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Rain Distribution in a Mountainous Watershed

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The orographic and temporal gradients of rainfall in a mountainous watershed in southwestern British Columbia have been analyzed and streamflow has been estimated using a watershed model. The study watershed is the Jamieson Creek watershed located approximately 30 km north of Vancouver in the Coastal Mountains. The purpose of the study was to determine whether rainfall follows a definable pattern in this mountainous watershed. Regression analysis has been performed for the total rainfall depth per event and hourly intensity for the period 1972-1975. Data is taken from the rainfall season of June to mid-November in order to avoid complications of combined rain and snow events. In this analysis, the rainfall data from a gauge at the lower elevation was used as the set of independent variables and the data from the other four gauges in the watershed as dependent variables. The results showed that the rainfall depth per event increased up to the mid-elevation of the watershed, and then decreased at the upper elevations. On the other hand, the hourly rainfall intensity was found to decrease with increase of elevation in the watershed, so that longer duration of rainfall events occurs at the middle and upper watershed. The regression equations, developed from the analysis of the distribution of the hourly intensity, were used for the prediction of rainfall events of the years 1976-1977. The agreement between the predicted and the observed rain was statistically good. Also, the simulation of the watershed streamflow using the predicted rainfall gave good results. Consequently, because the rainfall follows a definable distribution as a function of elevation, it is possible to use data from one station located at the lower elevation in combination with the developed predictor equations to accurately describe the rainfall over the watershed.

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Introduction

In mountainous areas, it is often difficult to install rain gauges at upper elevations because hillslopes are steep, weather is harsh, and lack of roads and transportation make the collection of precipitation data difficult. On the other hand, the physiographic features and the complex atmospheric processes significantly modify the distribution of precipitation. Hence, in the mountainous areas where large variability in the precipitation exists, the gauge network is never adequate to define the detailed precipitation distribution (Daly 1991). Furthermore, mountainous watersheds are often small and their runoff response is very fast, so that daily data are not adequate, and a shorter time resolution is required, perhaps of the order of one to two hours. This non-uniformity in the spatial and temporal distribution affects both the generation of runoff from the mountains and its reliable prediction (Barros and Lettenmaier 1991).

Previous studies have shown that rainfall and snowfall, the two major forms of precipitation, have quite different distributions (Fitzharris 1975; Storr and Ferguson 1972), so that recognition of the type of precipitation is crucial in the study of its distribution. This study will deal with rain events and with no snowmelt component. In addition, this study will focus only on frontal storms.

The present study has two objectives. Firstly, it investigates the variation of precipitation as a function of elevation. This variation includes the depth, the duration and the intensity of the precipitation. Secondly, the study examines if this variation of precipitation with elevation is reasonably constant. Then, the study determines whether data from a single station can be used as a good index of basinwide precipitation. This study is part of a larger project which started by examining the response of the study watershed to rainfall events (Loukas 1991). The data analyzed are from the period of June to mid-November because, at this stage, the study concentrates only on rainfall events.

Study Area

The data used in the present study have been measured in the Jamieson Creek watershed, which is a forested watershed located in the southwestern Coastal Mountains in British Columbia. Jamieson Creek is a tributary of the Seymour River and is approximately 30 km north of Vancouver (Fig. 1). This watershed was selected because a good database has been collected, including hourly data at five meteorological stations and hourly flow measurements at the mouth of the watershed (Fig. 2).

The precipitation is measured using Belford weighting-type precipitation gauges. The rain gauges have been installed at 425 m (14A), two at 640 m (21A, 21D), and

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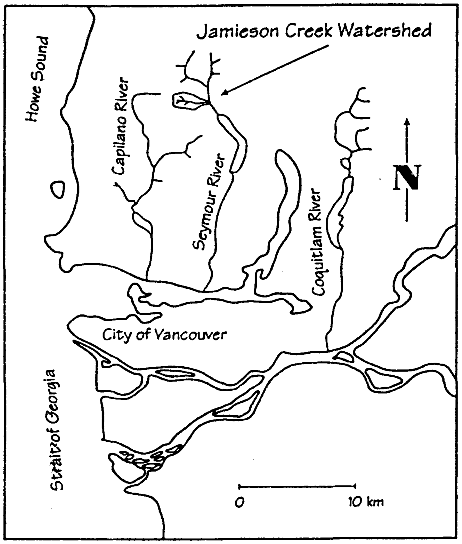

Fig. 1. The location of the Jamieson Creek watershed.

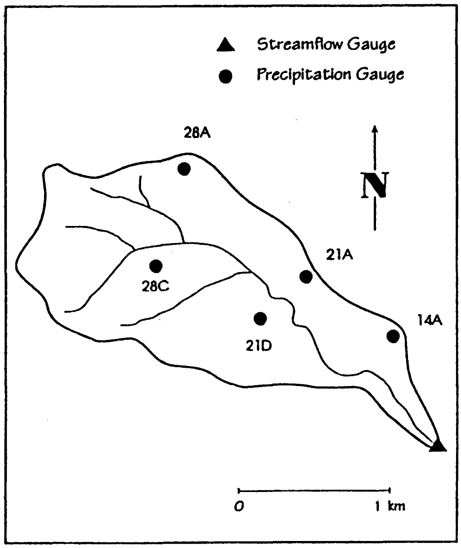

Fig. 2. The instrumentation of the Jamieson Creek watershed.

two at 850 m (28A, 28C). The stations have been installed on the two main hillslopes of the watershed. The stations 14A, 21A, 28A are located on the hillslope facing southwest and the stations 21D and 28C are located on the hillslope facing northeast (Fig. 2).

