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INLAND WATERS BRANCH

DEPARTMENT OF ENERGY, MINES AND RESOURCES

Measurement of Discharge Under Ice Cover

P.W.STRILAEFF and J.H.WEDEL

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Abstract

Many difficulties are encountered in the measurement of discharge under ice cover, particularly in the operation of hydrologic data-gathering networks located in Arctic and Sub-Arctic regions. Difficulties result from extreme ice thicknesses, double thicknesses of ice, large depths of slush ice, coincidence of spring flows with ice breakup, freeze-up of gauging equipment in sub-zero temperatures, etc. Some of these difficulties are discussed, and procedures used in the operation of networks in northern areas of Canada are outlined.

A possible technique for the estimation of river discharge using a single velocity in a cross-section is briefly described, and a comparison of accuracy between discharges derived using this technique and measured discharges using standard methods is demonstrated.

Measurement of Discharge Under Ice Cover

P.W.STRILAEFF and J.H.WEDEL

The collection of surface water data involves many problems which are believed to be common to all countries. One of the greatest problems, however, is the collection of continuous records under winter conditions in northerly and remote areas. Most of the equipment and techniques used have been developed for data collection in southern areas of the country, and have had to be adapted or modified to satisfy the requirements of work in the far north. These adaptations and modifications have been only moderately successful.

Collection of surface water data is also often frustrated by physical conditions such as severe low temperatures combined with high winds, "white out" conditions which make aircraft navigation difficult, extreme ice thickness combined with slush or frazil ice, and the coincidence of spring flows with ice break-up.

Measurement of discharge under ice conditions in northern Canada and, no doubt, other northern countries, therefore provides many challenges to the field personnel. Since this winter work represents a significant proportion of the total field activity in these regions to produce streamflow record, adequate solutions for the operational problems are vital.

Some of the problems in the northern areas of Canada, and the procedures used to overcome them are discussed in this report.

1. Navigation of Aircraft

Travel for the purpose of streamflow data collection in northern Canada is usually via single-engine aircraft, such as the DeHavilland Beaver or Otter. Common Arctic winter conditions, such as snow cover, drifting snow and ice-fog conceal river channels, lakes and other natural landmarks, making map-reading for navigational purposes extremely difficult. Although all the sparsely located settlements of the Canadian north are equipped with radio-beacons, which are invaluable when flying from settlement to settlement, they are of very little assistance when flying to a gauging site. It takes a great deal of concentrated effort under prevailing lighting conditions to locate a gauging station in these circumstances. Aircraft travel also becomes extremely frustrating when, for example, hours are spent getting ready to fly only to find a grey blanket of ice-fog settling in around the aircraft. These situations are frequent, and the successful arrival at a station is a major accomplishment. To assist navigation under the conditions described, gauging stations in the Arctic regions are normally equipped with marker pylons, which can best be described as steel tripods, approximately three meters in height, with large triangular plates mounted at the apex and painted fluorescent orange (Figure 1). Where possible, these markers are located on a prominent point of land. It has been found that the marker pylons greatly facilitate location of stations from the air under conditions of complete snow cover.

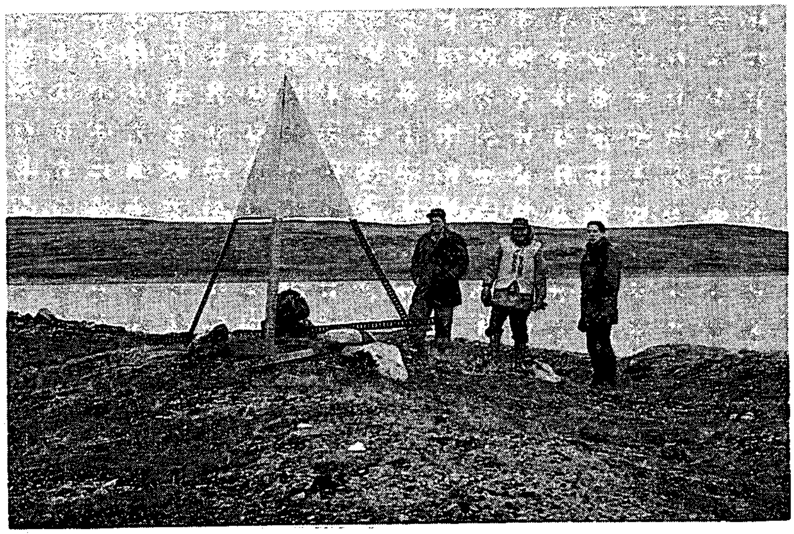

Figure 1. Marker pylon at gauging station.

