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A Review of Techniques used by Canada and other Northern Countries for Measurement and Computation of Streamflow under Ice Conditions

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In Canada, Water Survey of Canada, a division of the Water Resources Branch of Environment Canada, is responsible for the collection and processing of data from more than 3,300 active streamflow, water level and sediment data gauging stations. Because of the climatic conditions prevalent in Canada, an important part of the monitoring program is conducted under winter ice conditions. The determination of daily streamflow records during the winter period is important for several practical purposes, in particular for water power development. Essential to the computation of daily discharge records, are reliable streamflow measurements. However, discharge measurements under ice conditions are generally difficult to obtain because of severe weather conditions, hazardous field conditions, and ill-adapted field measurement techniques.

In this paper, the field methods and instruments, and computational methods used by Water Survey of Canada for streamflow measurement and computation under ice conditions are reviewed. Factors affecting the accuracy of discharge measurements performed under ice conditions are discussed. Newly developed instruments for use under ice conditions are described and their advantages discussed. A comparison between techniques used by Canada and other northern countries is also given. Areas of research and investigations for improvement in the overall quality of data are suggested.

Introduction

Water Survey of Canada, a division of the Water Resources Branch of Environment Canada, is responsible for providing comprehensive, accurate and timely data and information on the quantity of Canada's inland waters.

One of the components of the stream gauging program performed by Water Survey of Canada is the monitoring of streamflows under ice conditions.

The determination of daily river discharge in winter is very important for several practical purposes, particularly for water development. For example, in Canada water flow in the rivers in winter is generally lower than in summer, although the demand for energy in winter is on the contrary considerably higher. Also, the annual spring freshet rise in rivers occurs under ice conditions creating uncertainties in flood forecasts and in peak and flow volume computations. Information on low flow conditions in winter is also required for the design of water supply structures and in water quality investigations.

Reliable streamflow measurements under ice conditions are difficult to obtain because of severe weather, dangerous field conditions, ill-adapted field sampling techniques (instruments and methods), and other factors affecting the measurement of streamflow and collection of water level data.

Moreover, once the streamflow measurements have been obtained, the computation of daily discharges for the ice affected period using the standard stage-discharge relationship is complicated by the presence of other variables, such as: reduction of cross-section by ice growth, by frazil ice accumulation, formation of closed conduit flow, and changes in ice roughness from thermal processes.

In this paper, the field methods and instruments, and computational methods used by Water Survey of Canada for streamflow measurement and computation under ice conditions are reviewed. Factors affecting the accuracy of discharge measurements performed under ice conditions are discussed. Typical computational procedures as used by Water Survey of Canada are described.

A comparison between techniques used in Canada, and in other northern countries for measurement and computation of streamflow under ice conditions is also made.

Newly development instruments for use under ice conditions, such as plastic current meter rotors and the ultrasonic velocity meter, are described and their advantages discussed.

Solutions to flow measurement problems are discussed, and areas of research for improvement in the overall quality of data suggested.

A description of the techniques used for collecting and recording stage data is not included in this paper.

Description of Hydrometric Network Operated during Winter Period

Water Survey of Canada publishes data from a hydrometric network comprised of approximately 1,850 continuous (January to December) streamflow stations. The large majority of these stations are operated by Water Survey of Canada, with the exception of the Province of Quebec.

The large majority of these streamflow stations are affected by backwater every winter due to ice at the control, either permanently or sporadically during the winter period. Streamflow stations operated under winter conditions may be affected by a wide range of conditions, including: complete ice cover; partial ice cover; anchor ice; frazil ice; flow over ice; or, floating ice.

The extent of the winter ice period affecting streams in Canada can best be shown through an example. In 1986, the hydrometric network in the Province of Manitoba was composed of 223 streamflow stations (Environment Canada 1987). Of these 223 streamflow stations, 100 were operated on a continuous basis (*i.e.* from January to December). It is interesting to note that 78 % of the continuous stations were under ice conditions for a period of 4 months or more, with the majority of stations being under ice conditions for a period of 5 months (*i.e.* November to March). The remainder, 123 stations, were operated on a seasonal basis (*i.e.* March to October, or March to June). Of these 123 streamflow stations, 98 % were affected by ice conditions during one month (*i.e.* March).

Techniques for Streamflow Measurement under Ice Conditions

Access to the streamflow sites is by motor vehicle, airplane, helicopter, boat, or snowmobile. For safety reasons, most discharge measurements under ice conditions are performed by a two-person crew. After initial inspection of the metering site, an acceptable cross-section is selected based on the metering criteria given in Terzi (1981). The edge of water is located at both shores. Then, a minimum of 20 to 25 observation holes are cut through the ice for the current meter measurement of discharge, using motordriven or manual drill. The holes across the metering section should be distributed so that the discharge measured in any one panel is approximately 5 % of the total.

To determine the total width at the metering section, a tag line (nylon or metallic tapes) is used. The tag line is mounted on a reel, and graduated at regular intervals. The distance to any point in the metering cross-section is determined from an initial point on the bank. The effective depth of the water is computed as the total depth of water minus the distance from the water surface to the bottom of the ice surface or slush ice pack. The total depth of water is usually measured with an ice rod, with a sounding weight and reel, or with a hand line, depending on the depth. The distance from the water surface to the bottom of the ice is measured with an ice-measuring stick.

The procedure used to determine the effective depth when frazil ice is present in a particular vertical is to lower the current meter through the ice and frazil to the point where the water velocity makes the rotor rotate freely, and then it is slowly raised until the rotor stops rotating. If a heavy frazil ice concentration is encountered at the metering section, a frazil pole (long aluminum pole with a series of discs) is used to clear the path through the layer of frazil ice.

In making the discharge measurement under ice cover conditions, the two-point method (*i.e.* 0.2 and 0.8 depth method) is used for effective depths equal to or greater than 0.75 m, and the one-point method (*i.e.* 0.5 depth method) for effective depths less than 0.75 m. It is assumed that the average of the velocities obtained by the two-point method gives the mean velocity, but a coefficient of 0.88 is applicable to the velocity obtained by the one-point method.

It is recommended that the velocity at each point in the vertical be observed for a period ranging from 40 to 80 seconds. In practice the observation time is 40 to 50 seconds.

