Context of Extreme Alberta Floods

Introduction

Design of water management and stream crossing infrastructure requires determination of hydrotechnical design parameters. These parameters often consist of highwater level, mean channel velocity, peak flow, and runoff volume. In order to use parameters for design, some context on their significance is required. This context should account for physical factors and historic observations for a specific site, but also provide an ability to design to a consistent level across all sites in the infrastructure system.

Techniques that are commonly applied in the hydrotechnical design of stream crossing and water management infrastructure include flow frequency analysis and hydrologic modeling. Results are generally associated with a return period (e.g. 1:100 year flood), that is intended to provide consistency among designs for all sites and provide an indication of the severity or magnitude of the design parameters. However, due to issues with these techniques, results can vary greatly and are sometimes not consistent with the physical nature of the design site.

Observation and analysis of available hydrologic data-sets for Alberta suggest that there is a typical large runoff response that can be identified and used for design purposes. These observations include :

- analysis of rainfall data shows similarity between the storms that have resulted in the largest historic floods
- analysis of runoff data shows that envelope curves of peak flow and runoff volume for certain areas have a similar runoff response over the range of observed storm events
- analysis of the runoff response at gauging sites with long records show similarity in the highest runoff response at each site.
- analysis of observed highwater data relative to physical channel parameters shows similarity between runoff response at a wide range of sites

These observations have been used to develop hydrotechnical design guidelines[5] that result in parameters that can be considered equivalent to the largest historic event at a given site. No precise return period can be assigned to these parameters and it is still possible for larger events to occur. However, design parameters based on these guidelines should meet the goals of accounting for site physical parameters and historic observations, as well as providing a consistent level of design across the system.

Issues with Return Period Based Techniques

In the first part of the 1900's, stream crossing infrastructure was generally designed based on observed highwater marks and assumed flood conveyance based on observed channel properties. These techniques provided some physical and historic context for the selected design parameters at a given site. However, it was difficult to know if infrastructure was being designed in a consistent manner on a system wide basis.

In the latter part of the 1900's, frequency analysis techniques became prevalent. These techniques offered the ability to assign a return period (or probability of exceedance) to flow values. The benefits of assigning a return period to flow values include :

- design values across a range of structures should be consistent
- design parameters can be varied based on the importance of the infrastructure
- risk analysis can be performed with appropriate assignment of consequences to flow values.

With increases in the length of record and computing power, these techniques rapidly became the main tool used in determination of hydrotechnical design parameters. Unfortunately, these techniques are statistical in nature and the physical and historic context can be easily lost in the analysis. This problem is compounded by factors[1,2] such as :

- the technique of plotting a sorted set of annual maximum data on a log plot against a ranking will always result in a close to linear plot rising to the right, no matter what the data is. This can be misinterpreted as goodness of fit and justification for the process.
- most data-sets (even those with relatively long records) contain very few actual flood values, and represent the results of a mix of different physical processes
- potential data errors due to extrapolated rating curves and difficult measurement conditions may exist in the data, but cannot be identified statistically
- no actual probability distribution has been proven to be appropriate for runoff events and the variance in data-sets suggests that none exists
- the range of distributions and fitting techniques available results in a wide range of flow values, with no rational way of judging which is most appropriate
- in many cases, the selected return period requires a significant extrapolation from the observed data, with no physical guidance
- the need to transfer flow values from gauging stations to the design site, often done using basin area ratios that ignore hydrologic realities

These issues have resulted in a lack of confidence in the actual assignment of return periods[3], negating the potential benefits associated with the technique. Attempts to improve consistency in the application of flood frequency analysis[4] have done little to address the fundamental problems with the technique.

Hydrologic modeling is yet another technique that can potentially be used to derive design hydrotechnical parameters with associated return periods. However, modeling of actual rainfall-runoff or snowmelt processes has shown little success on large natural basins, and has generally only been applied to stormwater management studies in small, developed areas and to PMF studies, for which it is the only option. Reasons for the limited success[5] include :

- need for input with assigned return period (still dependent on statistics)
- non-linear response due to factors such as antecedent moisture (1:100 year rainfall does not necessarily produce 1:100 year runoff)
- complex inputs such as rainfall magnitude, timing, and geographic location or snow cover combined with temperature sequence
- many complex hydrologic processes that vary over a basin, resulting in many model parameters, many of which cannot be directly established
- limited data available for calibration of models to known events, and existing data-sets show no calibration to all events possible[6]
- extrapolation from observed conditions often involves different physical processes such as floodplain storage and inter-basin transfers

As with the frequency analysis approach, hydrologic modeling can yield a great range of results. Again, this technique provides little confidence in the ability to assign a return period to a given flow value. Attempts to improve consistency in the application of hydrologic modeling to PMF estimates[7] have done little to address the fundamental problems with this technique also.

Large Alberta Storms

A database of rainfall data has been compiled for Alberta and the surrounding region based on data published by Environment Canada, Alberta Environment, and the US government for the states just south of the border. Defining storm rainfall as the sum of 3 consecutive days of rainfall, analysis[8] of this storm data has identified about 140 past storms, dating back to 1908. Although there are about 1700 gauges in the database, not all gauges have been in operation at any given time. The earlier storms were picked up by about 150 gauges, whereas more recent storms have been recorded at about 650 gauges, enabling better definition of the storm magnitude and distribution.

Spatial analysis of each storm (Fig. 1) shows that with the exception of the July 31, 1987 storm, the depth-area relationship of the top 10 to 20 storms is very similar. The 1987 storm consisted of multiple distinct eyes located several hundred kilometres apart. For smaller areas (< 100km^2), there is significant variance between the largest storms, but this is likely due to the gauge network not always picking up the eye of the storm. For an area of 1000km^2, the mean rainfall for the highest storms is typically about 200mm +/- 25mm. Storms in this range have been responsible for most of the largest flooding events recorded in the province.