2. Ice Thickness

In Arctic and Sub-Arctic regions, ice thicknesses of three metres or more[1] combined with large depths of slush are not uncommon. However, it is possible to mitigate or circumvent the complicating factors associated with difficult ice cover of this nature by the judicious selection of winter measurement sites. For example, it is a rather common occurrence to find reaches of open water immediately below the outlets of large lakes and the erection of a cableway at such a location reduces the problems of winter measurements (Figure 2). Likewise, a satisfactory winter measurement section frequently can be located at the lip of a rapids where thin ice occurs, thus alleviating ice-cutting problems. In addition, backwater effect can be substantially reduced or eliminated entirely by locating the gauging station above a rapids or a waterfall. For example, at the Back River gauging station located at latitude 67° 40' North, backwater effect has not been known to exceed 35 centimetres even though ice thickness at the gauge site exceeds three metres during most winters; the rapids, which are the control for the station, remain free of ice with the exception of the river's edge (Figure 3).

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[1] Statistics in this paper are given in the metric system; original calculations were made using the English system.

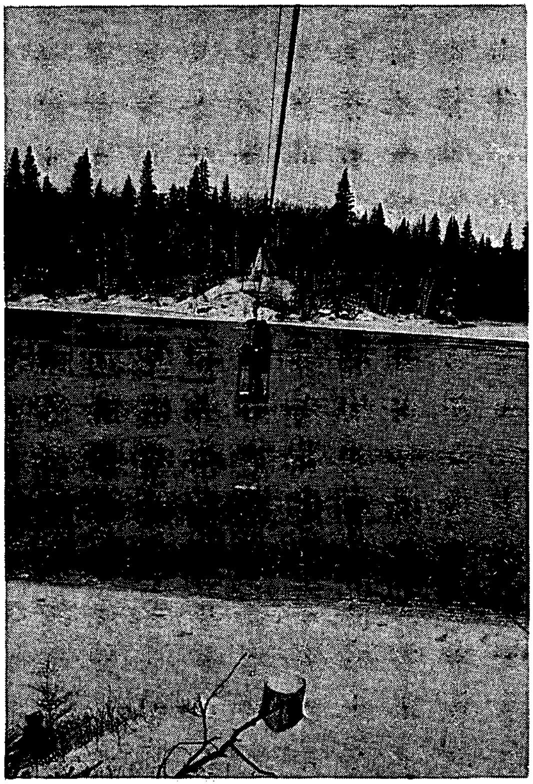
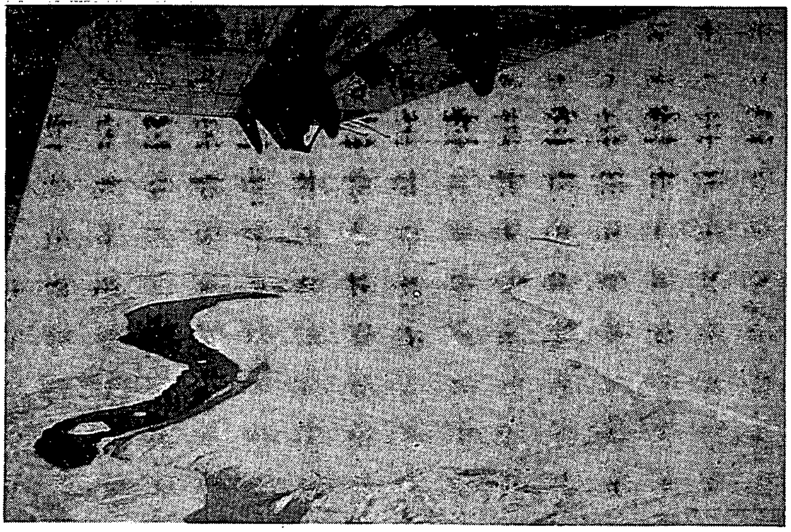


Figure 2. Metering river flow from a cableway.

Figure 3. A section of rapids which remains ice free the year around on the Back River (Latitude 67°40'N).



