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Northern Streams during Spring Break-up

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"PHOTOGRAMMETRIC MEASUREMENT OF DISCHARGE IN
ICE-CHOKED NORTHERN STREAMS DURING SPRING
BREAK-UP"

submitted by David Allan Sherstone, B.A., in partial
fulfilment of the degree of Master of Arts.

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CHAPTER 1

INTRODUCTION TO THE STUDY

1.1 Study Rationale

One facet of work in arctic hydrology involves the study of river ice break-up. The short period of ice destruction, particularly in northern streams, is responsible for sediment production, bank and bed scour, initiation of bank slumping and flooding from backwater effects of ice jams. Study of river ice break-up has been hindered by a lack of quantitative ice and water data. Stream velocity and water discharges cannot be obtained accurately throughout this period. In some locations bank scour and ice shove events destroy bubbler gauge and stilling well gauging equipment, while jam-induced backwater at the gauge site can cause large errors in recorded values. Additionally, development in northern areas, particularly when involved with large engineering projects, requires collection of hydrologic data in areas where data collection systems do not exist.

Discharge values are perhaps most important in understanding ice jamming and break-up events. A methodology is required to obtain discharge values for the break-up period. If possible a method of remote sensing of major hydrologic events on streams is to be desired. If discharge values at or near peak flow can be obtained from such a system then preliminary engineering design studies may commence without the need to visit each site. If discharge values could be obtained photogrammetrically it would further be desirable to develop a less sophisticated remote sensing system which was usable by field officers without specialist photogrammetric training.

What is proposed is to utilize aerial photography of northern rivers at break-up to obtain discharge values. Velocities determined from air photo stereopairs, used in combination with channel cross-profile data can be used to calculate discharges. From such work it is then proposed to further develop an analytical relationship between channel geometry and velocity which will permit calculation of discharge in areas where no stream gauging network exists. If such a method were feasible then development of an approach which permits use of non-metric, 35mm camera systems to obtain velocity data may be possible. The immediate scope of this thesis is to use aerial photography of northern rivers at break-up, with established ground control to obtain discharge values which can be compared with values published for the same sites, by Water Survey of Canada. This is to be done by; a) mapping the surface velocities of a test reach of river, b) from this surface velocity map the average channel velocity is calculated, c) a cross-profile in the test

reach is then used to calculate discharge from the equation $Q = VA^{(1)}$,
 d) the results from this approach are then compared with published discharge values for the same site on the same date to determine the accuracy of the method and the suitability of such an approach for operational use.

To this end two methods of obtaining discharge data were attempted. The first method evolved from velocity measurement studies first outlined by photogrammetric researchers such as Cameron (1962) and Forrester (1960), which combined a photogrammetrically derived velocity estimate in ice covered and/or turbid waters with cross-sectional data provided by the Water Survey of Canada. The second approach and that most applicable to isolated northern streams, uses a combined photogrammetric-analytic method, deriving some data from aerial photography and some additional empirical data through the application of Manning's equation and cross-sectional data.

The use of Manning's equation has appeal since the formula is widely known and used. The equation is developed such that;

$$V = \frac{R^{2/3} S^{1/2}}{n}$$

(1) where: Q = discharge, in $m^3 \cdot sec^{-1}$, A = cross-sectional area of the channel, in m^2 and V = average velocity at the cross-section, A , in $m \cdot sec^{-1}$.

where V = average channel velocity, in $\text{m} \cdot \text{sec}^{-1}$
 R = hydraulic mean radius, in 'm'
 S = longitudinal slope of water surface, in $\text{m} \cdot \text{km}^{-1}$
 n = Manning's resistance coefficient

Practiced engineers and hydrologists can estimate 'n' (roughness) values with reasonable accuracy. The data which must be collected at the site is thus reduced, a major benefit in isolated areas.

For use in discharge calculations however Manning's equation must be modified to permit solution with data obtained from aerial photography wherever possible. The hydraulic radius, R , for uniform rectangular channel, is equal to

$$\frac{A}{(2d + W)}$$

where d = channel depth, in metres

W = channel width, in metres

and $(2d + W)$ = the wetted perimeter.

Leopold, Wolman and Miller (1964; pp. 156-157) note that in extremely wide, shallow channels the wetted perimeter can be reduced to W . Then $R = \frac{A}{W}$. If these conditions exist Manning's equation can be modified to yield

$$V = \frac{\left(\frac{A^2}{W}\right)^{2/3} S^{1/2}}{n}$$

Figure 1-1a

**LOCATION OF LIARD
AND MACKENZIE
RIVERS WITHIN
NORTHERN CANADA**

Figure 1-1b

**LOCATIONS OF STREAM
VELOCITY TEST SITES,
MACKENZIE RIVER
BASIN, 1972 - 1974**

from which it can be found that;

$$A = W \sqrt{\frac{\bar{V}_n}{S^{1/2}}}^3$$

Theoretically the value required for 'S' can be determined photogrammetrically but in practice this is not possible with sufficient accuracy for the needs of this approach. Values for both 'n' and 'S' are obtained from ground based measurements.

1.2 Methodology Review

Examination of air photography taken by the Glaciology Division, Environment Canada (now the Snow and Ice Division, National Hydrology Research Institute) of the 1972 break-up of the Mackenzie River, N.W.T. (Figure I-1a), resulted in several observations related to ice in northern rivers. Where ice floes covered a significant area of the water surface and aerial photography was flown directly over and parallel to straight reaches of river a false parallax effect was apparent in the water surface. This false parallax, caused by movement of both the aircraft and the water surface relative to the stationary land mass, causes a 'hill-and-valley' topography to appear in the stereographic image of the ice debris on the water (Figure I-2). The apparent height or depth of individual ice blocks above or below the shoreline is a function of the magnitude of horizontal displacement between successive photo exposures. The use of a parallax bar to measure the apparent height or depth of individual blocks is then possible to estimate horizontal block displacement.

Figure 1-2

A STEREO-PAIR, A30460 IR 67-68, MACKENZIE RIVER; ILLUSTRATING TOPOGRAPHIC RELIEF EFFECT CAUSED BY ICE MOVEMENT

Subsequent study of 1972 false color, infra-red photography of the Sans Sault Rapids - Carcajou Ridge area of the Mackenzie River showed that when turbidity was high the water surface itself became sufficiently opaque to permit observation of topography in areas devoid of ice. Application of photogrammetric principles to these vertical displacements above a shoreline datum indicated that displacement of an ice block and/or the turbid water surface is a direct function of downstream velocity. That is, the greater the horizontal movement between consecutive exposures, the greater the apparent displacement relative to the shoreline, and the greater the downstream velocity component. The direction of aircraft flight relative to streamflow determines whether the water surface appears depressed or elevated on stereo photo pairs relative to the shoreline datum. If the camera aircraft travels upstream the surface appears depressed on stereo photo pairs, while flights downstream cause the apparent surface to be elevated.

The availability of a first order stereoplotter and a knowledge of topographical and thematic map production techniques suggested that contouring of the water-ice surface would be possible. This would permit the selection of velocity values at any point throughout a channel reach where moving ice was concentrated or the water extremely turbid.

In 1973 and 1974 photography was acquired along the Mackenzie River in conjunction with studies on the hydrologic aspects of Mackenzie Valley pipeline development (Figure I-1b). Examination indicated that study of the mechanisms of ice jam creation and destruction required stream velocity and stream discharge data.

Conventional methods of discharge measurement are unavailable on ice jams and many large jams occurred in regions where no measurements existed. For these specific situations the possibility of using photogrammetrically derived data to generate values for velocity and discharge were worth investigation.

CHAPTER 2

PREVIOUS WORK IN THIS FIELD

2.1 Initial Research by Cameron and Forrester

Early work on the determination of velocity or vector values of water masses from aerial photographs was by Cameron (1952, 1962) and Forrester (1960). Cameron in his 1962 paper "Water Current and Movement Measurement by Time Lapse Air Photography" was concerned with large, near shore current patterns and velocities through the straits of Canso, Nova Scotia, while Forrester described stream velocity measurement on the Rideau River, Ontario in his report "Plotting of Water Current Patterns by Photogrammetry".

Cameron used high altitude photography (of a type not specified) in an early Wild stereoplotter to map movement of visible surfines, wave crests or debris markers. Two conditions were recognized as necessary for airborne measurement of velocity; a marking of the water surface and a stationary reference to act as a baseline for calculations. His studies, which concentrated on natural markers such as foam or visible wave crests, used

photo scales from 1:6,000 to 1:60,000. Within this range accurate measurement of velocities from .40 km/h to 22.5 km/h were possible. The limiting factors were: marker displacement between successive photographs less than .01 mm at photo scale, areas of water surface without stereo definition; and separation of wind action from current action on small scale photography.

Forrester applied Cameron's concepts and techniques but advanced the method through the use of plywood targets, 1.2m x 1.2m, to provide visible identifiers on the water surface. Photography was obtained at larger scales by flying at 915 m and 1830 m altitudes and mapping at 1:2400 scale to ensure target and control point visibility. As with Cameron's investigations velocity vectors were calculated for each of the targets. Values obtained agreed well with metered values obtained from bridges with the test section. This test section exhibited considerable sinuosity and because of this discrete measurements of targets and visible foam patterns were made in both the X and Y directions using a Wild A-7 stereoplotter. Forrester did not quantify the accuracy obtained in his study, and claimed only that photogrammetric and ground obtained current velocity values had a "very good" agreement. (1)

(1) A detailed description of limitations and measurement techniques of high accuracy stereoplotters as pertains to X and Y directioned parallax, is in the Manual of Photogrammetry, 3rd edition, Vol. 2, pp. 610-612. It is ironic that the illustration used (p. 1111) shows ice debris in a channel bend, an unfortunate choice since this situation represents the most difficult measurement task possible for determination of the discrete block downstream velocity component.