These large storms have also been located in various areas of the province, with no significant geographic correlation apparent (Fig. 2). Some areas, such as portions of the eastern slopes of the Rockies and the Swan Hills, appear to get these large storms more frequently than other areas on the Prairies. However, the overall magnitude of the storms does not appear to vary significantly with location.

Analysis of available hourly storm data shows that the duration of these storms can range from 15 to 60 hours. However, most of the storms that have resulted in significant flooding appear to be in the 20 to 30 hour range.

System Runoff Analysis

While the storms that produce much of the largest runoff response in the province show similarity, the runoff response varies greatly. A database of runoff response has been prepared for Alberta, based on published WSC data. In addition to peak flow, the volume of runoff has been calculated based on hydrograph analysis for close to 4000 runoff events covering more than 100 years. Analysis of both peak flows[9] and runoff depth (volume)[10] has shown significant variance in runoff response across the province. This is to be expected, given the many parameters that affect rainfall-runoff response and the wide range in these parameters observed in Alberta.

Subdividing the province up into regions with similar climatic and landform characteristics (based on Environment Canada ecodistricts and ecoregions) still shows significant scatter in the runoff response. This highlights the importance of basin-specific factors such as basin storage and channel capacity to the runoff response. It is clear that drainage area alone is not sufficient for transferring flow values between sites.

However, the results do show that envelope curves for both peak flow (Fig. 3) and runoff depth (Fig. 4) can be prepared for these regions. These curves show a significant trend over the range of events recorded. These envelope curves are likely defined by the gauges in the region with the most effective drainage networks.

The envelope curves for prairie areas of the province (Fig. 5) are defined by snowmelt events. These curves show a different shape, but still a significant trend. Snowmelt events likely govern in these areas because larger volumes of runoff result, even though the events can be of much longer duration. The many events contributing to the snowmelt envelope curve cover a wide range of snow-on-ground conditions and temperature sequences. The envelope curve is still likely determined by gauges on basins with the most effective drainage systems, and the upper trend suggests that there is a typical snowmelt runoff supply rate for this area.

Site Runoff Analysis

Although runoff response can vary considerably between basins, most sites with long records show multiple events in the range of the highest recorded event. This can be seen for some of the WSC gauge sites with the longest records in Table 1. These gauges are located on each of the six large basins that drain the eastern slopes of the Rockies in Alberta. In addition to the values in this table, additional flooding has been recorded at structures due to ice jams. In the case of the Red Deer River, an additional 3 flooding events in the same range of highwater elevation as the 3 open water events listed, have been observed in 1920, 1929, and 1948 at bridge sites downstream.

This trend can also be seen in the runoff response for the Highwood River at High River[11] (Fig. 6). This site is located at a change in slope of the channel on a basin in an area of high runoff potential, resulting in frequent flooding. The reported flows at the higher end of the curve are somewhat suspect due to extrapolation of the rating curve and potential inaccuracy of some of the highest gaugings. However, almost 20 events have been recorded at the gauge (including data from the gauge just downstream) that are on the flatter portion of the rating curve, all within 0.5m of the largest recorded event. Three additional events have been recorded at the bridge at this site, including an event in 1932 that appears to have been slightly larger than the highest recorded stage at the gauge (1995 event).

These observations suggest that there is a typical large runoff response at a site, as opposed to the assumption of continuously increasing flows with decreasing probability of exceedance that is fundamental to return period based techniques. This observation is especially notable when considering the highwater elevation rather than flow, as flow values can be very sensitive to small increases in stage, are less accurate as they are not directly measured, and do not account for other processes such as ice jams. The highest recorded events at these sites could be considered as in excess of the 1:100 year event as they are the largest in a record that is typically in the range of 100 years (combining gauge records with other historical highwater information associated with development). Alternatively, due to the multiple additional events that have reached a similar stage, they could be considered to be much more frequent.

Highwater Observations

In addition to the WSC data, highwater information is available from other sources. An extensive source for highwater data in Alberta is the bridge system, which currently consists of about 15000 bridge size stream crossings. Many of these sites have histories dating back over 100 years. Much of the highwater data associated with large runoff events has been collected into a database and is available through the published Hydrotechnical Information System (HIS) tool[12].

Typical channel parameters, including bed width, top width, and bank height, are also collected in HIS. These parameters are considered representative of the overall reach, and not just based on a few cross sections. The parameters are based on cross sections, site observations, photos, airphotos, DTM data, and hydraulic calculations. The bank height value is based on the elevation above typical stream bed at which the top width starts to increase rapidly, resulting in activation of adjacent storage.

Comparison of channel parameters to the highest observed highwater data reveals a correlation between flow depth (Y) and bank height (h), as shown in Fig. 7. This data-set covers more than 1000 sites with a wide range of channel geometry and slopes. It is clear that most of the highest highwater observations are within a certain depth above the bank height, with the majority of the data being within 1m. Most of the points that exceed this value are due to backwater effects such as constricted openings, debris jams, or backwater from downstream confluences. This observed trend makes sense physically in that once the bank height has been exceeded, significant storage is activated on the adjacent floodplain. This would have a significant routing effect on the runoff response. It can also be argued that many of these channels have been formed by the range of flows that they have seen historically.

Hydrotechnical Design Guidelines

These observations of a typical large runoff response, combined with concerns with return period based techniques, have led to the development of a new set of hydrotechnical design guidelines[13] for use with Alberta Infrastructure and Transportation (AIT) projects These guidelines incorporate three components – channel capacity, historic observations, and basin runoff potential. For any given site, one of these three components may govern.