The total discharge using current meter measurement is determined by the summation of the products of the sub-section areas of the metering cross-section and their corresponding mean velocities. This discharge computational formula is known as the mid-section method. In this method, it is assumed that the velocity sample at each vertical represents the mean velocity in a rectangular sub-section. The sub-section area extends laterally from half the distance from the preceding observation vertical to half the distance to the next, and vertically from the water surface to the sounded depth.

The WSC winter current meter is used under ice cover. With the exception of the yoke design, the WSC winter meter is in every respect identical to the Price 622 type AA current meter used for open water conditions. The yoke of the WSC winter meter was designed primarily to allow the current meter to be used with the winter rod set.

Discharge measurements through the ice cover can be made using various equipment assemblies. The most commonly used are the winter rod set, "A" reel and tripod, and the winter metering sled. Hand lines have been used at locations where access to a station is difficult and the depths at the metering section are too great for the winter rod set. Various sounding weights that can pass through the 200 mm holes cut with the ice auger are available for use with the tripod, the metering sled or the hand line.

The current meters are individually calibrated on rod suspension, at the National Calibration Service at Canada Centre for Inland Waters, in Burlington, Ontario. The calibration tests include the development of a single linear rating equation (standard rating with 20 runs, *i.e.* at 20 different velocities) with velocities ranging from 10 to 250 cm/s, for each current meter. The WSC winter meter is calibrated every three years, or more frequently if damaged in service.

During stable ice cover conditions, the frequency of discharge measurements is generally one measurement per month, and twice over a 6 to 7 month period at remote stations. The frequency is increased during the break-up period.

Additional information on the techniques used by Water Survey of Canada for measurement under ice cover may be found in Terzi (1981), and Strilaeff and Wedel (1970).

Measurement Problems Generally Encountered under Ice Conditions

Under low air temperature conditions, the current meter will tend to freeze when it is taken out of the water (*i.e.* from one ice hole to another). The thermal shock may affect the performance of the current meter, by decreasing the response of the meter, *i.e.* under-recording the mean velocity. To avoid freezing of the current meter it is advisable to plunge it into a bucket of water taken from the hole in the ice immediately after finishing the measurement in the given vertical, or to wrap it in a warm material. A small portable heater may also be used to keep the meter ice free. If these measures do not prevent the freezing of the current meter, it should be immersed in the already prepared hole of the next vertical. After a few minutes the ice formed on the current meter will melt. The winter metering sled, equipped with a heater, is also used at sites affected by severe weather conditions (*e.g.* in northern Canada).

Depending on the concentration level of frazil (slush) ice in the metering section, the discharge measurement will be subject to several uncertainties. These uncertainties are related to the determination of the cross-sectional area, and of the mean velocity. Often a current meter has to be passed through a layer of frazil ice immediately below the ice surface, the thickness of which varies depending on several factors, before it reaches the flow of clear water. Under such conditions the cups of the rotor may be filled with frazil ice, thus affecting the original calibration. The results of experimental tests in the laboratory (Engel and DeZeeuw 1981), simulating level-full rotor cups (*i.e.* sealed cups), indicated that the maximum reduction in the rate of rotation of the rotor would be approximately 8 %. Another problem with the presence of frazil ice is that it may not be readily identifiable in the cross-section. In this case, the current meter also underestimates the mean velocity. In frazil ice there may also be undetected conduits of flow through the pack causing under estimation of the total discharge.

To eliminate the problems of frazil ice accumulation in the cups, and ice formation of the meter, a new plastic rotor (*i.e.* solid cup rotor in lexan) has been developed by the Water Survey of Canada, and by the U.S. Geological Survey for use with the standard Price meter yoke (Engel and DeZeeuw 1984a; Engel *et al.* 1985; Engel *et al.* 1986; Futrell 1986). Another purpose for developing plastic rotor for the Price meter, is to improve the performance of the Price current meter at low speed.

Another problem consists of determining the velocity through large frazil ice accumulation. In a recent study, Lawson *et al.* (1986) showed that water flow below the ice cover occurs in distrinct channels that are generally separated from each other by stagnant deposits of frazil ice. Electromagnetic water current meters have been found useful in delineating the locations of stagnant frazil ice deposits without flow, and in delineating the movement of water at the base of such deposits (Lawson *et al.* 1986). However, it has been stated in the literature that moving frazil ice may affect its accuracy by adhering or coating the meter sensor therefore reducing its sensitivity and producing low readings (Derecki and Quinn 1987; Lawson *et al.* 1986).

Because of the numerous measurement problems encountered when large accumulations of frazil ice are present in the cross-section, it is generally preferable to relocate the metering cross-section, if possible.

Due to changes in air temperature, changes in flow may occur, which may inundate the ice cover. The flow on the surface of the ice cover may then freeze, and thus etablish another ice cover, and if such process is repeated, several layers of ice will be formed. These conditions prohibit an accurate determination of discharge, and therefore, an alternative metering section must be located. Although the flow between each layer may be measured and combined to obtain the total flow, the overall uncertainty is very high, and the practice is not recommended.

Discharge measurements are desirable during the freeze-up and break-up periods, however, dangerous field conditions often make such measurements impractical and unsafe. For example, during the ice formation process, the ice cover may be too thin or weak to support field personnel and their equipment. At an open metering section the stream velocity may be too high in the channel or the stream too deep to safely perform a measurement by wading. This situation may also be complicated by the presence of ice in the channel. At break-up, floating ice may make the measurement of flow hazardous. During this period, it may be necessary to use procedures which reduce the measurement time. For example, by reducing: the number of verticals; the observation time; the number of points in the vertical or possibly taking surface velocity observations instead of velocity observations at standard depths. These time saving procedures are used in order to protect the technician performing the measurement and to reduce the time the metering equipment is in the water and exposed to potential damage. These procedures will produce a good estimate of the flow but will be of lesser accuracy than the "standard" streamflow measurement procedure.

Untertainties in Current Meter Measurements under Ice Cover

The overall uncertainty, random and systematic, in a single determination of river discharge using the velocity-area method in combination with a current meter, is due to the following uncertainties:

- in the determination of the cross-section area, *i.e.* in the determination of widths, and depths;
- in the determination of the individual measurements of the flow velocity necessary for the determination of the mean velocity;

- by approximation of the integral of the product of a velocity field over a cross-section by finite summations of the product of width, depth, and mean velocity.

