

Statistical Relationships between Topography and Precipitation in a Mountainous Area

Abstract

This study contributes to a goal of the Mackenzie GEWEX (Global Energy and Water Cycle Experiment) Study to model the water and energy balances of the Canadian Arctic Basin on spatial scales of 100 kilometres and time scales of one month. Accurate estimates of the spatial distribution of precipitation at these scales are critically important inputs into hydrologic models used to simulate these processes over complex terrain. The development of a suitable precipitation model for the Mackenzie basin is seen as an important step in our understanding of climate variability and climate change under conditions of increasing concentrations of atmospheric greenhouse gases. In this study, univariate linear regression is employed to determine the relationships between monthly precipitation and orographic parameters including elevation, aspect and slope in the mountainous terrain of Williston Basin located in north central British Columbia. Slopes, aspects and elevations are calculated using a 5-minute digital elevation model (DEM). The study finds several statistically significant ($p < .05$) correlations between elevation and monthly precipitation for terrain having either north or east aspect based on individual Julys between 1986 and 1990. Terrain having south or west aspect displays very low correlations for those same months. For winter conditions, the relationship between precipitation and elevation is generally weak for all aspects for individual Januarys between 1986 and 1990. The lack of correlation with wintertime precipitation may very well be due to the poor quality data related to snow undercatch which is estimated to be roughly 50 percent. The quality and quantity of the data generally is also suspect owing to the volume of missing records and the short period of record. Station elevations and DEM elevations correlate equally well with monthly precipitation, contrary to the findings of several recent studies which show better correlations using coarser resolution. The study found no consistent relationship between monthly precipitation and slope in summer or winter.

Introduction

This study was undertaken under the umbrella of the Global Energy and Water Cycle Experiment (GEWEX) project, the Canadian portion of which is referred to as the Mackenzie GEWEX Study (MAGS). A goal of GEWEX is to model the water and energy balances of the Canadian Arctic Basin on spatial scales of 100 kilometres and time scales of one month. The overall aim of this study was to model the effects of orographic enhancement on the spatial distribution of precipitation in mountainous terrain. The Williston basin was chosen because of the existence of a relatively dense hydrometeorological network operated by British Columbia Hydro. The approach was to determine statistical relationships in an area of rugged terrain which was well represented by climate data. The ultimate goal is to apply these relationships to more data-sparse regions of the Mackenzie basin. The development of a suitable precipitation model for the Mackenzie basin is seen as an important step in our understanding of climate variability and climate change under conditions of increasing concentrations of atmospheric greenhouse gases.

The objectives of this study were to determine the elevation, slope, aspect and exposure to southwesterly winds for 28 B.C. Hydro climate stations in the watershed; to develop and test statistical relationships between these orographic parameters and monthly or seasonal precipitation; and use these relationships to determine the average variance in precipitation that can be attributed to each of the orographic parameters.

A previous study of the Williston basin by Environment Canada (B. F. Findlay personal communication) showed only a weak relationship between monthly precipitation and elevation. The study cited gauge siting in narrow valleys oriented obliquely to the prevailing winds as a major reason for the weak statistical relationship. The study also advised caution in the use of B.C. Hydro data based on comparisons with Environment Canada principal station data within the same geographic region.

The first phase of the present study was to focus on statistical relationships between monthly and seasonal precipitation and the various orographic parameters. The second phase will be to develop a model based on these statistical

relationships and to apply the model to a meso-scale grid of the Williston Basin. The third and final phase of the project will apply the model to the more data-sparse regions of the Mackenzie basin. The purpose of this paper is to summarize the findings of the first phase of the project.

Background

The Williston Basin, including the region immediately to the east of the Rockies covers an area of more than six million hectares. The study area shown in Figure 1 is centered at roughly 56 degrees North and 124 degrees West in north-central British Columbia. The main body of Williston Lake is a prominent feature of the basin having a northwest-southeast orientation and lying in the Rocky Mountain Trench. The elevation of the lake is roughly 680 metres, and it is bordered on either side by mountain ranges rising to more than 2000 metres. Another arm of Williston Lake

branches eastward from the trench to the Bennett Dam which empties into the Peace River.

The region has a continental type of climate which is characterized by cold, dry winters and warm, somewhat wetter summers (Environment Canada, 1990). The Coast Mountains well to the west remove much of the moisture from the maritime air masses which eventually move across the province into the Williston Basin. The wettest season is the summer during which convective weather predominates. The winter and spring months become progressively drier with the driest months being February, March and April. The winter is characterized by frequent cold spells as dry, Arctic air forces its way southward and westward through the mountain passes from Alberta and the Northwest Territories. The prevailing flow at mid-atmospheric levels is generally from the west or southwest.