The Jamieson Creek has southeast orientation, and the dominant aspects of its slopes are southwest and northeast. The basin has an area of 2.99 km^2 and its elevation ranges from 305 to 1,310 m above mean sea level. Jamieson Creek is characterized by steep hillslopes having an average gradient of 48%.

The climate of southwestern British Columbia is characterized as a maritime climate, with wet and mild winters and dry and warm summers. Annual precipation averaged 3,600 mm during the period 1972-1977. Although about 90% of the precipation in the lower elevations is in the form of rainfall, during the winter, from late November to March, precipation in the upper watershed may fall as snow. Furthermore, snowmelt continues until late May. The six month period April-September is the driest period of the year with only 25% of the annual precipation whereas 75% of the annual precipation occurs during the months of October through March. The wettest month is November and the driest is August. For the study period of June to mid-November, the precipitation accounts for about 35% of the total annual precipitation. The precipitation during the wet period of the year is generated by strong frontal systems that impinge in the area from a south-southwest direction. In the summer months, precipitation is generated by weak

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frontal storms and occasional thunderstorms or convective rain showers. However, strong frontal storms during the summer can occur and sometimes record breaking rainfall events have been observed (Schaefer 1973). These summer frontal storms are similar in character to the winter frontal events, and are also approaching from the south-southwest.

Previous Studies in the Area of Interest

Previous studies in Jamieson Creek or in the vicinity give a good description of the general trend of the precipitation distribution in the area.

Examination of the annual precipitation at 38 stations in the Northern Cascades in Washington State, U.S.A. which is a similar environment to that of southwestern British Columbia, has been undertaken by Rasmussen and Tangborn (1976). The stations cover an area extending from the Canadian border southward for about 190 km. All stations are located in the western slope of the Cascades. The data showed that, even for a relatively local region, there was a wide variation in precipitation at a given elevation. However, the general pattern of the annual precipitation increased quite consistently up to about 800 m elevation, but was remarkably variable at higher elevations. A drawback of this study is that the precipitation was not separated into snowfall and rainfall.

This distinction between rain and snow is important because an earlier investigation of the distribution of winter precipitation on the southern facing slopes of Mount Seymour, north of Vancouver, showed that rainfall and snowfall have different distributions with elevation (Fitzharris 1975). Fitzharris showed that the rainfall increased with elevation up to the level of 800 m and then leveled off at higher elevations. The elevation of 800 m is approximately two thirds (2/3) of the height of Mount Seymour. The distribution of snowfall was completely different. The snowfall depth increased with elevation up to the height of maximum elevation at which measurements were taken (1,260 m).

In the Jamieson Creek watershed two studies have dealt with precipitation. In the older study, Jones (1974) analyzed the monthly precipitation, including both rain and snow, from 12 rain gauges distributed over the watershed area in order to optimize the rain gauge network. As a secondary result of his work, he found that the monthly precipitation increased with height up to the elevation of 500 m, and then decreased with additional increase in elevation.

The second study was undertaken by Hall (1989) in order to find the Intensity-Duration-Frequency (IDF) curves for the Jamieson Creek watershed. Hall analyzed data only from the rain gauges located on the hillslope facing southwest at elevations 853 m and 640 m (28A and 21A, respectively), and he found that the small duration intensities were higher at the lower elevation station (21A) than at the upper station (28A) for all return periods.

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Rainfall Distribution in the Jamieson Creek Watershed

For a detailed analysis of precipitation there must be sufficient data stations to give a good spatial resolution, and also the data interval must be short enough to provide an adequate temporal distribution. At the scale of the Jamieson Creek watershed the hourly data base is adequate because it is shorter than the response time of the system, and can give information on intensity as well as on longer term totals. In Jamieson Creek there are 5 stations in about 3 km^2 area, at different elevations and aspects, and this data base allows some analysis of spatial variability. The small time step of data gives the researcher the possibility to understand the temporal and spatial distribution of rainfall and the opportunity to examine whether the precipitation intensities and duration change with elevation.

In this study, the rainfall distribution in the Jamieson Creek is examined with the use of hourly rainfall data for each event. To avoid the complication of snowmelt and snowfall combined with rain, only data for the period of June to mid-November for the years 1972-1975 are analyzed. During this period the rainfall gauges were not charged with antifreeze and, therefore it was impossible to operate them during the snowfall season which starts at about the mid-November. Furthermore, the response of the watershed during rain on snow and snowmelt events is different from the response to purely rainfall events.

The data have been taken from the five rain gauges in the watershed (Fig. 2). Each one of the five rain gauges is located in the middle of a circular forest opening with a diameter of about twice the height of the adjacent trees. Gauge catch corrections, calculated by the equations given by Sevruk (1982), were found to be negligible, being between 0% and 1% for different elevations, because the wind speed in the forest clearing is usually less than 0.7 m/sec and the rainfall intensity is small to moderate (Beaudry and Golding 1985). Furthermore, the rain catch of two gauges with and without windshield has been compared, and no significant difference has been found (Kuochi Rae, personal communication). Because of the above reasons, the lack of wind speed observations, the mild climate of the study area and the method of the gauge installation, no corrections in the measurements are applied.

The rainfall events are categorized as small, medium and large events according to total rainfall depth. The small events are those with a rainfall depth smaller than 20 mm, the medium events between 20 and 60 mm and the large events greater than 60 mm of rain.