The uncertainty in sampling the mean velocity in time and in space is based on the uncertainty due to the limited time of exposure; the uncertainty due to the limited number of points taken in the vertical; the uncertainty due to the limited number of verticals; and the uncertainty in the current meter still-water calibration and its applicability to flowing water utilizing other than the standard suspension.

Some of these uncertainties will be further described below, however, for a more detailed discussion of the uncertainties in the velocity-area method using a current meter, the reader is referred to Pelletier (1988a).

The uncertainty in the width determination for a stream under ice cover, or partial ice cover arises because of the difficulties of locating the edges of flow under ice cover. Damages to the equipment (*i.e.* cutting blade of the ice auger) are likely to happen when the technician tries to locate edges of flow under ice. Also, for large streams, corrections for sag, pull, slope, and temperature of the measuring tape or wire should be made. Errors in depth soundings are likely to occur in cross-sections having great depths and velocities, and those with frazil ice accumulation. The ice thickness, and frazil depths are assumed to vary linearly between verticals or sampling points; however this is not necessarily the case, therefore introducing additional error in the cross-sectional area determination.

The mean velocity at any point, determined from a measurement during a certain time (*e.g.* 40 to 50 seconds), is only an approximation of the true mean velocity at any particular point. Therefore, an error is introduced, which is related to the time period of observation of velocity at a point. Although the majority of the investigations carried out to determine the uncertainty due to limited time of exposure were performed in open channels, they indicated that an observation time of 40 to 50 seconds is insufficient to obtain a measurement of sufficient accuracy.

In the computation of a discharge measurement, the depth and the velocity are assumed to vary linearly with the distance between the verticals in the cross-section. The value of the uncertainty depends not only on the number of verticals, but also on the size and shape of the channel, the variation in the bed profile and the horizontal distribution of the velocity profile. Based on several investigations, the minimum number of verticals taken in the cross-section (*i.e.* 20 to 25) is adequate in most situations. The computation of the mean velocity in a given vertical as an average or a weighted average of a number of point velocities results in an approximation of the true mean velocity in the vertical considered. Due to the roughness of the underside of the ice cover the location of the filament of maximum velocity is some distance below the underside of the ice. The velocity distribution under ice cover is similar to that in a pipe with a lower velocity near the underside of the ice.

It is generally assumed that a vertical velocity distribution curve for a stream under ice cover follows a logarithmic distribution. However, considerable uncertainties still remain in the shapes of the velocity distribution for ice-covered rivers. For example, Lawson *et al.* (1986) showed that velocity profiles ranged from logarithmic distribution to a very flat vertical distribution through most of the water column. In Canada, Alford and Carmark (1987a, 1987b), and this author (Pelletier 1989, 1988b) reported similar observations.

The standard procedure used by Water Survey of Canada for vertical velocity measurements under ice cover was developed by Barrows and Horton (1907). They analyzed 400 profiles from 25 gauging stations in five U.S. states. They found that the average coefficient for obtaining the mean velocity from the mean of the velocities at 0.2 and 0.8 depth was 1.002, and showed that the range was 0.98 to 1.04. Also, the average coefficient for obtaining the mean velocity from that at mid depth was 0.878, the range being 0.82 to 0.92. They suggested that vertical velocity profiles be taken and appropriate coefficients be derived from these at each metering site.

Barrows and Horton also showed that the coefficient changes for different types of ice cover (*e.g.* very rough ice). Lau (1982) suggested a guide for a better correction coefficient based on the ice and bed roughness, and showed that the velocities at 0.2 and 0.8 of the depth may deviate significantly from the overall average velocity.

The sampling of vertical velocity curves is not a standard procedure for Water Survey of Canada. Based on results of an investigation on the Red River in Manitoba (Pelletier 1989, 1988b), this author recommended that further investigations be undertaken to determine the variability in the coefficients, for Canadian streams, required for obtaining the mean velocity from the two- and the one-point methods. It was also recommended that vertical velocity curves be sampled to establish the appropriate coefficient for each particular stream.

The current meter is calibrated by towing the meter through still water at various constant speeds and recording the number of revolutions of the rotor in a measured interval of time. It is assumed that this rating or calibration is valid when the current meter is used to measure velocity of turbulent flow in open channels and in ice-covered rivers. Errors may be introduced by this assumption and by errors in the rating tank. The various factors affecting the overall uncertainty in the current meter calibration are: calibration procedure (*i.e.* number of tests, curve fitting technique, individual versus group rating); repeatability of calibration data; change in fluid densities (*i.e.* temperature and density); effect of suspension; boundary effects; effect of oblique flow; effect of vertical motion; and effect of turbulence. Some of these factors are further described below.

It was stated previously that WSC winter current meters are calibrated on rod suspension only, however, they often are used on cable suspension using a wide range of winter weight assemblies. Recent studies (Schneider and Futrell 1984;

Pelletier 1989, 1988b) have shown that if a meter is rated on rod suspension but used in the field on cable suspension, with winter weights used by Water Survey of Canada, significant differences would occur. For example (Pelletier 1989, 1988b), it was determined that the WSC winter meter rotates approximately 4 % to 17 % slower, depending on the velocity, when mounted with a winter weight assembly (*i.e.* Winnipeg type) than when mounted on a rod. Similar observations on the effect of suspension using open water weight assemblies were made by Engel and DeZeeuw (1984b).

It has been noted in the literature (Smoot and Carter 1968; Herschy 1982; Pelletier 1989, 1988b) that the uncertainty in a cup-type current meter increases as the velocity decreases. This is of particular importance at velocities lower than 0.3 m/s, which are often encountered under ice cover conditions. The results of an extensive literature review (Pelletier 1988a) showed the large differences and inconsistencies between the results of the different investigators and suggested that further investigations be carried out.

Techniques for Daily Streamflow Computations for Ice Period

The presence of ice at a stream's control causes the gauge height to indicate flow greater than the actual discharge. Generally, discharge measurements made during periods of ice effect plots on the left on a open water stage-discharge relation curve. The computation of discharge for a period when a stream is under ice conditions is a complex and highly subjective process, different for every gauging station in the country.

The quantity and distribution of winter streamflow are the results of the combination of factors that may be classified as climatic, geologic, topographic, and vegetational. Some of the climatic factors are precipitation, temperature, barometric pressure, and winds.