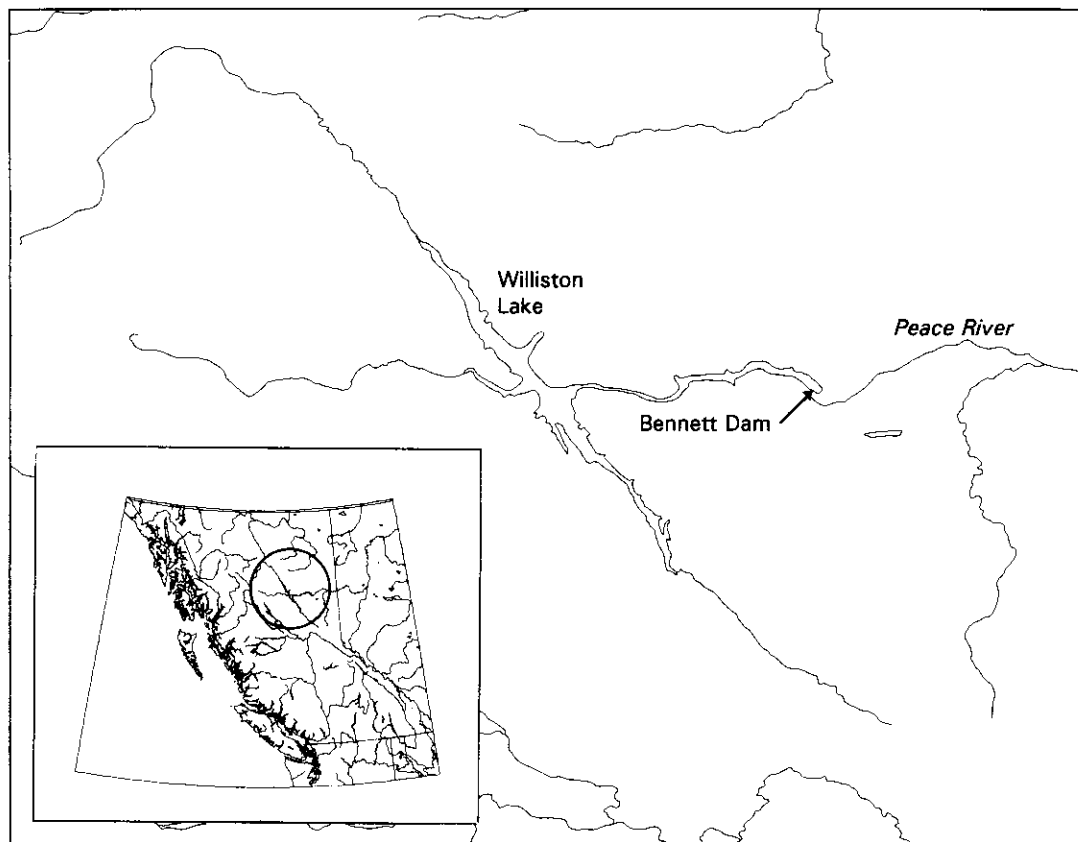


Figure 1. Map of Williston Basin. Inset: Map of British Columbia showing the study area.

Approaches to Estimating Precipitation in Mountainous Regions

The precipitation falling on a mountainous region may be thought of as having two components: an amount due to convergence which would occur in the absence of the mountains, and an orographic component which modifies these processes (Barry, 1981). The physical basis for orographic enhancement is that mountain barriers act on the flow of moist upper air in such a way as to deflect the airmass upward as it flows over the terrain, or to cause upward motion due to convergence in valleys. As this moist airmass rises it expands and cools thus enhancing condensation and the formation of precipitation. As a result, both the amount and the rate of precipitation are increased. Conversely, air subsiding down mountain slopes compresses and warms producing a drying effect in the lee of the mountains. Additionally, mountain barriers tend to retard the flow of air resulting in the modification of frontal systems in complex terrain. Mountains also promote local convection which produces showery summer weather (Bonacina, 1945).

The requirement for estimates of spatially distributed precipitation frequently arises in hydrologic modelling and in a variety of agricultural and natural resource applications. Generating these spatial distribution patterns usually involves interpolating from point station data to points on a grid for use in computer models. However, simple interpolation techniques fail to account for the effects of topography, which are a significant factor in the distribution and intensity of precipitation in mountainous terrain (Phillips et al., 1992). For example, it is well known that precipitation generally increases with elevation, and that the windward slopes of mountains typically receive much more precipitation than the leeward slopes. Thus, physical processes attributed to elevation, slope and aspect need to be included in any model if accurate estimates of the distribution of precipitation are to be obtained. To complicate matters, mountainous regions tend to be sparsely monitored by climate stations, and those stations that do exist tend to be sited at low elevations in valleys yielding little information about the relationship between topography and precipitation at higher terrain.

The need for interpolation techniques that account for the effects of topography on the dis-

tribution of precipitation in data-sparse mountainous regions has been the subject of much investigation. Daly et al. (1994) categorize approaches for estimating the spatial distribution of precipitation into three groups: graphical, topographical, and numerical. Graphical methods include isohyet mapping and Thiessen polygon estimation. The latter method utilizes the ratio of the zone of influence corresponding to each station to the total area of interest as a means of assigning weights to individual data points (Thiessen, 1911).

Topographical methods involve correlating point precipitation data with various topographical and meteorological parameters such as slope, elevation, aspect, orientation, and wind speed and direction. In a study conducted in western Colorado, Spreen (1947) found that about 85% of the variation in precipitation was accounted for by elevation, rise, exposure and orientation, while only 30% was attributable to elevation alone.

Numerical methods involve spatial interpolation techniques in which the data are weighted according to some function. For example, inverse distance weighting assigns weights to data inversely proportional to the distance between points. However, these distance weights are not necessarily optimal in producing the best estimate of precipitation. A class of methods for choosing interpolation weights so as to optimize the interpolation function is called optimal interpolation. Kriging is one type of optimal interpolation scheme whereby interpolation weights are obtained by fitting a semivariogram to the data (Burroughs, 1986). Tabios et al. (1985) systematically compared a variety of spatial interpolation techniques and found these so-called geostatistical methods such as kriging to be superior to other interpolation schemes including inverse distance weighting and Thiessen polygons.

As Daly et al. (1994) point out, the application of geostatistical techniques is limited to areas characterized by a single orographic regime which maintains a strong overall elevation-precipitation relationship. Such homogeneity is typically limited to relatively small areas of complex terrain. The relationship between elevation and precipitation, for example, over large, non-homogeneous regions may in fact be inverse. Such is the case when considering the region between the wet, coastal areas of British Columbia and the

higher, but drier, interior plateau regions (Basist et al., 1994).

A relatively new model known as PRISM, an acronym for Precipitation-elevation Regressions on Independent Slopes Model (Daly et al., 1994), combines physical and statistical approaches to the analysis of orographically enhanced precipitation. The PRISM model is based on the observation that relatively coarse scale "orographic" elevations are more highly correlated to precipitation than are point station elevations (Chuan and Lockwood, 1974). Accordingly, the model substitutes station elevations with digital elevation model (DEM) elevations using 5-minute latitude/longitude grid spacing. Each grid cell has an elevation and slope orientation (aspect) computed from the elevation gradients. Grid cells are then grouped into topographic facets according to the direction of their slope orientation (i.e. north, east, south, west).

In an evaluation of the model, PRISM was applied to the Willamette River basin in Oregon, allowing a direct comparison of model performance to the results obtained by Phillips et al. (1992) who used kriging, elevation-detrended kriging, and cokriging. In that region, PRISM performed better than any of the other methods as measured in terms of cross-validation errors. The PRISM model was also successfully applied to larger geographic areas including northern Oregon as well as the entire western United States with only slight deterioration in statistical performance. The superiority of PRISM lies in its ability to continuously adjust its frame of reference by using local precipitation-DEM elevation relationships.

The PRISM model may be compared to the "square grid technique" (Solomon et al., 1968) which was recently applied to the Mackenzie basin as part of the Mackenzie Basin Impact Study to model changes to runoff under different climate change scenarios (Soulis et al., 1994). Like PRISM, this technique also utilizes a 5-minute DEM and derives other physical characteristics such as slope and aspect for each grid cell from the elevation data. Multiple regression is then performed using these data on temperature, precipitation and evaporation which are then used as inputs to a runoff model.

