A rating curve based on lake levels: evaluating outlet flow for Clear Lake, Riding Mountain National Park, Manitoba

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Abstract: The stage-discharge relationship or 'rating curve' represents the integrated effect of stream geometry and hydraulic parameters, and is of fundamental importance in hydrologic studies as a means to convert records of water level to flow rates. At many hydrometric sites, the primary assumptions of stream regime (equilibrium or grade) and uniform flow require several years of measurement for validation. In 1993, record high water levels in Clear Lake, Manitoba spilled over the outlet berm and eroded an outlet channel that flowed into Clear Creek. The outlet channel has undergone significant geometric adjustment during the first three years of operation. This observation is supported by periodic discharge measurements (1994-1996) indicating significant variation in both channel geometry and stream flow. Attempts at developing a rating curve for Clear Creek in 1995 encountered problems associated with the measurement of stage. Specifically, beaver dam flooding and backwater submergence. This study employs recorded lake levels, channel staff gauged stage measurements and discharge measurements to develop rating curves for the outlet of Clear Lake. Results indicate that lake levels can be used as an effective alternative to channel stage in the construction of a rating curve for lake outlet streams. In the case of Clear Lake this eliminates the problems related to the measurement of stage caused by beaver dam flooding and backwater effects. The resulting curve and mathematical model can be employed to estimate daily outflow from the lake.

Key words: Clear Lake, lake levels, outlet discharge, stage/discharge, rating curve

Introduction

The Clear Lake watershed is centrally located on the Riding Mountain Uplands in southwestern Manitoba (Figure 1). The watershed drains an area of 142.18 km^2 of which over 65% is located in Riding Mountain National Park (RMNP). Clear Lake represents approximately 20.7% of the watershed area. Park managers have recognized the need to determine the hydrologic water balance of Clear Lake and the associated watershed (Dubois 1997). This scientific knowledge is fundamental to understanding the physical, chemical and biological processes, which occur in the watershed. The collection of baseline data will ultimately provide a sound foundation for the development of both short-term and long-term park management plans to preserve the natural state in the Clear Lake watershed.

Clear Lake covers an area of 29.37 km^2 and has a maximum recorded depth of 34.2 m with a mean depth of 11.5 m (Figure 2). The lake is oriented west-east, with a wider and shallower western portion and narrower and deeper eastern end. It is approximately 12,095 m in length along a mid-lake line and 4,524 m wide, and is estimated to hold approximately 338,075 dm^3 of stored water (McGinn *et al*. 1998).

Surface runoff drains into Clear Lake by way of Octopus Creek, Pudge Creek, Bogey Creek (Ministic Lake Creek), Picnic Creek (Glen Beag Creek) and six intermittent streams located along the north shore of the lake (Figure1). Three of the most prominent of these intermittent streams have been named Spruces Creek, Aspen Creek and North Shore Creek (McGinn *et al*. 1998). Although there is little information at this time, groundwater is also believed to contribute to the storage volume of Clear Lake.

Clear Creek, the outlet stream, is located at the western end of Clear Lake (Figure 1). Clear Creek had not been gauged by the Water Survey of Canada until recently, however, periodic observations suggest that the outlet stream can flow year round and that the mean discharge values are relatively small (0.0 - 2.0 $m^3 s^{-1}$). Clear Creek drains into the Little Saskatchewan River approximately six km upstream of Horod, Manitoba. Until 1993, the stream channel was overgrown and the flow impeded by numerous beaver dams and associated storage ponds. It is suspected that groundwater discharge may represent a significant outflow from Clear Lake particularly when the outlet channel has a beaver dam stair-step profile and is overgrown.