The calculation of velocity in each case involved a two stage plotting procedure. Since the flight lines were linear over sinuous channels the velocity vectors were not constantly parallel to the flight line. A stereoplotting instrument measures parallax in only one direction (X), once orientation of the photographs in the machine is complete. For the early studies it was necessary to identify the targets individually, measure the apparent parallax (displacement) in the X direction for these targets, and then rotate the photographic diapositives 90^0 , reorient the stereo model, and measure any displacement in the Y direction. The calculated vector values for specific points were then obtained, and direction and magnitude of velocity values for different channel surface areas interpolated by hand contouring.

2.2 Other Research

Initial work by Cameron and Forrester created little interest as a tool for river studies in North America. Other researchers; Oros (1952) and Keller (1963), applied the techniques to estuarine studies, and experimented with various manufactured marker materials (such as air mattresses filled to 1% bouyancy factor), in order to better match the response of the target to the water body. Keller (1975) repeated attempts to determine the movement of sediment or pollution in estuaries, shifts in channels, navigation aid studies and debris drift in navigable waters.

Accuracies obtained using such techniques have been high; where a detailed ground control network has been established. Duhaut (1972) compared both upstream and downstream flights over channel markers and shipwrecks in the Thames estuary. He found, using Multiplex stereoplotting equipment, that current speed and direction values derived photogrammetrically are within 0.02 - 0.05 m/sec of velocities determined by current meter.

Of the two limitations noted above the photogrammetric calculation of vector values can be significantly simplified by proper planning prior to the acquisition of photography. If the aircraft flies directly over and parallel to a straight reach of river then Y motion of the ice-water matrix need not be calculated. The apparent topography in the water surface is the result of parallax in the X (downstream) direction only. Where movement in the Y direction is large it will be viewed in the stereoplotter as an area in which the height measuring floating marks (or "dots") cannot be fused and thus cannot be plotted. Back eddies will appear as a series of oppositely displaced contours relative to those plotted for the main water body. Both Forrester (1960) and Moffit (1968) recognized that photography aligned over the centreline of a straight channel reduces Y-direction parallax. Moffit used a known straight channel (a flume) and aligned his cameras normal to the centreline.

From such a position he was able to produce diapositives from which almost complete removal of residual Y-direction parallax was possible during orientation in the stereoplotter since he was concerned with study of a

specific wave form during ship model towing trials. To define the water surface I.B.M. card punch confetti was broadcast over the surface prior to each trial, in many ways analogous to the use of ice debris in the current study. In measurements of stationary wave forms with what Moffit defined as, "...this relatively crude system", accuracies of 0.5 mm at the Balplex model scale were achieved. This represented an error of 0.8% of the maximum wave amplitudes measured in the towing tank.

Straight reaches in natural channels may not be common to all types of streams but the remote sensing techniques are of interest on streams too large to be measured easily on the ground. Smaller streams can be gauged from bridges, culverts, felled trees, etc., and stage gauges may survive a gentle break-up. Conventional methods are not useable on major streams, those likely to suffer the most violent ice action, backwater effects and flooding during ice clearance. The size of large streams, even if the channel meanders, is such that a relatively straight reach of appropriate length (1 km or so) can be selected at or near the desired discharge measurement site. Remote sensing by conventional aerial photography can provide, at the least, surface velocity values.

Russian experience in aerial stream velocity measurement using discrete markers on an operational basis (Kuprianov, 1978; Shumkov, 1973) supports the technique of remotely sensed measurement. From the Russian work one point is noteworthy, aerial measurement of velocity becomes more accurate with increased flow velocities.

Discharge measurements for streams with velocities from 1.0 - 2.0 m/sec varied by 5-6% from ground measured discharges (Kuprianov, 1978); streams with velocities between 0.1 - 0.5 m/sec however showed a variation of 10 - 15% from measured flows.

A curious difference in approach between that of Shumkov and the present study is that much of the Russian photography appears to have been flown normal to the direction of flow. The rationale behind this is not clear but may be related to the method used to drop targets aerially across the flow. Photography is then acquired on a return flight line over the same ground control used to locate the target drop area. As a result of this technique a complex analytical solution is required to obtain velocities in the section and calculate discharge.

Measurement of velocity by use of remotely sensed data has become widely accepted in the past decade usually through the use of discrete markers introduced to the flow. This requires costly equipment and/or time consuming ground support operations. A major advantage offered by turbid or ice-choked waters is that the density of ice wreckage and high turbidity provides a large number of points from which to extract data. The use of a few targets, which provide incomplete data, is avoided and a greater flexibility in the location for measurement becomes available. However, data from turbidity or broken-ice cover is available only for a short interval since ice break-up along any one river stretch is a short-lived phenomenon.

Present surface stream gauging methods are not effective in ice break-up periods and actual measurements of discharge under such conditions are impractical and unsafe. Published records of discharge for events in Canada during the break-up are actually estimated flows produced by extension of the corrected stage-discharge hydrograph, although calibrated cross-profiles are available at or near gauging stations for both winter and summer flows.

CHAPTER 3

METHODOLOGY OF PHOTOGRAMMETRIC DISCHARGE MEASUREMENT

3.1 General Approaches

Two approaches are available for calculation of discharge once average velocity and cross-sectional area are known. In the basic case the stage level value is used to determine the water level which exists on the date of photography and the cross-sectional area at that level calculated for input to the equation $Q = VA$. In a modification of this method a stage-discharge curve can be constructed for any long-term test site and stage readings, obtained from aerial measurement of stage below a fixed datum on the bank, used to yield the corresponding discharge values. See Figure 3-1.

Method 1.

If no ground data exists and the site is accessible only with extreme difficulty then another possibility, as yet untested, is to rephotograph the test section under late summer, low flow conditions. A contour map of the almost completely exposed channel would then provide an approximation of the

Figure 3-1

METHOD 1: GROUND PLUS REMOTE SENSING

channel cross-section. Such an approach might bypass all ground work but at reduced accuracy. Ideally however a technique which requires no directly measured data is desired. Church and Kellerhals (1970) in a study of arctic streams suggested that discharge calculations can be made using Manning's formula to estimate velocity for insertion into the formula $Q = VA$, where A is unknown. (See Figure 3-2, Method 2). In this approach remotely sensed data can provide all data except A and n ; of which n can be assigned after channel observation, and a value for A then calculated. This calculated value for A can then be used in $Q = VA$ to obtain discharge.

The first method is not completely a remote sensing technique since steps 1 and 2 of the ground derived data are necessary to obtain step 8 of the airborne - photogrammetric segment. An alternative to steps 1 and 2 is to obtain a cross-section at minimum low water condition and use this relatively water free cross-profile to calculate the area A . (See Figure 3-1).

The second method, which would permit completion of the task without extensive ground work combines data from remote sensing with the empirical approach used by hydraulic engineers for natural stream channels. With two exceptions all data can be obtained from aerial photography. Only values for water surface slope, " s ", and Manning's roughness coefficient, " n " are required from ground measurement. (See Figure 3-2).

Figure 3-2

METHOD 2: REMOTE SENSING/EMPIRICAL

3.2 Testing Required for Photogrammetric Approach

3.2.1 Aerial Photography

System constraints existed in the acquisition of aerial photography due to an inability to sustain flight about 10,000' (3,050 m) above sea level. This results from a lack of oxygen equipment for the aircrew and heating and pressurization systems for the aerial camera. Since the Wild RC-10 camera (240 x 240 mm; 9.5" x 9.5" format) utilizes a 151 mm (6.0") focal length lens, the maximum possible photo scale is 1:20,000. The available Wild A-7 stereoplotter can enlarge or reduce such photo scales by a factor of $\pm 3:1$.

The camera is equipped with an automatic shutter speed control 'slaved' to a Wild NF-2 navigation sight. This permits the operator to control navigation of the aircraft over the photo lines and prevents yaw or 'crab' errors caused by crosswind-induced aircraft drift (Figures 3-3 and 3-4).

Ideally photographs must be acquired along a flight line centred over the channel and include sufficient land area to allow orientation and clearing of parallax in each stereo model. The stereo-pairs must maintain this balance throughout the line.

Film selection is straightforward. Since water penetration is not required, in fact is not desirable, color photography offers no advantages. Similarly color or false color infra-red photography is not justified on the basis of the small water-definition gains when weighed against much higher

Figure 3-3 AERIAL CAMERA MOUNTED IN
BEECH 18 AIRCRAFT

Figure 3-4 NF-2 DRIFT SIGHT USED TO
CONTROL CAMERA

costs. Panchromatic film has been used on all test photography since 1974.⁽²⁾ The majority of work used Kodak XX, 2405 Aerographic film, but some was completed with Kodak Plus X, 2402 Aerographic or Kodak Tri-X, 2403 Aerographic films. The actual photos utilized for all stream velocity studies to date, and the pertinent data associated with these photos is presented in Table 3-1.

