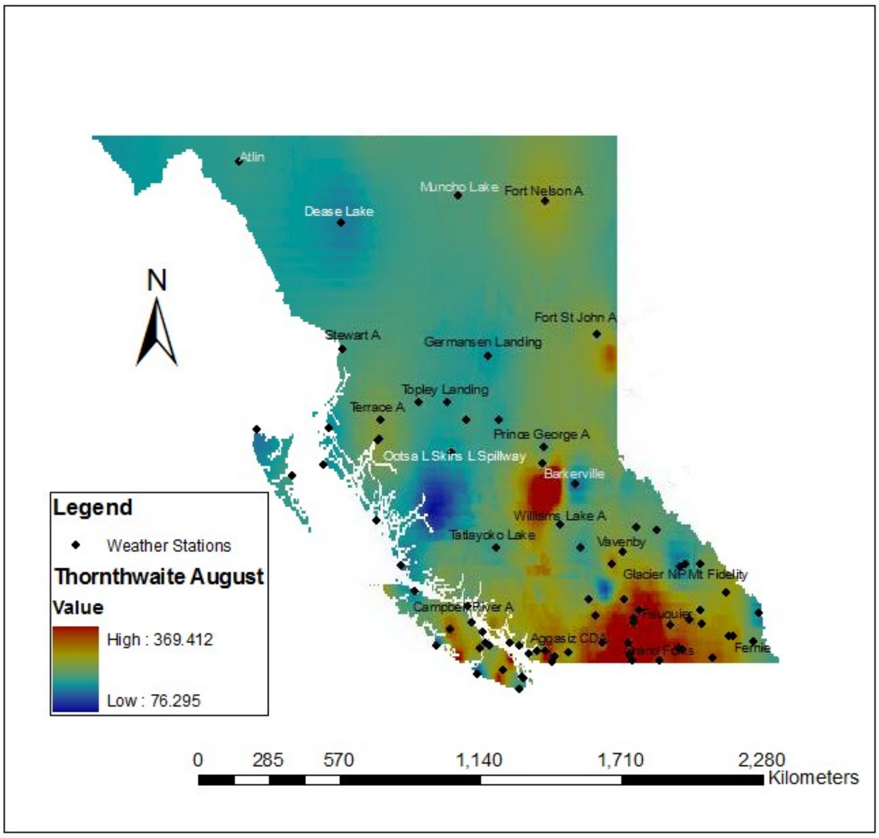
April



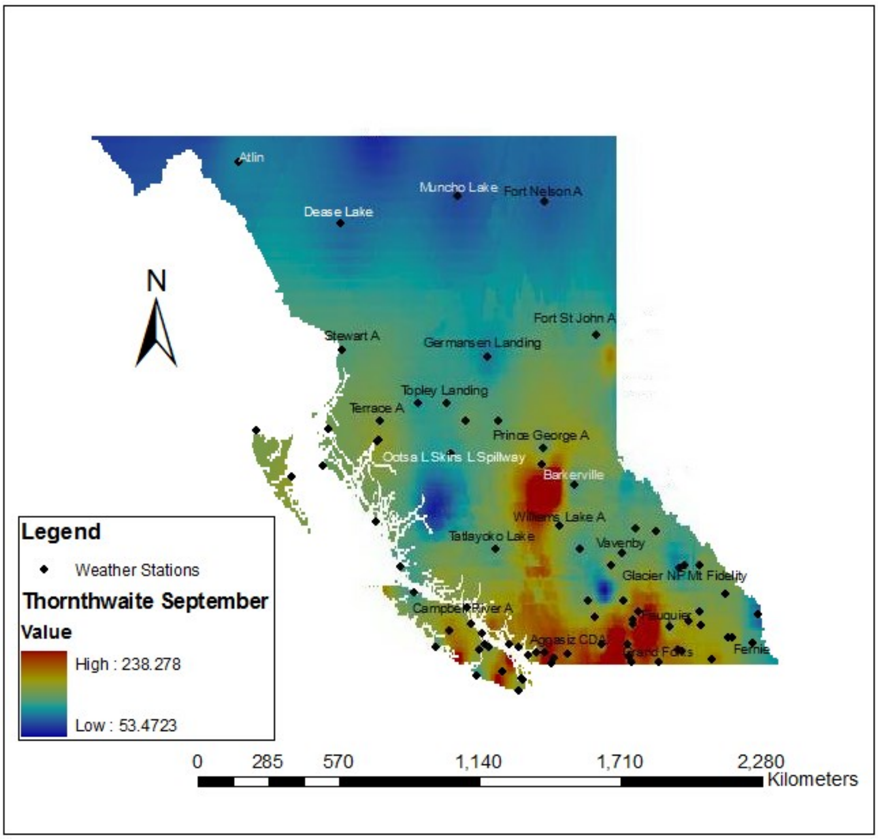
May


Atlin
Muncho Lake
Fort Nelson A
Dease Lake
N
Fort St John A
Stewart A
Germansen Landing
Topley Landing
Terrace A
Prince George A
Ootsa L Skins L Spillway
Barkerville
Williams Lake A
Tatlayoko Lake
Vavenby
Glacier NP Mt Fidelity
Campbell River A
Fauquier
Aggasiz CDA
Grand Forks
Fernie
Legend
Weather Stations
Thornthwaite June
Value
High : 372.384
Low : 82.2066
0
285
570
1,140
1,710
2,280
Kilometers
June


Atlin
Muncho Lake
Fort Nelson A
Dease Lake
N
Fort St John A
Stewart A
Germansen Landing
Topley Landing
Terrace A
Prince George A
Ootsa L Skins L Spillway
Barkerville
Williams Lake A
Tatlayoko Lake
Vavenby
Glacier NP Mt Fidelity
Campbell River A
Fauquier
Aggasiz CDA
Grand Forks
Fernie
Legend
Weather Stations
Thornthwaite July
Value
High : 472.215
Low : 92.445
0
285
570
1,140
1,710
2,280
Kilometers
July