The Recent History of the Clear Lake Outlet

In the spring of 1993, record high lake levels spilled over a sand and gravel berm at the western end of Clear Lake and began to erode the outlet channel towards the west. There had been no recorded flow along this channel (Clear Creek) since the 1970s and the stream channel was overgrown and clogged with sediment and debris. At first the new channel

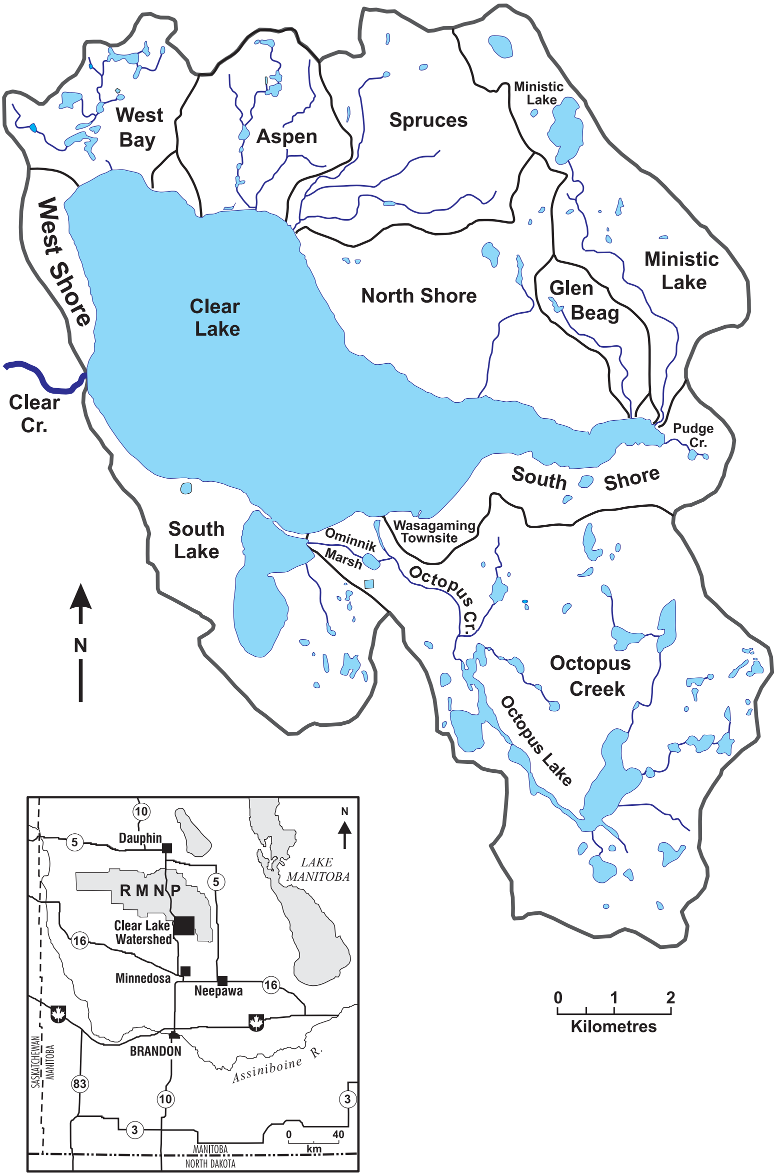
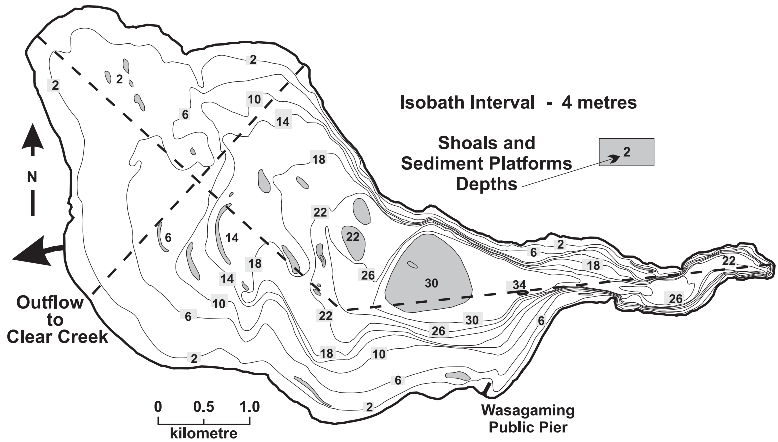