3.2.2 Stereoplotting

The actual construction of the test maps (plots) was completed on a Wild A-7 stereoplotter coupled to an autograph plotting table. In initial tests (Sherstone, 1973; Mackay, Sherstone and Arnold, 1974) various map scales were used. Control of the map's horizontal dimensions was obtained by plotting features easily identifiable on 1:250,000 or 1:50,000 maps as control points. After enlargement of the stereographic model to a convenient size for adequate surface water definition the actual scale of the plotted model was calculated. As long as X, Y and Z (vertical) ratios are correctly selected from those published in the stereoplotter manual for any given scale the values assigned to the contours can be directly translated to downstream velocities.⁽³⁾

(2) Some 1972 and 1973 photography utilized color positive or color infra-red film, since the original Mackenzie Valley photography program was designed around other uses.

(3) The contour interval used is determined by contour line separation in the most densely contoured zone (i.e. areas of highest velocity gradient) which will provide sufficient clarity for interpretation at the 1:10,000 scale. This requires a velocity contour line separation in the X and Y directions of at least 1.0 mm.

TABLE 3-1

DETAILS OF AIR PHOTOGRAPHY USED FOR STREAM VELOCITY STUDIES DESCRIBED IN THESIS: 1975-1978

ALL PHOTOGRAPHY 151 mm (6.0") FOCAL LENGTH

<u>Site No.</u>	<u>N.A.P.L.* Roll & Photo Nos.</u>	<u>Date Exposed</u>	<u>Flying Height (A.S.L.)</u>
76-3	A24002 256-259	May 7, 1975	2438 m (8,000 ft)
77-1	A24639 129-133	May 2, 1977	2438 m (8,000 ft)
78-1	A24861 19-22	May 5, 1978 ⁹	2073 m (6,800 ft)
79-1	A25112 236-239	May 12, 1979	2743 m (9,000 ft)
79-2	A25112 189-193	May 11, 1979	2347 m (7,700 ft)

* N.A.P.L. = National Air Photo Library
 Dept. of Energy, Mines &
 Resources
 615 Booth St., Ottawa

Figure 3-5

MACKENZIE RIVER A-7 TEST SITE #15B

MILE 606 (CARCAJOU RIDGE AREA)

HORIZONTAL SCALE: APPROX. 1:31,200

VERTICAL SCALE: APPROX. 1:8,333

CONTOUR INTERVAL; REAL, 1.0 mm.

~~APPARENT: APPROX. 65 FT.~~

PHOTO INTERVAL; 23 SEC.

WATER DATA AND SHORE DATA ARE NOT RIGIDLY
TIED VERTICALLY DUE TO EXCESSIVE RESIDUAL
PARALLAX ALONG RIGHT EDGE OF MODEL, SHORE
CONTROL POINTS FOR LEVELING ARE NOT READABLE
IN BOTH SET-UPS

To proceed beyond velocity values to discharge measurement, more accurate control of X and Y errors in the map base was required. Two measures were taken for the 1977 photography to upgrade the map accuracy. First a control grid network of Z (vertical) values was established, by barometer survey on May 3, 1977. Second a 1:50,000 topographic map (N.T.S. 95^H/13) was enlarged to produce a 1:10,000 scale base map. The vertical control was tied to known survey data at the Fort Simpson airport. With control points established along the shoreline, well away from the actual water surface on that date, it was possible to accurately level the stereo model. Surface water slope at the Liard test site was then correctly portrayed in the stereoplotter and used to obtain data for use in Manning's equation.

The use of an enlarged 1:50,000 map is not without difficulties. When enlarging such a map (particularly if preliminary N.T.S. sheets are used) errors and inaccuracies are increased by a factor of four. Without a new topographic base map being produced specifically for each velocity/discharge measurement site greater accuracy is not available. After map enlargement a best fit between control points on the photos and those on the ground is made, prior to compilation of each stereo overlap or 'model'. This scaling or fitting procedure is necessary since ground detail, when used to scale the model to the base map, eliminates any scale variation which would be caused by attempts to fit channel water surface width at different flow regimes to a single base map. If this fitting is not done then results are similar to velocity contour attempts made prior to 1975 where the horizontal and vertical are indicated as being "approximate", (Figures 3-5, 3-6 and 3-7). This is due to

cut line

MACKENZIE RIVER A-7 TEST SITE 73-1

MILE 375 (OCHRE RIVER AREA)

CONTOUR INTERVAL APPROX 0.14 m. sec^{-1}

NOTE 'DASHED' CONTOUR LINES INDICATE AREAS
OF SLIGHT RESIDUAL PARALLAX PREVENTING
COMPLETE CERTAINTY IN LOCATING CONTOURS

FEET 2000 1000
METRES 500 250

HORIZONTAL SCALE APPROX 1:18,800
0 2000
0 500

2000 4000 FEET
1000 1500 METRES

MACKENZIE HIGHWAY

3 of 3

AKE

MACKENZIE RIVER A-7 TEST SITE 73-2

MILE 280 (CAMSELL BEND AREA)

CONTOUR INTERVAL: APPROX. ~~54 M.P.H.~~ 0.24 m. sec⁻¹

FEET 2000 1000
METRES 500 250

HORIZONTAL SCALE: APPROX 1:15,000
0 2000
0 500

4000 FEET
1000 METRES

the use of spring break-up photography on a map base derived from late summer photography. When this occurs, particularly in broad shallow channels with wide floodplains, the river width in spring flood may be considerably greater than the channel shown on a topographic map. In the 1973-1975 examples the stream channels were matched in width, ignoring the scale variations thus introduced. In several cases such as the Sans Sault Rapids site (Test site #15B, 73-3; Figure 3-5) and Camsell Bend (Test site 73-2, Figure 3-6) the channel does broaden significantly in high flows without bank constraint. In a case such as Wrigley (Test site 73-1, Figure 3-7) a bed-rock channel and steep, relatively stable banks result in little change in width with increased discharge.

At the long-term Liard River test site no major difficulties were encountered in alignment of the barometric control points, aerial photography and enlarged base map, but changes in cultural (planimetric) detail are evident near the ferry crossing.

Once the stereo overlap is contoured and vertical values of several control points recorded the adjacent stereopair is oriented in the stereoplotter and contours are extended along the test reach through the second model. By repetition of this technique upstream and/or downstream of the initially contoured stereo model a complete test reach several kilometres long can be contoured to yield sufficient contours to allow determination of surface velocity across the channel surface at locations of known cross-sectional area. The contour intervals can then be assigned correct downstream velocity.

Figure 3-8

SIMILAR TRIANGLE SOLUTION FOR ICE BLOCK VELOCITY CALCULATION

values obtained from either measured displacements of individual ice blocks between successive photos, at photo scale or from calculation of displacement by distance-exposure interval relationships (Figure 3-8). The choice of approach is determined by convenience and the ability to identify discrete ice block features.

In the first case the displacements of several ice blocks between each successive exposure are recorded. Given the interval between each exposure (to the nearest half-second) the velocity of individual blocks can be calculated. Since the velocity contours are plotted as a displacement at map scale the unit velocity calculated from block measurement can then be assigned a velocity at the map scale. Each contour plotted is a multiple of unit velocity and a complete picture of downstream velocity values can be derived.

In the second method a similar triangle solution based on aircraft versus ice block movement in a fixed time interval (exposure interval) can be used to obtain a velocity value for each contour (Figure 3-8).

It should be emphasized that contouring is only possible when:

1. the water is sufficiently turbid to produce an opaque or near opaque surface, and/or,
2. heavy concentrations of ice debris are present in the channel surface area of the stereo model.
3. little residual Y parallax remains in the channel surface area of the stereo model.

If these conditions are not met the image appears unfocused and velocity contours cannot be plotted. This may only occur in a small area of the water surface and for this area data are extrapolated. In test site 73-3 (Figure 3-5) the lack of sufficient opacity of the water surface after orientation of the stereo model prevented determination of the mean cross-sectional velocity. Back eddies are plotted as 'depression' contours and can be assigned velocity values without difficulty.

Individual ice blocks may appear slightly elevated or depressed relative to the apparent water surface when contouring a water surface-ice matrix. This disparity and resultant variation in downstream velocity is due to different flow velocities of the water mass and the ice debris. The ice exhibits slippage between the individual block and the water mass. This is due to exposed sail area of the ice being acted on by wind combined with inertia forces on the block. As contouring proceeds the net effect of this action is to generate a variegated shape to the contours near the thalweg (generally the heaviest ice transport zone). Since contour data are converted to velocity values such contours can be smoothed or repeated velocity cross-sections can be averaged. Where velocities are low or ice buoyancy reduced, dampening wind action, the contours are sufficiently convolution-free to obviate any modification.

3.3 Discharge Values - Photogrammetric/Analytic Approach

Calculation of discharge commences with calculation of cross-channel surface velocities from the contoured test plot. The cross-section used for velocity measurement should, if possible be located at or close to the

cross-profile used to obtain cross-sectional area. Figures in Appendix A illustrate the cross-sections used for the 1977 tests.

With the remotely sensed technique only surface water velocities are available. Following accepted practice surface values must be multiplied by 0.80 to produce mean velocity values in the channel. While several authors suggest values from 0.75 to 0.95 of surface flow, the most widely accepted value (Water Survey of Canada; U.S.G.S.; Leopold, Wolman and Miller, 1964; Church and Kellerhals, 1970; and Kuprianov, 1978) is used within this report.