The storm duration of the events analyzed is very variable, ranging from 10 hours to 2 days. The smaller events usually last a few hours, whereas the large and medium events have duration of up to 2 days, and all events have moderate intensity. Storm duration for a given event changes slightly at different stations. It should be noted that the prolonged duration and low intensity are characteristics of frontal rains.

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Four years of data were available for analysis and during this period the return periods of the events were moderate, usually less than a 2-year annual return period. For the study period ten large, twelve medium, and twelve small events have been analyzed. All the events were considered frontal storms. The smaller events were generated by weak frontal systems whereas the medium and large events were strong frontal storms.

Total Event Rainfall

Comparison of rainfall at the various stations has been carried out using linear regression analysis. The analysis is separated in three parts which will be described in the next three paragraphs. It should be noted that since all the storms approach from a similar direction, the watershed slope and aspect should have a similar influence on all the storms.

Firstly, the storm rainfall at the station 14A is correlated with the storm rainfall at the stations 21A, 21D, 28A, and 28C. This analysis is used to assess the rainfall distribution with elevation at the two main watershed hillslopes facing southwest and northeast, respectively. The relationships included in Table 1 are the results of this analysis. From these equations, it can be seen that the rainfall depth for each event follows, on average, a consistent trend. The statistical measures are the coefficient of determination and the standard error of estimate. For the hillslope facing southwest, the rainfall depth increases only slightly from the elevation of 425 m (14A) to elevation of 640 m (21A), the increase being only 1.9% which is not significant at the 5% level. On the other hand, there is a dramatic decrease of about 40% in the rainfall depth between gauge 14A and gauge 28A at 853 m elevation, which is significant at the 5% level. This large average decrease is not consistent from storm to storm and shows a large variability, as indicated by the smaller coefficient of determination (Table 1). From the equations in Table 1, it can also be seen that the rainfall depth per event increases between the rain gauges 14A (425 m) and 21D (640 m) by about 14% but it only increases by 8% between 14A and 28C (850 m) for the hillslope facing northeast. The increase of the rainfall depth per event between points 14A and 21D, and 14A and 28C is significant at the 5% significance level. According to the equations in Table 1, the decrease of the rainfall depth between the points 21D and 28C is 6%. Hence, the rainfall depth per event for both the main hillslopes of the watershed, facing southwest and northeast, increases up to the mid-elevation, and then it decreases at the upper elevations. The high coefficients of determination show that the above trend is very consistent.

In the second part of the analysis the rainfall depth between stations at the same elevation but in opposite hillslopes were correlated. The stations used for this analysis are 21A and 21D, and 28A and 28C. The stations 21A and 28A have a southwestern aspect, whereas the stations 21D and 28C are located on the hillslope having northeastern orientation. This analysis is used to determine the effect of

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Table 1 – Regression equations for the total event rainfall (mm)

Equation	r^2	*See* (mm)
$P_{21A} = 1.019P_{14A}$	0.991	4.419
$P_{28A} = 0.618P_{14A}$	0.664	15.006
$P_{21D} \equiv 1.144P_{14A}$	0.983	7.479
$P_{28C} \equiv 1.083P_{14A}$	0.951	11.332

Note: r^2 is the coefficient of determination *See* is the standard error of estimate

Table 2 – Regression equations for the total event rainfall (mm) for the gauges in the same elevation and opposite hillsides

Equation	r^2	*See* (mm)
$P_{21D} \equiv 1.128P_{21A}$	0.996	3.779
$P_{28C} \equiv 1.592P_{28A}$	0.832	21.070

Note: r^2 is the coefficient of determination *See* is the standard error of estimate

aspect on rainfall distribution. The results of this work are the equations presented in Table 2. The first of these equations correlates the event rainfall depth at the gauges 21A and 21D both at 640 m elevation, and it shows that the point 21D on the hillslope facing northeast, receives about 13% more rain than the point 21A on the opposite hillslope. The second equation in Table 2 shows that the hillslope facing northeast at the point 28C receives about 59% more rain that the point 28A at the same elevation on the hillslope facing southwest. Both of the above increases are significant at 5% level. This above observation is very important for the hydrological study of the Jamieson Creek and the simulation of the runoff, since the hillslope facing northeast is more than twice the area of the opposite hillslope. Furthermore, the variation between the rainfall at stations 28A and 28C is very large. It is possible that the measurements of station 28A are affected by the topography of the immediate area. As a result, the rain recorded at this station is much more variable and smaller than at any other station in the study watershed.

In the third part of the analysis the rainfall was analyzed separately for the small, medium, and large events. These analyses are used to examine the effect of the size of the storm events on the rainfall distribution in the watershed. The results are presented in Table 3 and show that the distribution of the large events is similar to the distribution of rainfall obtained in the first part of the analysis where the events were not differentiated into small, medium and large (Table 1). The smaller values of coefficients of determination for the small events indicate that these events are more scattered than the medium and large events. On the other hand, the distribution of the large and medium events is highly consistent. Furthermore, the largest variation for all the types of events has been observed again for station 28A.