Based on the bridge highwater data, the channel capacity technique involves assigning a flow depth to typical channel geometry that exceeds the bank height by a specified amount, to ensure that over-bank storage is activated. Once the typical channel geometry is determined and the design flow depth assigned, simple hydraulic calculations can be used to derive mean velocity and flow. For stream crossings and protection works, this component guarantees a design that is compatible with the channel for a wide range of flow conditions.

The historic observations component involves examining all available highwater data for the reach of channel. This data may include direct flood observations collected by AIT or other agencies, highwater marks noted during site inspections, information from local residents, previous engineering reports, historic photos and airphotos, and anecdotal information based on the operation of previous infrastructure at the site. The reach based approach of the HIS tool facilitates consideration of all relevant highwater data, as not all events are reported at all sites. If confirmed highwater data notes an historic elevation in excess of the channel capacity estimate, then it would govern the design of the crossing. This component guarantees that all available historic information will have been considered in the crossing design, resulting in a defendable process.

The basin runoff potential component involves checking if there is enough potential supply of runoff from the basin to reach the values determined from the channel capacity technique. A unit discharge based on the AIT Runoff Depth map[10] (based on the system runoff analysis) is applied to the gross drainage area of the basin to estimate an upper bound to runoff assuming a well drained basin and no limitation due to channel capacity. If this flow estimate is lower than the channel capacity value, then this component will govern. Typically, this component only governs for small basins with relatively steep channels.

Conclusion

Observations of large storms, gauged runoff events, and highwater at bridges suggest that there is a typical large response for most sites. These observations are not consistent with the core assumption of return period based techniques that there is a continuum of increasing flows with increasing return period. Events larger than these typical large runoff events may occur, but they would likely be very infrequent and the increase in magnitude would likely be limited by the governing physical processes. The typical large response events could be considered equivalent to the largest historic event for a given site. It is impossible to accurately assign a return period to these events. However, hydrotechnical parameters can be calculated for these events at most sites and used for design of most stream related infrastructure. These designs should meet the goals of accounting for site physical parameters and historic observations, as well as providing a consistent level of design across the system.

Hydrotechnical design guidelines based on these observations have been applied to over 1300 stream crossing sites covering a wide range of channel geometry and basin size. Suitable design parameters have been developed for all of these sites, and included in the HIS database. New highwater data can still be considered to confirm assumptions and affirm validity of these parameters. However, each new event will not require recalculation of the design parameters, as would be required with frequency analysis techniques. Judgement is still required to define typical channel geometry and evaluate all available hydrotechnical data. However, discussion now focuses on physical parameters and processes, rather than statistical fits and gauge selection. A sensitivity analysis can quickly identify parameters that require further consideration. This approach has eliminated much of the uncertainty associated with return period based techniques.

Hydrotechnical parameters developed using these guidelines can be used to evaluate alternative solutions for a site as part of an optimization process. Different levels of risk may still be considered depending on the importance of the infrastructure. For example, an important highway crossing would be expected to remain open and sustain only minor damage during a design event, whereas it may be acceptable for a low volume local road crossing to be temporarily closed during the design event. Design parameters based on these guidelines should be suitable for most stream-related infrastructure. However, modifications would be required for high consequence of failure facilities, such as large dams. The “equivalent to largest historic” event will still provide context for the design parameters for these facilities, providing a baseline reference to assess the magnitude of proposed parameters.

Table 1 Historic Context of Largest Runoff Events

Stream	**Location**	**Gauge Record**	**A (km^2)**	**Year**	**Q (cms)**	**Stage (m)**
Oldman	Lethbridge	1912 - Present	17000	1995	4700	8.5
				1908	4500*	8.3
				1953	3100	7.1
Bow	Calgary	1911 - Present	7800	1879	2250*	4.5
				1897	2250*	4.5
				1902	2250*	4.5
				1932	1500	4
Red Deer	Red Deer	1913 - Present	11600	1915	1900	6.6
				2005	1500**	5.9
				1954	1500	5.9
North Saskatchewan	Edmonton	1911 - Present	28000	1915	5800	12.8
				1899	5100*	12.2
				1986	4500	11.6
Athabasaca	Athabasca	1913 - Present	75000	1954	5700	7.1
				1944	5000	6.8
				1971	4600	6.5
				1986	4500	6.5
				1980	4300	6.3
Smoky	Watino	1916 - 1921 1955 - Present	50000	1990	9400	10.4
				1972	9200	10.2
				1982	9000	10
				1987	7100	8.8