In the original study in 1968, the square grid technique was applied to Newfoundland, and its

accuracy was verified against measured precipitation. The island of Newfoundland has an area of 110 thousand square kilometres, and the investigators divided the island into two regions, an Eastern Region and a Western Region, each with its own unique precipitation regime. A unique multiple regression equation was found for each region. This procedure is also consistent with the premise of PRISM which considers only slopes which lie on topographic facets representing homogeneous orographic precipitation regimes.

The main difference between PRISM and the square grid technique is that PRISM is based solely on the relationship between elevation and precipitation within defined orographic regimes. The square grid technique, on the other hand, includes several independent variables such as distance from the sea, barrier heights, a latitude index, and the average slope of the grid square, from which multiple regression equations are derived with respect to precipitation.

Methodology

Precipitation data from B.C. Hydro's hydrometeorological network were obtained organized and verified. A terrain analysis was then performed using gridded DEM elevation data to obtain elevation, slope and aspect for each grid cell. Finally, a statistical analysis was undertaken to look for significant correlations between monthly and seasonal precipitation data and the orographic parameters. Each of these procedures will be discussed in turn.

Precipitation Data

The climate data for the study were provided by B.C. Hydro which operates a hydrometeorological network of 28 stations consisting of 18 stations upstream of the Bennett Dam in the Williston Basin and another 10 to the east of the Rocky Mountains (Figure 2; Table 1).

The network was created in 1980 with the installation of nine stations. Several more went into service between 1981 and 1983, and by 1984, 25 stations were operational. The last three were added between 1985 and 1988. The network was still in operation as of October, 1995, although data for this study were obtained for only up to 1992.

The precipitation data consist of hourly observations using Belfort automatic weighing-type

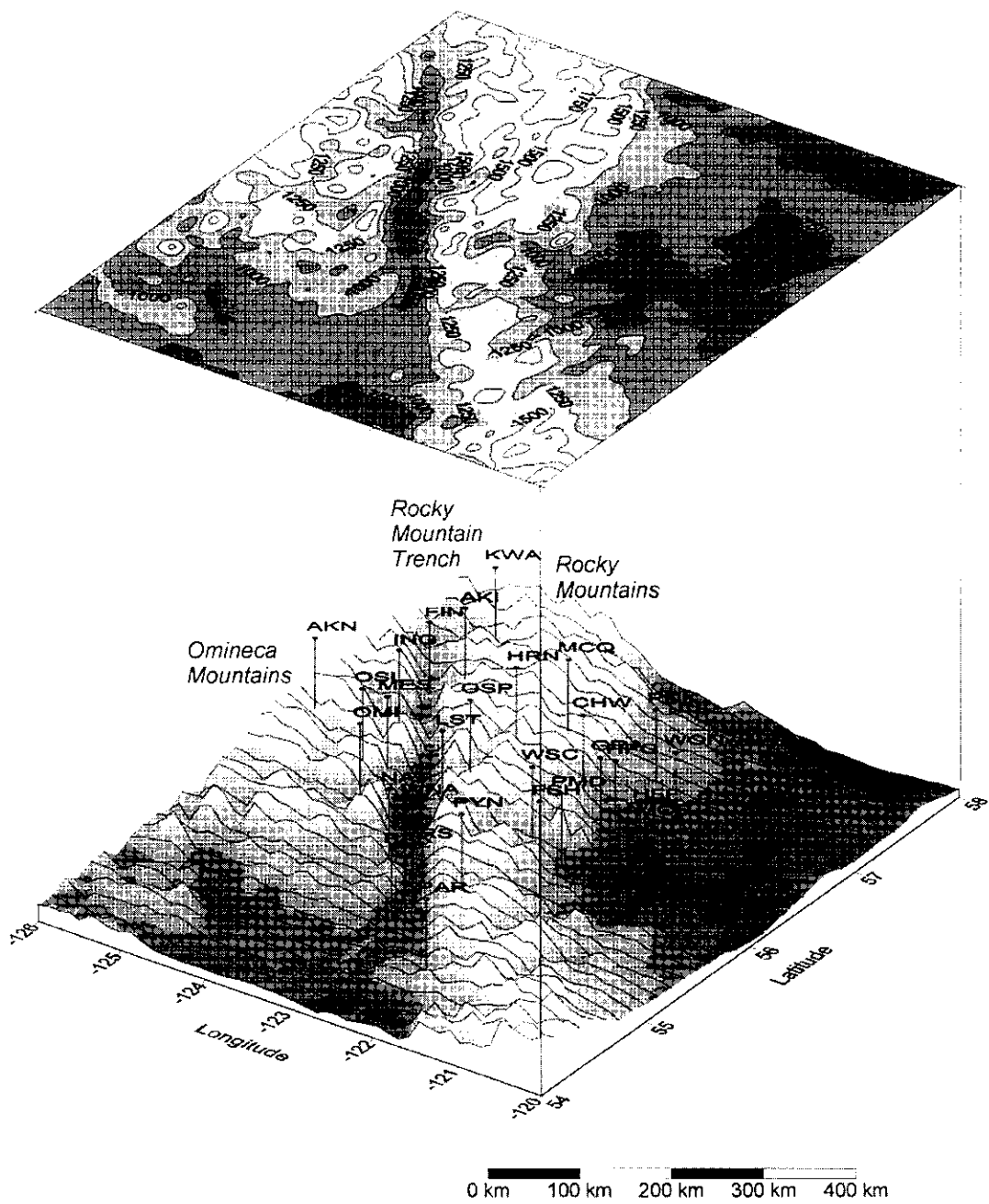


Figure 2. Topographic map of Williston Basin indicating the locations of BC Hydro hydrometeorological stations. The Rocky Mountain Trench, oriented southeast-northwest, separates the Omineca and Rocky Mountain ranges. Overlay shows elevation contours.

TABLE 1. List of stations within BC Hydro's Williston Basin hydrometeorological network indicating station identifiers, station elevations, DEM elevations, aspect and slope.

