Hydrologic response of three watersheds in the CWH near Prince Rupert BC.

Draft Final Report April 2003

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Introduction

High rainfall of >3000 mm/year, high humidity and cool temperatures contribute to the maintenance of open bogs, bog forests, and low productivity upland forests that cover the north coast of British Columbia. In 1996, the Prince Rupert Forest Region initiated an integrated forest research project to develop ecologically based guidelines to manage the low productivity Coastal Western Hemlock (CWH) forests that are outside the current operable land base. These forests are dominated by Western Red Cedar (Thuja plicata), Mountain and Western Hemlock (*Tsuga mertensiana*, and *Tsuga heterophylla*) and yellow-cedar or cypress (*Chamaecyparis nootkatensis*) located on poorly drained soils. Although the CWH is composed of mostly low productivity forests, it does contain high value cedar stands.

In 1995, the Chief Forester of BC considered expanding the operable land area for harvesting to include the CWH of the Prince Rupert Forest Region. However, the expansion could only take place after questions regarding the appropriate harvesting systems and capabilities of the CWH forests to successfully regenerate were addressed. The productive stands occur at low to middle elevations (0-600m) along the western slopes of the Coast Mountains. Although the sites are considered to be operable, there is very little operational experience. Current ecological information suggests the sites may be sensitive to harvesting. As a result, further research is needed to assess the feasibility of harvesting these potentially sensitive, slow growing sites in a responsible and sustainable manner before they can be added to the operable land base.

1. Background

The importance of hydrologic knowledge for sustainable forest harvesting is well known (Higgins et al. 1989). The knowledge is required for designing roads, bridges, culverts, and identifying the potential hydrologic consequences of forest harvest operations (Higgins et al. 1989, Binkley and Brown 1993). Understanding hydrologic responses at different watershed scales is recognized as a global challenge for the 21st century (Sidle 2000). Hydrologic response is the primary driver in watershed systems as it controls the timing, amounts and fluxes of water, sediment, organic materials and pollutants to larger watersheds and drainages. Without understanding the controls on these materials, it is difficult to formulate long term management decisions and policies. Basic hydrologic information describing event rainfall and associated runoff relationships for the north coast is completely lacking. For example, while there are four stream gauging stations located within an hours drive from Prince Rupert BC, two of the stations are located on flow-controlled streams. The remaining two are located on streams in glaciated watersheds.

Our current knowledge regarding rainfall and runoff in humid areas began with Hewlett and Hibbert (1967) who proposed the variable source area concept. The concept refers to the surface and subsurface quick flow for a particular basin that is generated by an expanding and shrinking zone that originates at the perennial channel and responds to rainfall by lengthening the channel network into draws, roads and shallow areas and by expanding the subsurface zones of excess soil water. Together these constitute the hydrologic depth factors. Subsequent research found that peakflows in headwater streams were a result of rainfall intensity and channel factors, and that stormflow volumes, the real cause of floods were affected by any factor that controlled the storage capacity (hydrologic depth factors) of the entire basin (Hewlett and Helvey 1970). Therefore it was felt that harvesting along a stream would enhance runoff through decreased interception and the delivery of water directly to the expanding channel (Hewlett and Helvey 1970).

Two fundamental aspects of stream response are hydrologic response and lag time. Hydrologic response or "flashiness" refers to the streamflow following rainstorms (Hewlett 1982). It is most commonly expressed as a ratio of stormflow divided by rainfall. Lag time is the time difference between the centroid of effective rainfall and the centroid of direct runoff (Simas and Hawkins 2002). Watershed characteristics and the rainfall event affect both the hydrologic response and lag time. Watershed characteristics include the size, form, shape, slope, topography, geology, vegetation and land use. Rainfall characteristics include intensity, distribution and duration (Simas and Hawkins 2002). A change in a watershed characteristic is expected to produce a change in runoff response.

Most watersheds along the coast receive snow and experience frequent rain-on-snow events. Elevations above 300 m are known to retain snow packs until the end of May. Rain on shallow snow packs often results in higher rates of water input to the soil than would occur with rain alone (Harr 1986). This, in turn, can lead to higher pore water pressure, decreased slope stability and higher streamflow. Logging in these areas can lead to increased runoff, peakflows and channel erosion and decreased slope stability and fish habitat (Harr 1986).

In southern coastal BC, the proportion of rainfall discharged as streamflow can range from 3% for small summer storms to >90% for major winter storms (Hetherington 1982, 1987). The rapid initiation of the storm hydrographs and magnitude of peakflows were attributed to antecedent moisture conditions and the presence of soil pipes that rapidly transported water downslope (Cheng et al 1975, 1988). The disturbance of the soil pipes by forest harvesting has been found to delay the time to peak and reduce the magnitude of the stream flowpeak by keeping the rainwater on the hillslope (Cheng et al 1975). Cheng (1988) also suggested that as stormflow increased the contribution of pre-storm old water decreased and the proportion of new waters (rainfall) increased. In essence a scenario that supported translatory flow where "new" water displaces "old" water. Investigations by Hutchinson and Moore (2000) found that the hillslope contributing within a basin area changed with a changing water table height. They also found the soil pipes were important for the rapid movement of water downslope to the stream channels. The occurrence and role of these pipes in temperate rainforests have been well documented (Cheng et al. 1975, Harr 1976, Hetherington 1982 and Uchida et al 2001). It can be assumed they provide a similar role on the north coast.