3. Ice Cutting

Where it is not possible to avoid cross-sections with large depths of ice, ice cutting becomes the major obstacle to the proper conduct of winter discharge measurement programs. In Canada, a powered ice drill is now a common tool for this purpose (Figure 4). Its power pack, weighing approximately 9 kilograms, consists of a three-horsepower, air-cooled, two-cycle engine such as is used in North America on lawn mowers or snow blowers; an appropriate set of reduction gears; and a clutch assembly. Fastened to the power pack by means of a splined connector is a flighted auger shaft and a toothed cutting head, the shaft being of appropriate length to penetrate the ice layer. In the District of Keewatin, where ice thickness averages 2.8 metres in late winter, it is common practice to drill the necessary holes in two stages; a 1.5-metre length of auger shaft is first used, followed by a second shaft of longer length (Figure 5).

A multi-purpose tool is used to measure ice thickness where only a simple ice cover exists (Figure 6). The graduated shaft of this measuring device is fabricated out of wood or metal and has attached, at its lower end, two perforated semi-circular plates which fold upwards from a normal horizontal position. When this tool is thrust downwards through the ice holes, the plates fold to allow easy passage. When it is raised the plates return to a horizontal position, thus permitting the detection of the underside of the ice for the purpose of determining ice thickness. When the tool is moved upward through the drilled hole, ice chips and fragments resulting from drilling are easily removed.

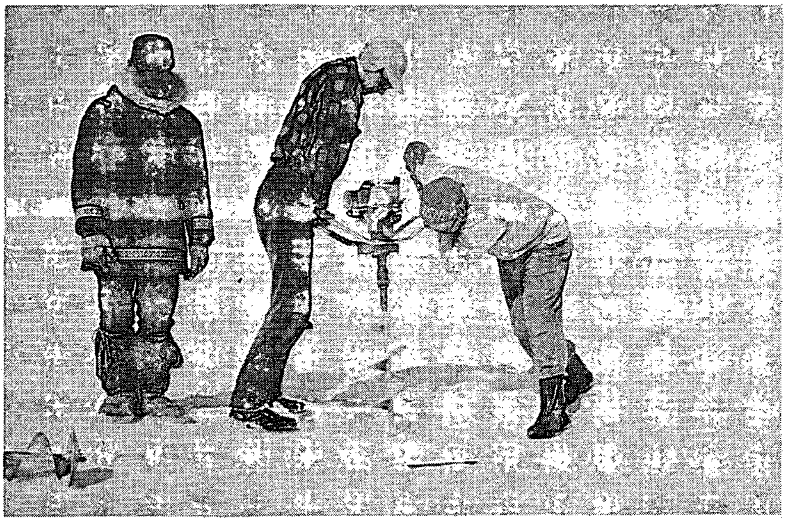


Figure 4. Powered ice drill.

Figure 5. Powered drill fitted with a long auger shaft.

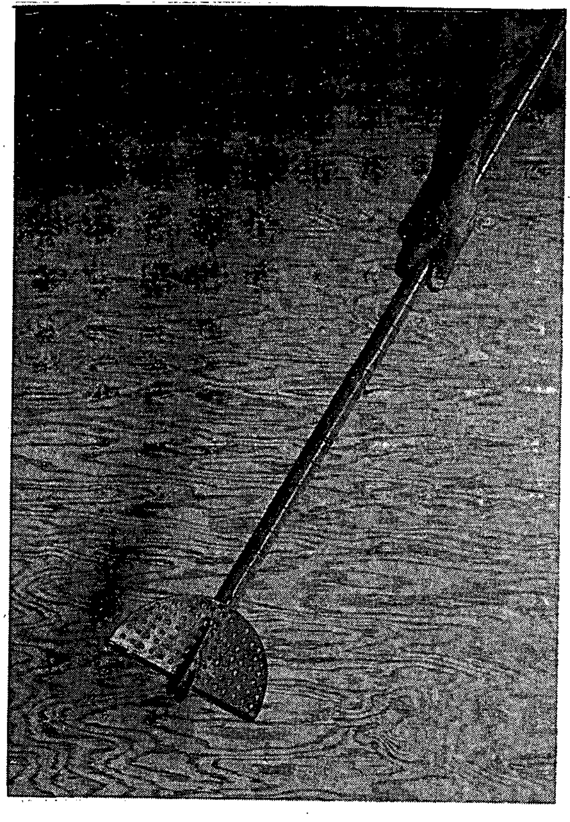


Figure 6. Multi-purpose tool for measuring ice thickness.

4. Observation of Water Depth and Velocities

Coincident with the increased use of the powered ice drill, it became necessary to re-design standard metering equipment in order that it might be accommodated in a drilled hole of approximately 20 centimetres in diameter. Two weight assemblies with a maximum diameter of 16 centimetres were developed. The "Calgary" type weighs 18 kilograms and employs a tear-drop shaped lead weight. The "Winnipeg" type weighs 8.2 kilograms and also employs a tear-drop shaped weight with some modification for lower resistance to the current (Figure 7). Both types have proven to be fairly stable in velocities under two metres per second. Incorporated within the framework for the weight is a modified pattern 622 Price-type current meter. The entire assembly fits easily through the drilled hole.