CHAPTER 4

HISTORY OF PRESENT PROGRAM AND SELECTION OF A STUDY SITE

4.1 History of Present Program

The Glaciology Division, operating its own aerial photography program in support of major research projects throughout arctic Canada, was able to photograph the Mackenzie River, N.W.T., before and during the spring break-up of 1972 and 1973. Examination of this photography in 1974 found extensive areas of topographic relief present in the water surface of photography acquired over broken ice cover. A search of the literature, outlined above, revealed that the principles of velocity measurement were known. Tests were made to determine the applicability of such techniques to northern rivers where complete survey of photogrammetric control was not available. With the realization that modification to or combinations of various existing techniques might yield data of interest to hydrologic researchers random samples of debris covered waters were plotted as part of a larger study on channel ice effects (Mackay, Sherstone and Arnold, 1974).

While surface water velocities were of interest, of greater value are discharge measurements. To obtain such values the cross-sectional area of any channel is required. Sites within the Mackenzie Basin which are gauged by the Water Survey of Canada were examined to determine a suitable location to determine discharge from aerial photography and act as a calibration point.

4.2 Selection of a Long-Term Test Site

The criteria for selection of a test site for photogrammetric measurement of discharge are complementary to those for establishment of a permanent gauging station. The criteria for photogrammetric measurements of discharge are:

- 1) a straight channel reach of sufficient length to obtain several overlapping stereopairs within the reach,
- 2) a channel width such that moderate aircraft altitudes (750 - 3000 m A.S.L.) provide both economical photo coverage and a photo scale that yields sufficient land detail on both sides of the channel to permit proper stereoplotter orientation,
- 3) a channel section of relatively constant gradient (i.e. no rapids or standing waves). This aids in establishing survey control for photogrammetric plotting by use of widely separated points along the shorelines,
- 4) a channel reach with a stable bed profile so that velocity-cross profile-discharge relationships will not change between successive photo flights.

Figure 4-1

LOCATION OF 1976-1979 LIARD RIVER
STREAM VELOCITY AND DISCHARGE
MEASUREMENT TEST SITES

The Water Survey of Canada, when establishing gauge site calibration profiles, attempts to locate a straight and stable reach in order to reduce the number of cross-profile transects required for gauge calibration each year. The stability of sections is particularly desirable in remote areas.

In 1972 and 1973 locations of aerial photography were beyond the control of the author. As a result velocity measurements could only be made with available photography. Additionally, since photography was taken to record the downstream advance of ice destruction much of the photography did not detail the required ice debris/turbid water zones upstream of the solid ice edge. In 1973 several locations were identified as frequent locations of ice jams, likely to contain upstream concentrations of ice debris, which met the qualifications noted above. Several of the sites were locations of proposed Mackenzie highway, ferry or gas pipeline crossings or proposed wharf sites. In only one case however was a gauge site or calibration cross-profile located at or near a proposed aerial study site.

This site, on the lower Liard River, N.W.T., near the Mackenzie Highway ferry crossing (Figure 4-1) has several advantages as a test site. These are:

- 1) a relatively straight reach with easily seen navigation targets for the photo aircraft,
- 2) a record of ice jamming at the midpoint of the section,
- 3) a Water Survey of Canada stage level recorder (bubbler type gauge) located upstream of the common ice jam locations,

- 4) the Mackenzie Highway, Liard ferry crossing at approximate midpoint of the stretch which provides road access to the test area throughout the year,
- 5) a Water Survey of Canada cross-profile calibration site, near the downstream end of the reach which provides cross-sectional data for the airborne method.
- 6) a major airport facility within 2 km of the site, useable as a base for the photo aircraft, which permits rapid response to ice break-up events,
- 7) surveyed markers at the airport terminal and perimeter which permit establishment of vertical control points at the test site,
- 8) access to cross-profile and flood level records obtained by private researchers engaged in proposed bridge studies for the upstream end of the test reach. This group also plotted the position of the thalweg through the test reach in 1975.

4.3 Description of Test Site

The test site is a stretch of the lower Liard River, N.W.T., lying 12 km to 19 km upstream of the confluence with the Mackenzie River (at approximately latitude $61^{\circ} 45' N$, longitude $121^{\circ} 13' W$) and 18 km from the settlement of Fort Simpson. (Figure 4-2). The Liard is the major tributary to the Mackenzie, and drains an area of $227,000 \text{ km}^2$ within the Northwest Territories, the Yukon Territory, and British Columbia.

During the spring flood period Liard discharge may contribute as much as 60% of total Mackenzie discharge at Fort Simpson. Spring ice break-up on the Liard acts as a trigger mechanism to initiate ice movement on the

Figure 4-2
 DETAILED VIEW OF
 1977-1979 LIARD RIVER
 VELOCITY AND DISCHARGE
 MEASUREMENT TEST SITE

Mackenzie River. In years of high flow and strong Mackenzie ice, ice jam floods have inundated the settlement of Fort Simpson.

The immediate region of the Liard-Mackenzie confluence is in the Great Slave Plain physiographic zone (Rutter, et al. 1973), generally an area of discontinuous permafrost in fine grained lacustrine deposits and glacial tills. The Liard has not altered course significantly since early post-glacial formation and is entrenched with valley walls from 22 - 38 m high. The floodplain is infrequent and narrow (Day, 1966). Deltaic sediments are common downstream of the test section, laid down when Lake McConnell existed in the early post-glacial period of the upper Mackenzie Valley.

The area on either side of the test section is covered by organic soils which overlay lacustrine or till deposits. Vegetation in well drained areas is white spruce and balsam poplar, while poorly drained organic soils are covered by lodgepole pine, jackpine and aspen (Tarnocai, 1973). In the immediate area, the right bank is composed of steeply sloped, eroded, lacustrine deposits and primarily stonefree sands, loams and silty clay loams. The left bank consists of less steeply sloped, eroded lacustrine sands and fine sandy loams (Day, 1966). The stream bed is alluvium, sand to silty clay in composition, with some gravel content. Low water sandbars exist near the left bank at the upstream end of the section and approximately .5 km downstream of the present ferry crossing. Dredging of the right bank shoals, to aid ferry access, results in a slight variation of the channel shape downstream of the crossing and localized increases in turbidity in spring

flows. A boulder pavement is developing above the edge of the occupied summer channel on the left bank, between km 17 and km 18.5. This is due to ice scouring action in spring break-up (Mackay and Mackay, 1977).

The region is underlain by Upper Devonian bedrock of the Fort Simpson Formation. Near the test area this is predominantly shale, with minor amounts of siltstone, sandstone and limestone (Rutter, et al. 1973). While bedrock surface expression is present upstream of the test section no bedrock is exposed within the reach.

The mean annual air temperature at Fort Simpson is -4°C . Total precipitation averages 358 mm, while snowfall is 130 cm per annum. Precipitation in the winters of 1977-78 and 1978-79 however was as much as 60% below the average.

The river freezes over completely by mid-November, and river ice achieves an average maximum thickness (in March) of 127 cm. Spring break-up, which occurs on the rising limb of the discharge hydrograph, is caused by increased snowmelt runoff, thermal weakening of the ice and increased water temperatures. Ice movement usually commences in early May and the channel is completely cleared of ice by late May.

Discharge in the system is variable, with winter flow approximately $425\text{--}510\text{ m}^3/\text{sec}$ (15,000 - 18,000 c.f.s.) and summer flows reaching values as high as $14,160\text{ m}^3/\text{sec}$ (500,000 c.f.s.). Maximum recorded flows are not

associated with spring break-up floods, but usually occur in June or July in response to heavy summer storm activity in the headwater basins.

The Liard is a major sediment contributor to the Mackenzie. While the channel is relatively stable over the lower 60 km major erosional and depositional action in headwater areas and in the Fort Nelson and South Nahanni tributaries results in a high turbidity throughout the year. Sediment loads during the spring break-up period can exceed 335 mg/l. (Grey 1978).

4.4 Channel Cross-Sections Within the Test Site

Cross profiles can be constructed from two sources, Water Survey of Canada gauge calibration cross-profiles for station 10ED002, and specially requested hydrographic sonar charts obtained by the Canadian Hydrographic Service in September 1977. In each case data recorded for the cross-sections does not correspond to river stage levels which existed when photography of the break-up was acquired.

In order to compensate for this factor modification of the cross-sections was required using stage level records provided by Water Survey of Canada. Details of cross-section construction and illustrations of the various sections are to be found in Appendix A.

Figure 5-1

EBA/NORTHWEST HYDRAULIC CONSULTANTS LTD. LIARD RIVER CROSS PROFILE
OBTAINED MAY 21, 1975 AND USED FOR SITE 76-3 DATA

CHAPTER 5

RESULTS OF PHOTOGRAMMETRIC TESTING 1976-1979

5.1 Introduction

Results of three approaches to velocity and discharge measurement are presented: use of a calculated cross-sectional area multiplied by velocities obtained from averaged contoured velocity values; a 20 sub-section approach similar to the Water Survey of Canada method; and a Manning's 'n' technique. In the original data collection, mapping and analysis these techniques were attempted sequentially, and modifications in data handling were made as the project progressed. Each year's data are not therefore completely identical to that of a previous year, the raw data either being refined prior to map plotting or supplemented to aid in elimination of difficulties.

5.2 Simple Approaches: Averaged Velocities

5:2:1 Case 1 (Site 76-3)

The cross-section used to determine channel velocities at this site (7km upstream of the ferry crossing, Figure 5-1), was measured by EBA/Northwest Hydraulic Consultants Ltd. This group also surveyed the river banks.