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Table 3 – Regression equations for the total event rainfall (mm) for large, medium and small events

Equation	r^2	*See* (mm)
Large Events (P > 60 mm)		
$P_{21A} = 1.008P_{14A}^*$	0.982	7.779
$P_{28A} = 0.564P_{14A}$	0.496	22.050
$P_{21D} = 1.148P_{14A}$	0.970	12.632
$P_{28C} = 1.067P_{14A}^*$	0.912	21.720
Medium Events (20 mm < P > 60 mm)		
$P_{21A} = 1.036P_{14A}$	0.965	1.757
$P_{28A} = 0.973P_{14A}^*$	0.455	7.563
$P_{21D} = 1.104P_{14A}$	0.771	4.613
$P_{28C} = 1.109P_{14A}$	0.700	5.243
Small Events (P < 20 mm)		
$P_{21A} = 1.107P_{14A}$	0.742	1.574
$P_{28A} = 1.118P_{14A}^*$	0.180	4.458
$P_{21D} = 1.177P_{14A}$	0.787	1.593
$P_{28C} = 1.448P_{14A}$	0.650	2.688

Note: r^2 is the coefficient of determination *See* is the standard error of estimate
*Not significant at 5% level

Hourly Intensity Distribution

A set of analyses similar to the one made for rainfall depth has been adopted for the analysis of the rainfall hourly intensity.

Firstly, the hourly intensities occurred at station 14A are correlated with the hourly intensities occurred simultaneously at the other four stations. This analysis is used to determine the distribution of the hourly intensities at different elevations, and to develop predictor equations for the rainfall distribution across the study watershed. More than a thousand sets of measurements are used in this analysis. Table 4 shows the equations derived from the regression analysis of rainfall hourly intensity. This analysis shows that the hourly rainfall intensity decreases with increasing elevation for both major hillslopes of the watershed. For the hillslope facing southwest the hourly intensity decreases, on average, between rain gauges 14A and 21A by 8.5% and between 14A and 28A by about 46% (Table 4). The average decrease between the points 14A and 21D is about 2% and between 14A and 28C about 9% (Table 4). The decrease of the hourly intensities at every gauge point is significant at 5% level.

Examination of the coefficients of determination indicates that the variation of the hourly intensity between the rain stations is much larger than the variation of

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Table 4 – Regression equations for the hourly intensities (mm/h)

Equation	r^2	*See* (mm/h)
$I_{21A} = 0.915 I_{14A}$	0.794	0.796
$I_{28A} = 0.544 I_{14A}$	0.292	1.058
$I_{21D} \equiv 0.978 I_{14A}$	0.757	0.937
$I_{28C} \equiv 0.913 I_{14A}$	0.646	1.064

Note: r^2 is the coefficient of determination *See* is the standard error of estimate

Table 5 – Regression equations for the maximum hourly intensities (mm/h)

Equation	r^2	*See* (mm/h)
$Imax_{21A} = 0.915 Imax_{14A}$	0.706	1.407
$Imax_{28A} = 0.754 Imax_{14A}$	0.010	4.402
$Imax_{21D} = 0.974 Imax_{14A}$	0.675	1.535
$Imax_{28C} = 0.918 Imax_{14A}$	0.373	1.688

Note: r^2 is the coefficient of determination *See* is the standard error of estimate

the storm rainfall. All the coefficients of determination for the hourly intensities are lower than the respective coefficients of determination for the total rainfall depth. Especially, it should be noted that the correlation of the hourly intensities between rain gauges 14A and 28A is very low ($r^2 = 0.292$) which indicates that the relation of intensity between these two points is inconsistent. The same result, but to a smaller extent, occurs between points 14A and 28C. These results imply that the distribution of rainfall in time may be different at the upper and lower watershed, or alternatively that the relationships for the hourly intensities at the five rain gauge locations do not remain constant for various events. The significance of the hourly intensity variation will be examined in the next section, where predicted and observed rainfall events will be compared.

In the second part of the intensity analysis, the maximum hourly intensity variation is examined and the maximum hourly intensities for each event at station 14A and the other four stations are correlated. This analysis shows that the peak hourly intensity decreases with increasing elevation (Table 5). For the hillslope facing southwest the peak intensity decreases, on average, by 5% between 14A and 21A and by 25% between 14A and 28A. The average decrease between the stations 14A and 21D is about 3% and between the stations 14A and 28C is about 8%. These average decreases of the maximum hourly intensity are not significant at the 5% level. In general, examination of the coefficients of determination indicates that the variation of the maximum hourly intensity is larger than the variation of the hourly intensity.

In the third part, a similar regression analysis, as above, has been performed for the hourly intensities of the previously classified events as small, medium, and

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Table 6 – Regression equations for the hourly intensities (mm/h) for large, medium and small events

Equation	r^2	*See* (mm)
Large Events (P > 60 mm)		
$I_{21A} = 0.951 I_{14A}$	0.783	0.930
$I_{28A} = 0.567 I_{14A}$	0.200	1.302
$I_{21D} = 0.982 I_{14A}$	0.759	1.008
$I_{28C} = 0.925 I_{14A}$	0.650	1.125
Medium Events (20 mm < P > 60 mm)		
$I_{21A} = 0.895 I_{14A}$	0.753	0.834
$I_{28A} = 0.535 I_{14A}$	0.235	1.235
$I_{21D} = 0.952 I_{14A}$	0.737	1.010
$I_{28C} = 0.905 I_{14A}$	0.636	1.166
Small Events (P < 20 mm)		
$I_{21A} = 1.001 I_{14A}$	0.564	0.960
$I_{28A} = 0.763 I_{14A}^{*}$	0.103	1.039
$I_{21D} = 0.992 I_{14A}$	0.585	1.153
$I_{28C} = 1.032 I_{14A}$	0.432	1.214

Note: r^2 is the coefficient of determination *See* is the standard error of estimate
*Not significant at 5% level

large. This analysis shows that the larger variation in the intensity is observed during the small events (Table 6). The variation decreases substantially for the large events. The results also indicate that the hourly intensity during small events remains relatively constant over the watershed (Table 6). In addition, the relationships developed for the large and medium events are similar to those of Table 4, developed for the hourly intensity distribution without categorizing the events into small, medium, and large. The smaller coefficients of determination have been observed again for the station 28A for all types of the events.