Where the depth of water is greater than three or four metres, a sounding reel or a handline is used to suspend the weight assembly. The reel is mounted on a collapsible support set on runners (Figure 8). Because of the extremely cold weather, the support is equipped with a chamber heated by catalytic heaters to prevent the meter from freezing while moving the equipment from one metering position to the next. Where the depth of water is less than four metres, a graduated steel wading rod is used.

Figure 7. Two views of weight assembly, Winnipeg type, incorporating a modified Price-type current meter.

Figure 8. A heated chamber below the reel prevents the meter from freezing when not submerged.

5. Slush Ice Conditions

The problems presented by extreme ice thickness are aggravated further during freeze-up by the formation of thick slush ice layers which adhere to the under-surface of the ice cover. Slush ice forms on the surface of moving water exposed to sub-zero air temperatures. The slush ice, in the form of ice panes, slivers and crystals, is swept under newly formed ice blankets and becomes trapped. Heaviest slush ice formations occur in the early winter and then gradually dissipate or form a part of the solid ice cover. Where the combined thickness of ice and slusn does not exceed 6 metres, a sectional, flanged slush pole is used initially to loosen the slush formations sufficiently to allow easy passage of the weight and meter assembly. Where the combined thicknesses are greater than 6 metres, a specially-designed, elliptical weight is used to penetrate the slush horizon (Figure 9). This weight, which has enlarged tail fins, is suspended at a point slightly off the centre of gravity, permitting it to assume a vertical, nose-up position when suspended in the air. When the weight is lowered through the slush ice in this position, the enlarged tail fins act as cutting and breaking edges. When lowered below the interface between water and slush, a slight current is sufficient to force the weight into a horizontal position. Accurate determination of the depth to the interface is obtained by raising the metering assembly until the meter rotor stops. The distance from the water surface to this point is then noted as ice thickness.

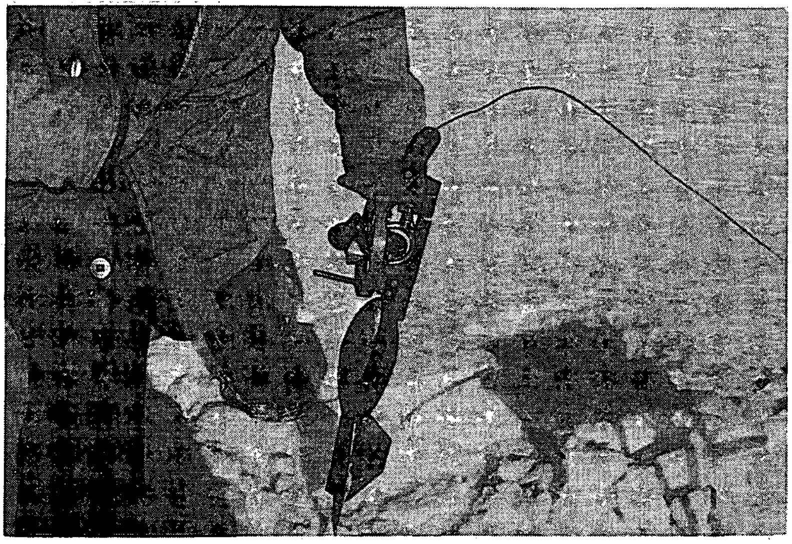
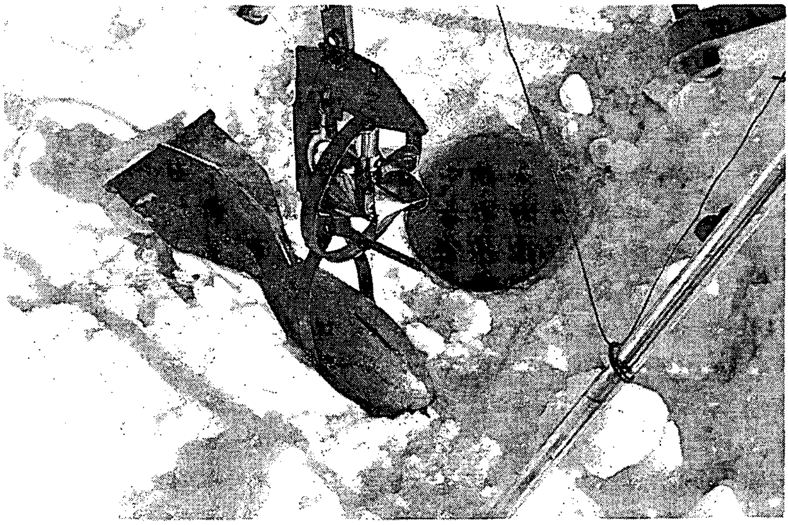


Figure 9. Specially-designed elliptical weight in nose-up position (above) and in simulated horizontal position for metering (below).