Figure 1: *The Clear Lake watershed.*



Clear Lake Statistics

Length	**12,095 m**
Width	**4,524 m**
Mean Depth	**11.51 m**
Maximum Depth	**34.20 m**
Maximum Fetch	**10,095 m**
Surface Area	**29.37 km^2**
Volume	**338,075.015 dm^3**
Flushing Period	**10.72 yrs**

Figure 2: *Clear Lake bathymetry.*

was less than 1.0 m in width and only a few centimetres deep (McGinn *et al*. 1998). Over the next two years the channel widened and deepened significantly working towards equilibrium (regime). By the spring of 1995, the flood stage channel width was recorded to be in excess of 10 m and the maximum channel depth exceeded 0.5 m.

In 1994, the Clear Lake Project was initiated to understand the water balance of Clear Lake. This involved primary research regarding the principal water balance parameters particularly, moisture inputs (rainfall and snowmelt), inflows, evapotranspiration loss, annual and long-term changes to lake storage volumes and outflow. As a consequence, Environment Canada began monitoring water levels on Clear Lake. From 1994-1997, a Stevens stage recorder (A-71) charted the instantaneous fluctuations in lake level and Environment Canada provided calculations of the mean daily lake level. Supplemental stage data were obtained from a staff gauge, read by Park officials. On March 24 1997, the stage recorder was converted to an automated Accubar pressure transducer. Water levels were averaged every two minutes and sent to a VADAS environment data acquisition system, housed in the pump house located in the town of Wasagaming (Figure 1), from which Environment Canada calculated the mean daily water levels. The Stevens stage recorder was removed in the spring of 1998. Park officials metered outlet discharge periodically throughout the 1994 and 1995 open water season and occasionally in 1996.

In the spring of 1995, at the request of officials from Riding Mountain National Park, Environment Canada personnel attempted to develop a rating curve (based on channel stage and metered discharge) for Clear Creek near the outlet. The gauging station was located approximately 90 m downstream of the outlet sill, at a site with a walking bridge and easy trail access. Upstream of the site, wetlands predominate and accessibility to the stream channel was difficult. Downstream, the channel has been modified by a series of beaver dams and is characterized as having a stair-step profile. A stilling well, 'doghouse,' Stevens stage recorder (A-71) and staff gauge were installed at the selected site and the stage surveyed to a temporary benchmark.

In 1995, Environment Canada was successful in developing the rating curve for Clear Creek during the spring freshet conditions when outlet discharges exceeded 0.8 m^3s^{-1}. At these discharges, the stream channel was relatively straight and clean. Most beaver dams downstream of the gauging site had failed and could not be repaired at flows exceeding 1.0 m^3s^{-1}. As outlet discharges dropped below 0.8 m^3s^{-1}, however, the beaver began to re-establish storage dams and the resulting backwater flooding generated significant problems in recording an accurate channel stage. Levelers were inserted into the newly constructed dams and in extreme cases the dams were removed. Levelers, based on the Clemson Leveler model (Clemson University 1991) were 8, 10 or 12 inch diameter drainage pipes inserted through the beaver dam and extended several metres into the storage pond. The upstream (pond) end was protected from beaver access by a wire basket approximately 1 m^3. Levelers could, more or less, control pond stage and backwater effects. Continual monitoring and maintenance, however, was required to attain the desired effect. It is important to note that stream discharge measurements during 1994 and 1995 were conducted approximately 75 m upstream of the stage recorder, 15 m from the lake outlet sill. This was necessary due to beaver dam backflooding at the stage recorder. The metering site, however, was considered unsuitable for the installation of a stage recorder.

Environment Canada stopped gauging operations in the fall of 1996 due to continual problems with the recording of channel stage (backwater effects and icing conditions). The stilling well and gauging equipment were removed in early 1997. As a result daily outlet discharges are, at best, informed estimates. By fall of 1997, lake levels had fallen significantly (one standard deviation) below the long-term average of 615.275 m elevation and during the low water months of October and November the outlet sill was exposed. This (fall of 1997) was the only time since 1992 that there has been no recorded flow from the Clear Lake outlet down Clear Creek.