The importance and contribution of runoff and storage water from source areas (riparian versus hillslope) for peakflows remains a matter of debate. McGlynn et al (2002) found that hillslope runoff contributed the dominant proportion of peakflow in a watershed in a high rainfall area of New Zealand. However, the ratio was small compared to other watersheds (McGlynn et al 2002). By comparison, FitzGerald et al. (2003) found that 95% of stream discharge originated from overland flow in the riparian area for a headwater swamp located near Prince Rupert, BC. In a nearby watershed, Gibson et al (2002) found that while new water contributions only accounted for 12% of discharge for a rainfall event, deep hillslope water only accounted for 3% of streamflow. Shallow groundwater accounted for the remaining 85% of streamflow. The shallow groundwater originated from short, subsurface flow pathways that terminated in local rills and seeps. Drainage from the slopes and riparian areas occurred via channeled flow in the rills and seeps that were typically connected to the main stream channel (Gibson et al. 2002). This would appear to support a model put forward by Sidle et al. (2000). Their model described dynamic hydrologic response as occurring from narrow riparian corridors, linear hillslope segments and geomorphic hollows. Preferential flow from each area contributes to stormflow in a non-linear manner depending on rainfall and antecedent wetness (Sidle et al. 2002).

A review of runoff from 168 watersheds in the US found that lag time was not constant for a watershed. There was no relationship between degree of saturation in the watershed and lag time; however, there was a tendency for constant values for the larger storms (Simas and Hawkins 2002). The variation in lag time was partly explained by geographical region, watershed management practices and storm size (Simas and Hawkins 2002).

To address the lack of hydrologic information about north coastal BC, rainfall, runoff and canopy interception data were collected in three forested watersheds near Prince Rupert from September 1998 to August 2001. This report provides a summary of rainfall inputs to the watersheds, watershed response, and annual water balances to identify the magnitude of the hydrologic fluxes within each watershed.

2. Site Descriptions

Three watersheds located 17 km south southeast of Prince Rupert were studied. One watershed was located on Smith Island near the town of Port Edward (Figure 1). The remaining two watersheds were located near the Diana Lake Provincial Park. All watersheds are within the Very Wet Hypermaritime Coastal Western Hemlock subzone (CWHvh).

The Smith Island and Diana Lake watersheds (upper and lower) have areas of 77 hectares (ha), 133.6 ha and 445.6 ha, respectively. The upper Diana watershed is a sub-basin of the lower Diana watershed. The Smith Island watershed has a northeasterly aspect, rises from sea level up to 380 m at its highest point and has a mean channel gradient of 33%. The lower Diana Lake watershed has an easterly to southeasterly aspect, rises in elevation from 75 m to 705 m at its highest point and has a mean channel gradient of 28%. The upper Diana watershed has a south to southeasterly aspect, rises in elevation from 87 m to 375 m and has a mean channel gradient of 11%.

Mean annual precipitation for the Prince Rupert airport, located 10 km to the south of Prince Rupert is 2,552 mm, of which 94% is rain (Environment Canada 1998). Although rainfall is the most common form of precipitation near sea level, snowfall often occurs during late fall and winter. Snow packs on the 300+ m hilltops can last until late May or June.

Soils in each watershed range from peaty organics to shallow mineral soils with thick surface accumulations of acidic forest humus. Mineral soils are derived primarily from colluvium and saprolite (decomposed bedrock). Plant rooting and most nutrient cycling occur near the soil surface.