* Estimated from HWM
** Peak attenuated by Dickson Dam, peak u/s similar to 1995

Figure 1 – Depth Area Curve for Large Storms in Alberta

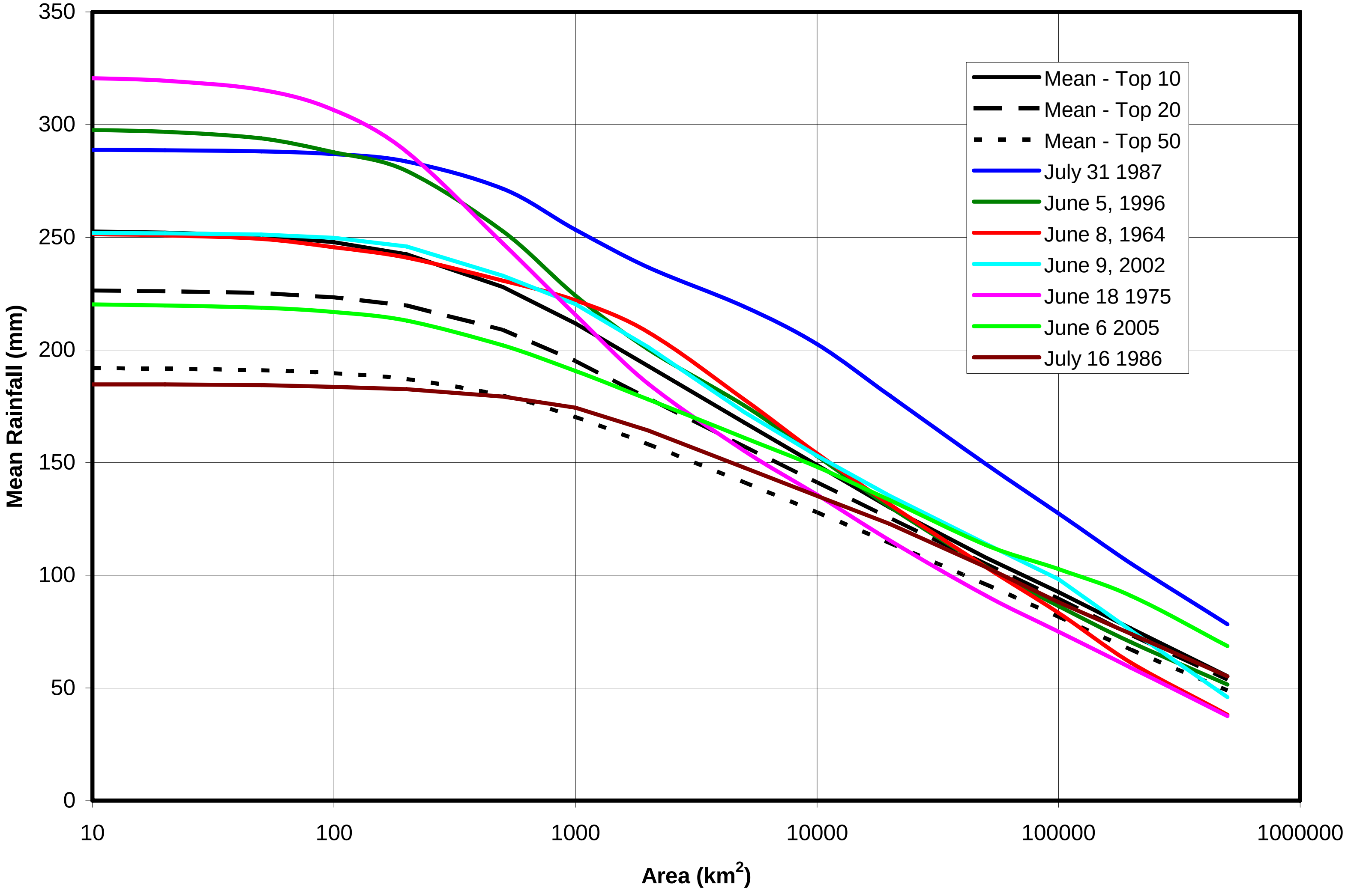