Objective of the Study

The objective of this study is to explore the use of lake levels as an alternative to channel stage in deriving the rating curve for a lake outlet stream.

Theoretical Considerations

The traditional rating curve:

A rating curve is a graphical representation of the stage-discharge values for a specified stream section (Lo 1992) which is considered to be 'in regime' or at equilibrium. The fundamental assumption for establishing a rating curve is the principle of regime. Channels, which are in regime tend to adjust themselves to average widths, depths, slopes and meander lengths, depending on the sequence of discharges, sediment loads and the conditions of the boundaries (Blench 1969).

The traditional rating curve based on channel stage and discharge values uses the channel stage or gauge height as a function of the discharge (Herschy 1985). That is, the channel stage is assumed to be dependent on the stream discharge. A sufficient number of discharge measurements (approximately 25), suitably distributed throughout the range in stage, are required to establish this stage-discharge relationship. The observations are plotted on arithmetic paper, with channel stage on the ordinate and discharge on the abscissa. A trend line is fitted to the scatter plot. The method of least squares has become the preferred procedure used to compute the line of best fit. Generally a linear plot in the form $S = m Q + b$ is preferred; where, 'm' is the slope of the straight line and 'b' is the intercept value (channel stage) when discharge (Q) is zero. The straight-line plot is described by a simple mathematical model, can be analysed for uncertainties and easily extrapolated.

The logarithmic rating curve:

When the initial scatter plot appears curvilinear, it is common to plot the logarithms of stage against the logarithms of discharge. Alternatively, the data can be plotted on logarithmic paper. In either plot the data are fitted with a straight line using the method of least squares. The equation of this plot, called a power function, is $S = a\,Q^{m}$; where, 'm' is the arithmetic slope of the line and 'a' is the intercept (channel stage) when discharge (Q) equals unity. As in the traditional plot, the power function (straight line) is described by a simple mathematical model, can be analysed for uncertainties and is easily extrapolated.

The lake stage rating curve:

A lake stage-outlet discharge rating curve is fundamentally different from the traditional rating curve. In this case, discharge is dependent on lake stage. Consequently the plot requires, at least in theory, outlet discharge to be plotted on the ordinate and channel stage on the abscissa. As with a traditional rating curve, a sufficient number of discharge measurements are required to establish this discharge-stage relationship. Either an arithmetic or logarithmic plot is acceptable.

Procedures and Methodology

A hydrometric metering site was established 15 m downstream from the lake outlet sill. At this site, the channel was well-formed, partly armoured, with bank to bank flow and little evidence of seepage loss to the surrounding wetlands. The site lay beyond the influence of lake waves. Measurements began on May 8, 2001 and continued weekly until October 10, 2001. Discharge measurements followed the mid-sectional method (15-20 verticals) employed by Environment Canada as outlined by Terzi (1981). Velocity was measured with a calibrated Price AA meter at 0.6 m depth in each vertical until mid-September. When the mean cross-sectional flow depth was less than 0.15 m, a calibrated Pygmy meter was employed. The hydrometric data were used to calculate mean outlet discharge (m^3s^{-1}). Lake stage for the date of the discharge measurement was recorded, as an elevation (m) above sea level, at the Wasagaming lake stage recording site (Figure 1). The gauge height (staff gauge), located at the 'old'

Environment Canada gauging site was also recorded. These measurements were recorded as metres above a selected base elevation.

Results

Table 1 summarizes the hydrometric measurements recorded during the 2001 study period. Outlet discharge during the study period ranged from a high of 1.4846 m^3s^{-1} on May 15, 2001 to the lowest value recorded (0.0090 m^3s^{-1}) on October 10, 2001. Calculation of the mean outlet discharge for the open water season in 2001 was 0.7587 m^3s^{-1} ± 0.52 m^3s^{-1}. Outlet discharge exceeded 1.0 m^3 s^{-1} throughout the spring and early summer, falling below 1.0 m^3s^{-1} on August 9 and below the annual mean on August 24, 2001. Outflow discharges continued to decline in September and by mid-October were near the limit of meterable flows (0.0090 m^3s^{-1}).