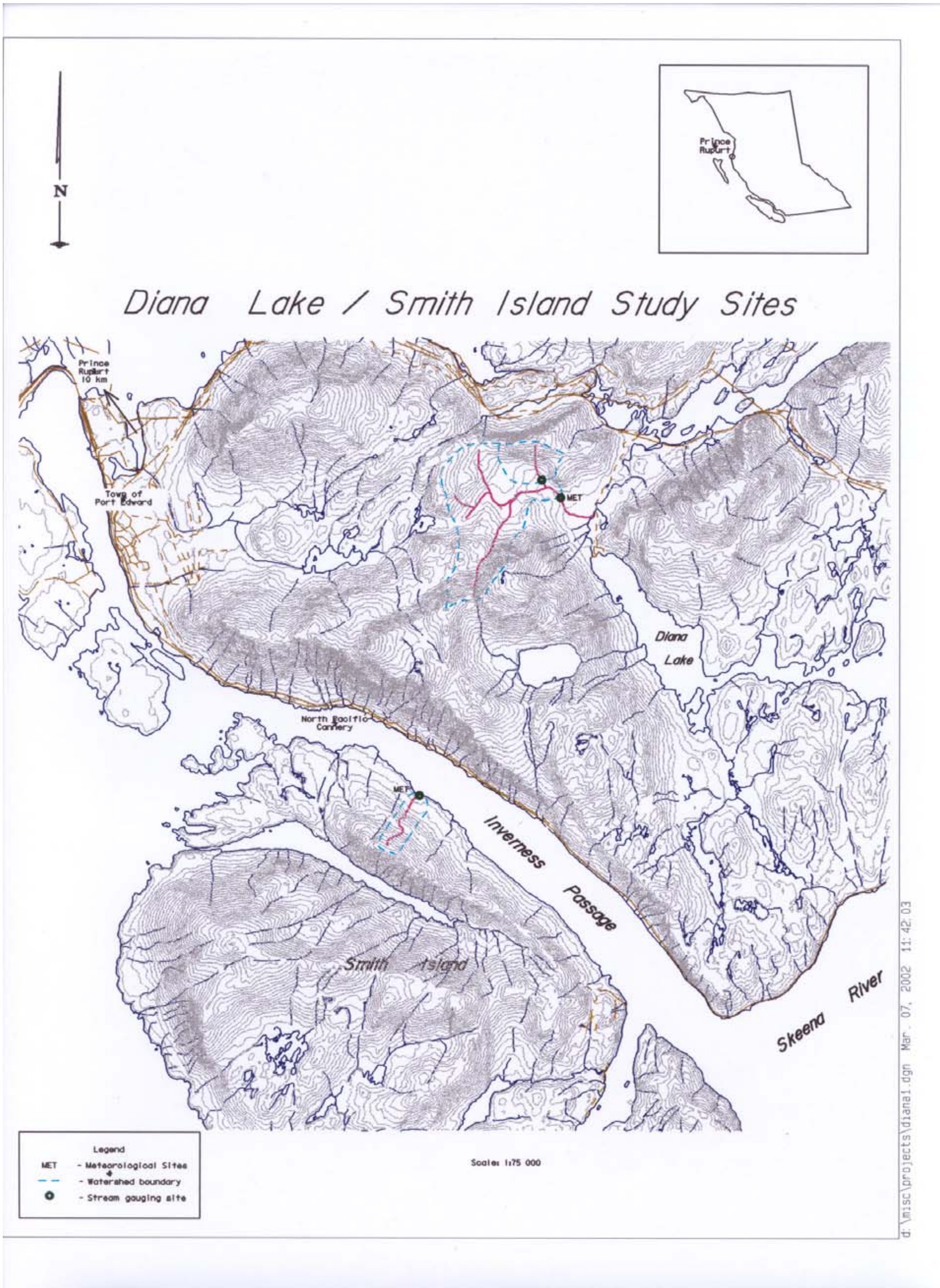

Figure 1: Location map of the Smith Island and Diana Lake watersheds.

3. Methods

Rainfall was measured with tipping bucket rain gauges at meteorological (MET) stations in the Smith Island (54 m.a.s.l.) watershed, and lower Diana (75 m.a.s.l.) watershed (Figure 1). The stations were operated year round unless disabled by freezing temperatures. One heated tipping-bucket rain gauge was maintained year-round at the North Pacific Cannery to record precipitation (rain and snow) at sea level for correlation with rainfall data from the other watersheds. High elevation (335 m.a.s.l.) rainfall in each watershed was measured by tipping buckets from July 12 to October 25, 1999 and May 12 to October 20, 2000 (Figure 1). All rain gauges were accurate to ± 1% over 5 tips.

Total rainfall within each watershed was estimated using a weighted average. Precipitation below the 200 m contour line was assumed to be similar to that of the MET site. Precipitation above the 200 m contour line was assumed to be similar to that of the high elevation site. Total monthly precipitation for the MET and high elevations sites were estimated using linear regression equations based on the sea-level cannery site data (discussed further in the orographic report).

Stage height in the main channel of each watershed, was monitored hourly by a pressure transducer connected to continuously monitoring data logger. Stream discharge was measured during low, moderate and high stage heights using a current meter. A stage-discharge-rating curve was then developed and related to stage height to provide continuous discharge data. Each rating curve was separated into two parts, an exponential curve for low to moderate flows, and a linear curve for high flows. The linear curve was thought to better estimate discharge for extrapolated values (when depth exceeded the maximum depth on the rating curve). At high flows, an increase in depth does not likely correspond to an exponential increase in discharge.

Watershed response to rainfall events was analyzed by the assessment of hydrologic response (flashiness), which is the ratio of event discharge (mm), to event input (mm). The timing of event flow following rainfall input was quantified by calculating the;

- response lag - the delay between beginning of rainfall input to beginning of rise in stage, and,
- centroid to centroid – the center of mass of rainfall input to center of mass of discharge event (Figure 1).

Event discharge was estimated through hydrograph separation. For this report, hydrograph separation was performed by arbitrarily drawing a straight line from the sharp break in slope where discharge begins to increase to a point where the recession limb begins to flatten out (Ward and Robinson 1990). A baseflow separation line was drawn between the two points for each hydrograph and used to define and subtract baseflow from each event (Figure 1).

For each selected storm event, the MET rainfall and discharge data was transferred from its raw format to a new excel file. A hydrograph and hyetograph were plotted for each event.

The hydrograph is a measure of discharge over time and begins at the slope break following the start of the rainfall event (A) and ends at an arbitrarily chosen point, usually the steepest break in slope, in the recession curve (B) (Ward and Robinson, 1990) (Figure 1). The hyetograph is a measure of rainfall over time and begins (C) and ends (D) when the hourly rainfall is zero for a minimum of four hours.