Discussion of the Results

Analysis of the events clearly indicates that the summer and fall rainfalls increase up to the mid-elevation and then decrease at higher elevations. These results are in agreement with observations of Jones (1974) in Jamieson Creek and Fitzharris (1975) in the nearby Mount Seymour as presented before.

At least two different mechanisms are involved in the generation of precipitation in the study watershed. During the summer months, the weak frontal systems coming from south-southwest direction impinge on the study area. These systems are quite stable and can penetrate the mountain region. However, the lifting of the air over the mountain slopes, and the convergence in the valleys could trigger

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convection and consequently precipitation (Smith 1989). The variability of precipitation during these events is large. The small events of the study period are possibly generated by this mechanism so that they are more variable than the medium and large events.

A second mechanism is the Bergeron's suggestion of two-cloud system. The upper "seeder" cloud is associated with the synoptic circulation, and is affected only by the regional topography (Barry 1992). The precipitation from this "seeder" cloud is partly evaporated on its way to the earth's surface. This reduces the rainfall rate, but at the same time it moistens the low level air. When this air is locally lifted by the terrain, it reaches saturation quickly and a dense low cloud is formed, the "feeder" cloud. Barry and Chorley (1987) have argued that the elevation of maximum precipitation is close to mean cloud base because the maximum size and number of falling precipitation droplets will occur at this level. For the nearby Mount Seymour, Fitzharris (1975) estimated the layer of mean cloud base at about 800 m or even lower. However, this layer changes from storm to storm, and depends on the area characteristics. As a result, higher rainfall depth and intensity are observed at the lower elevation. Such a situation has been identified in the northern slopes of the French Alps (Givone and Meignien 1990). This "seeder-feeder" mechanism is likely to produce the precipitation in the study area during strong frontal storms.

The above explanation is also in close agreement with the results of the analysis of the hourly intensity which showed that the rainfall intensity decreases with elevation, especially for medium and large events. This trend is in agreement with the IDF study in Jamieson Creek as presented before (Hall 1989). The above frequency study showed that the small duration intensities decreased with elevation from the rain gauge 21A at 640 m to the elevation of the gauge 28A (850 m). Furthermore, the larger variability of intensity during the small events can be explained by their generation mechanism, presented before.

The decrease of the hourly intensity at the upper and mid-elevations of the Jamieson Creek watershed, and the increase or the smaller decrease of the rainfall depth per event at the same elevations, indicate that the duration of the rainstorms at these points is larger than in the lower watershed. During the processing of the data, it was frequently observed that the rainfall at the upper elevations was prolonged by one or two hours when compared with the rainfall duration for the lower watershed.

Another important characteristic of the rainfall distribution in the Jamieson Creek watershed is the larger depth that is received by the hillslope facing northeast. The change of the wind pattern by the rugged mountain terrain may explain this distribution. Most of the frontal systems come from a south-southwest direction so that the larger rainfall for the Jamieson Creek hillslope facing northeast, compared with the adjacent Orchid Creek watershed, may be caused by the effect of the intervening ridge on the prevailing wind and rainfall.

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Finally, the larger rainfall events have a more consistent distribution pattern than the smaller storm events. This consistency can be explained because the larger storms are long duration frontal events, whereas the small storms are generated by weak frontal systems. The consistency of the rainfall distribution during large storms is important for the examination of the response of the watershed under large rainfall events and the production of flood runoff.

Prediction of Rainfall Distribution and its Effects on the Simulation of Runoff

The equations developed in the analysis of the hourly intensity, presented in Table 4, are used for the prediction of rainfall distribution assuming that the duration of each event over the watershed is the same as its duration at 14A station. The average basin rainfall obtained with the Thiessen polygon method from the actual data has been compared with the average basin rainfall assessed using the predictor equations. The comparison has been made for rainfall events from the years 1976 and 1977. It should be noted that the predictor equations have been developed from rainfall data for the years 1972-1975, so that the above comparison of predicted and observed rainfall is used as a verification of the prediction.

Five events, for which both rainfall and streamflow data exist, have been compared. Four of these events are medium and one is large according to the previous classification. Table 7 shows the predicted and the observed average rainfall depth and the top graphs of Figs. 3, 4, 5, 6 and 7 show their time distribution. From this comparison, it is clear that the agreement between the predicted average rainfall and the actual average rainfall is quite good, and the coefficients of determination are high. Furthermore, the temporal variation of the rainfall intensity is described quite well by the data from the lowest elevation gauge.