Table 1: *Hydrometric measurements at Clear Creek gauging site (2001 data).*

Date	Lake Stage m	Site Stage m	Trend	Discharge m^3 s^{-1}	Mean Velocity m s^{-1}	X-Area m^2	Top Width m	Mean Depth m
5/08/01	615.601	0.2650	rising	1.3430	0.7299	1.8400	6.69	0.28
5/15/2001	615.623	0.2900	rising	1.4846	0.5637	2.6337	8.96	0.30
5/22/2001	615.613	0.2750	falling	1.3976	0.5337	2.6185	9.00	0.29
5/29/2001	615.582	0.2680	falling	1.2273	0.7671	1.5999	5.11	0.32
6/05/01	615.559	0.2460	falling	1.1012	0.6781	1.6240	5.26	0.31
6/12/2001	615.543	0.2240	falling	1.0405	0.6747	1.5426	5.27	0.29
6/19/2001	615.541	0.2140	falling	1.0195	0.6544	1.5579	5.37	0.31
6/28/2001	615.583	0.2650	rising	1.1920	0.6838	1.7432	5.28	0.32
7/06/01	615.541	0.2290	falling	1.1653	0.7342	1.5872	5.28	0.32
7/13/2001	615.513	0.1960	falling	1.0069	0.6811	1.4824	5.28	0.29
7/20/2001	615.532	0.2300	rising	1.1849	0.7628	1.5534	5.28	0.29
7/27/2001	615.521	0.2060	falling	1.1554	0.7859	1.4701	5.27	0.29
8/03/01	615.489	0.1650	falling	1.0412	0.7728	1.3473	5.27	0.26
8/09/01	615.484	0.1420	falling	0.9195	0.7465	1.2318	5.26	0.24
8/17/2001	615.433	0.0840	falling	0.5367	0.6287	0.8536	4.88	0.19
8/24/2001	615.395	0.0420	falling	0.4610	0.5990	0.7696	4.80	0.23
8/30/2001	615.373	0.0170	falling	0.3215	0.5274	0.6096	4.55	0.21
9/06/01	615.331	0.2500	falling	0.1846	0.4062	0.4545	3.45	0.17
9/12/2001	615.329	0.3180	falling	0.1512	0.3296	0.4588	3.53	0.19
9/20/2001	615.306	0.2890	falling	0.1084	0.2800	0.3872	3.30	0.16
9/26/2001	615.291	0.2980	falling	0.0873	0.2732	0.3195	3.19	0.15
10/4/2001	615.275	0.2100	falling	0.0521	0.2365	0.2203	1.87	0.10
10/11/01	615.240	0.0360	falling	0.0157	0.1266	0.1240	1.65	0.09
10/18/01	615.228	-0.0860	falling	0.0090	0.1488	0.0605	1.05	0.07
Mean	615.455	0.2069		0.7586	0.5552	1.1704	4.79	0.24
Std. Dev.	0.128	0.0873		0.5165	0.2133	0.7342	1.89	0.08
Maximum	615.623	0.2980		1.4846	0.7859	2.6337	9.00	0.32
Minimum	615.228	-0.0860		0.0090	0.1266	0.0605	1.05	0.07
Range	0.395	0.3840		1.4756	0.6593	2.5732	7.95	0.25

There were no recorded lake outflows during November and December 2001.

With the exception of the October lake stages, lake levels, recorded for the open water season, were above the long-term mean of 615.275 m elevation (McGinn *et al*. 1998). Following the spring freshet in mid-May, lake stages generally fell throughout the year with the exception of lake stage responses to two periods of heavy rainfall on June 28 and July 20.

