Reconstructing the historical stream flow from stream morphology in Duck Mountain, Manitoba

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Abstract: Stream flow data have been collected in the Prairie Provinces for nearly 100 years. However, records are incomplete in some regions as a result of budgetary and voluntary cuts. One such region is Duck Mountain, Manitoba. The hydrology of this upland is critical to its surrounding area because it houses headwaters for a large number of local streams. For a number of these streams, channel features such as width, depth, slope and bed material were measured. Using Manning's equation these data were analyzed to reconstruct bank and scour flows. Flow records for these streams were used to help establish inter-annual variability and trends. Flood frequency graphs were created to assist flow predictions and to augment records. The purpose is to create a regional analysis that can help define natural conditions. Since commencement of water data collection in the region there has been increased human development. This paper discusses the methodology as well as some results of the research.

Key words: flood frequencies, stream morphology, flow probabilities, Manning's equation, reconstructing streamflow, Duck Mountain

Introduction

Channel width, depth, slope and scour are a direct result of previous stream flows. Leopold and Maddock (1953) recognized that as discharge changes, the channel adjusts to accommodate the flow by changing morphology. In the Prairies, snowmelt events have particular influences on stream dynamics and channel morphology (Newbury and Gaboury 1993). The proposed research uses channel features along with flow records to reconstruct historical flow. By interpreting regional stream channel dynamics and regional hydrologic records, the natural hydrology for the associated area can be reconstructed (Thorne 1998).

As suggested by Thorne (1998), stream morphology can be used to augment flow records and can provide more accurate analysis. By combining flow records and stream morphology researchers can predict trends (Yang and Stall 1973). Predicting outputs from watersheds enables the simulation of impacts of land use and climate change on water resources.

Human activities such as engineering, agriculture and forestry have altered the natural state of lands and rivers. In the Prairies, parks and parkland make up most of the area having minimal human impact. The hydrology of Duck Mountain, Manitoba is significantly different from but very important to the surrounding plains. Because of flooding and wet conditions in Duck Mountain, local populations and water managers divert streams and drain much of the land. Agricultural producers are pressuring local authorities to divert and dam natural streams to better suit their needs (Whitney *et al*. 1988). At the same time on the upland, the forest industry may be altering natural watersheds.

There has been an increasing concern about the effects of possible global warming on stream flow (Dvorak *et al*. 1997; Boorman and Sefton 1997; Whitfield and Cannon 2000). Nemec and Schaake (1982) noted that climate change would make it even more difficult to predict future flows when designing water resource structures. Yulianti and Burn (1998) investigated climatic change impacts on stream flow conditions in the Canadian Prairies and noted that flow decreased as temperature increased. Muzik (2001) concluded that there is a high probability of increased frequency and magnitude of storm events. In Britain, Arnell (1996) studied the impacts of warming trends on river flows and water demands concluding that demand would probably exceed supply. Such effects could dramatically affect water management projects in the Duck Mountain region.

Objective

The objective of this research is to determine the natural stream flow characteristics and to reconstruct the magnitude and frequency of historical floods in the Duck Mountain region based on historical data and field measurements. With the reconstruction of natural stream flow, impacts from forest harvesting, agriculture and climate change can be assessed. The goal is to contribute to the development of practices and strategies for water resource managers that account for the natural variation in geomorphic and hydrologic systems.

Study Area

The Manitoba Escarpment, which separates the Saskatchewan Plains from the Manitoba Plains, has four distinct physiographic units: Pembina Hills, Riding Mountain, Duck Mountain and Porcupine Hills. This research concentrates on the Duck Mountain region. Duck Mountain has steep slope gradients on the north and east sides, whereas the south and west sides have gradual slopes. Total relief is approximately 500 m. The top of the escarpment is topped by glacial drift, which can reach 300 m in thickness (Chapman 1987).

Because the surficial geology consists of glacial till there are high infiltration rates. The storage capacity of the hilly topography is evident in the numerous bogs and springs throughout the upland region (Whitney *et al.* 1988). Duck Mountain is strewn with numerous lakes and streams, is completely forested and considered part of the Boreal Plains Ecoregion. The escarpment is located within the humid continental climate zone with generally less than 60 cm of precipitation per year, of which one-third is winter snowfall (Chapman 1987). It was not until the completion of the Canadian National Railway to Swan River in 1899 that settlement occurred and soon after agricultural and forestry activities began (Manitoba Natural Resources 1997).