Figure 5.2

Table 5-1

DISCHARGE VALUES OBTAINED FROM AVERAGED
VELOCITY VALUE APPROACH

SITE 76-3

Section No.	Discharges from Point Velocity Average (in $\text{m}^3\text{sec}^{-1}$)	Section No.	Discharges from Contoured Velocity Average (in $\text{m}^3\text{sec}^{-1}$)
A-1/A-2	2236	B-1/B-2	2652
A-3/A-4	2184	B-3/B-4	2132
A-5/A-6	1846	B-5/B-6	2392
A-7/A-8	2054	B-7/B-8	1898
A-9/A-10	1846	B-9/B-10	1872
A-11/A-12	1534	B-11/B-12	1664
A-13/A-14	1768	B-13/B-14	1690
		B-15/B-16	1638
		B-17/B-18	1716
		B-19/B-20	1846
		B-21/B-22	1820
		B-23/B-24	2054
		B-25/B-26	1898
AVERAGE	1924		1944

Water Survey of Canada: Published Discharge for 2/5/75 $2070 \text{ m}^3\text{sec}^{-1}$

Cross-Sections used are detailed on Figure 5-3.

Water levels at this site were higher than simultaneous readings recorded at the Water Survey gauge site at the ferry crossing due to channel surface slope. From recorded water levels for the date of profile survey at both locations the slope can be calculated. A slope-water level - area nomograph was constructed to relate Water Survey stage data to site 76-3 (Figure 5-2). From this nomograph the water levels and cross-sectional area on the date of aerial photography were derived.

Photography of May 7, 1975 was plotted at a scale of 1:6350⁽¹⁾, and used to determine velocity for 20 cross-sections through the reach. Seven of these (A-1/A-2 through A-13/A-14) used contoured velocity data while 13 (B-1/B-2 through B-25/B-26) represented point velocity cross-sections (Figure 5-3; in pocket: Table 5-1).

Both point velocity and contoured velocity cross-sections were used to obtain a single mean velocity value ($\bar{V}$) for each section. These mean velocities were combined with the one (EBA) cross-sectional area (A), obtained from the nomograph to calculate discharge values for each section. The results of this approach are encouraging since the average of all calculated discharges using the point velocity averages was 93% of the published figure, while the contoured average velocity approach yielded a value of 94% of published values. The single worst case, that deviating most from published sources, was 128%, while the best single case was 99% of the published record.

(1) This area was outside of the available base map area for the remaining test sites and was plotted prior to standardization on 1:10,000 scale base maps.

Table 5-2

DISCHARGE VALUES OBTAINED FROM AVERAGED CONTOUR VELOCITY APPROACH
SITES 77-1, 78-1, 79-1, 79-2

1	2	3	4	5
Section				
No.	Site 77-1	Site 78-1	Site 79-1	Site 79-2
WSC-75	1007 ^(A)	977	819	2353
WSC-76	737 ^(A)	856	675	1921
63-64	n.a.	n.a.	n.a.	1717
67-68	n.a.	876	621	n.a.
73-74	1720	1118	965	2017
81-82	1627	843	618	1586
87-88	2443	1090	833	2718
91-92	2109	965	664	2030
99-100	2367	1009	727	2221
103-104	2273	938	647	1830
107-108	2597	936	786	1963
109-110	2490	859	683	1822
111-112	3690	1076	842	2264
Average				
Sections:				
WSC 75-81-82	1273	934	740	1919
Average				
Sections				
WSC-75 to				
111-112	2089	971	739	2017
Published				
WSC Discharge	1080	3115	1150	900

(A) values obtained through use of velocity values for 73-74
with area data for relevant cross-sections

5.2.2 Case 2 (Site 77-1)

Cross-sectional area data used at this site are from Hydrographic Surveys sonar profiles extrapolated above water-levels at the time of survey. Two Water Survey of Canada gauge site calibration cross-profiles are also included. Each cross-section has its own area and velocity estimate. When discharges are calculated for each of the cross-sections selected (Figure 4-2) the results show a trend of increased discharge values upstream, starting from section 73-74. Since this particular cross-section was plotted first, and prior to survey control being located at the ferry crossing, this increase in values was found to arise from absolute orientation of the stereopairs in the plotter without regard for the surface slope of the water.

As a result the stereopair first plotted, which contained cross-sections; WSC-75, WSC-76, 63-04, 67-68 and 73-74 exhibit minimal velocity errors due to this slope effect: For those sections located

- near the ferry crossing the average calculated discharge was $1273 \text{ m}^3.\text{sec}^{-1}$ compared to a published value of $1080 \text{ m}^3.\text{sec}^{-1}$. The
 - closest individual value, $1007 \text{ m}^3.\text{sec}^{-1}$ was 93% of the published value.
- Within cross-sections located beyond the immediate ferry crossing area (see Table 5-2) the closest value was $2109 \text{ m}^3.\text{sec}^{-1}$ (195% of published record) while the worst case was 342% of the accepted value. Those four values averaged for the ferry crossing area are within 18% of the published record.

5.2.3 Case 3 (Site 78-1, 79-1, 79-2)

The results of discharge calculations for these sites, using an averaged velocity approach, are presented as Table 5-2. For consistency these data are also subdivided into two groups, those near the

Figure 5-4

SITE 79-1, MAY 12, 1979 AT 0950h: NOTE GROUNDED ICE ISLAND AND NARROWED CHANNEL

ferry crossing and the remainder of more distant sections. Of these sites data from site 79-1 most closely approximates that of the published record. The averaged discharges of both the near-ferry and the complete data set are 64% of the published record. Data for sites 78-1 and 79-2 vary more widely, with the best group average of 213% and the worst 30% of the published value. The best individual values are 36% of the published sources for 78-1, 84% for 79-1 and 171% for site 79-2.

For these post-1977 test sites the apparent increase in discharge values upstream of the ferry crossing does not occur. This resulted from proper survey control of the stereo models. Still, values for sites 78-1 and 79-2 do not approach those published by Water Survey of Canada. Discharges for site 79-2 are high predominantly because of higher velocity values calculated for that date. While published discharge records may reasonably reflect the daily mean discharge (after removal of backwater and release effects), the recorded velocity values are most likely caused by a massive grounding of the ice downstream of the ferry crossing during this period (Figure 5-4). This caused a major reduction in the effective hydraulic cross-section. The resultant surface velocities would not therefore express the dominant velocities which existed throughout much of this period. It appears that backwater conditions also existed at the time of photography. The Water Survey practice of removal of such short term events prior to publication would result in an understatement of the actual discharges which occurred at (or after) the failure of an ice jam in this river reach. The photogrammetric method identifies velocities and thus should produce actual discharges at time of photographic overflights rather than a manipulated estimate of daily mean discharge.

It should be pointed out that throughout this study reference and comparison is made to "published values", "the published record", "accepted values", etc., when mentioning the Water Survey of Canada record of daily mean discharge data. Since the published values are often estimates, based on the open water stage-discharge curve, for a period when the recording gauges are inoperable there is in fact no absolute value which can be used to determine if the photogrammetric or the Water Survey value is correct. Water Survey values are widely accepted, and used by hydrologists and engineers, but it may be that the photogrammetric method produces more accurate data on instantaneous discharge. Such a possibility may explain the variation found in site 78-1. For a short explanation of Water Survey of Canada methods see Appendix B.

5.3 The 20 Sub-Section Approach

From the contoured velocity cross-sections, new velocity cross-profiles, sub-divided into 20 sub-sections were created. The 20 sub-section technique was chosen to simulate the field methodology used by Water Survey and other researchers to measure stream discharges (Wisler and Brater, 1959; Leopold, Wolman and Miller, 1964). The channel cross-sectional area was also subdivided into 20 equal width subsections. These velocity and area subsections were then used to calculate total instantaneous discharge in the manner;

$$Q_t = \sum_{i=1}^{20} \left[X \left(\frac{D_a + D_b}{2} \right) \times 0.8 \left(\frac{V_a + V_b}{2} \right) \right]$$

where: Q_t = total discharge, in $m^3 \cdot sec^{-1}$

X = horizontal distance, in m,
between vertical sections
(i.e. sub-sections width)

D_a = depth, in m, at beginning of
each subsection

D_b = depth, in m, at end of each sub-section

$Q.8$ = correction constant for velocity, to convert surface velocities to mean velocity

V_a = velocity, in $m \cdot sec^{-1}$, at the beginning of each sub-section

V_b = velocity, in $m \cdot sec^{-1}$, at the end of each sub-section

This technique was applied to all of the available test sites and the results are presented in Table 5-3. For consistency of presentation data after site 76-3 includes only those cross-sections which occur near the ferry crossing. This was done to eliminate increases in discharge values due to photogrammetric problems at site 77-1. For site 76-3 the averaged discharge was $1496 m^3 \cdot sec^{-1}$. The best value from this set was 83% of the published figure while the worst case yielded 59%. In the case of site 77-1 the average discharge was 136% of that published while the best and worst cases were 96% and 179% respectively. Site 78-1 has averaged discharges of 30% of the published value. Values for sites 79-1 and 79-2 are 58% and 185% respectively.