Several methods are available to compute daily discharge for streams affected by ice conditions. In Canada, a wide range of climatic conditions, and flow regimes are encountered. However, only very limited effort has been made to classify the domain of application of a particular method based on stream types and on climatic conditions (Rosenberg and Pentland 1983). In practice, the selection of a particular method will depend on the hydrometric technician's knowledge and past experience with a particular technique, and the amount of available data. However the decision should be based on the quantity and quality of hydrometric and climatic data, on the knoweldge of historical ice affected flows at a gauging site, the number of discharge measurements, and the availability of hydrometric and climatic data at neighbouring sites which may or may not be affected by ice.

The computatitonal methods available to estimate daily discharge records at streams affected by winter conditions, are briefly described below. More detailed explanation on some of these methods and others may be found in Hoyt (1913), Kolupaila (1938), Collier (1962), Rosenberg (1966), Bennett (1968), Environment Canada (1980), WMO (1981), ISO (1982), Rantz *et al.* (1982b), Morton (1983), Rosenberg and Pentland (1983), Environment Canada (1984), Santeford (1986).

The *backwater method* requires the measured discharges and related gauge height for the measurement, the mean daily gauge height, and the open water stage-discharge relation. First, the difference between the gauge height at the time of the measurement and the gauge height that would occur for the measured discharge if the stream was under open water conditions, is calculated, and defined as the "backwater effect". These differences (*i.e.* backwater values) are calculated for each measured discharge and then plotted against time. The mean daily air temperatures are also plotted against time. A "backwater" curve is then drawn with reference to the air temperature graph, and to the mean daily gauge heights graph. Then, daily effective gauge heights are computed by subtracting the daily "backwater effect", as indicated by the "backwater" curve, from the recorded daily gauge heights. These effective daily gauge heights are then applied to the open water stage-discharge relation to produce daily discharges.

The *adjusted discharge method* requires the same amount of information as the backwater method. First, the equivalent open water discharges are obtained by applying the open water stage-discharge relation to the recorded daily gauge height record. Then, the equivalent open water discharges are plotted against time. The daily maximum and minimum (or mean) temperature, and daily mean precipitation are also plotted against time. The available values of the discharge measurements are then ploted on the graph on the appropriate days, and the plotted points are joined, using the temperature, precipitation, and open water discharge graph as a guide to the position of the curve.

The *interpolated discharge method* only requires the measured discharge(s), meteorological data, and discharge measurements of nearby streams. The measured discharges obtained during the winter period are plotted on the appropriate days, and a hydrograph of daily discharge for the winter season produced by joining the plotted points, using temperature and precipitation data (rain and snow), and any other additional information (*e.g.* flow in adjacent streams), as a guide in shaping the hydrograph.

In the *effective gauge height (effective stage) method*, the effective gauge heights are computed for each discharge measurement using the open water stage-discharge relation. These effective gauge heights are then plotted on a hydrograph of mean daily gauge heights, and a hydrograph of effective gauge heights is interpolated between the discharge measurements using the stage hydrograph and the temperature and precipitation graphs. Daily mean discharge are then computed using the effective gauge heights and the open water stage-discharge relation.

In the *modified backwater method*, the discharge measurements are used to compute A, in the following equation

$$B = A \log \left(\frac{Q_e}{Q_i} \right) \tag{1}$$

where

B – the backwater in appropriate stage units;
A – the constant;
Q_e – the equivalent ice free discharge from stage-discharge relation; and
Q_i – the discharge at freeze-up.

The value of A is interpolated between discharge measurements and the value of B computed for each day using the above equation. Then daily discharges are computed as in the *Backwater method.*

The *recession curve method* may be applicable in estimating winter streamflow records at large rivers, especially those having significant lake storage, which may exhibit a semi-logarithmic form of recession from the time of formation of an ice cover until breakup of the ice cover. The mathematical form of the equation is:

$$Q_2 = Q_1 \, C^{-dt} \tag{2}$$

where

Q_2 – the discharge at time t_2
Q_1 – the discharge at time t_1
C – the recession constant; and
dt – the elapsed time interval (t_2-t_1)

If the slope of the recession line C is invariant from one year to another, a single discharge measurement can be used to define the recession. The daily discharges are computed utilizing the recession equation or a graphical semi-logarithmic plot of discharge versus time.

In the *K-factor method*, for each winter discharge measurement, a K factor is calculated using the following equation

$$K = \frac{Q_m}{Q_o} \tag{3}$$

where

Q_m – the measured discharge; and
Q_o – the open water discharge at the same gauge height.

The values of K are generally less than unity. The K value for each measurement is plotted on the appropriate days, and a curve of K for each day constructed by joining the plotted points, using meteorological data as a guide. The daily discharge for the winter period is then calculated by multiplying the equivalent open water discharge from each day's gauge height by the corresponding K factor from the curve.

Some rivers, particularly large ones, may have winter ice regimes that are so consistent from winter to winter that it is possible to develop a winter stage-discharge relation. This method is called *the winter rating curve method*. After the existence of such a relation has been verified by discharge measurements, daily mean discharges are computed from the winter stage-discharge relation and gauge heights.

One or more of the above methods of computation may prove to be satisfactory for computation of daily mean discharge under ice cover at a particular gauging station. In theory, several methods should be tested and the method which produces the best results selected as the standard method for the particular gauging station. However, in practice, the daily streamflow computation of the winter period is done manually and is time consuming, making difficult and impractical an inter-comparison of the techniques.

Using hydrometric data at seven streamflow stations across Canada, Rosenberg and Pentland (1983) tested three of the methods described in the previous section, *i.e.* Backwater, Adjusted Discharge, and Interpolated Discharge methods. They concluded that the standard error expressed as a percentage of the mean tends to decrease as mean discharge increases. They showed that applicability of a computational method for a particular stream may be categorized using mean winter air temperature (December to February) and discharge. The classification was as follows:

- for large streams, in frigid zones, all three methods give good results (low uncertainties);
- for medium to large streams in the intermediate temperature zone, the adjusted discharge method using gauge height data appeared to give slightly better results than the interpolated discharge method, and much better results than the backwater method;
- for small streams, and streams in the moderate temperature zone, all three methods give unsatisfactory results (*i.e.* very high uncertainties).

The techniques available for computation of daily discharges for streams affected by ice conditions are not significantly different. The estimation and computation of daily discharge data is generally performed manually, and remains largely a subjective process. They generally require the following information: actual discharge measurements, open water stage-discharge relation, and climatological data and streamflow data from nearby stations. Note also that climatological data and streamflow data from nearby stations are used qualitatively only.