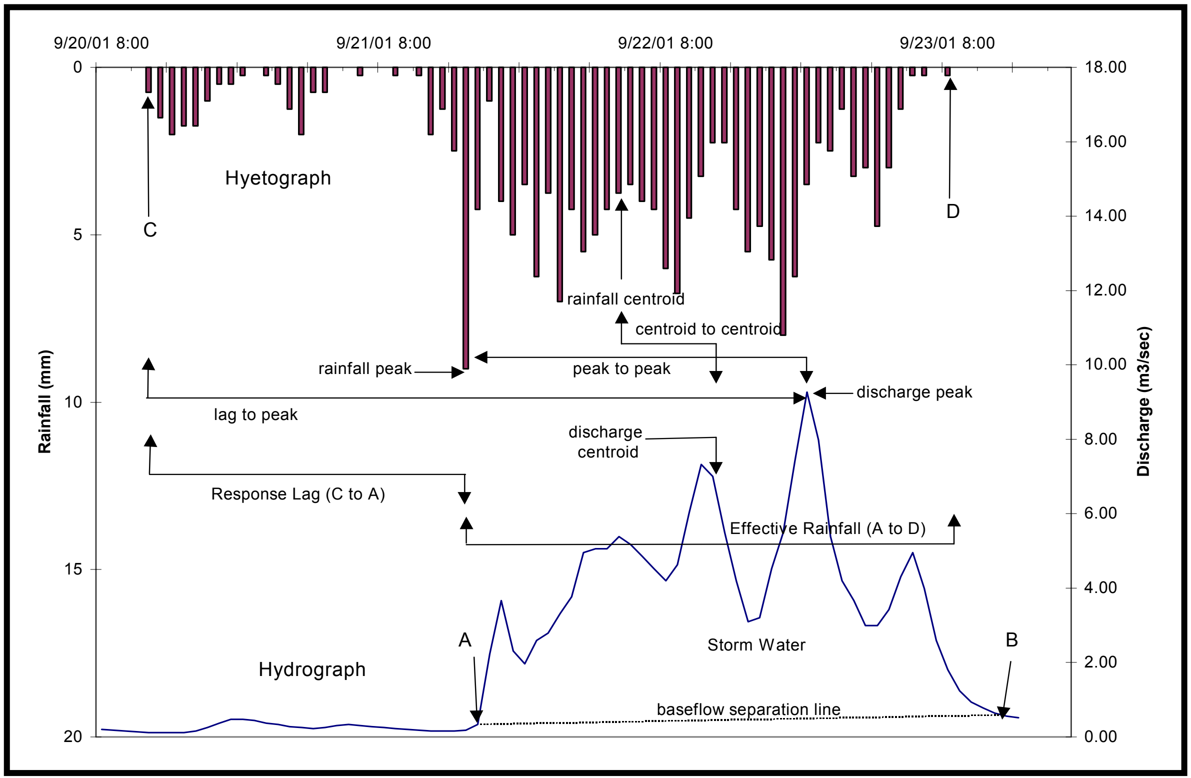

Figure 1. Example of the hydrograph and hyetograph that were plotted and defined for each storm event.

These graphs were used to visibly determine:
peak rainfall, the maximum hourly rainfall on the hyetograph, and,
peak discharge, the maximum instantaneous discharge on the hydrograph (Figure 1).

Storm event characteristics were compiled for all rainfall events greater than 40mm in each area. Approximately 60% of the events between 20mm and 40mm were selected for each site based on the following characteristics (where possible):

- An equal number of MET events from 20 to 30mm as from 30 to 40mm;
- A balance of MET events with a high previous 48 hour MET rainfall and low prior dry hours as those with a low previous 48 hour MET rainfall and high prior dry hours;
- MET events with complete data including average winter temperatures above 0 °C

A rainfall/runoff event was removed from the analysis process under the following circumstances:

- Hydrograph starts before hyetograph.
- Hydrograph starts after hyetograph ends.
- Rainfall centroid occurs AFTER runoff centroid.
- Hydrograph contained more than one equal peak.

4. Results and Discussion

4.1 Rainfall Intensity and Frequency

Rainfall on the north coast is frequent and can be of long duration and high intensity. During the 1998 to 2001 study period, the Cannery raingauge recorded 9664 mm of precipitation. The average monthly totals for the study period are provided in Table 1. The comparative totals reflect trends of the 30-year averages (Environment Canada 1998). The summer months of June and July were generally the driest, while the fall and winter months were generally the wettest. Rainfall events in excess of 40 mm's were recorded in all months except June.

Table 1 : Combined monthly rainfall totals for the North Pacific Cannery (Aug. 1998 - Nov. 2001).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec*	Total
3 yr. study period average	314	219	301	276	269	136	147	290	383	473	262	151	3221
30 yr. avg.	251	217	188	181	142	120	113	163	245	379	284	270	2553

* Data missing for periods in December 1999 and 2000, and January 1-11th, 2001.

A frequency distribution of rainfall events by size category, total rainfall and number of events during the monitoring period is provided in Table 2. The 1–39.9 mm events accounted for 58.4% of total precipitation and 92.5% of the rainfall events.

Table 2: North Pacific Cannery rainfall frequency distribution.

Event size (mm)	Total Rainfall (mm)	% of total	Total # of events
1.0-19.9	3087	31.9	583
20.0-39.9	2558	26.5	94
40.0-59.9	1186	12.3	24
60.0-79.9	995	10.3	15
80.0-99.9	459	4.7	5
100.0-119.9	621	6.4	6
120.0-139.9	245	2.5	2
140.0-159.9	310	3.2	2
160.0-179.9	0	0.0	0
180.0-199.9	0	0.0	0
200.0-219.9	230	2.1	1
Total	**9664**	**100**	**732**

Note: Data missing for the periods of December 1999 and 2000, and January 1 – 11th 2001.

A total of 210 ice-free events >20mm were selected for hydrograph separation. Table 1 shows the event totals by year (1999 to 2001) and by site Large Diana (LD), Upper Diana (UD) and Smith Island (SI).

Table 3. Number of ice-free events >20mm selected for hydrograph separation between 1999 and 2001 for three sites, LD, UD and Smith.

Year	Lower Diana (LD)	Upper Diana (UD)	Smith Island (LS)	**Year Totals**
1999	32	34	26	**92**
2000	26	12	27	**65**
2001	19	14	20	**53**
Site Totals	**77**	**60**	**73**	***210***

A total of 59 winter events were selected for hydrograph separation. Table 2 provides these event totals by year (1999 to 2001) and by site LD, UD and SI.

Table 4. Number of winter events >20mm selected for hydrograph separation between 1999 and 2001 for three sites, LD, UD and LS.

Year	Lower Diana (LD)	Upper Diana (UD)	Smith Island (LS)	**Year Totals**
1999	7	6	4	**17**
2000	2	1	7	**10**
2001	11	11	10	**32**
Site Totals	**20**	**18**	**21**	***59***

4.2 Hydrologic Response

Hydrologic response was highly variable, and dependent on antecedent soil moisture conditions (Table 5). Large rainfall events following a wet period produced the highest response. Small rainfall events following a dry period produced the lowest response. Large events following a dry period and small events following a wet period were intermediate. The largest response following wet conditions when the available soil moisture storage capacity in the watersheds had been depleted. The hydrologic responses for the Smith and Diana watersheds were similar to a coastal watershed near Barrow Alaska. In Barrow, the hydrologic response varied from 0.01 for dry conditions to 0.63 following wet antecedent conditions (Dingman 2002).