Methodology

Data used in the analysis include digital maps of topography, soils, surficial geology, and forest cover. Environment Canada has supplied hydrometric data dating back to the early 1900s for numerous stations in and around Duck Mountain. A digital elevation model (DEM) was used to determine slopes, elevations and drainage basin areas. Field data were included such as stream slope, depth, width, velocity and channel shape. As well, bedload size was measured to reconstruct scour and bankfull flows.

Before any field data were collected, mean annual, mean monthly and maximum monthly hydrographs were constructed for each gauged river using data from Environment Canada (Environment Canada 1996). Figure 1, shows the mean annual hydrograph for Swan River indicating wet and dry periods and extreme years. Figure 2, shows the mean and maximum monthly hydrograph for North Duck River indicating the magnitude and length of spring runoff.

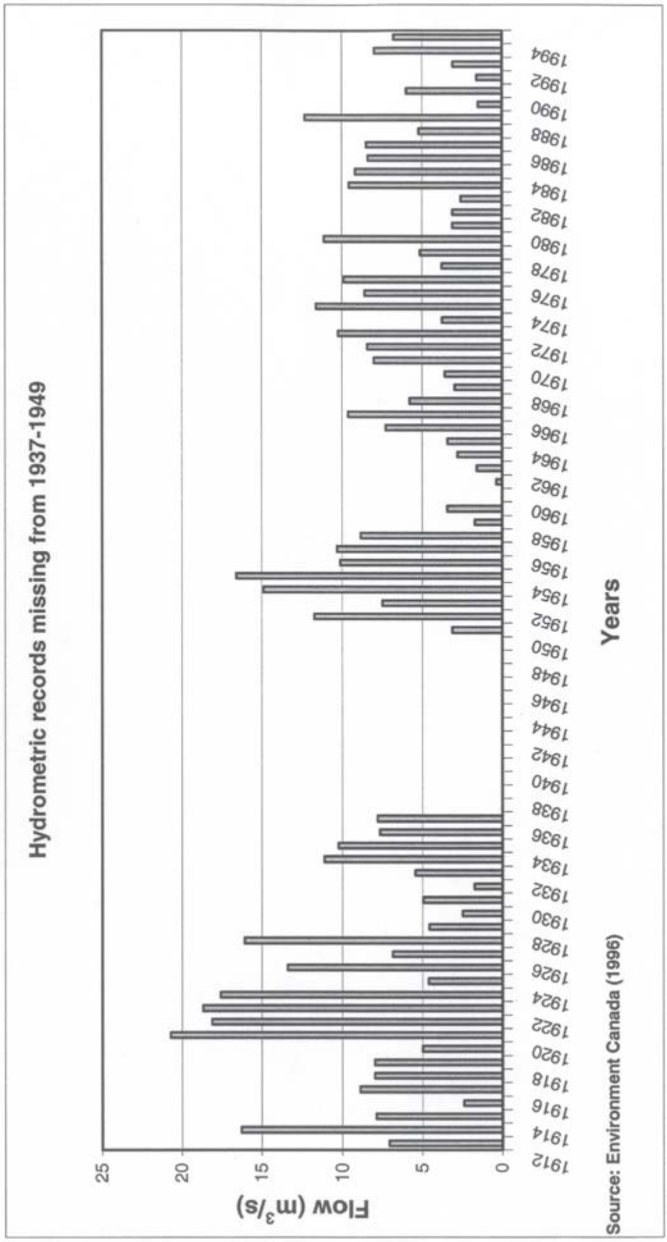

Figure 1: *Mean annual flow hydrograph for Swan River at Swan River, Manitoba, 1912-1994.*

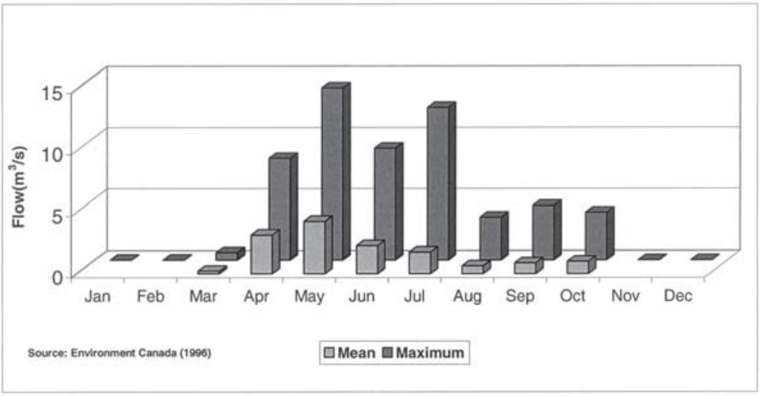

Figure 2: *Mean monthly flow hydrograph for North Duck River at Cowan, Manitoba (05LG004).*