Instrumentation capable of recording continuous mean velocities (*e.g.* ultrasonic velocity meter) and other hydraulic and climatic parameters will play a major role in the development of improved streamflow computation methods for rivers under ice conditions.

For example, an ultrasonic velocity meter (UVM) was installed on the Red River at Emerson (Manitoba, Canada) for collecting water velocity and sound velocity measurements during the 1987-88 winter period. The velocity of sound in water may be transformed into water temperature using a model proposed by Drenthen (1983), therefore providing additional information for the computation of streamflow. The UVM at Emerson, is a single-path system, and is known as AFFRA, *i.e.* Acoustic Flowmeter For Remote Areas. This system was developed by Stedtnitz Maritime Technology, in Ontario.

There is a definite need for developing new and improved techniques for the computation of daily streamflow records at sites affected by ice conditions. Ideally, these methods should be computerized, and make full use of hydraulic and climatological parameters as provided by existing and new instrumentation.

Techniques used by other Northern Countries

Greenland (Denmark)

In Greenland (Kern-Hansen 1987) current meters with metal propellers and individual calibration are the only ones used. They are used for rivers with subcritical flow conditions (when cross-section is ice-free) or when measurements can be made from the ice. Current meters with plastic propellers and general calibrations were tested and found to be not accurate enough and also proved to be less reliable under the conditions experienced in Greenland. The current meter is generally mounted on rod suspension to perform discharge measurements from an ice cover.

The number of verticals is selected on the basis of the World Meterological Organization (WMO) standard (WMO 1981), which is as follows:

- the spacing between two verticals must not exceed 1/20 of the overall width of the watercourse;
- the difference in discharge between two consecutive verticals must not exceed 10% of the total discharge of the watercourse.

The number of points in each vertical will depend on the location of the measured vertical in the cross-section. It is considered more important to have a higher number of points in any deep main current than in a shallow area close to the shore.

Several methods are used, and they include:

- 1 point method (0.6 depth);
- 2 point method (0.2 and 0.8 depth);
- 3 point method (0.2, 0.6, and 0.8 depth);
- 5 point method (close to surface, 0.2, 0.6, 0.8, and close to bed)

Finally, in addition to the velocity-area method, the dilution method with salt (NaCl) is used to a certain extent, in Greenland. It is used for rivers having supercritical flow conditions and for measuring at streams partly packed with ice.

Daily discharge data are estimated using discharge measurement(s), precipitation and temperature data, and streamflow data at nearby stations.

Finland

In Finland (Hyvarinen 1986) about 100 of the 300 streamflow stations are affected by ice. Discharge measurements are performed at these gauging stations generally twice every winter.

The velocity measurements are made through ice holes using a propeller type current meter (Ott) attached to a special rod with a turning point. To cut the holes through the ice manual and motor-driven drills, and chisels are used.

The daily discharge data are estimated graphically on the basis of the actual measurements (*i.e.* two field measurements, one in the first part of the winter, and one at the end of winter), uncorrected discharge and other data, such as air temperature and precipitation (Hyvarinen 1984).

The technique is based on the assumption that the winter discharge in central and northern Finland generally decreases exponentially

$$Q(t) = Q_o e^{-kt} \quad (4)$$

where

Q_o – the discharge before the formation of ice;
k – a constant which varies from one site to another and from winter to winter;
t – the time.

Norway

In Norway (Petterson and Skofteland 1986) approximately 400 of the 700 streamflow gauging stations are affected by backwater every winter due to ice on the control, either permanently or sporadically.

To obtain streamflow records for the winter period, one winter discharge measurement is taken at approximately 160 stations, and 2 or more at 5-6 stations of special importance. The measurement is generally taken in the February-April period, or the last most stable part of the winter, when the flow is often close to the absolute minimum for the year. The velocity-area, using a current meter (propellertype), is the only method used for winter discharge measurements in Norway, with, depending on effective depth, up top five velocity measurements in each vertical. The holes are drilled, either with motor-driven or manual equipment. To lower the current meter through the drilled holes, a special rod with a turning point is used.

The "backwater" method is used in Norway to estimate records of discharge for stations affected by ice. This method is graphically-based, and requires values of observed gauge height, actual discharge measurement, open water stage-discharge relation, and available information on ice conditions, air temperature, and precipitation. A graphical comparison with daily hydrographs unaffected by ice from nearby stations is extensively used when adjusting for the backwater effect.

Sweden

In Sweden, approximately 160 gauging stations are affected by ice. Only one discharge measurement is taken during the winter season.

Discharge measurements under ice conditions are performed using the velocity-area with a propeller type current meter (CURRENTMASTER) on rod suspension. The two-point method (0.2 and 0.8 depth) is generally used, but in shallow section the 1-point method (0.6 depth) is used.

The method for calculating daily discharges (Westman 1987) is based on the graphical analyses of diagrams. Each diagram includes two years of data and shows 2 to 4 streamflow stations, air temperature and precipitation from a nearby climatic station and generated runoff as computed with a simplified runoff model (HBV). The corrections of the discharge for ice effects are made manually on the diagram by the hydrologist responsible for the district, who is knowledgeable of the conditions at the station.

U.S.A.

In the U.S.A. (Corbett *et al.* 1957; Buchanan and Somers 1980; Rantz *et al.* 1982a, 1982b; Cobb and Latkovich 1986; Cobb and Parks 1986) the techniques used for measurement under ice cover are similar to the ones used by Water Survey of Canada.

The effective depth is determind as the distance from the bottom side of the ice or frazil ice (if present) to the streambed.

The 0.2 and 0.8 depth method is used for effective depths of 0.76 m or more, and the 0.6 depth method for effective depths less than 0.76 m. A coefficient of 0.92 is required to correct velocities obtained by the 0.6 depth method.

A vane ice meter is recommended for use under ice cover because the vanes do not plug-up with frazil ice as do the cups of the Price-type meter. The vane type meter is recommended only for use with a rod suspension, because it requires a large variable correction coefficient (Schneider and Futrell 1984). This coefficient is required to convert a vane meter rated on rod to the same meter rated on cable suspension.