Except in the case of site 79-2 the averaged discharge values obtained with 20 sub-section approach are further removed from the published data than those of the averaged contour velocity approach (Table 5-2) and/or the point velocity averaged approach (Table 5-1). Throughout this 20 sub-section method individual values closely approach the published record but averaged data is consistently at odds with published data for sites 78-1 and 79-2. Some explanation for site 79-2 values has been given above (Chapter 5, section 5.2.3)

Table 5-3

DISCHARGE VALUES OBTAINED USING 20 SUB-SECTION
APPROACH; FOR ALL TEST SITES

Section No.	Discharges $M^3 \cdot sec^{-1}$				
	Site 76-3	Site 77-1	Site 78-1	Site 79-1	Site 79-2
A-1/A-2	1714				
A-3/A-4	1678				
A-5/A-6	1435				
A-7/A-8	1602				
A-9/A-10	1430				
A-11/A-12	1224				
A-13/A-14	1391				
WSC-75		1032 (A)	860	622	1615
WSC-76		934 (A)	825	528	1480
63-64		n.a.	n.a.	n.a.	1800
67-68		1650	843	557	n.a.
73-74		1930	1158	995	1748
81-82		1780	908	647	1693
AVERAGE	1496	1465	919	670	1667
WATER SURVEY OF CANADA: PUBLISHED DISCHARGE FOR SAME DATE AS TEST					
	2070	1080	3115	1150	900

(A) values obtained through the use of velocity values
for section 73-74, with area data for relevant
cross-sections

Table 5-4

SAMPLE SURFACE VELOCITIES FOR LIARD RIVER FROM
AERIAL PHOTOGRAPHY AND GROUND MEASUREMENT

Readings at Cross-Section 109-110: from Ground

May 2, 1975 @ 1345 h Average Velocity 1.1 m.sec^{-1}

Readings at Cross-Section 109-110: from Aerial Photos

May 2, 1975 @ 1040 h Max. Vel. of Ice Blocks 0.99 m.sec^{-1}
 Average Velocity 0.81 "

Readings at Cross-Section: Ferry Crossing: from Ground

May 2, 1975 @ 1430 h Average Velocity 1.2 m.sec^{-1}

Readings at Cross-Section 87-88: from Aerial Photos

May 2, 1975 @ 1040 h Max. Vel. of Ice Blocks 0.78 m.sec^{-1}
 Average Velocity 0.69 "

Note: Readings were taken at different times in the day which explains some of the difference between values measured by different techniques. When working on the ground only the largest, fastest and most easily identified blocks can be observed. Discharges increased throughout the day. For these two examples aeriaily measured values are between 74% and 93% of ground measured velocities. ♦

Table 5-5

DISCHARGES CALCULATED USING $\bar{V}$ VALUES DERIVED FROM AERIAL PHOTOGRAMMETRY
 WITH CROSS-SECTIONAL AREAS FROM SITE 76-3 EBA/NORTHWEST
 HYDRAULIC CONSULTANTS LTD DATA

Transect	Date	Stage Level (at WSC Gauge)	Area (m^2) (from nomograph)	Mean Velocity ($m.sec^{-1}$)	Discharge (m^3sec^{-1})
67-68	2/5/77	119.3	2690	n.a.	n.a.
73-74	"	"	"	.41	1103
81-82	"	"	"	.43	1157
AVERAGE					1130
WSC PUBLISHED DISCHARGE					1080
67-68	5/5/78	119.2 m(A.S.L.)	2650	.39	1034
73-74	"	"	"	.42	1113
81-82	"	"	"	.41	1087
AVERAGE					1078
WSC PUBLISHED DISCHARGE					3115
67-68	12/5/79	117.9	1895	.57	1080
73-74	"	"	"	.66	1251
81-82	"	"	"	.69	1308
AVERAGE					1213
WSC PUBLISHED DISCHARGE					1150
67-68	n.a.	n.a.	n.a.	n.a.	n.a.
73-74	11/5/79	117.6	1830	1.22	2233
81-82	"	"	"	1.68	3074
AVERAGE					2654
WSC PUBLISHED DATA					900

but this sub-section approach does not benefit the data for site 78-1.

Throughout these approaches the variation in the data suggests that the difficulty in accurate discharge calculation may lie in the determination of cross-sectional area. Velocity data calculated photogrammetrically have been widely accepted and those obtained in this study by simplified aerotriangulation approach those obtained by rough ground measurements made by the author at similar periods (Table 5-4). In the case of test site 76-3, where a measured cross-section and surveyed bank profile was available, the values derived from the photogrammetric approach are consistently close to published records.

5.4 A Hybrid Approach to Attempt to Test Validity of Area Data

To check on the validity of the area data generated from the Hydrographic Survey sonar profiles a hybrid approach using cross-sectional area data from the 1975 EBA/Northwest Hydraulic Consultants Ltd. study (in nomographic form, Figure 5-2) with velocity data for the cross-sections near the ferry crossing was attempted. Results are presented in Table 5-5. Sites 77-1 and 79-1 are close to published discharges, at 105% for both cases, while those for sites 78-1 (35%) and 79-2 (295%) are well outside expected values. Thus the attempt to combine downstream velocity cross-sections with an upstream area cross-section offers no advantages in reduction of spurious values.

5.5 Discharge Calculations With Modified Manning's 'n' Approach

The final approach to discharge determination was to use the modified Manning's equation to obtain a value for discharge, as outlined in Chapter 1. From field observations a roughness value of $n = .035$ appeared appropriate, while slope calculations from

Table 5-6

CALCULATED DISCHARGES: FROM MANNING's 'n' APPROACH
SITE 76-3

Section No.	Discharge ($M^3.sec^{-1}$)	Section No.	Discharge ($M^3.sec^{-1}$)
A-1/A-2	1227	B-1/B-2	1862
A-3/A-4	1125	B-3/B-4	1079
A-5/A-6	664	B-5/B-6	1398
A-7/A-8	836	B-7/B-8	719
A-9/A-10	592	B-9/B-10	634
A-11/A-12	396	B-11/B-12	845
A-13/A-14	516	B-13/B-14	660
		B-15/B-16	631
		B-17/B-18	457
		B-19/B-20	510
		B-21/B-22	457
		B-23/B-24	476
		B-25/B-26	574
AVERAGE	765	AVERAGE	792

Water Survey of Canada: Published Discharge = $2070 M^3sec^{-1}$

Table 5-7

DISCHARGE VALUES OBTAINED FROM MANNING'S 'n' APPROACH
SITE 77-1

Section No.	DISCHARGES: $M^3 \cdot sec^{-1}$					
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
73-74	235	43	288	529	449	1006
81-82	344	62	417	766	650	1458
87-88	601	110	734	1349	1144	2568
91-92	567	101	679	1245	1056	2374
99-100	634	116	775	1423	1208	2711
103-104	625	114	764	1403	1191	2683
107-108	856	156	1046	1921	1630	3657
109-110	921	168	1125	2067	1753	3935
111-112	1453	265	1775	3261	2766	6208
AVERAGE	693	126	845	1551	1316	2956

WSC Published Discharge $1080 M^3 \cdot sec^{-1}$

Case 1 $n = .035$
 $s = .000354$

Case 3 $n = .040$
 $s = .000354$

Case 5 $n = .035$
 $s = .00015$

Case 2 $n = .035$
 $s = .00342$

Case 4 $n = .060$
 $s = .000354$

Case 6 $n = .060$
 $s = .00015$

Table 5-8

MANNING'S ROUGHNESS VALUE, 'n', AND CHANNEL SLOPE VALUE, 's' CALCULATED FROM
MANNING'S FORMULA WHERE AREA, 'A', WIDTH, 'W' AND MEAN VELOCITY 'V' ARE KNOWN

SECTION	SITE 76-3		SITE 77-1		SITE 78-1		SITE 79-1		SITE 79-2	
	n	s	n	s	n	s	n	s	n	s
A-1/A-2	.052	.000159								
A-3/A-4	.054	.000146								
A-5/A-6	.069	.000091								
A-7/A-8	.064	.000107								
A-9/A-10	.075	.000077								
A-10/A-11	.086	.000058								
A-12/A-13	.067	.000097								
63-64			n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	.025	.000687
73-74	n.a.	n.a.	.165	.000016	.109	.000036	.067	.000096	.033	.000406
81-82			.125	.000028	.121	.000030	.079	.000070	.016	.001625
87-88			.111	.000035	.096	.000047	.053	.000156	n.a.	n.a.
WSC - 75	n.a.	n.a.	.062	.000114	.115	.000033	.069	.000090	.019	.001158
WSC - 76			.068	.000094	.108	.000037	.062	.000112	.017	.001417
AVERAGES	.067	.000105	.106	.000057	.110	.000037	.066	.000105	.022	.001059

Since none of these cases yield values which appear reasonable and/or approach published data a check on the method was required. Rather than use the modified Manning's equation to calculate the area, area values previously obtained from Hydrographic Surveys cross-sections were assumed correct and values for 'n' and 's' calculated. To calculate 'n' a value was assigned to 's' from previous work (i.e. 0.000354). Similarly a value of $n = 0.035$ must be assumed to permit the calculation of 's'. For these conditions the values calculated are presented in Table 5-8. The average 'n' values ranged from 0.022 for site 79-2 to 0.110 for site 78-1 (overall 'n' average: 0.074). Only one cross-section, 73-74 of site 79-2 produced a value of 'n' close to that assigned on the basis of observation. Averaged values of 's' ranged from 0.00037 to 0.00159 (overall 's': 0.00272) with only one value, again for section 73-74, site 79-2 close to the calculated value (0.000406 vs 0.000354).