6. Recording of Water Levels

Low temperatures, permafrost and rocky terrain preclude the use of conventional float-operated, water stage recorders. Two types of pressure water level recorders, both of which utilize nitrogen bubble systems to transfer river stage to the recording pen, are being used exclusively to record stages at isolated locations in northern Canada. One type of recorder is the mercury manometer gauge which balances a column of mercury against the pressure due to river stage (Figure 10). The other type of recorder is the "Winnipeg" type pressure gauge in which the pressure due to river stage is transferred to the recording pen by means of mechanical linkage (Figure 11).

To operate at prevalent temperatures, it is necessary to provide a heated shelter for the mercury manometer gauge in order to maintain the temperature of mercury above its freezing point. The "Winnipeg" type gauge does not require heat for its operation. However, the Stevens strip chart drive, which is common to both of these instruments, is unreliable at temperatures of about -40°C; consequently, a variety of propane fuelled heaters are in use in northern Canada. Experimentation with electrical heat, provided by a wind-driven generator (Figure 12), was carried out in the Northwest Territories, but fuelled heaters were found to be more reliable and economical. Experimentation with special low-temperature lubricants such as "Moebius Syntalube" indicates that the reliability of the Stevens strip chart recorder can be improved to temperatures of -45°C.

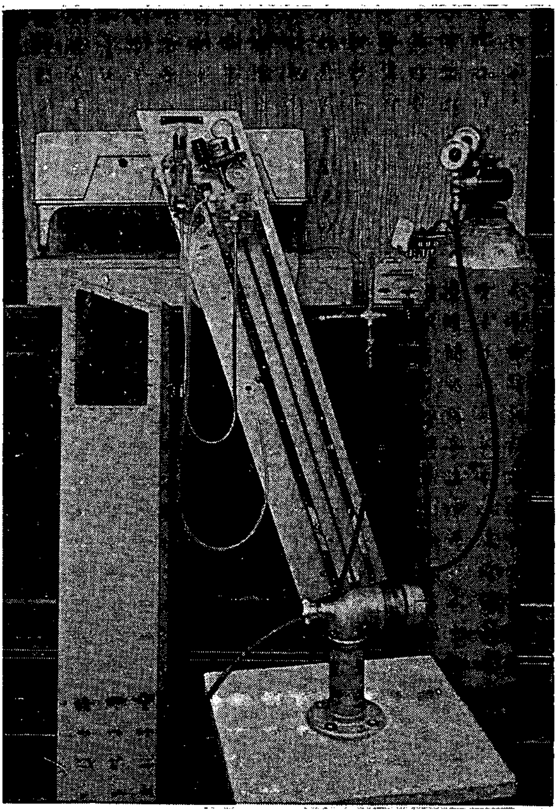


Figure 10. Automatic mercury manometer water level recorder.

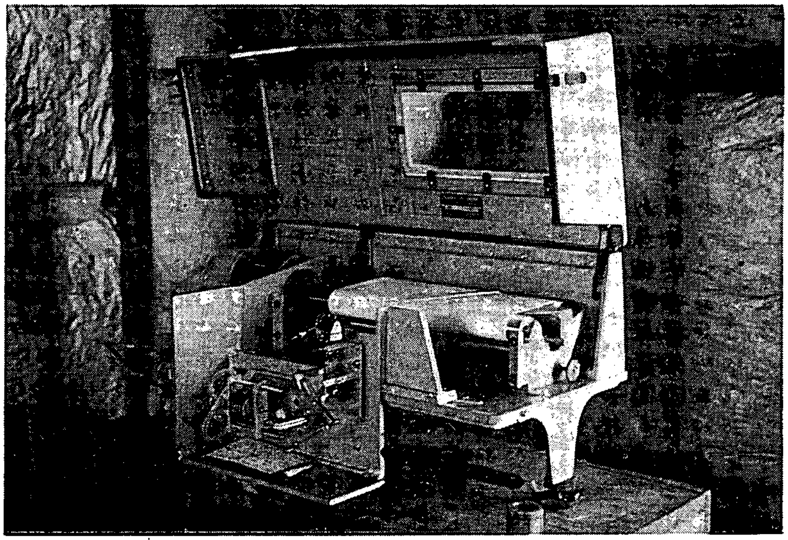


Figure 11. Automatic "Winnipeg" type pressure water level recorder.