Reference sites were located for each stream according to the following criteria (Harrelson *et al.* 1994): 1) what do we want to know about the stream or drainage; 2) what geographic variations (geology, elevation, land use) exist in the area; 3) what is the most useful comparison with the fewest sites; 4) how can this site contribute in determining natural hydrologic conditions; and, 5) how much can be accomplished with present resources? Reference site selection also depended on the size of the stream, accessibility, stability and hydraulic conditions (Herschy 1985). Sites were ruled out if there seemed to be disturbances from humans and wildlife. To maximize reliability of these sample sites, the reach lengths were set at 100 m to include an entire meander with hydraulic evidence sufficient to accurately characterize the streams (Herschy 1985). In all 12 streams were selected and a total of 42 reference sites were established. The cross-sections were then located where the best evidence exists for the channel boundaries. The procedures and techniques for surveying stream cross-sections are common (Herschy 1985; Harrelson *et al*. 1994; Thorne *et al.* 1996; Thorne 1998). The field manual compiled by Newbury and Gaboury (1993) was followed.

Cross-sections representative of the stream reaches and channels were created for all research streams. On larger streams, Environment Canada has predetermined reference sites and gauging stations. Wherever possible these predetermined reference sites were used in the analysis. Figure 3, shows the cross-sections for Roaring River. Cross-sections were surveyed using a stadia rod and automatic level. Special attention was paid to

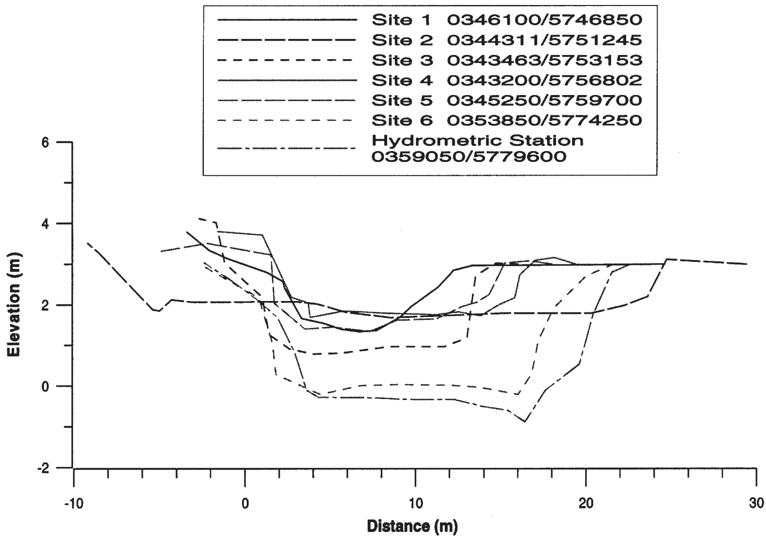

Figure 3: *Cross sections at reference sites and hydrometric station on Roaring River, Manitoba.*

determining banks and locating scour marks. Cross-sections were then overlain to compare channel shape and symmetry among reaches.

At each reference site depth, width, velocity, discharge, slope and bed load were measured. Depth and width were measured using a measuring tape, stadia and automatic level. To determine discharge, a *Price 1210 AA* flow meter was used to measure velocity. Velocity was measured at 6/10^{ths} the depth across the stream in a number of equally sized increments based on uniform bed conditions. Discharge (Q = VA) was determined for each reference site by summing the unit discharges across the stream (Newbury and Gaboury 1993).

Slope was determined using the automatic level and stadia. Measurements were taken at the water's surface from pool to pool or riffle to riffle. Where possible the measurements included at least two complete meanders in order to get a true reading of the slope. In some cases two to three slope measurements were averaged in order to determine true slope in short river bends.