Two rating curves were constructed (Figures 3 and 4). Figure 3 illustrates the traditional plot of channel stage (staff gauge at the 'old' Environment Canada gauging site) and stream discharge for Clear Creek. The plot clearly illustrates the influence of beaver dam flooding and variable backwater submergence on the stage-discharge correlation at low flows. Two trend lines have been constructed based on least squares techniques. The linear equation S = 0.08 Q + 0.13, shown by the solid black line in Figure 3, clearly is not representative of the stage-discharge relationship. Correlation analysis indicates a weak positive correlation (r = 0.4) and an explained variance (r^2) of 16.4%. The ellipse highlights those low water discharges and variable stages influenced by the construction of beaver dams. The second trend line S = 0.25 Q - 0.06, the

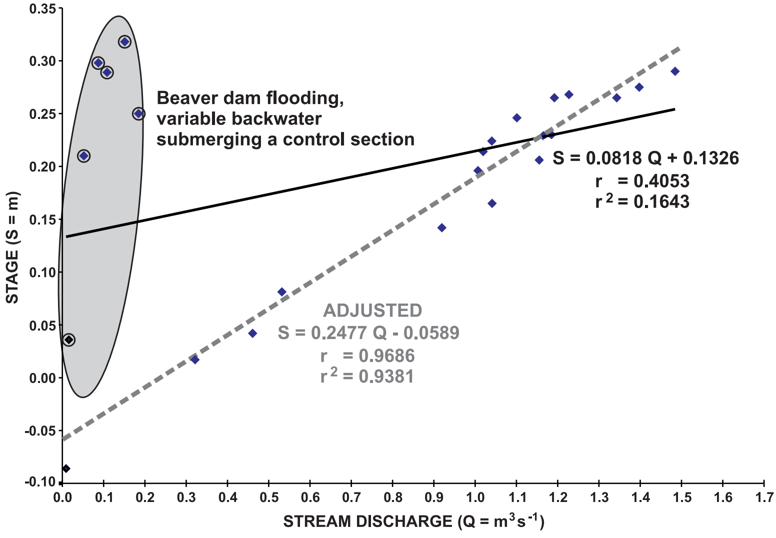


Figure 3: *Rating curves: Clear Creek near the outlet of Clear Lake (2001 data).*

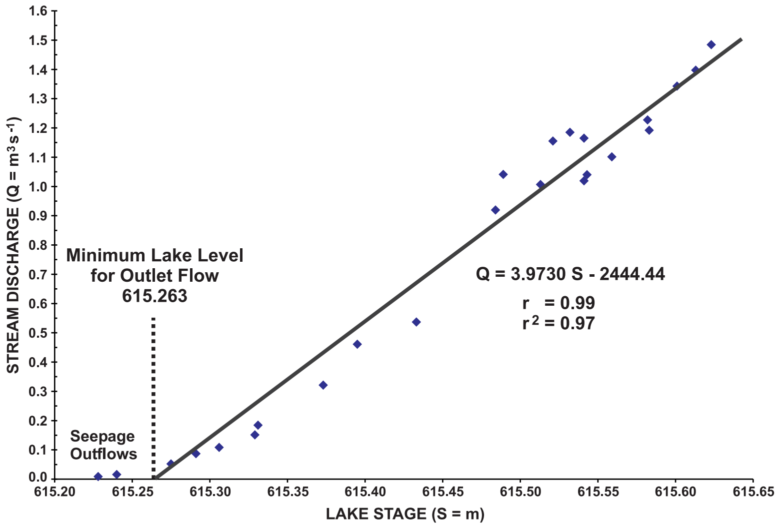


Figure 4: *Rating curve: Clear Lake outlet (2001 data).*

dashed grey line in Figure 3, represents the least squares regression function for the 2001 data excluding the highlighted low flow discharges and associated staff gauge heights. The r^2 value for this linear equation (0.94) indicates that a non-beaver-affected rating curve can be constructed for Clear Creek.

Figure 4 illustrates the constructed rating curve for lake stage and outlet discharge. The plot deviates from the traditional model in that stream discharge is dependant on lake stage. Consequently, discharge is plotted on the ordinate and lake stage on the abscissa. A linear trend line has been constructed based on least squares techniques. The linear function Q = 3.97 S - 2444.44, best represents the lake stage-discharge relationship. Regression analysis indicates a 0.99 positive correlation coefficient and 97.1 percent variance explained.