Table 5: Hydrologic response following rainfall events.

Location	**Hydrologic Response**	**Lag Time (hrs)**
Smith	0.05 – 0.86	1 – 15
Upper Diana	0.04 – 0.81	1 – 13
Lower Diana	0.03 – 0.54	1 – 19

Total discharge per rainfall event was plotted for each watershed. The data for Smith Island, Upper and Lower Diana respectively are presented in Figure's 2, 3 and 4. The scatter for any particular rainfall event is due to storm length, canopy condition, antecedent soil moisture, and time of year. For example, in Figure 2, the summertime range of 5mm to 25 mm for discharge for a 65 mm rainfall event was due to canopy dryness, soil moisture content, water table height, storm duration and intensity. Conversely, point "A" in Figure 3, a 100 mm discharge response to a 70 mm rainfall event resulted from a winter time rain-on-snow event. Point "B" in Figure 4, a 20 mm response to a 115 mm rainfall event resulted from a Fall event where rainfall occurred at low elevation and snow occurred higher up.

Although the north coast has a distinct wet and dry season, no seasonal or obvious difference in magnitude of runoff response to rainfall events was apparent. Large rainfall events can occur in any season (Figure's 2, 3 and 4). Consequently, runoff response to large rainfall events was similar for all seasons. The only obvious difference occurred for a rain on snow events.

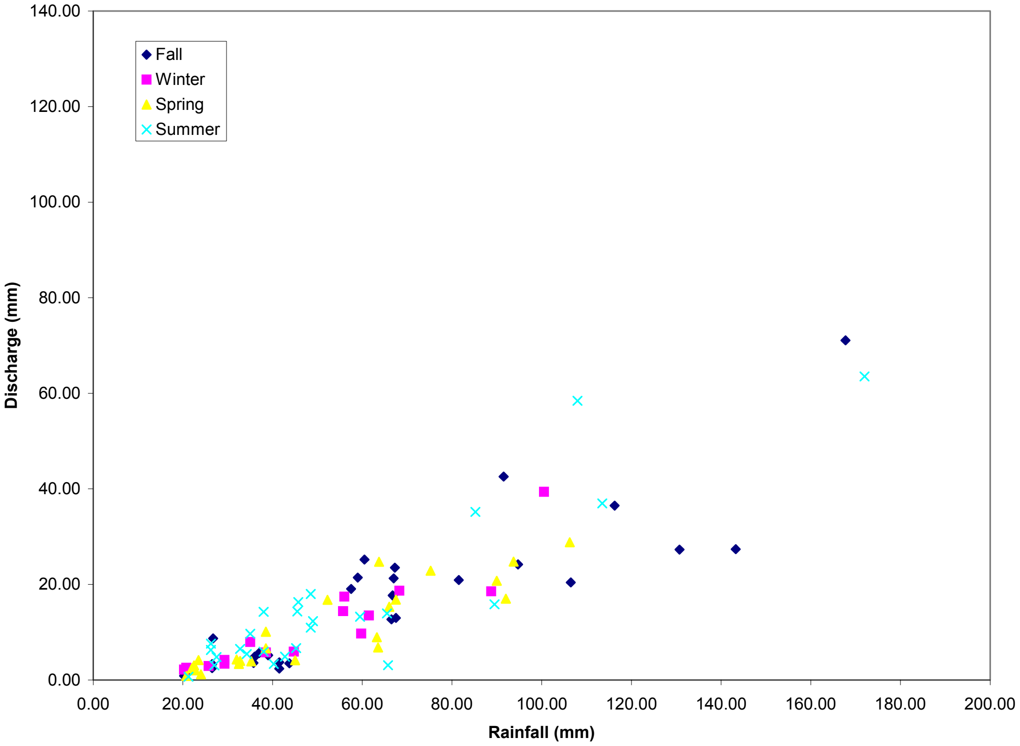

Figure 2: Smith Island. Total discharge per rainfall event by season. Best-fit line is, y=0.3698x-7.1831, $r^2 = 0.7752$.

