SQUARE-GRID SPATIAL INTERPOLATION OF SNOW COVER

FOR A HYDROMETEOROLOGICAL INFORMATION SYSTEM

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ABSTRACT

Alcan Smelters and Chemicals Ltd operates a multi-reservoir hydroelectric system in the Saguenay-Lac St-Jean region of Quebec. Watersheds feeding this system extend over 73,000 square kilometers. A snow cover survey is conducted at the end of January, February and March at up to 19 observation stations. A computer-based Hydrometeorological Information System (HIS) has been developed to better use hydrometeorological measurements and data in direct support of the operational management of the hydroelectric system. As part of the HIS, it was deemed necessary to have a method for spatial interpolation of snow cover observations to (1) estimate average snow cover by watershed, (2) estimate average snow cover by grid square for digital mapping, (3) estimate missing observations, and (4) be capable of estimating historic snow cover for newly defined watersheds. This paper discusses a method which achieves these objectives by relating snow cover to physiographic characteristics represented according to a 10 km x 10 km square grid system. It is felt that the procedures programmed in the HIS represent an effective means of transforming snow cover measurements into meaningful information for reservoir management.

INTRODUCTION

Alcan Smelters and Chemicals Ltd operates a multi-reservoir hydroelectric system with an installed capacity of 2,687 MW in the Saguenay-Lac St-Jean region of Quebec. Watersheds feeding this system extend over a total area of 73,000 square kilometers and stretch 550 kilometers from north to south. A snow cover survey is conducted towards the end of January, February and March at up to 19 observation stations, and reasonably compatible data are available from 1955 on. Figure 1 shows the distribution of the observation stations over the total watershed and illustrates how the total watershed is subdivided into 5 separate watersheds which are sources of uncontrolled inflows at specific powerhouses or reservoirs. Table 1 gives surface area and inflow statistics for the various watersheds.

The snow cover observations associated with each station represent the average water equivalent snow cover measured along a snow line at 5 points at 200 foot intervals. Prior to 1979, the measurements were taken with a Mount Rose snow sampler. In conjunction with the Service de la Météorologie, Ministère des Richesses Naturelles, Gouvernement du Québec, this was changed to a Carpenter snow sampler starting in 1979. Of the 19 stations currently in use, the 6 most northerly are accessible only from the air. The 13 others are accessible by road, and it takes 3 or more days to complete this part of the survey. Meteorological conditions can delay visits to the 6 northern sites, but every effort is made to have them coincide with the southern sites.

In order to better use hydrometeorological measurements and data in the operational management of the Alcan hydroelectric system, major emphasis has been placed on the development of a computer-based Hydrometeorological Information System (HIS) (Thompstone et al.,1978). As part of the HIS, it was deemed necessary to have a method for spatial interpolation of the snow cover observations in order to:

Proceedings of the Eastern Snow Conference, 36th Annual Meeting, Alexandria Bay, N.Y., June 7-8, 1979.