Within the Manning's 'n' approach no single case yields values which are close to the published record. Manning's 'n' discharge values fall below those calculated by simpler methods. Selection of an 'n' value of .035 followed an examination of the channel area during low water, late summer conditions, and cognizant of the fact that broken ice cover would increase hydraulic resistance. In view of the ice resistance factor those cases selected for additional testing (cases 2 through 6) examined only 'n' values higher than the 0.035 value assigned after site examination.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary

From the data presented for the five test sites it would appear to be unfeasible to obtain discharge values close to those published through the use of photogrammetric techniques in spring break-up conditions. The most important constraint on such a system is the need for accurate determination of the channel cross-sectional area occupied at the time of aerial photography. In the case of site 76-3, where cross-sectional area could be calculated reasonably, the discharge values closely approach those published. Similarly those cross-sections near the ferry crossings for sites 77-1 and 79-1 are reasonably close to the Water Survey values. Data for site 79-2 was expected to vary from published data due to the unique short-term flow conditions which existed at the time of photography. The variation at site 78-1 is more difficult to explain, although there remains the possibility of a major hydrograph adjustment by Water Survey personnel prior to data publication.

It may be possible, under ideal conditions, given sufficient ground control and cross-sectional area data, to provide discharges for ice-choked waters on a regular basis if velocities only are obtained photogrammetrically. It is not possible however, to obtain sufficient, accurate data (without extensive ground surveys) to permit analytical determination of discharge from a modified Manning's 'n' formula. Major shortcomings in this approach, when it is used with reasonable values for roughness (n) and slope (s) do not permit serious consideration of this method for precise discharge determination

(see section 6.5 for a more detailed discussion of this technique).

Difficulties in a photogrammetric technique for discharge calculations occur in four broad areas. These are: errors in the photogrammetric technique; problems in calculation of accurate cross-sectional areas; hydrologic factors which affect remotely-sensed discharge measurements; and theoretical "stumbling-blocks" to a photogrammetric approach.

6.2 Errors in the Photogrammetric Technique

Photogrammetric problems which affect velocity values do not, cumulatively, produce major errors in discharge values. Aerial camera exposure intervals vary from frame to frame by as much as .25 of a second. In the similar triangle solution for velocity value determination this may alter velocity values by .1 of 1%.

Accurate plotting of successive photo centre displacements (the second approach to assignment of velocity values to the contoured plot) introduces some error, since photo scale is calculated from aircraft flying height. Altitude information is obtained from either the aircraft altimeter (usually of doubtful accuracy) or the aerial camera's internal altimeter (which contains markings no finer than 25 m). Either method yields similar velocity value accuracies (within 4-6% of each other).

Lack of precise vertical control at a test site introduced errors at the mapping stage. In test site 77-1 the establishment of a zero vertical datum at the shoreline and then mapping upstream (or downstream) from the initial stereo-model induces increasing (decreasing) velocity estimates with distance from the initial stereo-model, and thus increased (decreased) discharge values. Survey control established near the Liard ferry crossing successfully eliminated this difficulty, but only

at the major expense of a rapidly-transportable remote-sensing technique. The actual control installed was established by helicopter barometer survey. Vertical accuracy of the control points is thus no better than ± 0.3 m. This is less than the 0.15 m resolution capability of the A-7 stereoplotter when using 1:20,000 scale photography.

Lastly, while every opportunity was taken to align the photo flights directly over, and parallel to, the centrelines of straight river reaches, there will remain some flow normal to the flight direction. Errors are then generated because flow measurement in directions other than downstream ($\pm 10-15^\circ$) or upstream (eddies) is not possible from a single stereo-model set-up. Work by previous researchers (Duhaut, 1972 and Moffit, 1968) indicated that the portion of the velocity vector not measured by a simple, single stereo-model set-up employed here can be ignored as a significant error source.

The velocity values obtained in this study, together with those from previous work on the Mackenzie, yield results which fall within predicted and/or measured ranges. Ground-based velocity measurements within a few hours of photography have produced similar values. Similar measurements on Liard Tributary streams, the Fort Nelson and Muskwa Rivers (Sherstone, 1978 and 1980) support such conclusions.

6.3 Errors in Calculation of Cross-Sectional Areas

Errors in the determination of cross-sectional areas are a major source of errors in this approach to discharge calculation. Without extensive, contemporaneous measurement of cross-sectional areas to be used in discharge calculations accuracies are neither high enough nor consistent enough to produce useful values for purposes beyond initial field reconnaissance. Three types of cross-sectional areas were used; those from Water Survey of Canada stream gauge calibration cross-profiles, those from Hydrographic Survey sonar traces and that from EBA/Northwest

Hydraulic Consultants Ltd. None of these results is an accurate cross-sectional area estimate, if published discharge values are taken as the standard. The Water Survey cross-sections, located in a "stable" reach, do in fact change over a one year period. Since the Water Survey staff do not always recalibrate the cross-section each year the use of outdated information may introduce an unquantifiable error.

Hydrographic Survey data, obtained in low-water conditions of mid-September (used in the creation of most of the cross-sections used for discharge calculation) required major extrapolation of the bed/bank profile to permit determination of the actual cross-sectional areas occupied at the time of photography. This area extension (detailed in Appendix A) resulted in a variation of more than 100% in cross-sectional area estimates in several cases. Extensive changes in channel width, which in the Liard River result from only slight depth increases, magnify areal errors in short-lived events such as ice break-up or sudden summer storms.

A possible solution to this difficulty, mentioned in Chapter 3, section 3.1, but untested for this study, was to photograph stream channels at minimum flow conditions and photogrammetrically construct a channel cross-profile. This technique would be particularly applicable to mountain basins where late summer flows can be almost non-existent. Should such an approach prove feasible one of the major difficulties to accurate area determination would be solved.

Where measured cross-sectional areas and surveyed bank profiles do exist, values for discharge approach those expected (i.e. for site 76-3). In such cases individual variations in velocity cross-sections may cause spurious discharge readings (compared with published data) and the averaging of several discharge calculations should be used only for discharge estimation. Attempts to use accurate areas from one river

reach with velocities from another adjacent reach did not produce more accurate discharge values (see Table 5-5).

It should be remembered that the photogrammetric method of discharge determination was originally put forward around the need to obtain discharges in areas where no extensive hydrographic network exists and when ground - (or boat) based measurements are not possible. If any photogrammetric method requires extensive ground work and/or detailed stage-area monitoring then the applicability of the method is limited and should be considered as a technique to supplement records or to provide "scale" reconnaissance estimates of instantaneous discharges in areas where hydrographic services already exist.

6.4 Hydrologic Problems

The hydrologic regime during the spring break-up introduces factors which cause photogrammetrically-derived data to vary from Water Survey of Canada published data. Ice choked waters, due to the presence and/or collapse of ice jams undergo short-term fluctuations in velocity, discharge, surface slope and backwater which are not reflected in the published record. Each of these agents does in fact affect the aerial determination of discharge and the ground-based discharge estimation and thus this remotely sensed method of discharge measurement would actually supplement the Water Survey of Canada approaches.

Backwater effects due to ice jams artificially increase the stage. If aerial photography is used for stage determination in order to calculate cross-sectional areas this effect cannot be eliminated. In a period of a few hours an ice jam well downstream of the test reach can cause wide stage fluctuations in the test reach (Sherstone 1978, 1980). Backwater events are excluded from the published records through graphical manipulation and this would explain a variance of photogrammetric discharges from published values: if the photogrammetric data consistently overstate published records or if Water Survey

Figure 6-1

WATER LEVEL INCREASES & BACKWATER EFFECTS: FORT SIMPSON AREA

manipulation is consistently appropriate and accurate. As the data for sites 78-1 and 79-1 shows (Table 5-2) this is not always the case. For site 78-1 photogrammetrically-derived data is roughly 30% of published figures. Additionally, sites 79-1 and 79-2 acquired during a period when published data indicates discharge was increasing, calculated photogrammetrically, result in an apparent decrease in discharge. Backwater effects during this period would be significant however (Figure 6-1) due to an ice jam located approximately 18 km downstream of the test site. The increased cross-sectional area thus used to calculate discharge would explain the much higher value calculated photogrammetrically for site 79-2.

Additionally Water Survey records reflect daily mean discharges and ignore diurnal and short term fluctuations. As a result within a moderate range the photogrammetric data may over or understate discharge. On a large river such as the Liard however, diurnal variations during break-up are usually masked by ice jamming, backwater and the general upward trend of the discharge hydrograph. Observations on the Liard in the period 1975-1980 (Sherstone, 1978, 1980) have generally found these fluctuations to be not more than ± 0.25 m about the median water levels. For 1976 this maximum fluctuation would represent a variation in discharge of $\pm 400 \text{ m}^3 \cdot \text{sec}^{-1}$. This could in many cases have a serious impact on the discharge values calculated photogrammetrically and would result in calculated discharges which are accurate but which do not match those Water Survey published values.

6.5 Theoretical "Stumbling Blocks"

Areas in which theory is unable to handle the photogrammetric approach are restricted primarily to the analytical, Manning's 'n' approach. From the results of area calculations alone (Table A-1) it is apparent that in a river such as the Liard, with temporal variation in bed profile, the value for wetted perimeter ($2d + W$) cannot be

reduced to the single measurement 'W' for use in the modified Manning's equation. The required input of photogrammetrically calculated mean velocity values is also a shortcoming since any error in the previously derived velocity values serves to magnify errors in the calculated areas.