Station id	Station Name	Station Elevation (m)	DEM Elevation (m)	Aspect	Slope (m/km)
AKN	Aiken Lake	970	1385	W	34
AKI	Akie River	760	1320	W	40
CHW	Chowade Upper	1480	1228	N	34
FIN	Finlay above Akie	710	873	E	28
FSH	Fisher	750	972	N	13
PMD	GMS Hudson Hope	720	803	E	33
GRA	Graham River	700	812	N	9
HFF	Halfway River near Farrel Creek	480	635	S	3
HFG	Halfway River near Graham River	650	792	S	4
HRN	Horn Creek	1450	1561	E	21
ING	Ingenika River	700	895	S	2
KWA	Kwadacha River North	1554	1309	S	11
MCQ	McQue Terrace	1200	1481	N	2
MES	Mesilinka River	715	1199	E	55
MOB	Moberly River	600	659	N	5
NAT	Nation River	725	909	E	30
OMI	Omineca River above Osilinka	715	1029	W	35
OSL	Osilinka River	775	1235	W	17
OSP	Ospika River	750	1045	E	42
PAK	Pack River	675	775	N	4
PAR	Parsnip River Upper	790	895	S	17
PRS	Parsnip River above Misinchinka	700	852	N	16
PYN	Pine Pass	1400	1249	S	7
PNK	Pink Mountain	1204	1012	E	7
LST	Williston Lake at Lost Cabin	690	1006	W	28
WNA	Williston Lake at Nation Arm	680	748	E	10
WSC	Willison Lake nar Schooler	680	925	S	21
WON	Wonowon	910	842	S	3

precipitation gauges, and data are transmitted via satellite by means of data collection platforms. The contents of the gauge are weighed by means of a spring potentiometer. These gauges are reported to be accurate to 0.6 mm and the accuracy is temperature dependent (B.C. Hydro, 1994). A thin film of oil floats on the surface of the water in the container to prevent evaporation. During the winter, propylene glycol is added to the container to inhibit freezing. Some of the precipitation gauges at the 28 stations are shielded by means of an Alter shield which consists of a circular array of pickets surrounding the gauge to deflect the wind. A very limited amount of snow pack data is also available; three stations (Aiken Lake, Kwadacha River North, and Parsnip River Upper) are equipped with snow pillows which provide daily snow water equivalent measurements

during the winter. Temperature data are also collected at each station. Servicing, which was performed four times per year in the past, has been recently reduced to three times per year. Beginning in 1991, B.C. Hydro began changing its entire network to standpipe gauges which are larger in diameter and have a greater holding capacity. However, most of the data used in this study were obtained from Belfort gauges.

Data from the hydrometeorological network are routinely quality controlled by B.C. Hydro and codes are manually assigned to each hourly observation as "good", "accumulated", or "missing". Accumulated precipitation amounts are obtained by recording the contents of the gauge following a period of time when either the instrument failed or when there were data transmission prob-

lems. Missing data are coded as such when no accumulated amount is obtainable. For example, when the gauge is filled to capacity, subsequent precipitation is coded as missing until the station is serviced.

Daily totals are obtained simply by aggregating hourly data, and the quality of the daily data is coded according to the poorest hourly observation during that day. For instance, if one hour of data is missing on a given day, then the daily total is coded as missing even though the other 23 hours may consist of good data. Approximately 20 percent of all daily hydrometeorological data are coded as either missing or accumulated.

The accuracy of snowfall measurements is problematic generally. The WMO, for instance, conducted an extensive study which concluded that snow in Scandinavia is underreported by automatic stations by about 50% (George Taylor, personal communication). A significant undercatch may result from blowing snow which is not detected by the gauge during windy conditions. The use of an Alter shield at some B.C. Hydro sites reduces the effects of wind but does not completely eliminate them. Also, only those sites which are highly exposed are shielded, so many of B.C. Hydro's gauges do not have shields.

Another problem that leads to underestimation of snowfall at B.C. Hydro sites is snow capping (Eric Weiss, personal communication). This occurs when the instrument is completely capped over with thick wet snow such that subsequent snow accumulations do not fall into the bucket and are not recorded by the gauge. This condition is most frequent when the temperature is near freezing and the snow is heavy and wet. Freezing can occur at sufficiently low temperatures when the glycol mixture becomes diluted as a result of the bucket being near capacity. Additional accumulations are not recorded once the mixture becomes frozen.

To assess the extent of the problem of underreporting of snow at B.C. Hydro stations, use was made of snow pillow data from one of the three stations. Aiken Lake, where such data is collected. An examination of the data shows a steady increase in the snow pack from about November through March each year, after which warm spring temperatures begin to melt the snow pack and values then decline. Using this fall-winter period of rising snow pack values, monthly ag-

gregates of daily precipitation were compared to the corresponding monthly increase in the snow pack. Assuming negligible snowmelt during this period of low temperatures, it was found that only about 40% of the snow falling on the pillow is being detected by the Belfort precipitation gauge.

As a further assessment of the quality of B.C. Hydro data, monthly precipitation amounts were compared to those obtained for the same period from five Environment Canada (AES) stations located within the basin. Since AES climate observations are taken by human observers and the data are rigorously quality controlled, these stations serve as ideal benchmarks for determining the accuracy of the B.C. Hydro data. Only B.C. Hydro data coded as good quality were used. Of the 28 B.C. Hydro stations, 24 were found to have correlation coefficients of $r > 0.7$ with at least one AES station, indicating good agreement. However, a comparison of snowfall between pairs of neighbouring AES and B.C. Hydro stations corroborated previous evidence of underreporting of snow at the automatic stations.

An underlying assumption of this study is that a spatial analysis can only be valid if the same set of precipitation events are observed from a number different points. For example, it would not be valid to compare monthly averages at two stations using different years of data to compute these averages. This requires that all stations have identical periods of record. However, because of the volume of missing data and the unequal periods of record at these stations, there is necessarily a trade-off between the number of stations which can be included and the length of record needed to obtain overlapping data.

The problem of large gaps in the records of some stations combined with the gradual introduction of new stations are limiting factors in the amount of data available for use. Confidence in monthly averages is improved by increasing either the number of events or the number of observation points. When data are missing at a particular station for a given period, a choice must be made to either drop the station from the analysis or reduce the period of record to be included. The trade-off is that the longer the common period of record desired to compute monthly averages, the fewer stations there are for which an uninterrupted period of record exists. Conversely, the more stations one may want to include, the shorter the period of record these stations have in common.

To maximize both the length of record and the number of stations with exactly overlapping periods of record on a monthly or seasonal basis, the year with the largest number of stations with good data was found. Then, subsequent years were added while dropping stations along the way whose period of record no longer overlaps that of the remaining stations. For example, to obtain five years of common record for a given month by this process, the number of stations was reduced from the original 28 to between nine and 15 depending on the month. To obtain a seasonal average for the combined summer months of June, July and August, the number of stations with five years of common period of record was ten.

The method of sampling is very important in the study of orographic precipitation because precipitation varies substantially both spatially and temporally. Using only ten stations in order to get five years of overlapping summer data has the effect of substantially reducing the sample size such that the topography-precipitation relationship may be inadequately sampled. On the other hand, while using a single month or season of data maximizes the sample size, the precipitation data could hardly be considered representative of longer term averages due to the high temporal variability in precipitation.