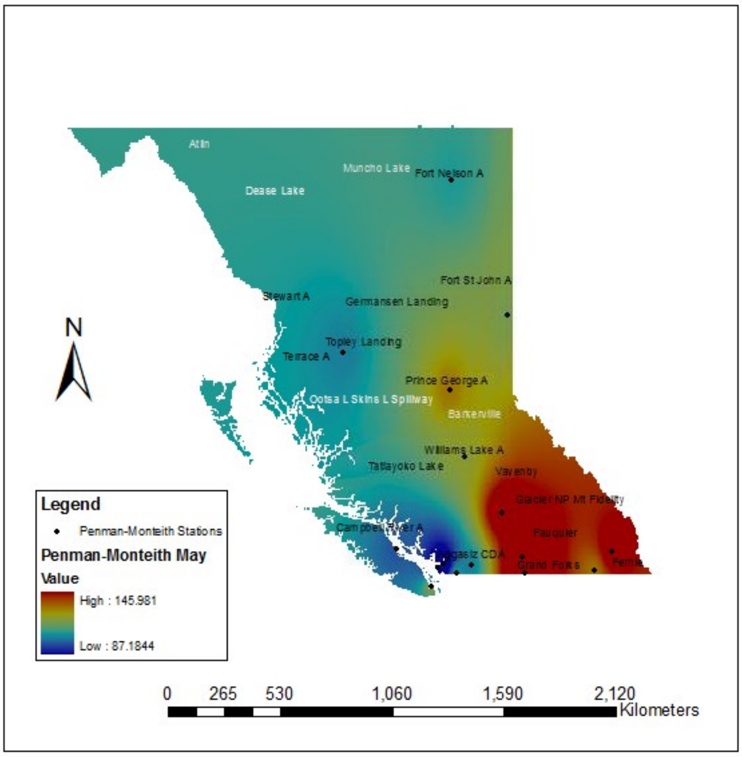


August

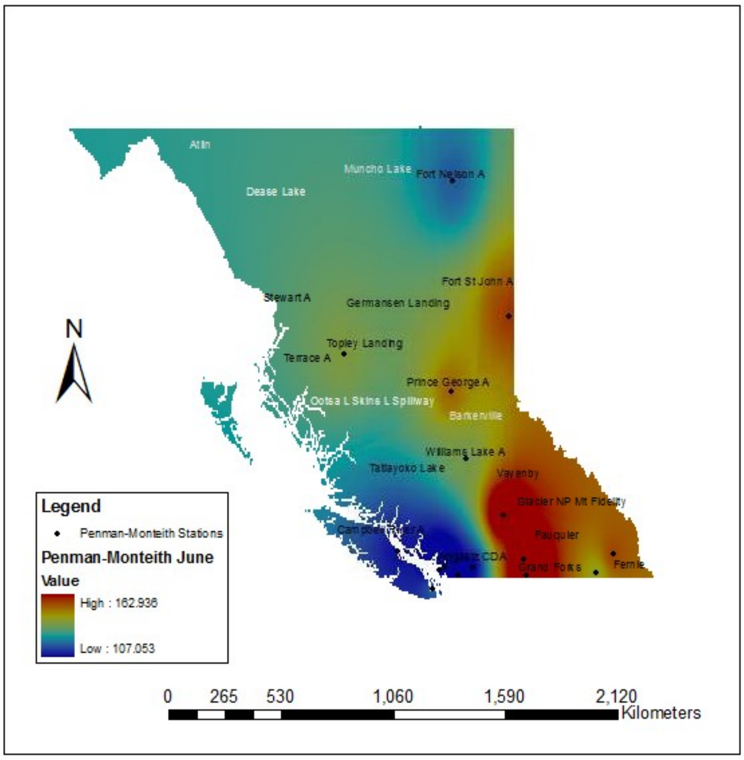


September

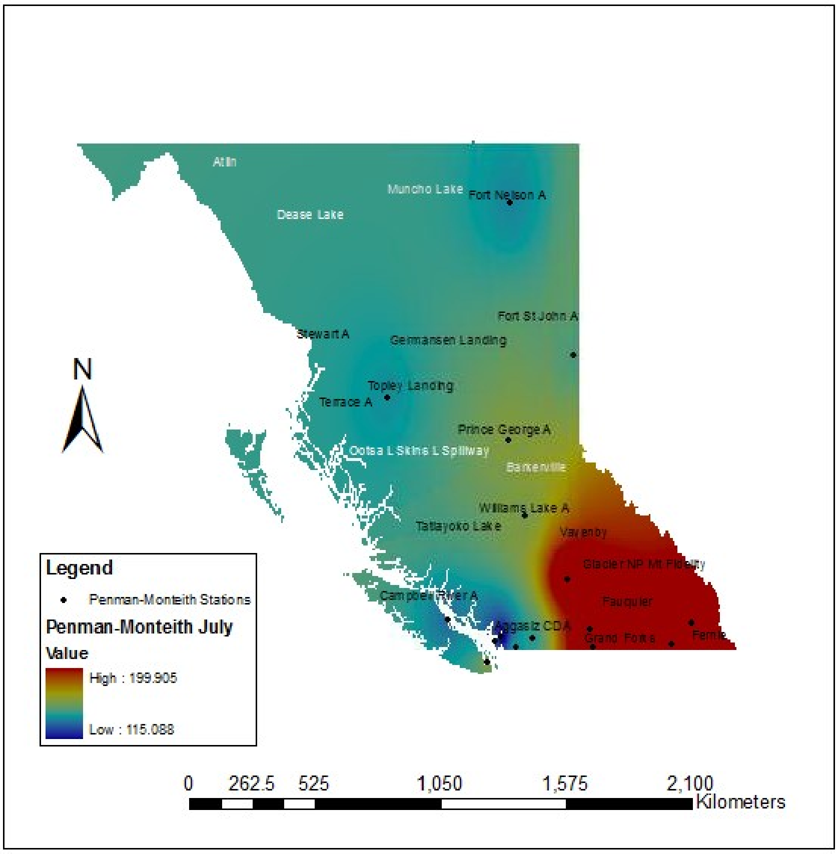
APPENDIX E- PENMAN-MONTEITH MONTHLY PET DISTRIBUTION IN BC



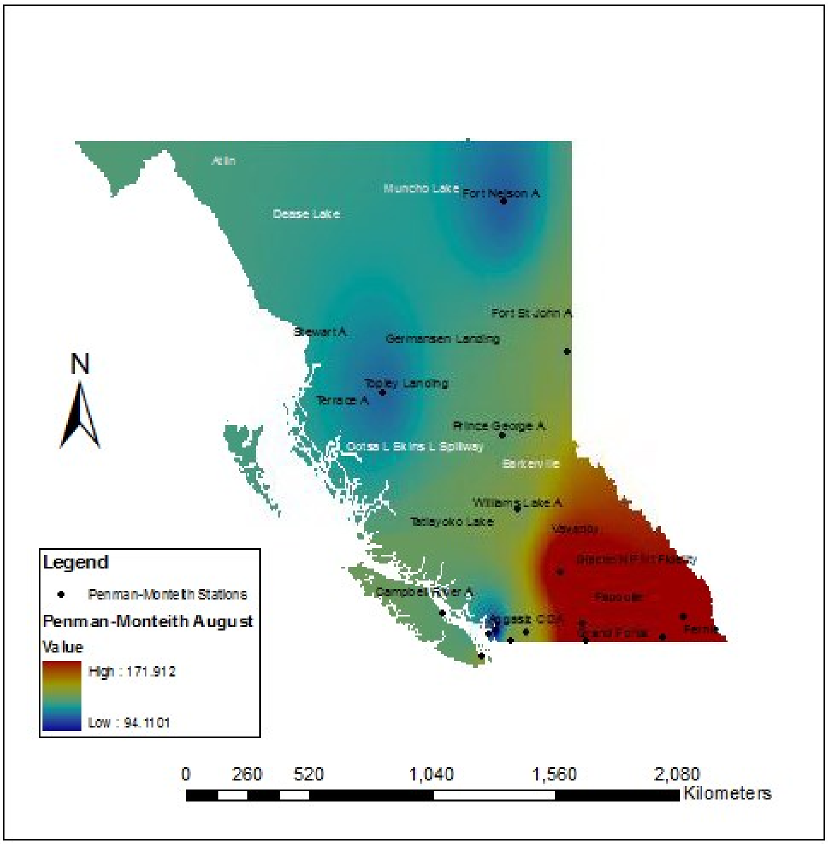
May



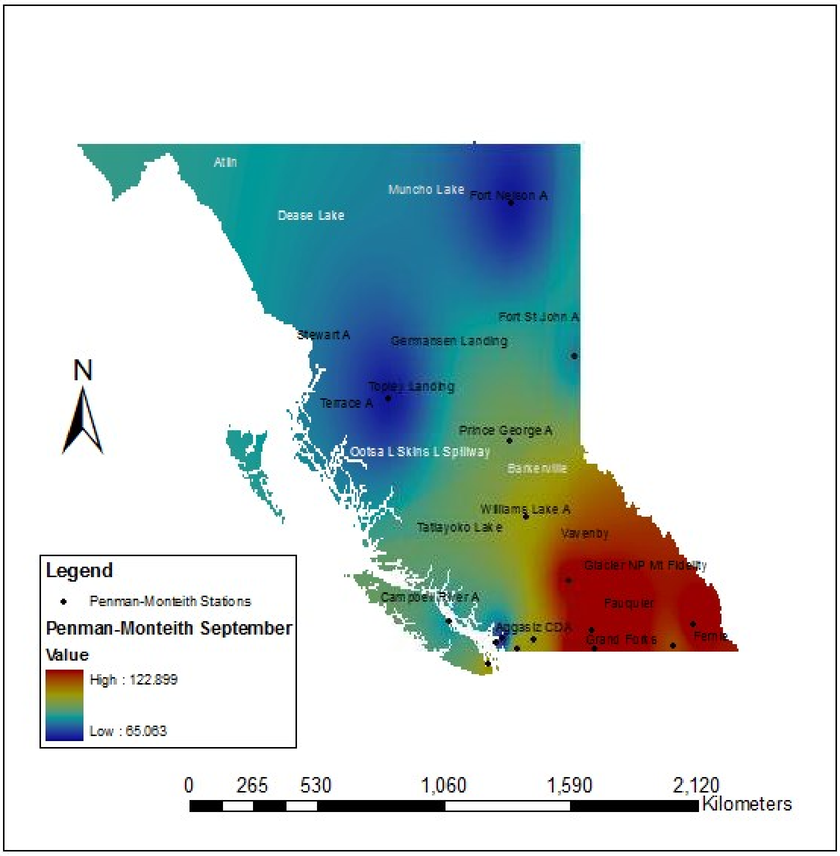
June


Atlin
Muncho Lake
Fort Nelson A
Dease Lake
Fort St John A
Stewart A
Germansen Landing
Topley Landing
Terrace A
Prince George A
Ootsa L Skins L Spillway
Barkerville
Williams Lake A
Tatlayoko Lake
Vavenby
Glacier NP Mt Fidelity
Campbell River A
Fauquier
Agassiz CDA
Grand Forks
Fernie
N
Legend
Penman-Monteith Stations
Penman-Monteith July
Value
High : 199.905
Low : 115.088
0
262.5
525
1,050
1,575
2,100
Kilometers

July


Atlin
Muncho Lake
Fort Nelson A
Dease Lake
Fort St John A
Stewart A
Germansen Landing
Topley Landing
Terrace A
Prince George A
Ootsa L Skins L Spillway
Barkerville
Williams Lake A
Tatlayoko Lake
Vavenby
Glacier NP Mt Fidelity
Campbell River A
Fauquier
Agassiz CDA
Grand Forks
Fernie
N
Legend
Penman-Monteith Stations
Penman-Monteith August
Value
High : 171.912
Low : 94.1101
0
260
520
1,040
1,560
2,080
Kilometers