Finally the accuracy of Water Survey of Canada records must be addressed. In that portion of the hydrologic year for which the photogrammetric technique was designed gauge records are generally suspect or non-existent. Thus for many dates during the ice break-up period the published values have been extrapolated from stage discharge curves, corrected to reflect open water flow conditions. Indeed several times between the commencement of this study and its completion the Water Survey has revised preliminary and/or published figures.

6.6 Closing Remarks

The photogrammetric method tested in this study does not seem to represent an operational means, at the present time, of obtaining precise discharges in remote areas. With some additional ground survey data, specifically accurately measured channel cross-sections and river bank profiles, and some type of stage-area relationship, discharge measurements of reasonable accuracy are possible. The major source of error in this series of tests has been due to miscalculation of the cross-sectional areas to be used in the area-velocity formula for discharge calculation. Thus the photogrammetric method is useful to generate discharges for presently gauged rivers in a period when normal techniques are not practical and to obtain discharge values of a reconnaissance nature for ungauged streams. While discharge values obtained may not replicate Water Survey published records there remains the possibility that photogrammetrically obtained discharges do in fact represent valid instantaneous discharge values in a rapidly fluctuating hydrologic regime.

The photogrammetric approach does hold promise for use as a reconnaissance or research tool in the examination of northern rivers at break-up. In the case of site 79-2 the photogrammetrically derived discharge was significantly greater than that published by Water Survey of Canada. However the unique conditions (ice jam failure, high surface velocities and backwater) which existed when photography was acquired support the aerially obtained value. Where researchers are concerned with processes responsible for creation, maintenance and destruction of river ice jams the photogrammetric technique offers the unique opportunity to determine the actual discharges responsible for ice behavior. Similarly engineers charged with the design of bridges, transportation or hydro-electric facilities in northern streams may more accurately predict ice impact forces on proposed structures where peak discharge and ice/water velocities are calculated photogrammetrically.

Figure A-1

WATER SURVEY OF CANADA CHANNEL CROSS-
PROFILES USED TO CALIBRATE GAUGE RECORDS
FOR STATION 10ED002, LIARD RIVER, NEAR
FORT SIMPSON, N.W.T.

DATE - JULY 22, 1974

MAX DEPTH - 9.8m

AREA - 4915 m²

DATE - JULY 25, 1975

MAX DEPTH - 9.0m

AREA - 4140 m²

DATE - JUNE 17, 1976

MAX DEPTH - 9.8m

AREA - 4834 m²

HORIZONTAL SCALE 1:10,000

VERTICAL SCALE 1:200

APPENDIX A

CONSTRUCTION OF CROSS-SECTIONS FOR CALCULATION OF DISCHARGE

A.1 Construction Techniques

Channel cross-profiles or cross-sections can be constructed from Water Survey of Canada data for gauging station 10ED002 (Figures 4-1 and A-1) for the following dates; July 22, 1974, July 25, 1975 and June 17, 1976. Gauge calibration cross-profiles were not obtained in 1977 or 1978.

A complete series of cross-profiles, from the mouth of the Liard to a point 5 km upstream of the study site was constructed from sonar data supplied by the Canadian Hydrographic Service for September 17, 1977 (Figure A-2). These profiles are spaced approximately 250 m apart. The location of and a selection of cross-profiles are presented in Figures 4-2 and A-3.

Additional cross profiles are available from other sources for the same reach for 1972 (Hench) but such data are of only limited use to this study due to the coarse nature of recording channel bed details. Because of this such data was ignored for this study.

Figure A-3-2

HORIZONTAL SCALE - 1:10,000

VERTICAL SCALE - 1:200

Figure A-3

CHANNEL CROSS-PROFILES THROUGH TEST SITE
FROM HYDROGRAPHIC SURVEY OF CANADA DATA
ACQUIRED SEPTEMBER 17, 1977

HORIZONTAL SCALE - 1:10,000 (1mm = 10m)

VERTICAL SCALE - 1:200 (1mm = .2m)

Figure A-2

CHANNEL CROSS-SECTIONS OBTAINED BY HYDROGRAPHIC
SURVEY SHIP C.S. LOON, ON LOWER LIARD RIVER,
SEPT. 16 & 17, 1977: FROM RADIO ECHO SOUNDER
COLLECTOR FOR C.H.S. CHART NO. 6410

A major difficulty in the use of cross-profile data obtained from the above noted sources is that the available cross-profiles do not represent the cross-sectional areas occupied by water on the date of aerial photography. The stage levels for the date of survey (Sept. 17, 1977) and for the date of aerial photography was extracted from Water Survey records and this data were then used to establish the proper water surface elevations (Figure A-4). If water levels on the dates of photography were lower than those of the date of a ground-based survey, only the area beneath the lower water level elevation line was used to determine the area (A) to be used in calculation of discharge. If break-up photography water levels were higher than those of the ground survey the correct water level was graphed and the curve of the stream bed extended to intersect the new water surface. The enlarged areas (A) thus formed were used for calculation of discharge, as outlined in Chapter II, Section A.

The cross-profile data presented in Figures A-3 and A-4 illustrates the high variability in shape and wide variation in cross-sectional areas, (Table A-1) which requires that velocities vary significantly throughout the reach to produce a constant discharge. This assumes no temporary storage (backwater conditions) exists through the test reach.

Figure A-4

ILLUSTRATION OF METHOD OF OBTAINING CHANNEL CROSS-SECTION
FOR DATE OF AERIAL PHOTOGRAPHY FROM SONAR SOUNDING
CROSS-PROFILES OBTAINED BY HYDROGRAPHIC SURVEY OF
CANADA, SEPT. 17, 1977

TABLE A-1

SUMMARY OF CROSS-PROFILE DATA

	Hydrographic Survey	Water Survey of Canada Survey (2)	Combined Data All Surveys
Max. Calculated			
Area - m ²	4898.4	3802.5	4898.4
Min. Calculated			
Area - m ²	3758.3	2899.0	2899.0
Average Calculated			
Area - m ² (3)	4130.3	3352.7	3963.7
Variation Max. to Min.	1140.1	903.5	1999.4
% Variation, as a Function of Average			
Area	27.6	26.9	50.4

- NOTES: (1) Maximum and Minimum values for calculated are for cross sectional areas which were constructed to represent the water surface elevation on the date of aerial photography.
- (2) Values shown are extrapolated values for W.S.C. calibration cross-profiles for date of aerial survey, using calibration work sheets for 1974, 1975, and 1976. Calibration of the gauged section has not been undertaken in 1977, 1978 or 1979.
- (3) Hydrographic Survey Averages are from a sample of 11 cross-sections, Water Survey of Canada Averages are from 3 cross-sections. (See Figure 4-2).

APPENDIX B

WATER SURVEY OF CANADA MEASUREMENTS

Water Survey of Canada procedure for calculation of discharge during the spring break-up period varies from region to region and from stream to stream (dependent upon size). Three approaches can be used. In the first technique discharge is measured under solid ice conditions as close to break-up as safely possible and again immediately after open water conditions commence. The open water stage-discharge hydrograph is then extrapolated between these two points, based on the technician's experience with a particular river (L. Williams, Water Survey of Canada, Yukon Regional Office, Whitehorse: personal communication).

A second approach is to measure the stage throughout the break-up period by means of a bubbler gauge or stilling well apparatus, plot the data after subtraction of known backwater effects and compare the resultant curve to that of the open water hydrograph for the balance of the year. Where a portion of the break-up record is lost due to gauge orifice destruction or ice action to the recorder the missing record is interpolated. This shortened hydrograph is then adjusted to the open water hydrograph to provide a smooth transition over a longer period than that of break-up alone. Again decisions on backwater must be made in the field by the technician.

The third method, detailed by Bruce and Clark (1956), requires the installation of a second gauge upstream of the primary gauge. A relationship between the two gauges is established which permits calculation of actual discharge by the method; $\frac{Q}{\sqrt{F}} = Q_p$

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where: Q = discharge at lower gauge, in $m^3 \cdot sec^{-1}$,
 $\sqrt{F}$ = square root of "fall" or height difference
 between gauges, in m.,
 Q_p = corrected discharge, without backwater, in
 $m^3 \cdot sec^{-1}$.

This technique, because of the expense of station installation and increased manpower for operation is unlikely to be used except in strategically important situations.

Bruce and Clark note (1966, p.92) that interpolated streamflow records under an ice cover are not as accurate as those obtained from an open water rating curve and that for, ".....some streams....." (types unspecified) interpolated values may be, "..... 25 per cent in error, although the estimates of the mean flow during a month will probably be considerably less." Generally Water Survey personnel expect discharge values to fall within ± 5 per cent of the long-term hydrograph curve (H. Woods, Water Survey of Canada, Inuvik Office - personal communication).

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FIGURE 5-3
TEST SITE 76-3
LIARD RIVER N.W.T.

LINE M-5 SOUTH OF
FERRY CROSSING: JUST
UPSTREAM OF SAWMILL ISLAND

A24002 #256-259

MAY 7, 1975

CONTOUR INTERVAL 1 VERTICAL UNIT = .1 m

GROUNDING SHORE ICE

100

98

FIGURE 5-3
TEST SITE 76-3
LIARD RIVER N.W.T.

LINE M-5 SOUTH OF
FERRY CROSSING: JUST
UPSTREAM OF SAWMILL ISLAND

A24002 #256-259

MAY 7, 1975

CONTOUR INTERVAL 1 VERTICAL UNIT = .1 m

END

2 3 1 2 8 1 1

FIN