The average rainfall for the above five events has been used as input to an event based watershed model developed for the study of the hydrologic response of the Jamieson Creek. The watershed model uses the linear reservoir routing technique and simulates the fast runoff with two cascading reservoirs and the slow runoff with

Table 7 – Statistical parameters of flow simulation with observed and predicted rain

Event	Rain Observed (mm)	Rain Predicted (mm)	r^2	Simulated flow with observed rain E_f	Simulated flow with observed rain r^2	Simulated flow with predicted rain E_f	Simulated flow with predicted rain r^2	r^2 between simulated flows
15-17/8/1976	29.27	31.08	0.92	0.92	0.93	0.80	0.89	0.99
26-30/8/1976	31.56	36.40	0.95	0.95	0.97	0.90	0.98	0.99
4-8/9/1976	112.93	105.62	0.87	0.98	0.98	0.84	0.97	0.98
16-17/7/1977	33.85	39.01	0.98	0.93	0.94	0.93	0.95	0.99
23-25/8/1977	48.77	54.82	0.99	0.61	0.63	0.62	0.63	0.99

Note: r^2 is the coefficient of determination E_f is the model efficiency

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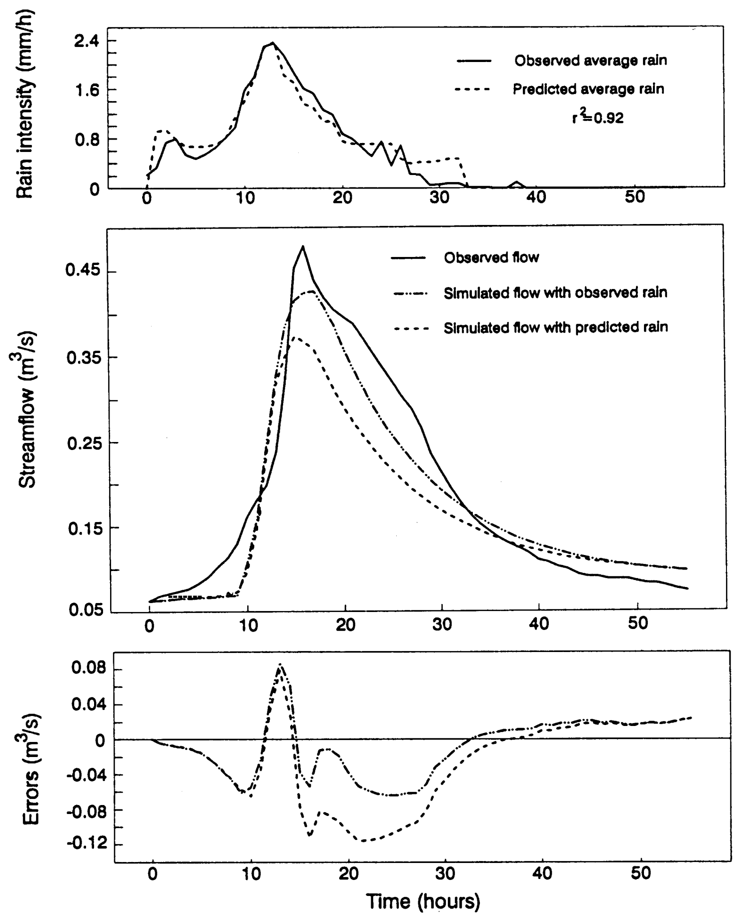

Fig. 3. Effect of predicted rain on simulation of streamflow (event 15-17/8/1976).

one large reservoir. Application of the model to the Jamieson Creek showed that during each event a constant amount of precipitation is diverted to the slow runoff and the rest is delivered to the stream as fast runoff. This model was kept deliberately simple for a first analysis, with the intention of adding more complexity to handle soil moisture. However, the model was found to perform well, so that no additional complexity was added to it. More detailed information about the model can be found in an earlier paper (Loukas and Quick 1991).

Figs. 3, 4, 5, 6 and 7 show the comparison of the simulated flow, using observed and predicted rainfall data, with the observed flow. Table 7 shows the statistical parameters of the simulated flow using observed and predicted average rainfall with the observed flow. The two parameters used for the comparison are the model efficiency E_f introduced by Nash and Sutcliffe (1970) and the coefficient of determination r^2.

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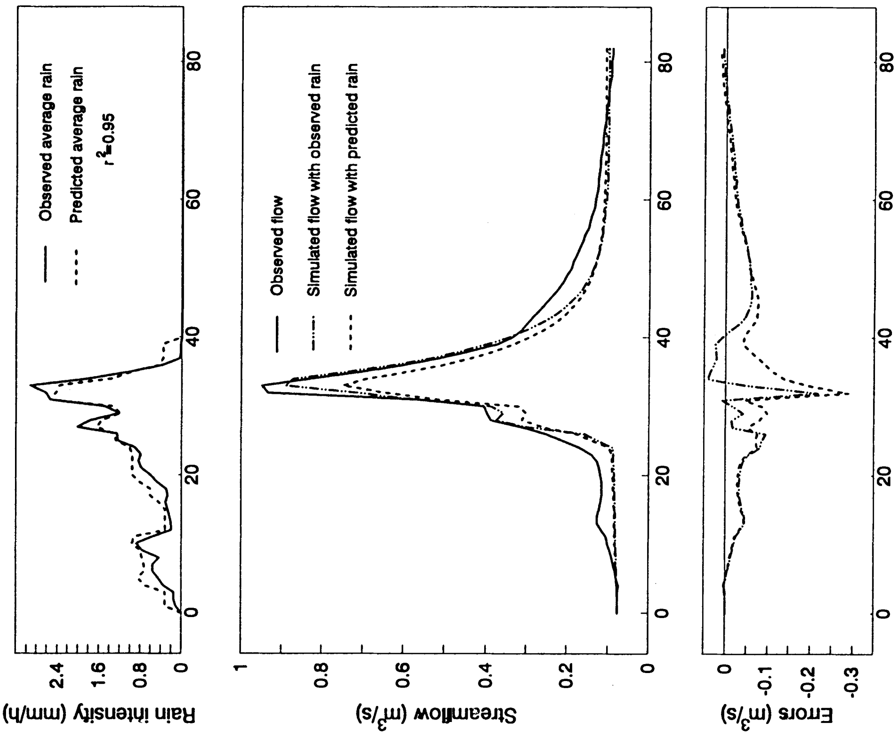

Fig. 4. Effect of predicted rain on simulation of streamflow (event 26-30/8/1976).