Figure 2 – Geographic Distribution of Large Rainfall Events

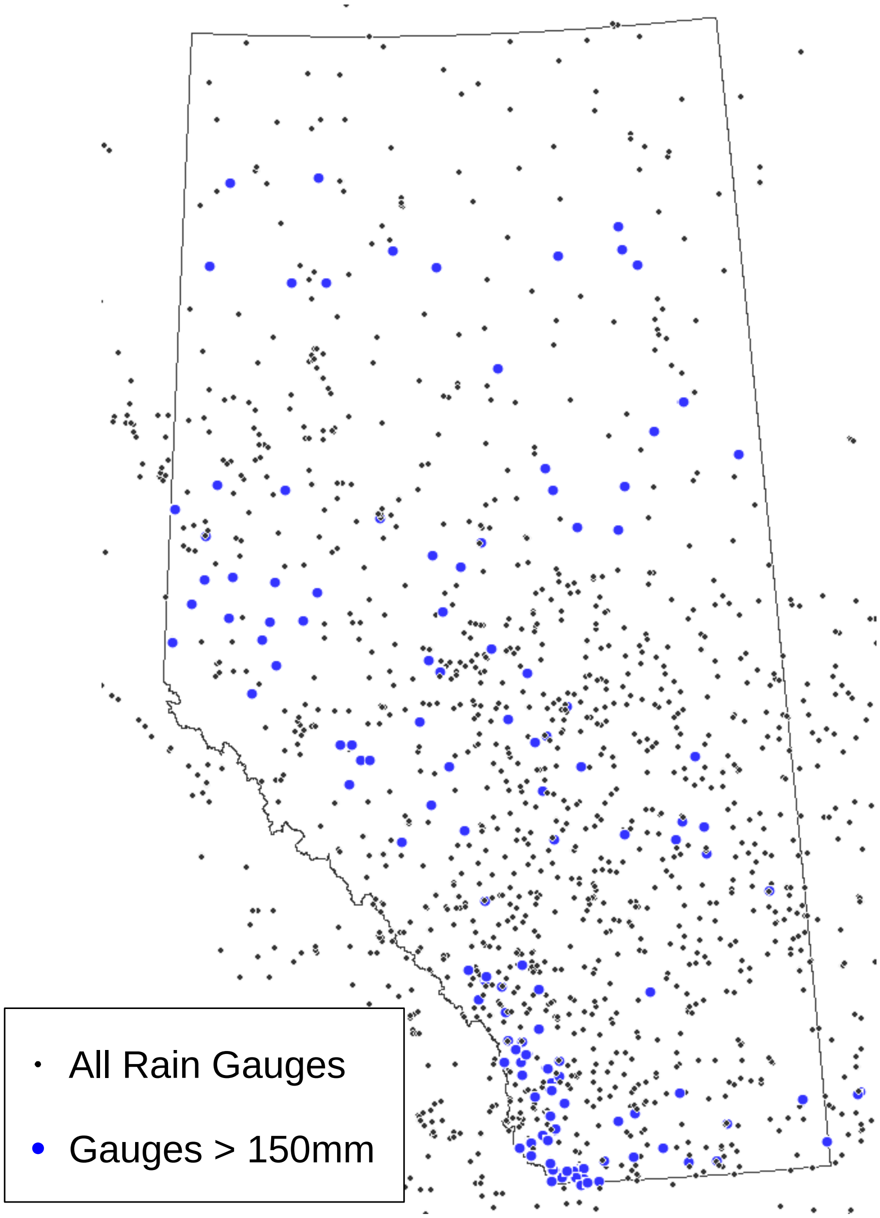


Figure 3 – Peak Flow Envelope Curve – Oldman River Basin