The temporal scale over which the precipitation-elevation relationship is valid, as well as the minimum averaging period required, remains uncertain (Daly, 1994). For this study, short periods such as monthly totals and five-year monthly averages were chosen in order to maximize the sample size. However, no attempt was made to optimize the precipitation-elevation relationship by using different time scales.

Terrain Analysis

A number of topographic parameters have been used in a variety of studies to explore the relationship between topography and monthly, seasonal and annual precipitation. Most were mentioned in the previous section. For the purpose of this study, relationships between elevation, slope and aspect and monthly precipitation were examined. A digital elevation model (DEM) was used for ease of computation of various orographic parameters, and to explore the difference between orographic (DEM) elevations and station elevations in terms of the elevation-precipitation rela-

tionship. In addition, an analysis of upper level winds was included as a basis for explaining the physical processes behind apparent statistical relationships between orography and precipitation.

A five minute DEM called TerrainBase (National Geophysical Data Centre, 1995) was used, and the same procedure employed by PRISM to calculate orographic elevations and slope orientations was applied to this analysis (Daly, 1994). According to this procedure, the orographic elevation of a station was calculated based on the elevations of the cell within which the station lies as well as the four adjacent cells. Cell elevations were weighted according to the inverse distance of the station from the centre of each of the five cells. In addition, station elevations were also obtained from the B.C. Hydro records for inclusion in the analysis. All elevations are expressed in metres.

Determining the aspect, or slope orientation as it is referred to by PRISM, of a grid cell entailed calculating north-south and east-west elevation gradients from pairs of adjacent cells. Each cell was categorized as either flat, north, east, south or west according to the orientation of the maximum gradient. A cell was considered flat if its east-west and north-south gradients was less than 15 metres.

Slope was defined as rise over run where the rise for each grid cell was defined by the maximum of the east-west and north-south gradients. The run was defined as the centre to centre distance between adjacent grid cells, ie. 10 minutes of latitude for north-south gradients and 10 minutes of longitude for east-west gradients. The units of slope are expressed in metres per kilometre.

Since terrain features such as aspect and orientation have meaning only in relation to the wind direction, an analysis of 700 millibar winds was undertaken to establish the prevailing wind direction during precipitation events. The nearest upper air station, operated by Environment Canada, is Prince George, located about 100 kilometres south of the study region. The 700 millibar wind record was obtained for the period of 1980 to 1990 and categorized according to eight cardinal directions. Precipitation data were then obtained for the same period for Mackenzie, an Environment Canada station within the basin for which the climate record is continuous for the same period as the upper air station. None of the B.C. Hydro

stations has an unbroken daily record for that period.

According to this analysis, roughly 35 percent of the annual precipitation at Mackenzie falls when the upper winds at Prince George are less than 10 knots which is typical of spring and summer. Roughly 55 percent of the annual precipitation occurs when the winds are stronger, above 10 knots, and when the upper wind direction is from the west (24 percent), southwest (21 percent), or south (11 percent). Such winds tend to be more typical of fall and winter. The remaining 10 percent of precipitation is accounted for by winds ranging from northwest clockwise through southeast.

Results

Simple linear regression of elevation and slope on precipitation was performed for a typical winter month, January, and a typical summer month, July. Five individual years between 1986 and 1990, as well as the average of these five years, were used in the study. By choosing individual years, the largest sample is obtained since the number of stations is maximized. Conversely, by choosing a five year average, the variability is reduced, but the sample is much smaller because only a few stations have a five-year period of record in common. The analysis was then extended from monthly to seasonal data by aggregating precipitation totals for June, July and August, into five year averages. Regression analysis was performed on the entire set of available data, then on subsets of data according to aspect. In analyzing the relationship between precipitation and slope, only slopes greater than or equal to 5 metres per kilometre are included to eliminate flatter terrain.

The two accompanying tables are divided into three sections: station elevations, DEM elevations and slope. Under each section, the results are first shown for all data followed by the results of partitioning the data according to aspect. A number of selected scatterplots are included for illustrative purposes. Data points are labeled for map reference.

January: individual years from 1986 through 1990: Table 2 shows correlation coefficients for five individual Januarys from 1986 through 1990 as well as the five-year average. The number of stations varies from 18 to 24.

With the exception of the year 1989, there does not appear to be a strong and consistent relationship between January precipitation and either station elevation or DEM elevation for the unpartitioned data. When aspect was taken into account, correlations remained generally low, and the precipitation-elevation relationship was evident in only a few cases. In 1989 the correlation between precipitation and DEM elevation is greater than 0.7 for north, east, and west aspects, but not south. Despite the high values, only east aspect is statistically significant at the 95 percent confidence level for 1989 because of the small sample size. In some cases, the elevation-precipitation relationship is inverse as indicated by the negative correlations for north aspect in 1988 with both station elevation and DEM elevation. Overall, DEM elevation does not appear to be more strongly correlated with precipitation than does station elevation with respect to individual Januarys.

The relationship between slope and precipitation is quite inconsistent across all years with almost as many negative correlations as positive irrespective of aspect. Only two statistically significant correlations between slope and precipitation were obtained: a positive correlation for north aspect in 1989 and an inverse relationship for west aspect in 1990.

January five year average, 1986 to 1990: Six stations were found with good January data for 1986 to 1990. Of these six, four had east aspects. An analysis of these four indicates strong, but not significant ($p < .05$) correlations between station elevation and DEM elevation and precipitation, as well as between slope and precipitation. The relationship between DEM elevation and precipitation is stronger than that of station elevation based on this rather small sample. Scatterplots of these data using five year averages are shown as Figures 3 and 4.

July: individual years from 1986 through 1990: As shown in Table 3, a much stronger relationship between elevation and precipitation was found using July data than with the January case. The sample size is slightly larger ranging from 21 to 26 stations. Both DEM elevation and station elevation appear to be about equally correlated with precipitation. Of the five individual years, only 1987 stands out as a poor example. The other four years show either station elevation or DEM elevation to be significantly correlated with

TABLE 2. JANUARY (1986-90). Correlation coefficients of monthly precipitation vs. station elevation, DEM elevation, and slope, individual years and a five year average, with stations taken as a whole and partitioned according to aspect. Statistically significant ($p < .05$) correlations are indicated by bold italics.