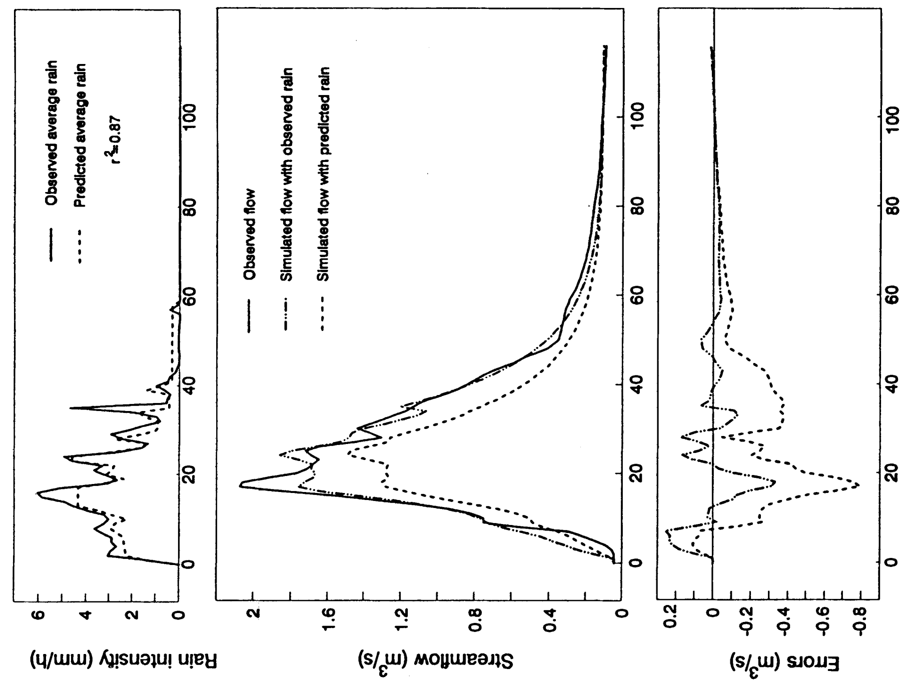

Fig. 5. Effect of predicted rain on simulation of streamflow (event 4-8/9/1976).

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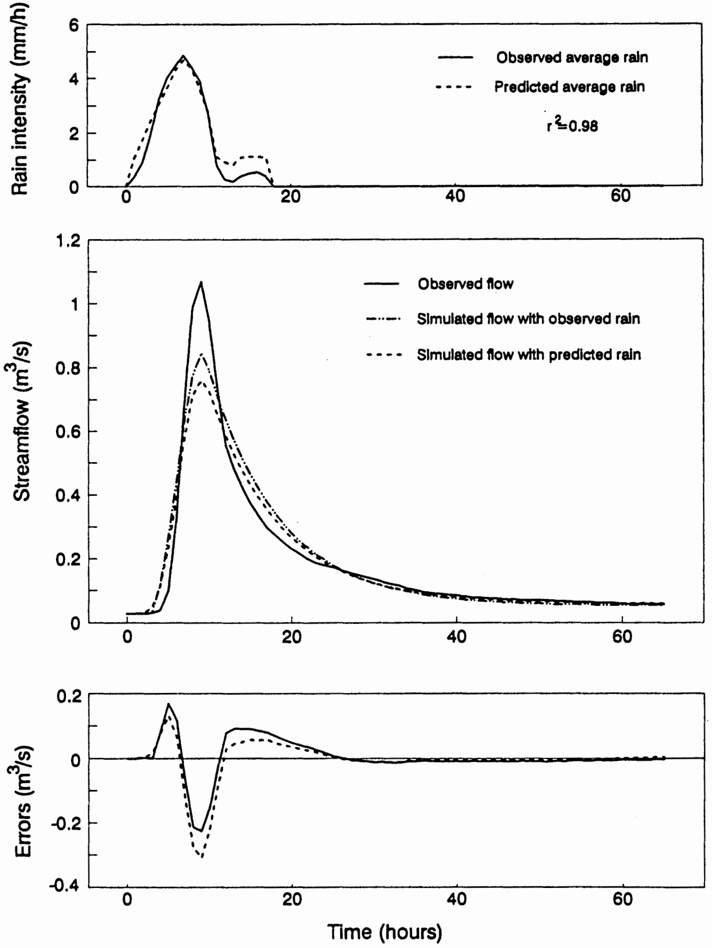

Fig. 6. Effect of predicted rain on simulation of streamflow (event 16-17/1977).