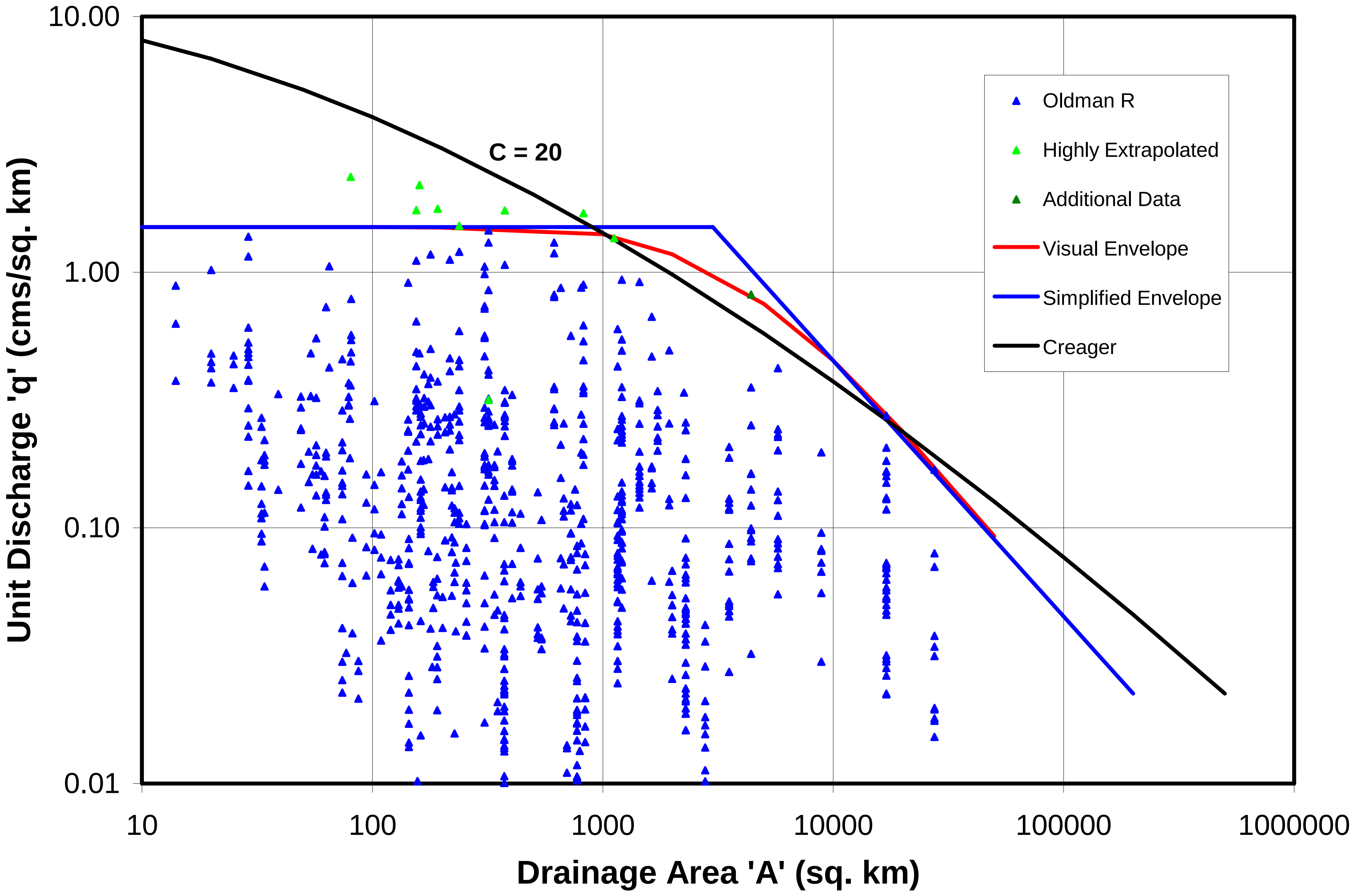


Figure 4 – Runoff Depth Envelope Curve

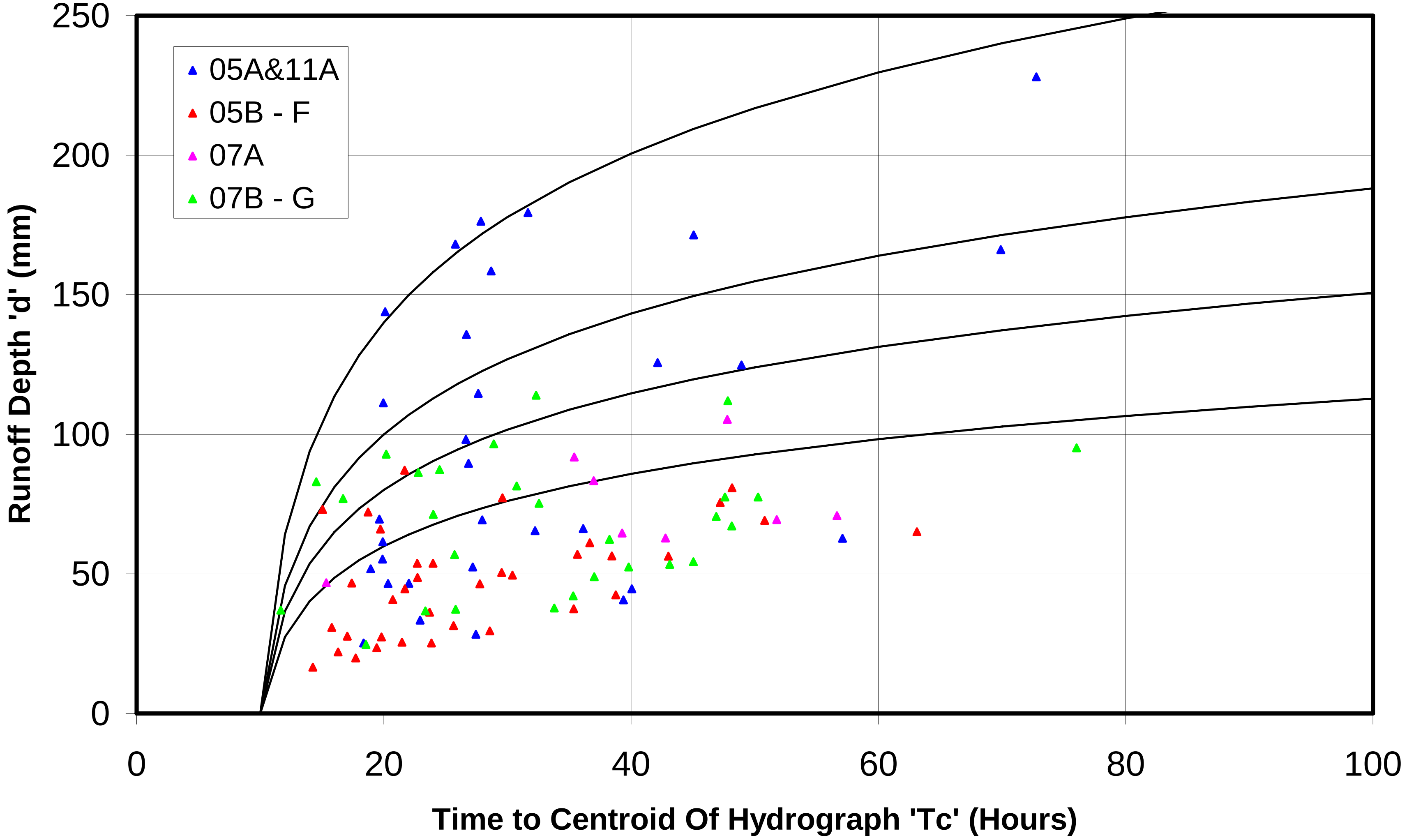


Figure 5 – Snowmelt Runoff Depth Envelope Curve