Bedload was sampled and measured by wading through the channel and selecting clasts at random intervals (Newbury and Gaboury 1993). Each sample consisted of thirty clasts of various sizes and shapes. For

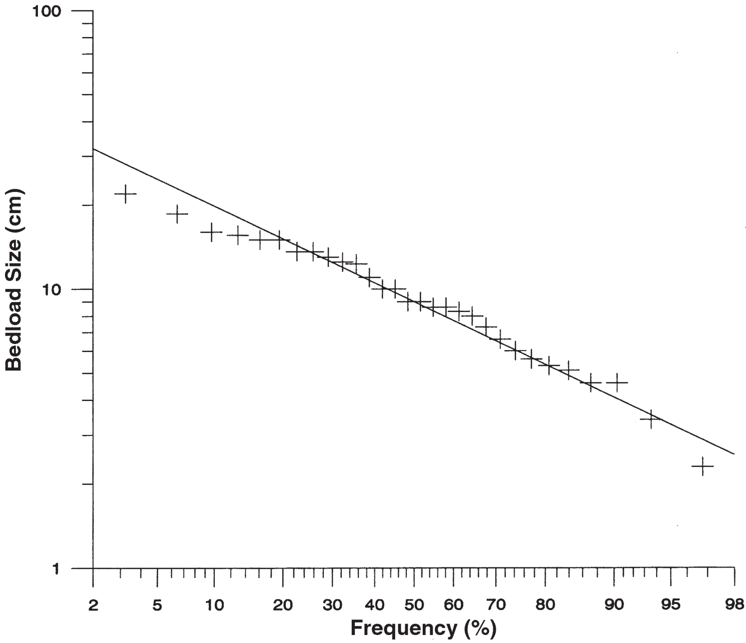

Figure 4: *Bedload frequencies of Site 1 for Fishing River, Manitoba (0391850/ 5700010).*

each sample the tri-axial mean was calculated. Figure 4 shows the frequency distribution of bed material at one site on the Fishing River. Bed materials smaller than certain sizes are moved and deposited during channel maintenance flow or bankfull flows (Hickin 1995; Baker 1973; Newbury and Gaboury 1993).

Bank flow discharge was then estimated using Manning's equation (Herschy 1985; Newbury and Gaboury 1993; Harrelson *et al.* 1994; Newson 1994; Petts and Amoros 1996):

$$v = \frac{R^{2/3} s^{1/2}}{n}$$

$$R = A / p$$

v = mean velocity
R = hydraulic radius of flow
s = average reach slope
n = Manning's roughness factor
A = cross-sectional area of flow
p = wetted perimeter of flow

When applying Manning's equation a channel resistance or roughness factor 'n' must be determined. This resistance factor can be directly related to bedload size using the empirical relationship derived by Strickler in 1923 (Newbury and Gaboury 1993). When the depth of flow is three or more times greater than median size of the bed material:

$$n = 0.04 \times d_{50}^{1/6}$$

n = Manning's roughness factor
d_{50} = median bed paving material size

Bank flow discharge 'Q_b' and scour discharge 'Q_s' can then be calculated from the estimated bank flow velocity and cross-sectional area (Q = VA). Annual flood frequency graphs were created for each stream by ranking the highest flows and assigning frequencies. The magnitude and frequency were graphed to indicate probabilities. The flood frequency for Shell River, Figure 5, includes the bankfull and scour discharges calculated using Manning's equation.

Results

The mean annual hydrographs show extended wet and dry periods and extreme years of the past century. The mean monthly hydrographs provide response times and duration of spring runoff while the maximum values give an indication on the magnitude of runoff events. As noted, this region receives a moderate amount of snow but the temperatures usually do not increase to above freezing until mid to late April. As shown in the monthly hydrograph in Figure 2, the runoff response begins in April and in most cases continues until June. By analyzing the maximum monthly flow values the severity of spring events can be compared to those of summer months.

The cross-sections created indicate the symmetry of the channels within each reach and can indicate deviations from the overall channel shape. This can signify stress on the system as well as possible alterations by humans or wildlife. In Figure 3 the cross-section at Site 2 for the Roaring River differs from the other surveyed channel shapes. Site 2 is near a farmhouse the occupants of which may have altered the channel.

From the bedload plots one can determine the frequencies of bed paving material and estimate the size of material moved during channel maintenance flow. From the constructed bedload frequency graphs materials within the 50% to 70% frequencies corresponds to material being