Figure 12. Wind-driven electric generator.

ALTERNATIVE STREAMFLOW MEASUREMENT TECHNIQUE

Standard procedure in the making of a current meter discharge measurement requires that the total area of the cross-section at the place of measurement be divided into small or partial sections, and the area and the mean velocity at each section be determined separately. The sum of the discharges in all the partial sections is the discharge of the stream.

If correctly applied, this procedure is the most accurate of the known methods of measuring discharge of a stream. However, this procedure is time consuming, and a demonstration of one possible alternative is described below.

This alternative is based on the belief that a relationship exists between the discharge computed on the basis of a single velocity in a cross-section and that obtained using the standard method in the same cross-section. In pursuit of this possibility, a limited analysis was made of four gauging stations located at points ranging from the U.S.-Canada border to near the Arctic circle. This analysis indicates that such is the case. If further study confirms this relationship, then this time-saving technique in taking discharge measurements could be introduced.

Method of Analysis

Results of discharge measurements for several years were listed as shown in Table 1, columns (1) to (4) for:

Seal River below Great Island

Location - Latitude 58° 53', Longitude 96° 16', Manitoba

Drainage Area - 48,200 square kilometres

Gauge - Recording

Operation - Continuous

Maximum Discharge - 1,300 cubic metres per second

Minimum Discharge - 70.4 cubic metres per second

Each discharge measurement was examined, and the maximum velocity in the cross-section at 0.2 depth was listed in column (5). Where possible the same vertical was used whether or not maximum velocity occurred each time at that vertical. However, since verticals used for each measurement are not always coincident, a deviation of ± 3 metres was allowed in the selection of the vertical.

The velocities listed in column (5) were then multiplied by the area for the measurement (column 3) and the results listed in column (6). The discharge figures in column (6) were then plotted against the measured discharge listed in column (4), and correction factors computed (Figure 13).

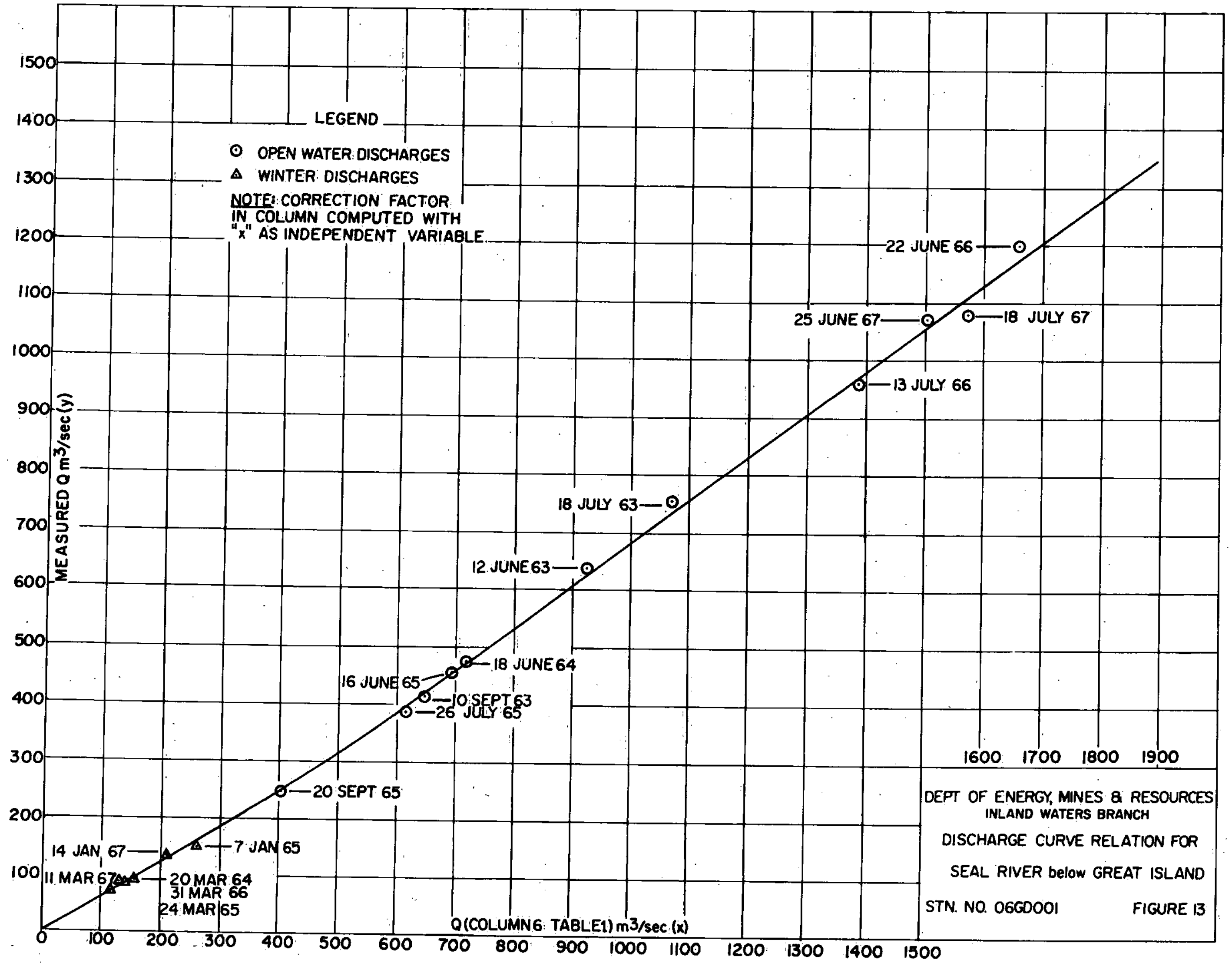
Discharges on the basis of a single velocity in the cross-section were then arrived at by multiplying the values in Column (6) by the correction factor, and these results, together with per cent deviation from the measured discharge, were listed in the last two columns of each table. These discharges were then plotted against gauge height and maximum deviation from the curve computed.