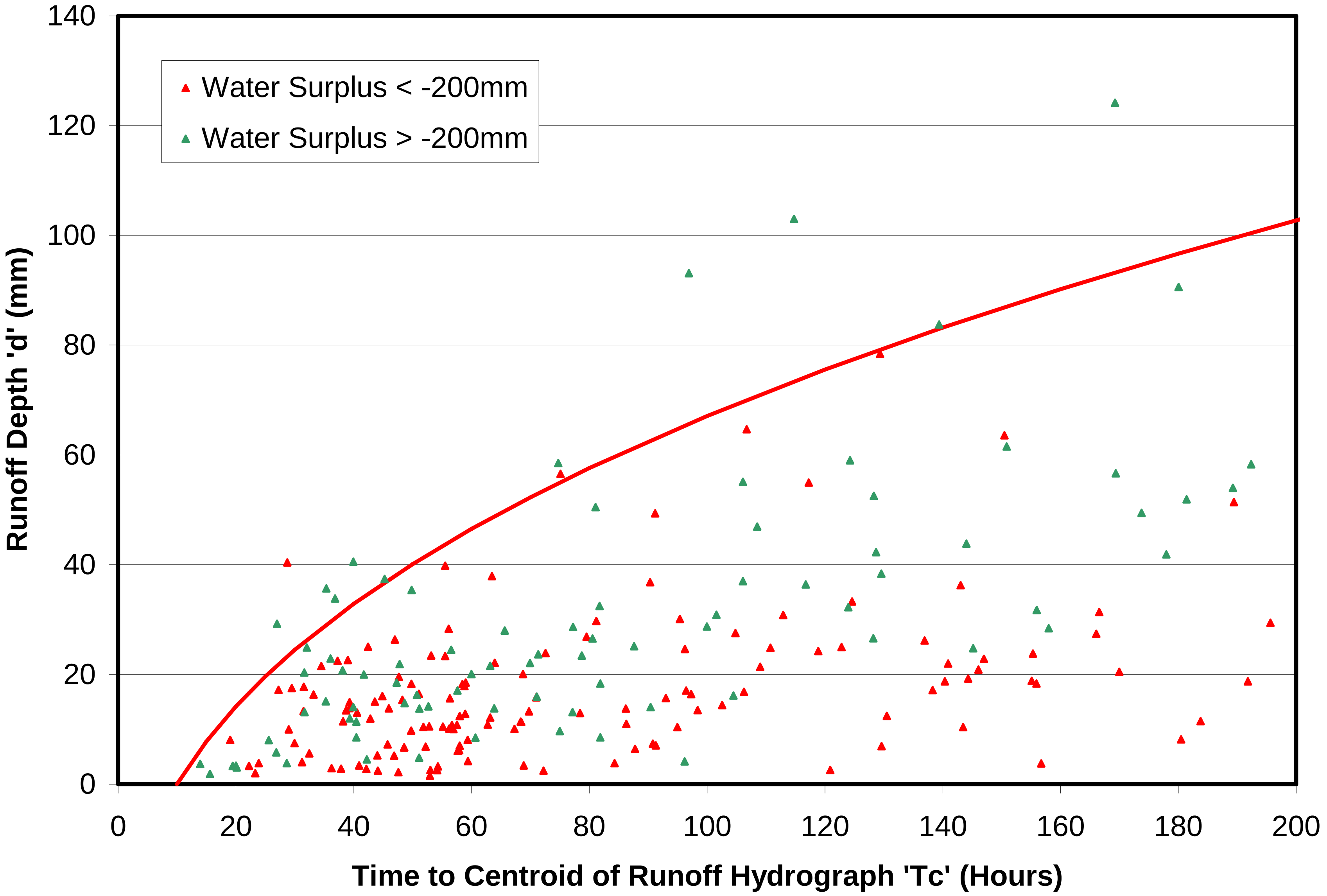


Figure 6 – Highwood River Rating Curve

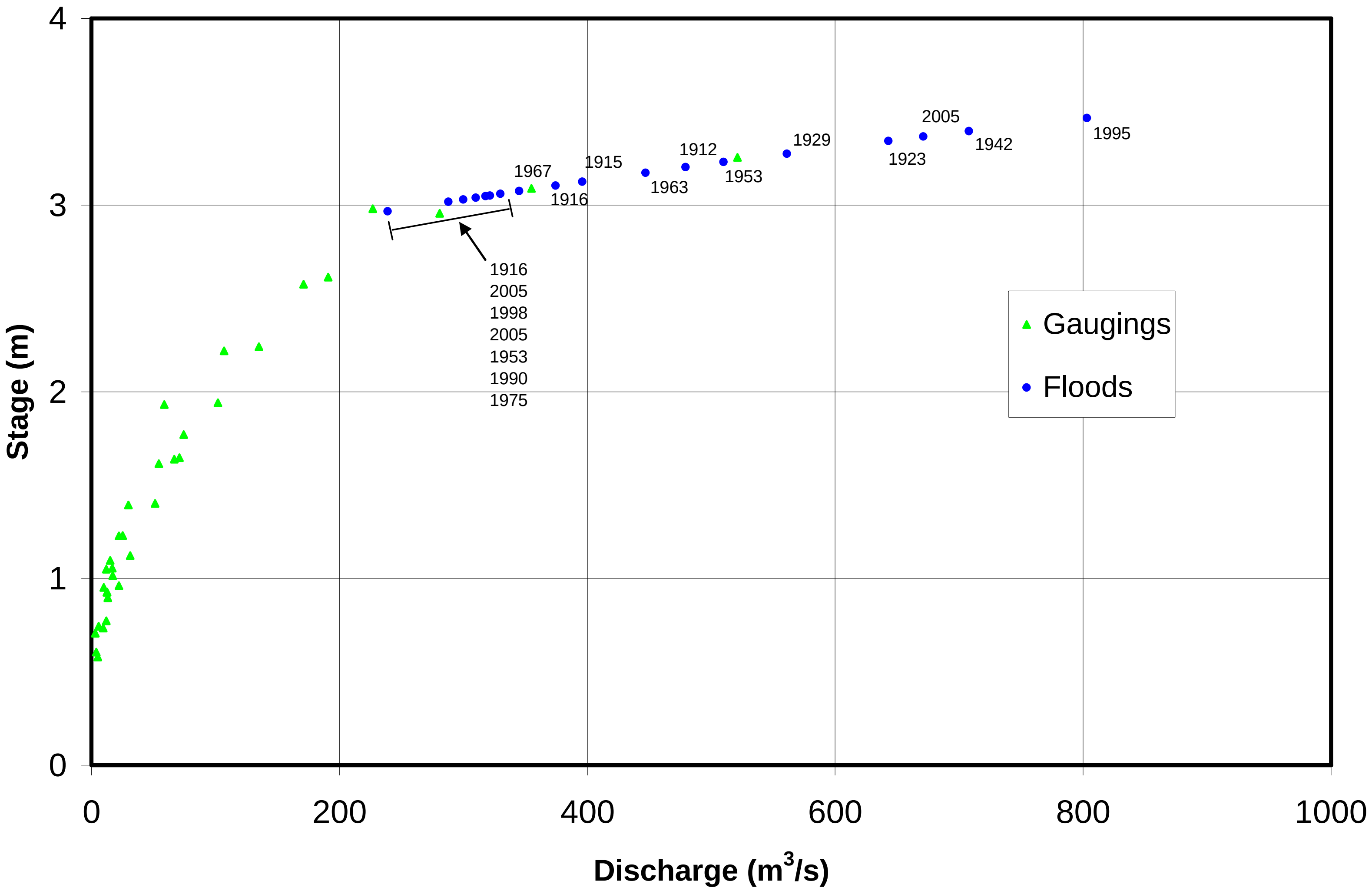
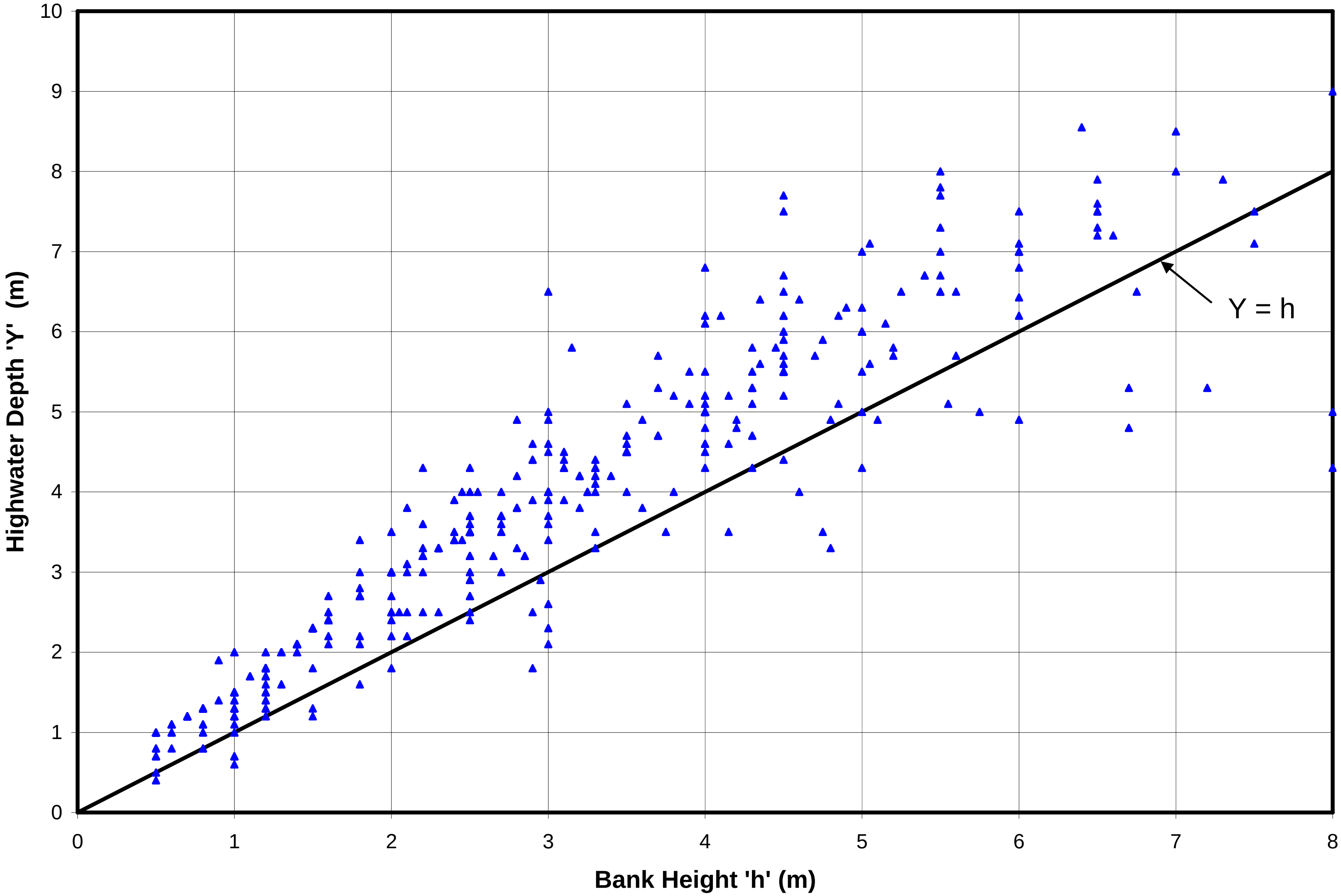