The Price type AA current meter is also used occasionally. If the depths are large, larger holes (standard are 0.15 m) are drilled and the measurements are made with open water suspension equipment (weights of 7, 14, or 23 kg). Canadian winter weight assemblies are also used by some field personnel. Other meter suspension equipment include: hand lines, and sled-mounted reels.

To measure current velocities, both magnitude and direction, electromagnetic water current meters are also used for discharge measurement in ice-covered rivers.

The most common method for daily discharge computation and estimation, used by the U.S. Geological Survey, during periods of ice cover is the hydrographic and climatic comparison method. This method uses discharge measurements, hydrographic comparison with available and appropriate open water streamflow records, and comparison with appropriate climatic records.

Other methods include: the discharge-ratio method (also known as the Lithuanian method); and the shifting-control method (also known as the Stout method). Detailed discriptions of the three methods used by the U.S. Geological Survey may be found in Rantz *et al.* (1982b).

U.S.S.R.

In the U.S.S.R. (MAHS, 1975 a) during periods when ice formations are present, or ice hamper the flow of the water and cause a rise in water level not connected with an increase in water content, metering of discharge is done in accordance with fluctuations in water level, making allowance for the growth of ice formations;

- in autumn, from the first appearance of significant shore ice strips (more than 1/5 or the river's width) or, if they are absent or narrow, from the first day of downstream ice movement, measurements are carried out in accordance with weather conditions. During stable below-freezing weather with no thaws, water discharge measurements are made every 3-5 days until the ice drift becomes so thick that discharge measurements cannot be taken. If the weather is unstable, with thaws and rains, measurements are taken more frequently.
- during the winter ice regime, from the moment when the ice cover is thick enough for work to be done on it safely, water discharge is measured every 5 days for the first 20 or 30 days. After that, under stable below-freezing weather conditions without thaws, discharge is measured less frequently, *i.e.* at 15 to 20-day intervals. In the event of thaws, during which rain may fall and snow may melt, measurements are made as frequently as possible whenever is it possible to work safely.

Discharge measurements are generally performed by an observer. However, on large rivers, where the gauging of water discharge involves considerable difficulties that are insurmountable for an observer, it is carried out by an engineer or technician, and the observer acts in this case as their assistant.

Propeller-type current meters are used (GR types) for discharge measurement under ice cover with the type of meter and suspension dependent on the working depths (MAHS 1975b).

Under ice conditions at most of the stations in the U.S.S.R., velocity observations are taken at three points in the vertical, *i.e.* at 0.15, 0.5, and 0.85 of the total depth from the water surface. The mean velocity is determined from the arithmetic mean of the value of velocity at these three points. For depth less than 40 cm, the velocity is measured only at 0.5 of the total depth, and the mean velocity computed from the value of velocity at this point multiplied by 0.9. The velocity at each point in a vertical is measured for a minimum of 100 seconds.

A more detailed method is also used in the U.S.S.R. in which velocity observations in a vertical are taken at the under-ice surface, 0.2d, 0.4d, 0.6d, 0.8d, and at the bottom.

Summary of International Comparison

The techniques for discharge measurements under ice cover used by North American data collection agencies (*i.e.* Canada and U.S.A.) are different than techniques used in Northern Europe (*i.e.* Denmark, Finland, Norway, Sweden, and U.S.S.R.). An important difference resides in the instrumentation used, *i.e.* vertical-axis current meters in North America, and horizontal-axis current meters in Northern Europe. Other differences were noted: in the sampling of velocity observations in the vertical, *i.e.* generally fewer points are sampled by North American agencies when compared to Northern Europe agencies; and in the frequency of discharge measurements, *i.e.* the frequency is generally higher in North America when compared to Northern Europe, with the exception of U.S.S.R. The duration time of velocity observation, and the number of verticals sampled in the metering cross-section are also different, but the extent of these differences were not defined.

The techniques for computation of daily discharges for stream affected by ice conditions used by North American and Northern Europe agencies are not significantly different and remains largely subjective. To estimate daily flows, actual discharge measurements are generally used, in combination with the open water stage-discharge relation, climatological data and streamflow data from nearby stations.

Finally, it is interesting to note that at present no international standard exists for the measurement of streamflow under ice conditions. The unavailability of a standard has been recognized internationally, and efforts are being made by the International Organization for Standardization (ISO) for producing such a standard. Moreover, at the Eight International Northern Research Basins Symposium (Sweden 1990), the IHP Regional Working Group on Northern Research Basins established a task force on winter discharge measurement and computation techniques.

Conclusions

Generally, an ice cover will significantly modify the characteristics and morphological processes of rivers. The hydraulic processes are more complex than open channel conditions and are not well understood.

Changes in river flow from ice-free flow to ice flow regimes have been identified mainly by theoretical and laboratory analyses. These studies have shown that an ice cover generally increases the normal flow depth and decreases flow velocity. An ice cover modifies the velocity and shear stress distributions. The precise form of these distributions, under different winter flow regimes encountered in Canada, remains in question. The variables of heat transfer, ice physics, and ice and flow history makes the solution complex.

In general, winter discharge measurements are less accurate than measurements made under open water conditions for the following reasons:

- the presence of ice in the river, either covering the surface, attached to the bottom or banks in the form of anchor ice, or floating throughout the cross-section as frazil ice;
- the inability of the cup-type current meter to accurately measure low velocities (less than 0.3 m/s) as is often encountered during the ice period;
- the freezing of the meter while the technician is passing it from one measuring point to another, or making necessary repairs;
- the accumulation of frazil ice in the cups of the current meter, resulting in under-estimation of the mean velocity;
- the inability of the hydrometric technician to detect under surface ice eddies or other conditions that disturb the distribution of the flow, and the tendency to measure velocities at too few points;
- the impossibility of measuring the effective cross-section as accurately under ice cover as in open water, especially when frazil ice is present;
- hurry in the work, due to physical discomfort of the technician making the discharge measurement;
- the possibility of the stream having a different velocity profile that the standard assumed for winter measurements; and
- presence of thin or moving ice or overflow, making the physical access to the flow cross-section unsafe or simply impractical.

Once the streamflow measurements have been obtained, the computation of daily discharge for the ice affected period can not be computed by the standard stage-discharge relation because of the presence of other variables. Variables or factors that may come into play are:

- growth of ice due to temperature;
- formation of closed conduit flow;
- reduction and/or blockage of the cross-section due to ice growth and/or frazil ice;
- changes in roughness of ice from thermal processes;
- formation of frazil and/or anchor ice in response to weather and flow conditions;
- a wide range of freeze-up processes from the slow thermal growth to the episodic formation of frazil ice dams; and
- ice break-up, jams, and releases as determined by ice flow channel characteristics.