TABLE 1

Discharge Measurements of Seal River below Great Island

1 Date	2 Gauge Height	3 Area	4 Meas. Q.	5 Max. Vel. @ Pt. **	6 5x3	7 Corr. Fac. 4/6	8 Corr. Fac. Fr. Crve	9 Est. Final Q Fr. Crve	10 % Dev. of 9 frm 4
	metres	m^2	m^3/sec.	m/sec.				m^3/sec.	
1963									
June 12	121.87	564.5	638	1.64	926	0.69	0.68	626	-1.9
July 18	122.17	588.7	753	1.82	1,070	0.70	0.69	734	-2.6
Sept. 10	121.45	463.1	414	1.40	648	0.64	0.65	419	+1.2
1964									
March 20*	121.25	309.7	90.7	0.50	155	0.59	0.61	95.0	+4.5
June 18	121.44	510.6	476	1.41	720	0.66	0.66	472	-0.8
1965									
Jan. 7*	121.72	401.8	150	0.65	261	0.57	0.62	161	+6.8
March 24*	121.24	281.8	72.0	0.41	116	0.62	0.61	710	-1.4
June 16	121.43	489.2	456	1.42	695	0.66	0.65	455	-0.2
July 26	121.31	470.6	389	1.31	616	0.63	0.64	396	+1.8
Sept. 20	120.88	388.7	247	1.04	404	0.61	0.62	249	+0.8
1966									
March 31*	121.04	300.4	86.5	0.46	133	0.63	0.62	85.0	-1.8
June 22	122.75	723.5	1,200	2.29	1,660	0.72	0.71	1,170	-2.6
July 13	122.44	651.9	960	2.13	1,390	0.69	0.70	971	+1.1
1967									
Jan. 14*	121.04	333.9	134	0.63	210	0.64	0.61	129	-3.9
May 11*	120.88	279.9	86.8	0.48	134	0.65	0.61	82.5	-5.0
June 25	122.65	665.9	1,070	2.26	1,510	0.71	0.70	1,060	-0.9
July 18	122.59	692.9	1,080	2.27	1,570	0.69	0.71	1,110	+2.7
					Mean:	0.65	0.65		

* Winter measurements.
** At vertical located 340 feet from initial point.