August


Atlin
Muncho Lake
Fort Nelson A
Dease Lake
Fort St John A
Stewart A
Germansen Landing
N
Topley Landing
Terrace A
Prince George A
Ootsa L Skins L Spillway
Barkerville
Williams Lake A
Tatlayoko Lake
Vavenby
Glacier NP Mt Fidelity
Campbell River A
Pauquier
Agassiz CDA
Grand Forks
Fernie
Legend
Penman-Monteith Stations
Penman-Monteith September
Value
High : 122.899
Low : 65.063
0
265
530
1,060
1,590
2,120
Kilometers

September

APPENDIX F- EXTRA TABLES AND FIGURES OF INTEREST

	Northern Latitudes											
Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0°	14.8	15.3	15.4	15.0	14.2	13.7	13.9	14.6	15.2	15.2	14.8	14.6
2°	14.5	15.1	15.4	15.1	14.5	14.0	14.1	14.7	15.2	15.1	14.5	14.2
4°	14.1	14.8	15.3	15.2	14.7	14.3	14.4	14.9	15.2	14.9	14.2	13.9
6°	13.8	14.6	15.2	15.3	14.9	14.6	14.7	15.1	15.2	14.7	13.9	13.5
8°	13.4	14.3	15.1	15.4	15.1	14.8	14.9	15.2	15.1	14.5	13.6	13.1
10°	13.1	14.1	15.0	15.5	15.3	15.1	15.1	15.3	15.1	14.3	13.2	12.7
12°	12.7	13.8	14.9	15.5	15.5	15.3	15.4	15.4	15.0	14.0	12.9	12.3
14°	12.3	13.5	14.7	15.5	15.7	15.6	15.5	15.5	14.9	13.8	12.5	11.9
16°	11.9	13.1	14.6	15.5	15.8	15.8	15.7	15.5	14.8	13.5	12.1	11.4
18°	11.4	12.8	14.4	15.5	15.9	16.0	15.9	15.6	14.7	13.2	11.7	11.0
20°	11.0	12.4	14.2	15.5	16.0	16.1	16.0	15.6	14.6	12.9	11.3	10.5
22°	10.6	12.1	13.9	15.4	16.1	16.3	16.2	15.6	14.4	12.6	10.9	10.0
24°	10.1	11.7	13.7	15.3	16.2	16.4	16.3	15.6	14.2	12.3	10.4	9.6
26°	9.6	11.3	13.4	15.2	16.2	16.6	16.4	15.6	14.0	11.9	10.0	9.1
28°	9.2	10.9	13.2	15.1	16.3	16.7	16.4	15.5	13.8	11.6	9.6	8.6
30°	8.7	10.5	12.9	15.0	16.3	16.8	16.5	15.5	13.6	11.2	9.1	8.1
32°	8.2	10.1	12.6	14.9	16.3	16.9	16.6	15.4	13.3	10.8	8.6	7.6
34°	7.7	9.6	12.2	14.7	16.3	16.9	16.6	15.3	13.1	10.4	8.1	7.1
36°	7.2	9.2	11.9	14.5	16.3	17.0	16.6	15.2	12.8	10.0	7.7	6.6
38°	6.7	8.7	11.6	14.3	16.2	17.0	16.6	15.0	12.5	9.6	7.2	6.1
40°	6.2	8.3	11.2	14.1	16.2	17.0	16.6	14.9	12.2	9.1	6.7	5.6
42°	5.7	7.8	10.8	13.9	16.1	17.0	16.6	14.7	11.9	8.7	6.2	5.1
44°	5.2	7.3	10.4	13.7	16.0	17.0	16.5	14.5	11.5	8.3	5.7	4.6
46°	4.7	6.8	10.0	13.4	15.9	17.0	16.5	14.3	11.2	7.8	5.2	4.1
48°	4.2	6.4	9.6	13.1	15.8	17.0	16.4	14.1	10.8	7.3	4.7	3.6
50°	3.7	5.9	9.2	12.9	15.7	16.9	16.3	13.9	10.4	6.9	4.2	3.1
52°	3.2	5.4	8.7	12.6	15.5	16.9	16.2	13.7	10.1	6.4	3.7	2.7
54°	2.8	4.9	8.3	12.2	15.4	16.9	16.1	13.4	9.6	5.9	3.2	2.2

Approximate mean monthly extraterrestrial solar radiation (Hargreaves & Merkley, 1998)