Figure 7 – Highwater Observations at Stream Crossings



References

1. Klemes, V. 2000. Tall Tales About Tails of Hydrological Distributions. Journal of Hydrologic Engineering, ASCE, pp 227-231.

2. Neill, C.R., and Watt, E.W. 2001. Report on Six Case Studies of Flood Frequency Analyses. Prepared for Alberta Transportation, Civil Projects Branch. (http://www.infratrans.gov.ab.ca/INFTRA_Content/doctype30/Production/ffasixcase.pdf).

3. Alberta Infrastructure and Transportation, Bridge Engineering Section 2003. Frequency Analysis Critique. (ftp://www.tu.gov.ab.ca/bridge/pub/Hydrology/Frequency Analysis Critique.ppt).

4. Alberta Transportation, Civil Projects Branch 2001. Guidelines on Flood Frequency Analysis.

5. Alberta Infrastructure and Transportation, Bridge Engineering and Water Management Section 2007. Uncertainty in Hydrologic Modelling for PMF Estimation. (http://www.infratrans.gov.ab.ca/INFTRA_Content/docType30/Production/unhydmodel.pdf).

6. Alberta Infrastructure and Transportation, Bridge Engineering and Water Management Section 2007. Alberta Rainfall Runoff Response. (http://www.infratrans.gov.ab.ca/INFTRA_Content/docType30/Production/rainrunresp.pdf).

7. Alberta Transportation, Civil Projects Branch 2004. Guidelines on Extreme Flood Analysis. (http://www.infratrans.gov.ab.ca/INFTRA_Content/docType125/Production/gdlnextrmfld.pdf).

8. Alberta Infrastructure and Transportation, Bridge Engineering and Water Management Section 2007. Large Alberta Storms. (http://www.infratrans.gov.ab.ca/INFTRA_Content/docType30/Production/lrgabstorm.pdf).

9. Alberta Infrastructure and Transportation, Bridge Engineering and Water Management Section 2007. Alberta Flood Envelope Curve Analysis. (http://www.infratrans.gov.ab.ca/INFTRA_Content/docType30/Production/fldenvcurv.pdf).

10. Alberta Infrastructure and Transportation, Bridge Engineering and Water Management Section 2007. Development of Runoff Depth Map for Alberta. (http://www.infratrans.gov.ab.ca/INFTRA_Content/docType30/Production/dvrnoffdmap.pdf).

11. Alberta Infrastructure and Transportation, Bridge Engineering and Water Management Section 2007. Case Study : Highwood River at High River.

12. Alberta Infrastructure and Transportation, Bridge Engineering and Water Management Section 2006. HIS Tool Overview. (ftp://www.tu.gov.ab.ca/bridge/pub/Hydrotechnical Information System/HIS Tool Overview.pdf).

13. Alberta Infrastructure and Transportation, Bridge Engineering and Water Management Section 2006. Hydrotechnical Design Guidelines for Stream Crossings.

(http://www.infratrans.gov.ab.ca/INFTRA_Content/docType30/Production/hydgnglstcr.pdf).