Some factors of winter hydrology are not fully understood nor quantified, making the data interpretation, estimation and computation process subjective and difficult. Examples include: flow change due to the initial ice cover formation; effect of temperature change on groundwater releases; abstraction of flow to form fixed ice.

The problems described in this paper may be divided into three main areas for further investigations. They are: streamflow measurement; daily flow computation and estimation; and winter hydrology. Accurate discharge measurements are essential to accurate daily discharge computations, and to the understanding of winter hydrology. Therefore, emphasis and research effort should first be placed on resolving the problems and uncertainties in streamflow measurement techniques under winter ice conditions.

The cost of obtaining discharge measurements under winter ice conditions is considerably higher than at other periods of the year, due to factors such as: the time required to access the metering site and to perform the measurement; and the need for two-person field crews because af dangerous field conditions. Not only are discharge measurement obtained under ice conditions more costly, and more difficult to obtain, but also very often they are considered to be less accurate than open water discharge measurements.

Over the last four years increasing effort (Lawson *et al.* 1986; Alford and Carmark 1987a, 1988b; Pelletier 1989, 1988b) has been made to better understand the factors modifying the flow regime of streams affected by ice conditions. These investigators generally noted that systematic, quantitative field studies of ice-covered rivers were lacking, and therefore recommended that further investigations be carried out.

Since the problems described in this paper are commonly encountered in northern countries, and the solutions to these problems may be applicable to other countries, joint international investigations, will be beneficial and cost effective in resolving uncertainties in streamflow measurement and computation under winter ice conditions. Such joint studies may lead to the development of an international standard on the techniques for measurement and computation of streamflow under winter ice conditions.

The problems and uncertainties encountered in the collection of hydrometric data at sites affected by winter ice conditions have generally been recognized by agencies from various northern countries. In order to resolve these problems and therefore improve the overall quality of hydrometric data collection under ice conditions, a cooperative research plan should be formulated between data collection agencies and hydrologic institutes of each of the northern countries. The plan should include the followings:

- an exhaustive survey of the conditions encountered in each country;
- an assessment of the present techniques (methods and instruments) used to measure and compute streamflow at sites affected by winter ice conditions;
- the determination of uncertainties in measured discharge, and in daily computed discharge; and
- the development of new instrumentation, such as plastic current meter rotors with an optic head, and an ultrasonic velocity meter.

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References

Alford, M. E., and Carmack, E. C. (1987a). Observations on Ice Cover and Streamflow in the Yukon River near Whitehorse during 1984/85. Environment Canada, National Hydrology Research Institute, NHRI Paper No. 34, IWD Scientific Series No. 155, 24 pp.

Alford, M. E., and Carmack, E. C. (1987b). Observations on Ice Cover and Streamflow in the Yukon River near Whitehorse during 1983/84. Environment Canada, National Hydrology Research Institute, NHRI Paper No. 32, IWD Scientific Series No. 152, 63 pp.

Barrows, H. K., and Horton, R. E. (1907). Determination of Stream Flow During the Frozen Season. U.S. Geological Survey, Water – Supply and Irrigation Paper No. 187, Series M, General Hydrographic Investigations, 19, 93 pp.

Bennett, R. M. (1968). The Stage-Discharge Relationship and Winter Discharge Under Ice Cover for the Peace and Slave Rivers, Utah University, M.Sc., 63 pp.

Buchanan, T. J., and Somers, W. P. (1980). Discharge Measurements at Gaging Stations. U.S. Geological Survey Techniques of Water Resources Investigations, Chapter A8, 65 pp.

Cobb, E. D., and Latkovich, V. T. (1986). A Summary of Methods Used by the U.S. Geological Survey for the Measurement of Streamflow Under Ice Cover. Proceedings of the 6th Northern Research Basins Symposium/Workshop, Michigan Technological University, January 26-30, 9 pp.

Cobb, E. D., and Parks, B. (1986). Problems Encountered and Methods Used in the U.S. Geological Survey for the Collection of Streamflow Data Under Ice Cover. Cold Regions Hydrology Symposium, American Water Resources Association, 9 pp.

Collier, E. P. (1962). Investigation Into the Accuracy of Winter Streamflow Records on Some Foothills Streams in Alberta. Department of Northern Affairs and National Resources, Water Resources Branch, Unpublished Report, 38 pp.

Corbert, D. M. *et al.* (1957). Stream-Gaging Procedure. U.S. Geological Water-Supply Paper No. 888, 245 pp.

Derecki, J. A., and Quinn, F. H. (1987). Use of Current Meters for Continuous Measurement of Flows in Large Rivers, *Water Resources Research, Vol. 23,* No. 9, pp. 1751-1756.

Drenthen, J. G. (1983). The Velocity of Sound in Water. Stork Servex, The Netherlands, 8 pp.

Engel, P. *et al.* (1986). Improvements to the Low Speed Response of the Plastic Rotor for the Price Current Meter – Phase II. Environment Canada, National Water Research Institute, Report 86-121, 16 pp.

Engel, P. *et al.* (1985). Improvements to the Low Speed Response of the Plastic Rotor for the Price Current Meter – Phase I. Environment Canada, National Water Research Institute, Report 85-140, 15 pp.

Engel, P., and DeZeeuw, C. (1984a). On the Effect of Changes in Geometry and Submerged Weight of the Price Meter Rotor. Environment Canada, National Water Research Institute, Report 84-24, 17 pp.

Engel, P., and DeZeeuw, C. (1984b). The Effect of Columbus Type Sounding Weights on the Performance of the Price Current Meter. Environment Canada, National Water Research Institute, Report 84-30, 31 pp.

Engel, P., and DeZeeuw, C. (1981). Sensitivity of the Price Current Meter to the Effects of Frazil Ice. National Water Research Institute, Hydraulics Division, Report 81-25, 10 pp.

Environment Canada (1987). Surface Water Data – Manitoba, 1986. Environment Canada, Water Resources Branch, 183 pp.

Environment Canada (1984). Methods for the Estimation of Hydrometric Data. Environment Canada, Water Resources Branch, 1st Edition, 23 pp.