Discussion

In the traditional rating curve linear model where S = m Q + b, gauge height or stage is a function of stream discharge plus a constant. The slope (m) represents the rate of change in stage as a response to variation in the stream discharge. But in the lake stage-outlet discharge linear model, Q = m S + b, the slope (m) represents the rate of change in outlet discharge as a function of changes in lake stage. Parameters that account for lake stage variation are associated with the water balance of Clear Lake. These factors include: precipitation (rain and snow) directly deposited on the lake, rainfall and snowpack water equivalent depths over the watershed, runoff volumes, net groundwater effects, and evapotranspiration losses.

In the traditional rating curve, the intercept value (b) is indicative of zero outlet flow. The correlative in the lake stage-outlet discharge model is the intercept with the abscissa (b/m), which is representative of the elevation of the lake outlet sill. For the 2001 data lake stage rating curve, the intercept value representative of the Clear Lake outlet is 615.26 metres above sea level (Figure 4). The lake stage must be at a higher elevation for significant flow over the outlet sill. This critical elevation may be affected by many factors such as lake-ice effects, channel armouring and outlet scour, all of which have varied over the first nine seasons of operation. In 1994 and 1995, the mean elevation of the outlet sill was 615.39 m. ± 0.01 m. During the 1996 open water season the sill was eroded 15 cm to a base elevation of 615.24 m. In 1997, expanded lake-ice was observed to shove quantities of sand, pebbles, large cobbles and the occasional boulder on top of the outlet berm. This process raised the mean elevation of the outlet sill 4 to 8 cm. Higher outflows associated with the 1997 spring freshet winnowed the fines from the channel near the lake outlet and created a channel armour resistant to scour under normal flow conditions.

A grain size analysis of the outlet channel armour using the Wolman (1954) sampling methodology (N = 500 pebbles), indicated a median pebble size of 30.0 mm and a mean size of 33.2 ± 20.0 mm. The D_{65} and D_{90} percentile values (‘b’ axis diameter of the 65th and 95th largest rock) were 36 mm and 66 mm respectively. Galay (1971) suggests that bed material in this size range requires a mean cross-sectional velocity exceeding 1.13 m s^{-1} for entrainment (the critical erosion velocity). In 2001, the maximum recorded daily mean cross-sectional velocities during the spring freshet were calculated to be less than 0.8 m s^{-1}, a value well below the estimated critical erosion velocity of the bed armour. While there were no outlet discharge measurements recorded from 1998-2000, it appears that the Clear Lake outlet has been stable and has remained at the elevation of 615.26 m ± 0.02 m for the past five years (1997-2001).

The data set was expanded to include the discharge measurements recorded in the channel regime adjustment years 1994, 1995 and 1996 and the corresponding lake stage measurements. Figure 5 illustrates the