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DISCHARGE CURVE RELATION FOR

SEAL RIVER below GREAT ISLAND

STN. NO. 06GD001 FIGURE 13

DISCUSSION

1. From the four gauging stations studied, it appears that:

   (a) An estimate of discharge to approximately ± 10% accuracy can be computed using the formula;

   $$Q = A \times 0.70\ V\ max.$$

   Where Q = discharge in cubic metres per second

   V max = Velocity at 0.2 depth at maximum velocity point within the cross-section

   0.70 = Correction Factor

   (b) The correction factor (0.70) appears to be constant regardless of the latitude location of gauging stations studied, with the possible exception of Seal River where the average factor appears to be 0.65. It is not essential that the correction factor be constant, although this is of considerable interest.

2. The above relationship was developed using velocities as observed at 0.2 depth at the maximum velocity point within the river cross-section. Since velocity distribution in the vertical is normally a parabola it is possible that a similar relationship exists using a velocity observed at a constant depth, say one metre above streambed.

3. The study made is of a preliminary nature only and no final conclusions can be drawn from it as yet.

Possible Application of the Single-Velocity Method, if Proven Correct

1. If a differentiation in streamflow data requirements can be made between those south of latitude 55° and those north of this latitude, perhaps this alternative method for streamflow measurement could be adapted for the northern areas.

   For example: It is possible that publication of "estimates" of flows to within ± 10% accuracy is adequate for streams located north of latitude 55°.

2. To utilize the potential of this method fully, it is necessary to:

   (a) develop an instrument which could be anchored firmly on the streambed to measure and transmit velocities and, possibly, water levels.

   (b) develop an instrument which could be installed on the river bank to receive and record the velocities and water levels transmitted by (a).

3. While the instrumentation described above is being developed, it may be possible to use this method with conventional instruments in selected areas of Canada in the interest of reducing manpower requirements in hydrometric surveys.

Current Technical Bulletins

No. 18 The effects of the W.A.C. Bennett Dam on downstream levels and flows. A. Coulson and R.J. Adamcyk, 1969.

A report summarizing the expected effects of the W.A.C. Bennett Dam on levels and flows in the Mackenzie River basin.

No. 19 Airborne techniques in climatology; oasis effects above prairie surface features. R.M. Holmes, 1970.

A report describing a pilot study of oasis effects in southern Alberta using a specially-instrumented aircraft and a mobile ground station.

No. 20 Hydrogeological Reconnaissance of the North Nashwaaksis River Basin, New Brunswick. J.E. Charron, 1969.

A description of a hydrogeological reconnaissance carried out as part of an International Hydrological Decade study of the hydrology of the North Nashwaaksis Basin.

No. 21 An instrumented experimental site for the investigation of soil moisture, frost and groundwater discharge. R.A. Freeze and J.A. Banner, 1970.

A report describing an instrumented experimental site at Calgary, Alberta, to provide integrated measurements of the subsurface moisture regime in saturated and unsaturated zones. A summary of the first year's operation is included.

No. 22 Detergents, phosphates and water pollution. W.J. Traversy, P.D. Goulden and G. Kerr, 1970.

A report on the results of chemical analyses of phosphate content in detergents and washing products. The report traces the development of washing products from organic soaps to modern phosphate-based detergents and describes the relationship between phosphates and the eutrophication process.

No. 23 Regional Groundwater Flow Between Lake Ontario and Lake Simcoe. C.J. Haefeli, 1970.

A report on the hydrogeological conditions to the north of Toronto with a view to determining if the terrestrial water balance of the Lake Ontario Basin is affected by a major seepage from Lake Simcoe.

No. 24 Application of Regression Analysis in Hydrology. N. Tywoniuk and K. Wiebe, 1970.

A description of the applications (and limitations) of regression analysis and a discussion of the distinction between regression - and correlation analysis.

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A review of streamflow measuring techniques applicable to rivers with peak flows up to 10,000 cfs.

No. 26 The Control of Eutrophication. Canada Centre for Inland Waters, Burlington, Ontario; Fisheries Research Board of Canada, Winnipeg; Inland Waters Branch, Ottawa, 1970.

A discussion of the respective roles of phosphorus, nitrogen and carbon as critical elements in limiting the eutrophication process.

No. 27 An Automated Method for Determining Mercury in Water. P.D. Goulden and B.K. Afghan, 1970.

A description of a method for determining mercury concentrations as low as 0.05 µg/l. The method can be applied to water samples containing both inorganic and organo-mercury.

No. 28 Wave Agitation Study in a Small Boat Basin at CCIW. T.M. Dick, 1970.

A complete list of titles in the Technical Bulletin Series and copies of any of these publications may be obtained from the Director, Inland Waters Branch, Department of Energy, Mines and Resources, Ottawa, Ontario.