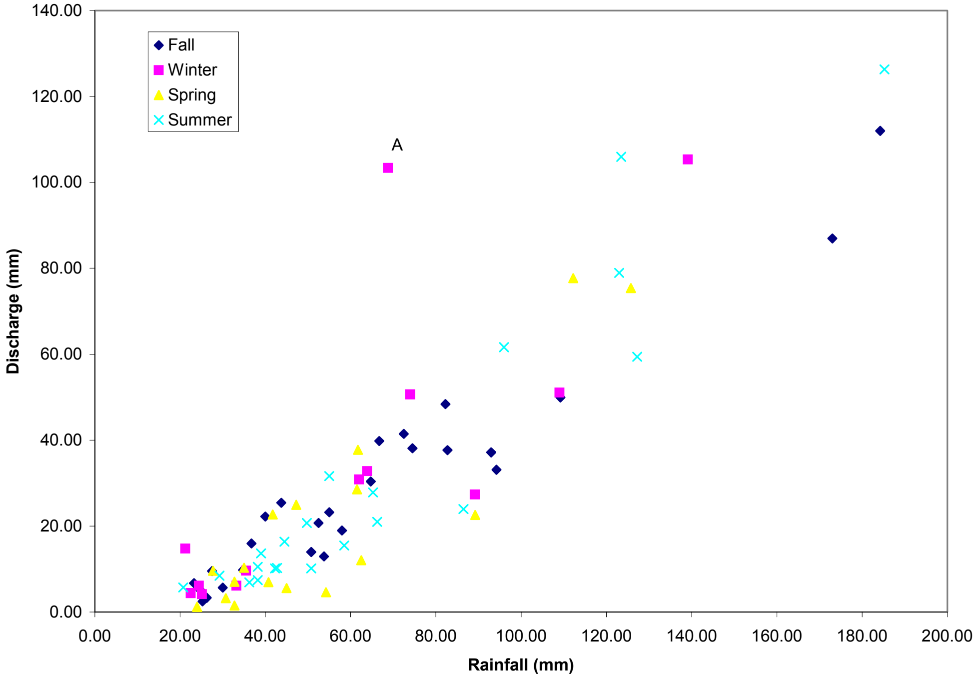

Figure 3: Upper Diana. Total discharge per rainfall event by season. Best-fit line is, y=0.6893x-14.183, $r^2 = 0.8002$.

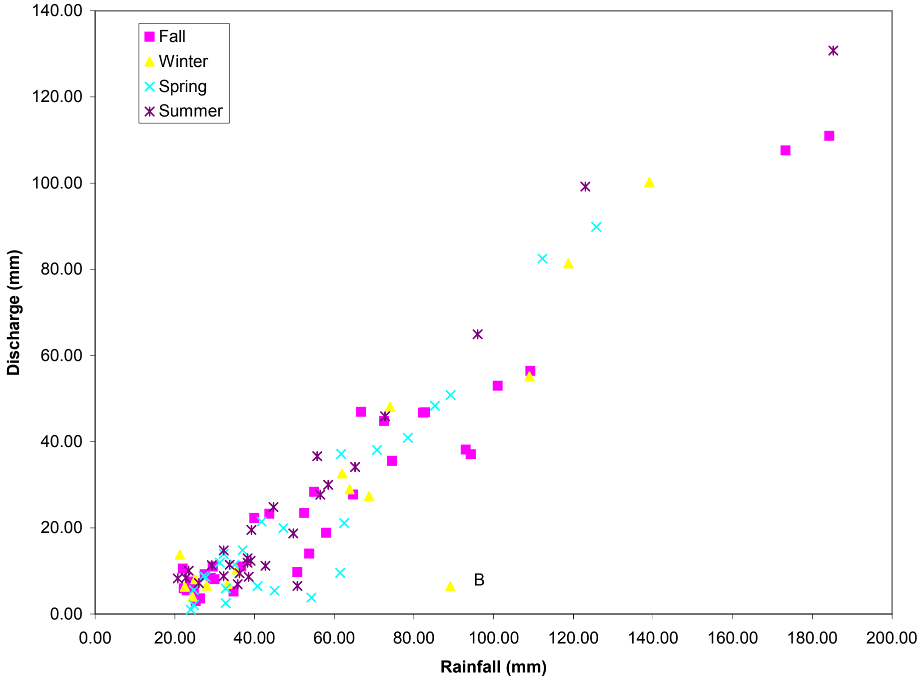

Figure 4: Lower Diana. Total discharge per rainfall event by season.. Best-fit line is, y=0.7311x-9.7004, $r^2 = 0.8914$.

The magnitude of the hydrologic response is due to the geology, slope and soils of the watershed than land use (Hewlett 1982). On the north coast, the thin soils combined with high rainfall resulted in little available soil moisture storage capacity. The reduced soil water storage capacity especially in the riparian zone meant most rainfall was channeled downslope via shallow soil matrix flow, soil pipes, seeps or channels. Overall, the data suggest the thin soil, geology and antecedent soil moisture conditions all contribute to the rapid hydrologic responses (Dingman 2002).

No significant trends were found between rainfall event size and response time (rainfall centroid to discharge centroid) using standard methods (Figure 5). In all watersheds, increased discharge began within 1 – 19 hours of rainfall initiation (Table 5, Figure 6). The only observable difference was that response lag times were slightly delayed following dry periods compared to wet periods. The relationship between variable lag times and antecedent moisture conditions can be explained by the variable source area concept put forward by Hewlett in 1960 (Hewlett 1982).

Typical hydrograph response to a rainfall event is evident in Figure 6. The rainfall event began at 1400 hours on September 27th, 2000 and ended at 0900 on September 30th. Total rainfall for the event was 109.25 mm. The rainfall event followed a 5-day dry period.