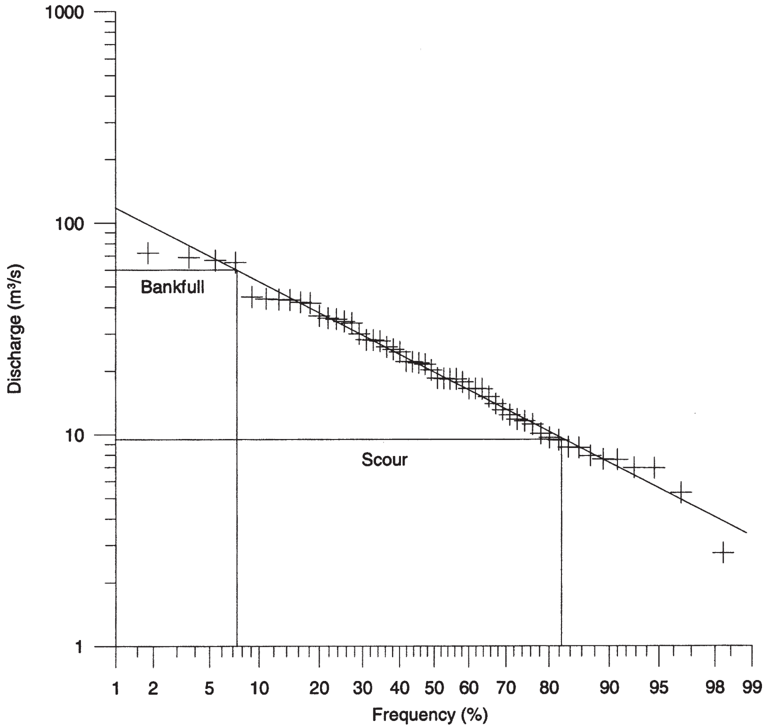

Figure 5: *Annual flood frequency of Shell River at Asessippi/Inglis, Manitoba (05MD001/05MD005).*

moved during bankfull flow. Figure 4, indicates that these frequencies correspond to mean bedload sizes ranging from 6 to 8 cm.

Using Manning's equation, the bank flow and scour discharges for Shell River were 60.4 m^3/s and 9.42 m^3/s, corresponding to approximately 7% and 82% of historical flows. The bank and scour discharges indicate the historical magnitude of floods in the Duck Mountain region. Table 1 shows the calculated bankfull and scour discharges for all of the reaches studied. The undetermined values for the scour discharges were the result of absent or conflicting scour marks within the channel. Where possible the scour and flood values were graphed with the flood frequencies to help determine associated probabilities.