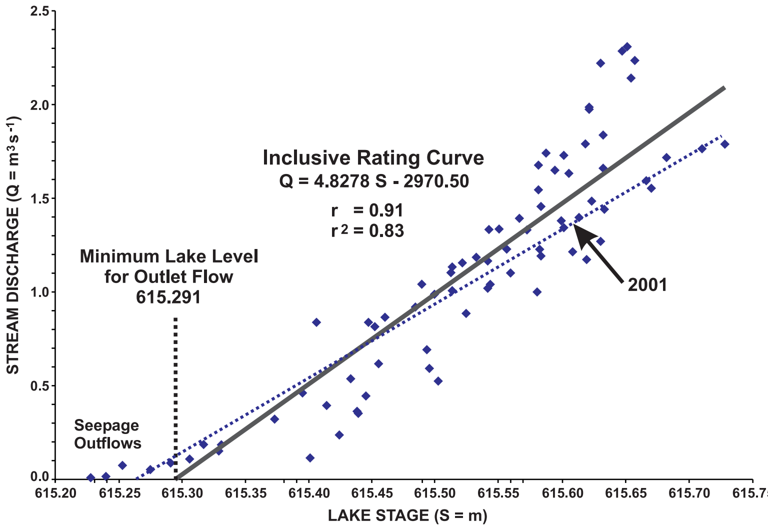


Figure 5: *Rating curve: Clear Lake outlet (1994, 1995, 1996 and 2001 data).*

constructed lake stage rating curve (the inclusive rating curve) and the results of the correlation and regression analyses. The linear model Q = 4.83 S - 2970.50 best fits the plot. The r^2 value indicates that the regression equation accounts for 83% of the variation in the data set. The calculated slope (4.83) is similar but steeper than the calculated slope (3.97) of the 2001 rating curve (the dashed line). The intercept value (615.291 m) is 2.8 cm higher than the intercept value calculated for the 2001 rating curve.

The inclusive rating curve, illustrated on Figure 5, has been influenced significantly by the 1994 and 1995 data. The calculated rating curve equation for these years (Q = 5.372 S - 3305.53) is similar in slope and intercept values to the Figure 5 inclusive plot. The 1994-1995 rating curve equation has a calculated r^2 value of 0.84, also similar to the 0.83 r^2 value for the inclusive rating curve. While these r^2 values (explained variance) are acceptable and imply that the inclusive rating curve is a reliable model for predicting outflow discharges, the fundamental assumption for the construction of a rating curve, that of channel regime, appears to have been violated. From 1994-1995, Clear Creek was not in regime, but degrading as it adjusted the stream channel geometry, specifically the elevation of the outlet sill, to accommodate outlet flows from Clear Lake. Consequently, the inclusive rating curve for Clear Creek should not be used for the estimation of outflow discharges from Clear Lake. In 1996 the rating curve intercept value was 615.24 m. The comparative value, five years later, in 2001 was 615.26 m, suggesting that the average outlet sill elevation had not changed significantly since 1996 and that Clear Creek had achieved regime. That being so, it is the 2001 rating curve (Figure 5) that should be used to estimate outflow discharges from Clear Lake.

Conclusion

From 1993 to 1996, Clear Creek has adjusted its geometry (average width, depth and slope) to the sequences of outlet discharges from Clear Lake. Since 1997, the outlet stream has achieved regime, predominantly by stabilizing the elevation of the outlet sill with a channel armour resistant to normal spring outflow discharges.

This study indicates that lake levels can be used as an effective alternative to channel stage in the construction of a rating curve for lake outlet streams which have achieved regime. In the case of Clear Lake this eliminates the problems related to the measurement of stage caused by beaver dam flooding and variable backwater effects. The resulting curve and mathematical model can be employed to estimate daily outflow from the lake.

References

BLENCH, T. 1969 *Mobile-Bed Fluviology* (Edmonton: University of Alberta Press)

CLEMSON UNIVERSITY 1991 'Clemson beaver pond leveler' *Clemson University Department of Aquaculture, Fisheries and Wildlife AFW Leaflet 1*

DUBOIS, J. 1997 'Riding Mountain National Park Ecosystem Conservation Plan' *Canadian Environmental Assessment Act Registry Number RMNP000017*

GALAY, V.J. 1971 *Some Hydraulic Characteristics of Coarse-Bedded Rivers* unpublished PhD Thesis, University of Alberta

HERSCHY, R.W. 1985 *Streamflow Measurement* (New York: Elsevier Applied Science Publishers)

LO, S. 1992 *Glossary of Hydrology* (Taipei, Taiwan: Sheng Te Printers).

McGINN, R.A., PARSONS, F.S. and ROUSSEAU, P. 1998 'Snowmelt and Lake Levels in the Clear Lake Watershed' *Technical Report* (Wasagaming, Manitoba: Riding Mountain National Park)

TERZI, R.A. 1981 *Hydrometric Field Manual - Measurement of Streamflow* (Ottawa: Inland Waters Directorate, Water Resources Branch)

WOLMAN, M.G. 1954 'A method of sampling coarse river gravel' *Transactions of the American Geophysical Union* 35:6, 951-956