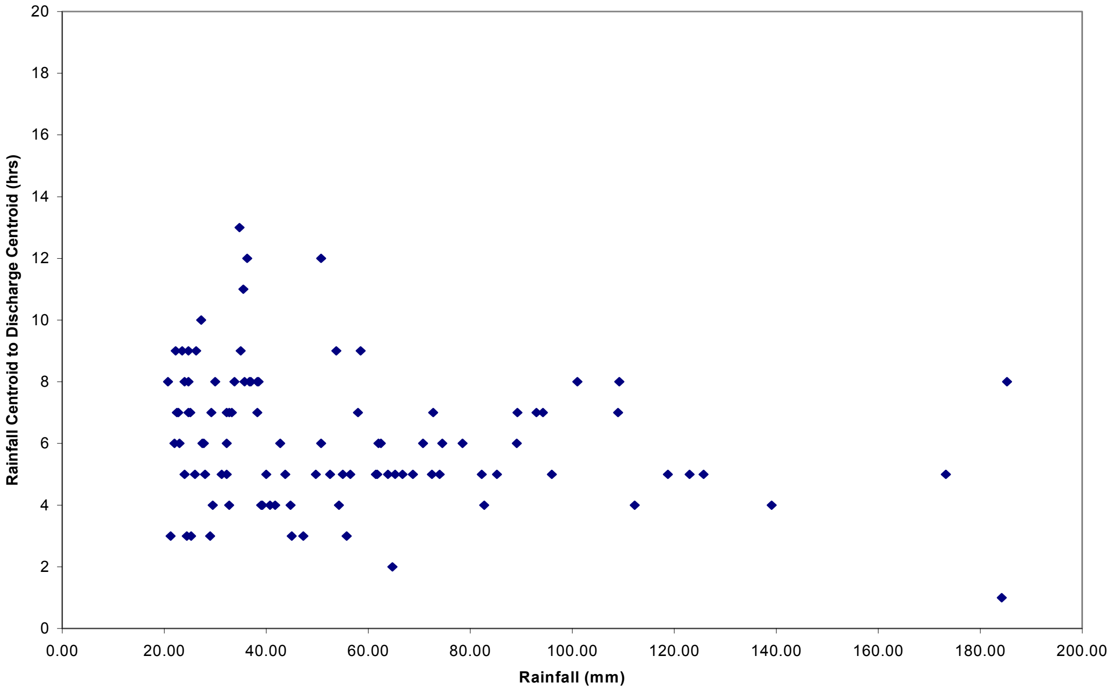

Figure 5: Lower Diana watershed, time difference between centroid of rainfall and centroid of discharge compared to rainfall event size.

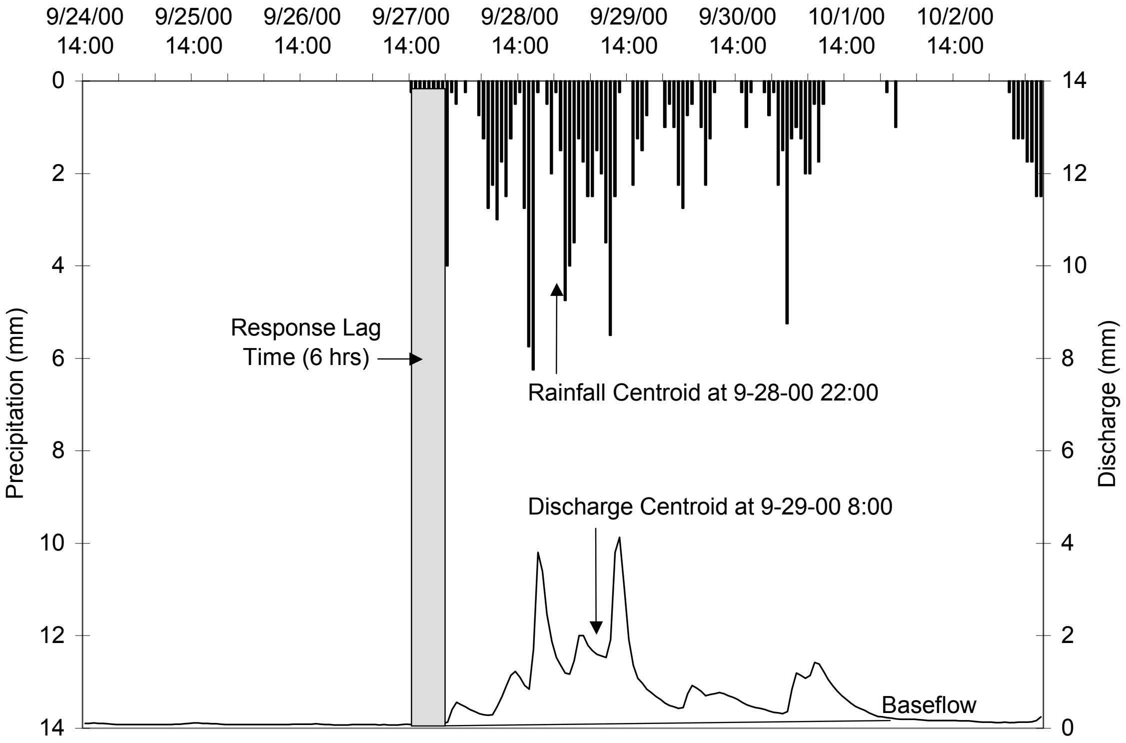

Figure 6: Upper Diana hydrograph response to a large rainfall event beginning on Sept. 27, 2000.

The data illustrates a typical long duration, multi-peaked, moderate to high intensity rainfall event that is common for the north coast. The hydrograph response was rapid. The time from the beginning of rainfall to the initial rise in the hydrograph (response lag) is 6 hours (shaded area in Figure 6). The time from the initiation of rainfall to the peak discharge (highest peak) was 48 hours, while the time from the rainfall centroid to the discharge centroid time was 10 hours. However, these are misleading as the hydrograph does not have a single peak and the rainfall event had a duration of 68 hours. The hydrograph response also mirrored the change in rainfall intensity. Peaks in rainfall had matching peaks in discharge.

The multi-peaked shape of the hydrograph was due to the watershed's small size. Small watersheds, typically <50 km^2 have a hydrograph that is controlled by the hillslope/channel bank response mechanisms compared to larger watersheds where the hydrograph is controlled by channel-hydraulic effects through the stream network (Dingman 2002). The rapid response time of the hydrograph to rainfall and the high hydrologic response result from the large saturated source area adjacent to the stream channel (riparian area). The saturated area is maintained by frequent rainfall events. During a rainfall event, the initial rapid rise in the hydrograph was due to the direct input of rainfall into the channel. However, within several minutes, the saturated area alongside of the channel (source area) expanded and began to contribute water into the channel by the displacement of old water in the channel banks and seeps. New water was also added by direct flow from pipes, overland flow if the local water table rose to the ground surface, and lateral matrix throughflow occurs through expanding channel banks (Hewlett 1982, and Ward and Robinson 1990).