	1986	1987	1988	1989	1990	Five Year Aver.
Station elevation						
All aspects	-.13 N=19 p=.58	.03 N=19 p=.90	-.27 N=18 p=.28	.40 N=24 p=.06	.18 N=19 p=.46	.69 N=6 p=.13
North aspect	n/a N=2	-.28 N=5 p=.65	-.90 N=3 p=.29	.69 N=6 p=.13	.35 N=5 p=.56	n/a N=0
East aspect	-.26 N=7 p=.58	.09 N=6 p=.87	-.37 N=7 p=.41	.15 N=7 p=.75	.64 N=76 p=.17	.51 N=4 p=.49
South aspect	.22 N=6 p=.68	.76 N=5 p=.14	.83 N=4 p=.17	.27 N=7 p=.55	.89 N=4 p=.11	n/a N=1
West aspect	.50 N=4 p=.50	.89 N=3 p=.30	.01 N=4 p=.99	.99 N=4 p=.00	-.32 N=4 p=.68	n/a N=1
DEM elevations						
All aspects	.08 N=19 p=.74	.13 N=19 p=.61	-.18 N=18 p=.46	.48 N=24 p=.02	.03 N=19 p=.92	.69 N=6 p=.13
North aspect	n/a N=2	-.26 N=5 p=.68	-.95 N=3 p=.20	.74 N=6 p=.09	.27 N=5 p=.66	n/a N=0
East aspect	.35 N=7 p=.44	.19 N=6 p=.72	.23 N=7 p=.62	.79 N=7 p=.04	.47 N=6 p=.35	.87 N=4 p=.13
South aspect	.22 N=6 p=.67	.92 N=5 p=.03	.82 N=4 p=.18	.24 N=7 p=.60	.11 N=4 p=.90	n/a N=1
West aspect	-.06 N=4 p=.94	.79 N=3 p=.42	-.30 N=4 p=.71	.80 N=4 p=.20	-.57 N=4 p=.43	n/a N=1
Slope						
All aspects	.17 N=16 p=.54	-.04 N=14 p=.90	.50 N=14 p=.07	.35 N=18 p=.15	-.21 N=15 p=.46	
North aspect	n/a N=2	.91 N=3 p=.28	n/a N=1	.96 N=4 p=.04	.32 N=3 p=.80	n/a N=0
East aspect	.66 N=7 p=.11	-.16 N=6 p=.76	.70 N=7 p=.08	.47 N=7 p=.29	.28 N=6 p=.59	.81 N=4 p=.19
South aspect	-.02 N=3 p=.99	n/a N=2	n/a N=2	-.29 N=3 p=.82	n/a N=2	n/a N=1
West aspect	-.54 N=4 p=.46	-.41 N=3 p=.73	.02 N=4 p=.98	.22 N=4 p=.78	-.95 N=4 p=.05	n/a N=1

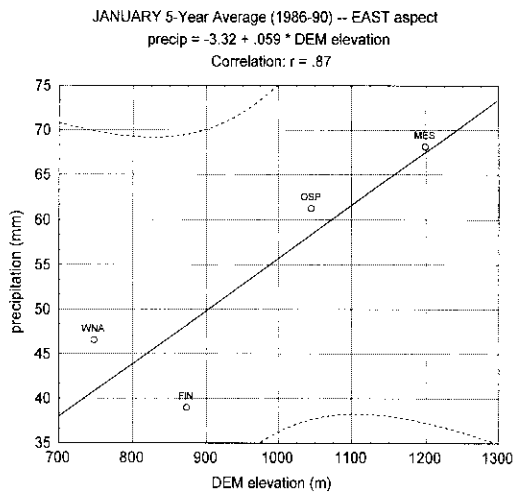


Figure 3. DEM elevation vs. JANUARY five-year average (1986 to 1990) precipitation for stations with EAST aspect.

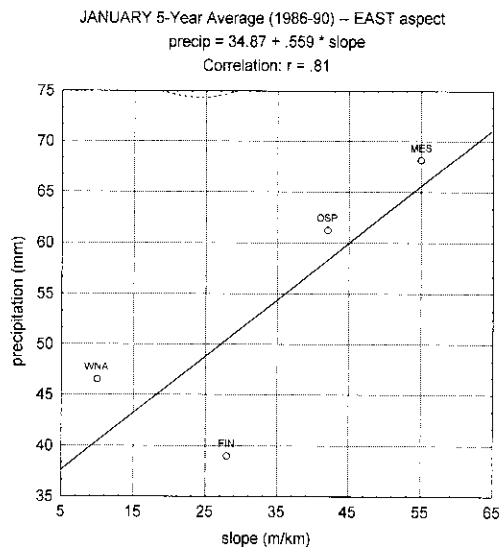


Figure 4. Slope vs. JANUARY five-year average (1986 to 1990) precipitation for stations with EAST aspect.

precipitation without further segmentation of data according to aspect.

When the data are partitioned according to aspect, the most noticeable effect is that, in general, precipitation at stations with either north or east aspects tends to be highly correlated with both categories of elevation. The elevation-precipitation relationship involving south and west aspects tends to be uniformly poor and in some

cases negative. Regarding slope, there does not appear to be any relationship with precipitation, and there are nearly as many negative as positive correlations regardless of aspect.

July, 1989 was examined in detail. Scatterplots are included as Figures 5(a) to 5(d) and show the relationship between DEM elevation and precipitation by aspect. Of the 26 stations, five have north aspects, eight are east, eight are south and five are west. The best correlations are with north and east aspects.

To attempt to explain a physical basis for these results, 700 millibar wind data were examined for July, 1989. Morning and afternoon soundings show the winds to be light, less than 10 knots, and variable most days of that month. This is a typical summer wind pattern for Williston Basin, and precipitation is usually the result of convective activity at this time of year. Accordingly, the concept of orographic enhancement occurring as a result of large scale ascent by topographic forcing may not be valid in this case. In the absence of wind, a more likely mechanism for the occurrence of precipitation may be the formation of convective clouds on sunny mountain slopes. However, it is not known why a stronger precipitation-elevation relationship would be found on north and east facing slopes.

July five year average, 1986 to 1990: Sixteen stations with July data for the period were found. Stations with either east or south aspects demonstrated moderately strong correlations between station elevation and precipitation although only one was significant at the 95 percent confidence level. DEM elevations appear to be somewhat better correlated with precipitation than are station elevations. Stations with west aspect showed high negative correlations, however, the sample includes only three stations. Slope and precipitation are all negatively correlated according to this rather small sample. Scatterplots of the five year average for July are included as Figures 6(a), 6(b) and 7.