Table 1: *Hydrometric variables and calculated bank and scour flow values.*

					Scour					Bank		
Stream	**Location**	**Site**	**w (m)**	**d (m)**	**A (m^2)**	**V (m/s)**	**D (m^3/s)**	**w (m)**	**d (m)**	**A (m^2)**	**V (m/s)**	**D (m^3/s)**
Pine River	0375200/5739750	1			undetermined			12.10	1.02	12.34	2.64	32.58
	0379250/5740300	2			undetermined			21.93	0.89	19.41	3.78	73.37
	0381850/5739600	3			undetermined			21.39	1.22	26.10	3.60	93.96
	0384950/5738990	4			undetermined			21.29	1.58	33.52	4.51	151.18
	0389350/5739600	5			undetermined			20.37	1.64	33.30	1.60	53.28
	0392300/5740100	6	13.70	0.63	8.63	1.50	12.95	20.01	1.10	21.91	2.17	47.54
Site # 05LG001	0394350/5742100	7			undetermined			15.00	1.50	22.49	0.91	20.46
Roaring River	0346100/5746850	1	9.70	0.95	9.22	2.98	27.50	17.20	1.12	19.18	3.32	63.60
	0344311/5751245	2			undetermined			23.80	1.56	37.13	4.42	164.10
	0343463/5753153	3			undetermined			14.30	1.91	27.31	2.68	73.19
	0343200/5756802	4			undetermined			15.40	1.55	23.87	2.25	53.71
	0345250/5759700	5			undetermined			15.03	1.43	21.42	1.90	40.59
	0353850/5774250	6	15.00	1.07	16.05	4.68	75.11	21.95	2.52	55.20	6.07	335.06
Site # 05LE005	0359050/5779600	7	16.50	1.12	18.48	0.75	13.86	22.00	1.72	37.85	0.99	37.47
Ruby Creek	0335500/5744200	1	5.50	0.39	2.17	3.18	6.90	8.25	0.60	4.97	4.22	20.96
	0335650/5744600	2	4.10	0.52	2.13	1.16	2.47	8.30	0.71	5.92	1.43	8.46
	0334300/5747450	3	4.20	0.16	0.66	1.89	1.24	10.02	0.63	6.31	4.78	30.16
	0340100/5753500	4	7.30	1.03	7.52	0.41	3.08	9.70	1.14	11.06	0.44	4.87
	0343250/5760000	5	6.70	0.59	3.95	0.49	1.94	16.23	1.64	26.62	0.96	25.56
East Favel River	0362971/5758525	1	7.20	0.47	3.38	3.32	11.22	10.81	0.76	8.22	4.58	37.65
	0360950/5765650	2	7.90	0.70	5.54	1.17	6.48	13.63	1.17	15.88	1.65	26.20
	0359500/5773650	3	9.20	0.93	8.52	1.79	15.25	13.93	1.89	26.33	2.88	75.83
West Favel River	0359950/5758450	1	11.30	0.69	7.74	3.47	26.86	20.28	1.35	27.28	5.43	148.13
	0357350/5763950	2	11.60	1.03	11.95	3.07	36.93	17.36	1.20	19.83	3.42	67.88
	0358400/5775800	3	9.20	0.96	8.83	1.82	16.07	15.04	2.11	31.73	3.08	97.73
Favel River	0360600/5781500	1	11.20	1.13	12.66	1.32	16.83	13.23	2.48	32.80	2.29	75.11
Fishing River	0391850/5700010	1	3.10	0.26	0.82	2.87	2.34	12.52	1.15	14.40	5.62	80.93
	0393550/5797150	2	4.50	0.26	1.17	1.28	1.50	18.75	0.67	12.62	3.38	42.66
	0401750/5701950	3	5.60	0.69	3.84	2.02	7.76	9.95	0.84	8.36	6.22	51.99
	0404950/5702550	4	4.60	0.60	2.77	0.87	2.37	15.50	0.79	12.20	2.66	32.45
Sclater River	0381200/5753700	1	10.20	0.69	7.04	4.60	32.38	16.11	1.22	19.57	6.71	131.31
	0389850/5755050	2	10.00	0.92	9.16	2.39	21.90	14.41	1.49	21.47	3.31	71.07
	0385700/5755000	3	7.70	0.74	5.67	1.98	11.23	12.62	1.06	13.31	2.52	33.54
North Duck River	0377940/5764290	1	16.80	1.27	21.25	3.85	81.80	18.65	1.48	27.51	4.27	117.47
	0384050/5764300	2			undetermined			20.77	1.41	29.29	2.87	84.06
Site # 05LG004	0386850/5765670	3	16.30	0.99	16.17	0.52	8.40	18.60	1.44	26.78	0.67	17.95
Garland River	0386800/5724250	1	5.70	0.47	2.70	2.02	5.45	24.80	1.60	39.68	3.88	153.96
	0391000/5724970	2	5.10	0.57	2.93	2.10	6.15	13.10	1.49	19.52	3.97	77.49
	0393990/5725250	3	6.80	0.70	4.77	1.05	5.01	8.85	1.51	13.36	1.75	23.38
Valley River	0360763/5685330	1	20.50	0.81	16.56	1.48	24.51	23.00	1.02	23.40	1.73	40.56
	0360368/5681458	2	14.20	0.82	11.60	3.67	42.57	23.20	1.44	33.40	5.35	178.69
	0370800/5672500	3	12.10	0.69	8.32	2.90	24.13	23.30	0.76	17.70	3.10	54.87
Fork River	0388210/5710750	1	7.10	0.54	3.83	3.26	12.49	12.52	1.15	14.40	5.62	80.93
	0391010/5710700	2	5.80	0.41	2.36	2.42	5.71	18.75	0.67	12.62	3.38	42.66
Shell River	0337280/5648090	1	15.00	0.44	6.54	1.44	9.42	27.00	0.94	25.27	2.39	60.40
South Duck River	0391200/5749850	1	5.70	0.52	2.96	1.14	3.37	8.89	1.22	10.85	2.01	21.80

Summary

The goal of this research was to determine the frequency and significance of previous floods in Duck Mountain. Data on the cross-sectional geometry of stream channels, and the distribution of flood deposits enable the reconstruction of peak stream flows, thus augmenting the existing hydrometric records. The results can be used to predict thresholds associated with future runoff and storm events. Combining geomorphological reconnaissance with historical records provides the best route in understanding and predicting natural streams (Thorne 1998).

The research design suggests that a program of long-term monitoring of runoff be developed in close consultation with forestry, agriculture and water authorities such that they will inherit the program by using the established reference sites and the sampling protocols to analyze ongoing human effects on the hydrology of these regions. Long-term hydrometrical and morphological monitoring represents the best way to understand fluvial systems and study reaches (Downs and Thorne 1996).

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