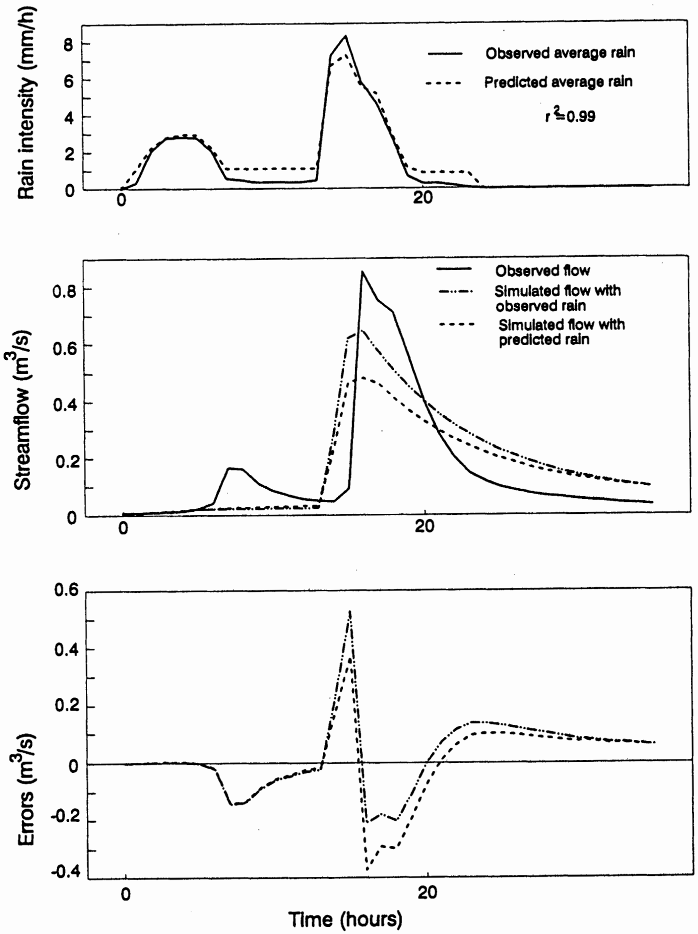

Fig. 7. Effect or predicted rain on simulation of streamflow (event 23-25/8/1977).

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From the simulation results it can be seen that the volumes of the simulated hydrographs using observed rain compare reasonably well with the observed volumes. However, the simulated hydrographs have a slightly lower peak than the observed hydrographs. This is a shape problem which results from using a very simple model. Furthermore, the volumes of the simulated hydrographs using predicted rain compare quite well with the observed volumes, except for the event of 4-8/9/1976 (Fig. 5). For this event the volume of the simulated hydrograph is underpredicted because the total rainfall has been underestimated by the predictor equations (Table 4). Again, the peaks of the simulated hydrographs using predicted rain are underestimated for all the events. However, the statistical parameters for both simulations with observed and predicted rain are high for four of the five events (Table 7). The simulation of the fifth event (Fig. 7) is poor. The assessment of the soil moisture of the watershed and timing error are possible reasons for the poor simulation of the fifth event.

To test the value of predicting the basinwide precipitation using only one station, the predicted rain has been used to simulate basin runoff and these simulated flows have been compared with the flows calculated from the observations at the five rain stations. The last column of the Table 7 shows the coefficients of determination between these two simulated flows which are almost perfect.

The above results suggest that the basinwide rainfall in the Jamieson Creek watershed can be assessed by the rainfall data from a single rain gauge as an index in combination with the predictor equations developed for the hourly intensity distribution over the watershed. This is highly significant from an economic point of view since only one station at low elevation assesses quite successfully the basin rainfall.

Conclusions

Examination of the rainfall distribution in the Jamieson Creek watershed reveals a distinct pattern of rainfall distribution. The storm rainfall for each event increases up to the mid-elevation of the study watershed, and then decreases at higher elevations. On the other hand, the hourly intensity decreases with height in all elevation bands of the watershed, so that the maximum intensity occurs at the lower elevation. The findings of this study are in good agreement with the results of previous studies in the southern boundary of Coastal Mountains. The results of the present study are not adequate to prove that the rainfall intensity decreases with elevation during severe storms, because the events analyzed had return periods of less than 2 years. But the analysis of the rainfall distribution with respect to the size of the event indicated that large events have a more consistent distribution with elevation. This finding is promising for the estimation of flood runoff from the study area.

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Further study has been undertaken to investigate both the spatial and temporal distribution of precipitation in the Seymour river basin, part of which is the Jamieson Creek watershed. As part of this study, extreme storms and the watershed response to these storms will be examined.

The results of the rainfall analysis show that the duration of the rainfall events is prolonged in the upper and mid-elevation of the Jamieson Creek because the hourly intensity decreases with elevation while the total rainfall depth increases up to the mid-elevation and then decreases at the upper elevations, but at a smaller rate than the intensity. Also, the maximum hourly intensity remains relatively constant with elevation.

Furthermore, the aspect, the slope, and the position of the watershed affect the distribution of rainfall in the Jamieson Creek. Conclusions on the influence of aspect can be drawn because all the storms in the study period approached from a similar direction, between south-southwest. It was observed that the steeper hillslope facing northwest receives about 30% more rainfall than the opposite hillslope facing southwest. This result is very important for the analysis and simulation of the runoff from the watershed, since the hillslope which receives more rain is about twice the size of the more sheltered hillslope in the watershed.

For summer and fall frontal storms, the rainfall distribution over the basin may be well represented if predictor equations developed from the analysis of the hourly intensity distribution are used in combination with rainfall data from one rain gauge at the lower elevation. This is very important from an economic point of view since data from only one rain gauge at the lower watershed will still give reasonable predictions of the basin rainfall and runoff.

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