Summer, five year average, 1986 to 1990: The results of a five year average of total precipitation for the combined months of June, July and August are shown in Figure 8. Only 10 stations have data for this five year period. Of these ten, one has a north aspect, six are east, two are south, and one is west. Only stations with east aspect are shown in the figure. The scatterplot obtained

TABLE 3. JULY (1986-90). Correlation coefficients of monthly precipitation vs. station elevation, DEM elevation, and slope, individual years and a five year average, with stations taken as a whole and partitioned according to aspect. Statistically significant ($p < .05$) correlations are indicated by bold italics.

	1986	1987	1988	1989	1990	Five Year Aver.
Station elevation						
All aspects	<i>.64</i> N=21 p=.00	.02 N=23 p=.91	.29 N=21 p=.20	<i>.38</i> N=26 p=.05	<i>.57</i> N=23 p=.01	<i>.68</i> N=16 p=.00
North aspect	.86 N=4 p=.14	<i>.94</i> N=4 p=.05	-.60 N=4 p=.40	.68 N=5 p=.20	.70 N=5 p=.19	n/a N=2
East aspect	<i>.91</i> N=6 p=.01	-.01 N=7 p=.99	.42 N=8 p=.30	<i>.95</i> N=8 p=.00	<i>.92</i> N=8 p=.00	<i>.87</i> N=6 p=.02
South aspect	.35 N=7 p=.45	-.16 N=7 p=.73	.09 N=5 p=.89	.16 N=8 p=.70	-.03 N=6 p=.95	.55 N=5 p=.34
West aspect	-.26 N=4 p=.74	-.04 N=5 p=.94	-.34 N=4 p=.66	-.22 N=5 p=.72	-.27 N=4 p=.73	-.98 N=3 p=.14
DEM elevations						
All aspects	.29 N=21 p=.20	-.09 N=23 p=.67	<i>.50</i> N=21 p=.02	<i>.53</i> N=26 p=.01	<i>.43</i> N=23 p=.04	.37 N=16 p=.15
North aspect	<i>.97</i> N=4 p=.03	.93 N=4 p=.07	-.67 N=4 p=.33	.74 N=5 p=.15	<i>.88</i> N=5 p=.05	n/a N=2
East aspect	.60 N=6 p=.21	-.17 N=7 p=.72	.64 N=8 p=.09	<i>.73</i> N=8 p=.04	<i>.75</i> N=8 p=.03	.62 N=6 p=.19
South aspect	.26 N=7 p=.57	-.02 N=7 p=.96	-.28 N=5 p=.65	.40 N=8 p=.33	-.30 N=6 p=.56	.63 N=5 p=.25
West aspect	-.81 N=4 p=.19	-.35 N=5 p=.56	.27 N=4 p=.73	.28 N=5 p=.64	.28 N=4 p=.72	-.90 N=3 p=.28
Slope						
All aspects	-.23 N=16 p=.39	.02 N=17 p=.95	.33 N=17 p=.20	.10 N=20 p=.66	-.05 N=18 p=.86	-.07 N=12 p=.83
North aspect	.74 N=3 p=.47	n/a N=2	-.06 N=3 p=.96	.53 N=3 p=.61	.40 N=3 p=.74	n/a N=1
East aspect	-.57 N=6 p=.24	.07 N=7 p=.88	.17 N=8 p=.68	-.36 N=8 p=.38	-.32 N=8 p=.43	-.27 N=6 p=.60
South aspect	.01 N=3 p=.99	.72 N=3 p=.49	n/a N=2	.60 N=4 p=.40	-.14 N=3 p=.91	n/a N=2
West aspect	-.32 N=4 p=.68	-.74 N=5 p=.16	.50 N=4 p=.50	.25 N=5 p=.69	.67 N=4 p=.33	-.41 N=3 p=.73

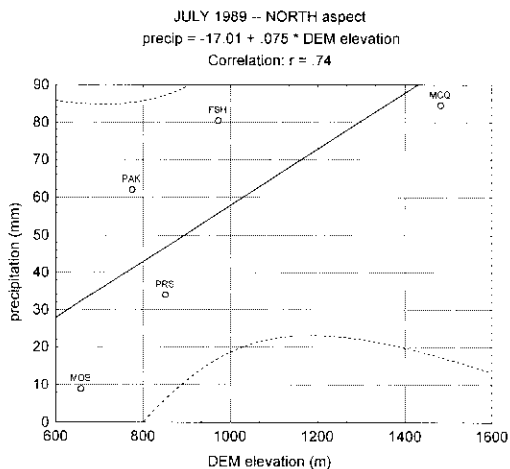


Figure 5(a). DEM elevation vs JULY 1989 precipitation for stations with North aspect.

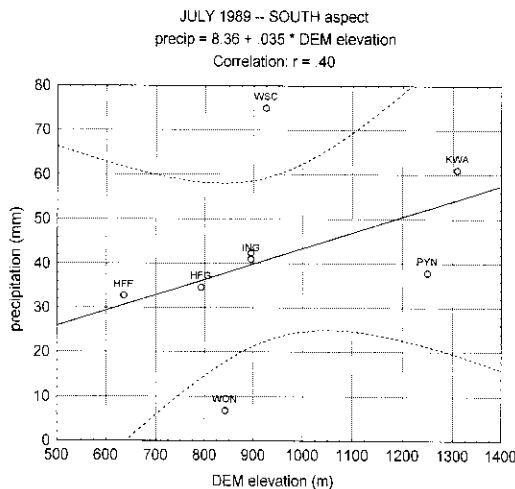


Figure 5(c). DEM elevation vs. JULY 1989 precipitation for stations with SOUTH aspect.

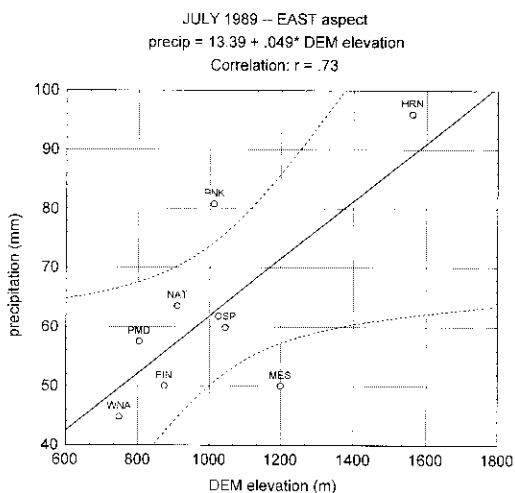


Figure 5(b). DEM elevation vs. JULY 1989 precipitation for stations with EAST aspect.