During a dry period the saturated source area adjacent to the stream channel shrinks, and the watertable drops. Subsequent rainfall events respond more slowly as additional rain water is required to recharge the water table and raise it to the surface. As a result, there is an increase in the response lag time and a decrease in hydrologic response (Hewlett 1982, and Ward and Robinson 1990).

The rapid watershed response to rainfall events indicates a saturated riparian area and hillslopes that are well connected to the stream channels. This connection is most likely by soil pipes, preferred pathways (seeps) along the organic/mineral soil interface and to a much lesser extent by lateral flow through the soil matrix. The importance of soil pipes in transporting water downslope has been well recorded (Uchida 2001). The lateral flow of water through the soil matrix for several coast BC watersheds has been found to vary from 0.16 m/day (Beaudry and Sagar 1995) to 8.64 m/day (Hutchinson and Moore 2000). Due to these low rates, soil matrix flow is not a rapid means of transporting water downslope.

A comparison of watershed runoff per unit area is provided in Figure 7. Lower Diana recorded the greatest amount of runoff per unit area. Upper Diana was least while. Smith Island was intermediate. The magnitude of runoff was most likely controlled by watershed site conditions. Large Diana ranged in elevation from 72 m to 700 m and had a mean channel gradient of 28%. As the watershed was backed by mountainous terrain, soil cover was thin. In addition, only 56% of the watershed was forested. The remaining 44% was swamp forest and open bog. By comparison, Upper Diana ranged in elevation from 85 m to 370 m, had a mean channel gradient of 33%. However, 71% of the watershed was forested. The remaining 29% was open bog. Smith Island ranged in elevation from sea level to 360 m and had a mean channel gradient of 33%. It was similar to Smith Island in that it was 72% forest. The remaining 28% was open bog.

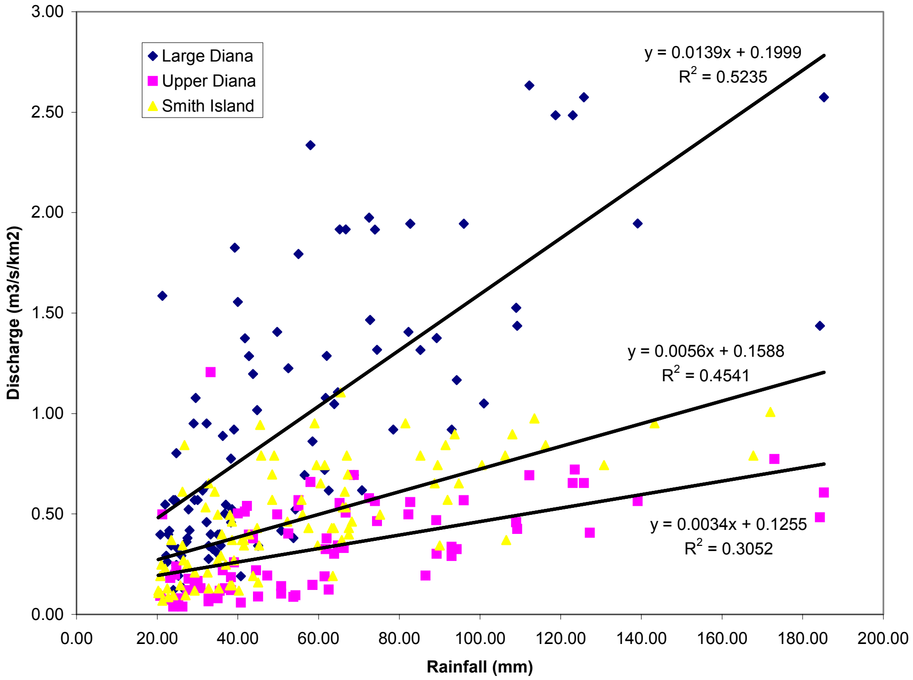

Figure 7: Discharge per unit area for all three watersheds.

Management Implications

North coast sites receive in excess of 2500 mm of rainfall per year. Local soils are frequently saturated and are prone to erosion/damage. Watershed drainage is rapid which suggests an organized drainage network. Runoff source areas are principally riparian areas and tributary channels. Secondary sources are upslope seeps and soil pipes. Damage to either source can result in water being held on a slope and promoting soil saturation, slope failure, or redirection. The result of either alteration will result in site erosion, stream capture/piracy, increased peakflows, decreased water quality due to increased sedimentation and channel erosion.

Riparian harvesting will decrease forest canopy interception and increase soil saturation. The result will be higher water tables, faster runoff and increased peak flows. The magnitude of each will depend on the amount of harvesting, road and drainage ditch construction.

Approximately 42% of annual rainfall at the Cannery site arrives in events larger than 40mm meaning rainfall events that produce a large hydrologic response are frequent. This has important implications for harvesting, road, and drainage structure construction since the current precipitation shutdown guidelines allow for up to 40 mm of storage capacity. Precipitation-based operational shutdown guidelines are currently in the process of being reviewed for the north coast (AGRA 1996; Price 2002). These new guidelines will (should) take into account the influence of both the limited water storage capacity and orographic rainfall in the mountainous watersheds of the region.

Conclusions

North coast watersheds receive frequent rainfall events. Large rainfall events can occur in any season. Approximately 90% of all events were <40 mm. These events accounted for >58% of total rainfall during the 1999 to 2001 study period. Hydrologic response for the events ranged from 0.03 to 0.86. Lag response varied from 1 to 19 hours. The timing was variable and depended on the sites antecedent moisture condition. The source areas for the hydrologic response appear to be the channels riparian zones. Geology, slope, soil and forest type determined the magnitude of watershed response.

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