Environment Canada (1980). Manual of Hydrometric Data Computation and Publication Procedures. Environment Canada, Water Resources Branch, 5th Edition, 51 pp.

Futrell II, J. C. (1986). Ice Metering System and Ice Chisels. Proceedings of the 6th International Northern Research Basins Symposium/Workshop, Michigan Technological University, January 26-30, pp. 119-132.

Herschy, R. W. (1982). Current Meter Calibration – Individual Rating Versus Group Rating. Advances in Hydrometry, Proceedings of the Exeter Symposium, IAHS Publication No. 134, pp. 25-36.

Hoyt, W. G. (1913). The Effect of Ice on Stream Flow. U.S. Geological Survey, Water-Supply Paper 337, 77 pp.

Hyvarinen, V. (1986). Some Practical Aspects of Graphical Ice Reduction. Proceedings of the 6th International Northern Research Basins Symposium/Workshop: Field Measurements Under Winter Conditions, Michigan Technological University, Jan. 26-30, pp. 25-29.

Hyvarinen, V. (1984). Graphical Ice Reduction. Proceedings of the 5th International Northern Research Basins Symposium, Vierumaki, Finland, March 10-23, pp. 3.11-3.14.

ISO (1982). Liquid Flow Measurement in Open Channels – Part 2: Determination of the Stage-Discharge Relation. International Organization for Standardization (ISO), ISO 1100/2-1982, 33 pp.

Kennedy, E. J. (1983). Computation of Continuous Records of Streamflow. U.S. Geological Survey Techniques of Water-Resources Investigations, Chapter A13, Book 3, Applications of Hydraulics, 53 pp.

Kern-Hansen, C. (1987). Measuring Water Level and Discharge: Practical Experiences in Greenland. Nordic Expert Meeting on River Ice, Espoo, Finland, November 2-4, 18 pp.

Kolupaila, S. (1938). The River Flow Beneath the Ice. Transactions of International Commissions of Snow and Glaciers, 23, pp. 297-308.

Lau, Y. L. (1982). Velocity Distributions Under Floating Covers, *Canadian Journal of Civil Engineering, Vol. 9, No. 1*, pp. 76-83.

Lawson, D. E., *et al.* (1986). Morphology, Hydraulics and Sediment Transport of an Ice-Covered River – Field Techniques and Initial Data. U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory (CREEL), Report 86-11, 37 pp.

MAHS (1975a). Manual for Hydrometeorological Area Centres and Stations, 8: General Concepts on Water Discharge and its Measurement. Main Administration of the Hydrometeorological Service attached to the Council Ministers of the USSR (translated from Russian into English by Department of the Secretary of State, Ottawa, 1976), 18 pp.

MAHS (1975b). Manual for Hydrometeorological Area Centres and Stations, 9: Water Discharge Measurements. Main Administration of the Hydrometeorological Service attached to the Council Ministers of the USSR (translated from Russian into English by Department of the Secreatry of State, Ottawa, 1976), 69 pp.

Morton, G. H. (1983). Peace River and Slave River Studies, Arctic Rivers Work Group, 56 pp.

Pelletier, P. M. (1989). Uncertainties in Streamflow Measurement Under Winter Ice Conditions – A Case Study: The Red River at Emerson, Manitoba, Canada, *Water Resources Research, Vol. 25, No. 8*, pp. 1857-1867.

Pelletier, P. M. (1988a). Uncertainties in the Single Determination of River Discharge: A Literature Review, *Canadian Journal of Civil Engineering, Vol. 15, No. 5*, pp. 834-850.

Pelletier, P. M. (1988b). An Investigation of the Measurement of Streamflow Under Winter Conditions – International Hydrometric Gauging Station on the Red River at Emerson, Manitoba, Canada. Environment Canada, Inland Waters Directorate, Water Resources Branch, Report No. IWD-WRB(W)-HI-88-1, 166 pp.

Pettersson, L.-E., and Skofteland, E. (1986). Winter Discharge Measurements and the Routine Processing of Winter Stage and Discharge Records in Norway. Proceedings of the 6th International Northern Research Basins Symposium/Workshop, Michigan Technological University, January 26-30, pp. 11-23.

Rantz, S. E. *et al.* (1982a). Measurement and Computation of Streamflow, vol. 1: Measurement of Stage and Discharge. U.S. Geological Survey Water-Supply Paper No. 2175, 284 pp.

Rantz, S. E. *et al.* (1982b). Measurement and Computation of Streamflow, vol. 2: Computation of Discharge. U.S. Geological Survey Water-Supply Paper No. 2175, 346 pp.

Rosenberg, H. B. (1966). Evaluation of Streamflow Determinations Under an Ice Cover, Workshop Seminar on Ice Formation and Breakup in Lakes and Rivers, November 9-10, 15 pp.

Rosenberg, H. B., and Pentland, R. L. (1983). Accuracy of Winter Streamflow Records. Inland Waters Directorate, Reprint of Eastern Snow Conference (1966), pp. 51-72.

Santeford, H. S., and Alger, G. R. (1986). Stage, Discharge, and Ice. Proceedings of the 6th International Northern Research Basins Symposium/Workshop, Michigan Technological University, January 26-30, pp. 183-208.

Schneider, V. R., and Futrell, J. C. (1984). Performance of Ice Meter and Weight Assemblies. U.S. Geological Survey, Water Resources Investigations Report 84-4035, 26 pp.

Smoot, G. F., and Carter, R. W. (1968). Are Individual Current-Meter Ratings Necessary? *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, Vol. 94*, No. HY2, pp. 391-397.

Strilaeff, P. W., and Wedel, J. H. (1970). Measurement of Discharge Under Ice Cover. Department of Energy, Mines, and Resources, Inland Waters Branch, Technical Bulletin No. 29, 14 pp.

Terzi, R. (1981). Hydrometric Field Manual – Measurement of Streamflow. Environment Canada, Inland Waters Directorate, Water Resources Branch, 37 pp.

Westman, S. E. (1987). Adjustments for Backwater Effects Due to Ice Cover – The SMHI Method. Nordic Expert Meeting on River Ice, Espoo, Finland, November 2-4, 14 pp.

WMO (1981). Guide to Hydrological Practices – vol. 1: Data Acquisition and Processing. World Meteorological Organization, 4th Edition, Chapters 2 and 4.

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