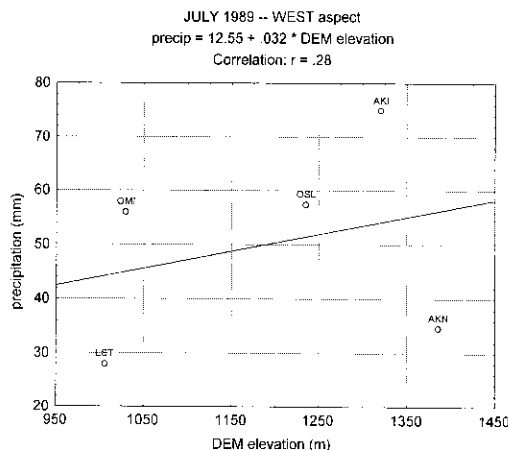


Figure 5(d). DEM elevation vs. JULY 1989 precipitation for stations with WEST aspect.

using June/July/August data is very similar to that obtained when only July data are used for the same five year period.

Conclusion

The aim of this study was to determine statistical relationships between precipitation and orographic parameters such as elevations slope and aspect in the Williston Basin. At the present time, however, the development of a suitable statistical model is limited by the lack of good quality data. The most encouraging result of this study was a crude relationship between summer precipitation and

elevation for terrain having north or east aspects. Individual months appear to provide a better basis for statistical modelling than five-year monthly averages, mainly due to the reduced sample size arising from missing data as the period of record is increased. Because of high interannual variability, a statistical model based on individual years of data would be limited in its applicability to other years. In order to have more universal application, perhaps 10 to 20 more years of data would need to be collected in order to mitigate the trade-off between sample size and length of record. This is especially true when partitioning

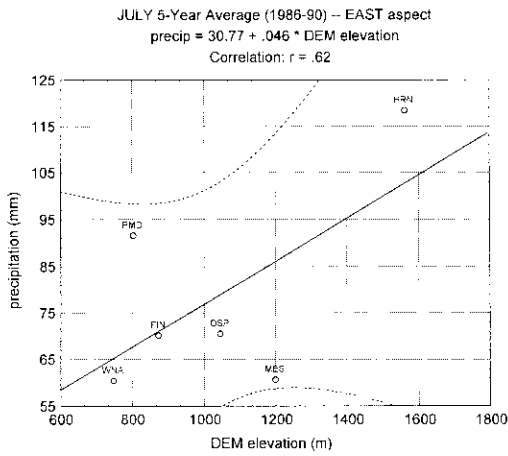


Figure 6(a). DEM elevation vs. JULY 5-year average (1986-90) precipitation for stations with EAST aspect.

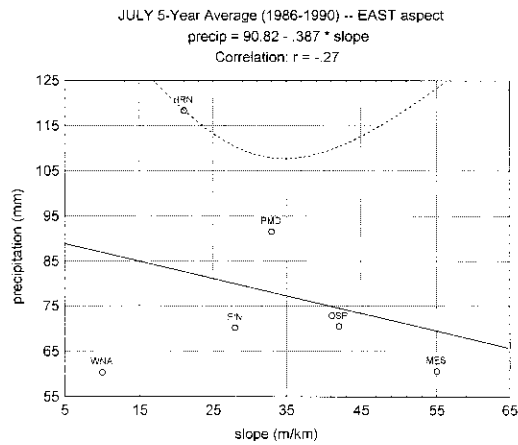


Figure 7. Slope vs. JULY 5-year average (1986-90) precipitation for stations with EAST aspect.

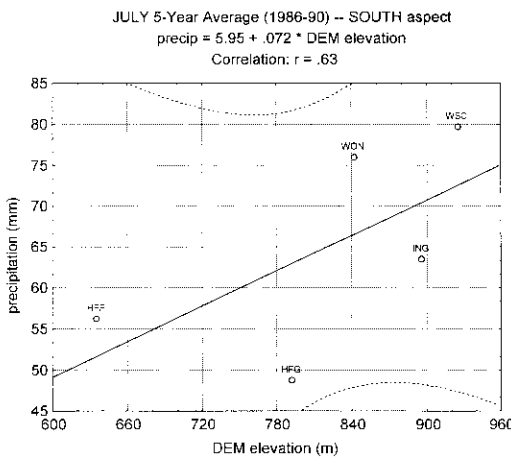


Figure 6(b). DEM elevation vs. JULY 5-year average (1986-90) precipitation for stations with SOUTH aspect.

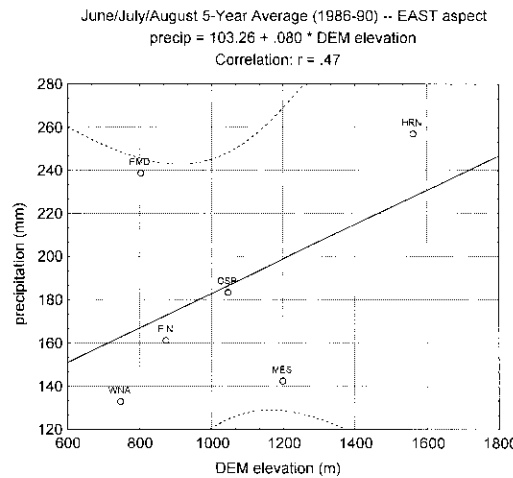


Figure 8. DEM elevation vs. total June/July/August five-year average precipitation (1986 to 1990) for stations with EAST aspect.

the data according to aspect into still smaller subsets.

Given the extent of underreporting of snow in Williston Basin, as in other mountainous regions, the opportunities to statistically model orographic effects during the winter period are severely limited. This problem is being addressed by B.C. Hydro through the conversion of its network to the larger standpipe type of gauge. However, several years of data using new instrumentation would be needed to reach any conclusions about the orographic enhancement of snow in this basin. For GEWEX purposes, statistical model-

ing would necessarily be limited to summer precipitation due to the questionable quality of the winter precipitation data.

According to this study, the precipitation-elevation relationship appears to be just as valid for station elevations as for DEM elevations. This is in contrast to other studies which showed coarser scale elevations to be better correlated with precipitation than point elevations. No consistent relationship between precipitation and slope was found.

Within these limitations, it would appear that any of the interpolation techniques discussed

earlier, including kriging and PRISM, may be appropriately used with summer precipitation data. The study did not attempt to geographically stratify the data according to different climate regimes, and if the Williston basin is not characterized by a single orographic regime, then some means of dividing the region into sub-regions would have to be done prior to performing kriging. One of the strengths of the PRISM model lies in its ability to continuously adjust its frame of reference to local precipitation-elevation relationships, thereby enabling it to maintain its accuracy over large non-homogeneous regions. Regardless of the technique chosen, the quality of the precipi-

tation data will continue to be a limiting factor in the accuracy of the model results.

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