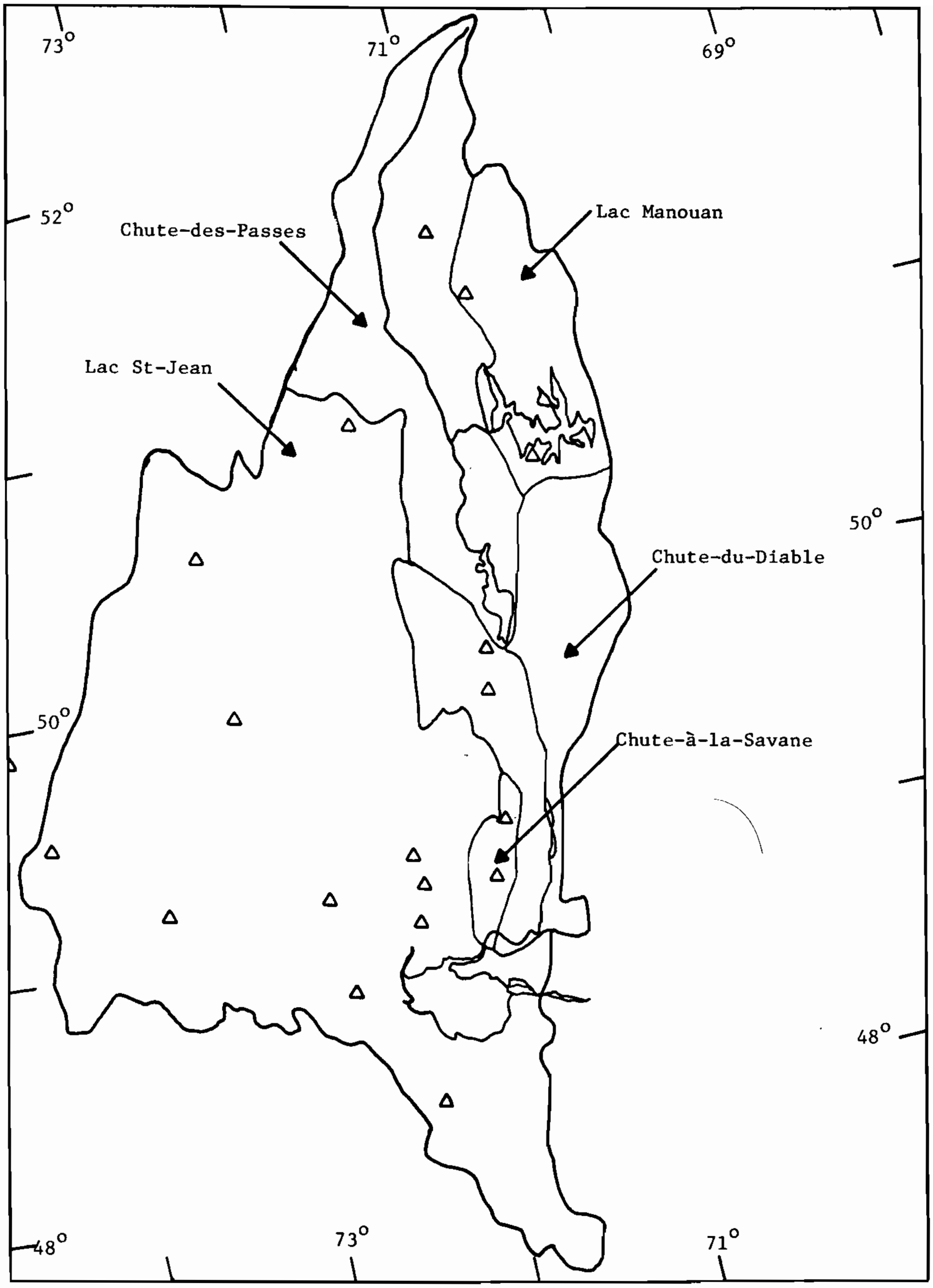

Figure 1: Map of Saguenay-Lac St-Jean watershed showing division of total watershed into five separate watersheds and location of 19 snow survey stations considered in study.

Table 1: Watershed Data

Watershed	Area	Average inflow 1953-1977	Average annual inflow 1953-1977	Average inflow 1 April-15 June
	(km^2)	(m^3/s)	($10^9 m^3$)	($10^9 m^3$)
1. Lac Manouan (LM)	5,000	113.14	3.57	1.23
2. Chute-des-Passes (CDP)	11,000	248.59	7.84	2.90
3. Chute-du-Diable (CD)	9,700	210.98	6.67	2.80
4. Chute-à-la-Savane (CS)	1,300	35.48	1.12	0.48
5. Lac St-Jean (LSJ)	46,100	833.63	26.36	11.57
6. Upper Watershed (UW) (LM+CDP)	16,000	361.73	11.41	4.13
7. Lower Watershed (LW) (CD+CS+LSJ)	57,100	1080.09	34.15	14.85
8. System (SYS) (LM+CDP+CD+CS+LSJ)	73,100	1441.82	45.56	18.98

(1) estimate average snow cover by watershed for use in forecasting spring inflow events (Thompstone et al.,1979),

(2) estimate average snow cover by grid squares for use in digital mapping of snow cover or updating distributed conceptual hydrologic models (Morin et al.,1979; Fortin et al., 1979),

(3) estimate missing observations for current or historic snow cover surveys, and

(4) estimate historic snow cover for any newly defined watershed.

This paper deals with procedures which achieve these objectives by relating snow cover to physiographic characteristics represented according to a 10 km x 10 km square grid system. The chosen methodology and results are described in detail. Relevant sections of the HIS are documented, as are those sections of the management reporting system which output tables of snow cover by station and watershed as well as a digital map of snow cover over the total watershed. It is felt that the procedures programmed in the HIS represent an effective means of transforming snow cover measurements into meaningful information for reservoir management.

METHODOLOGY

The methodology used for the spatial interpolation of the water equivalent of snow cover consists of certain set-up steps which must be performed at the start of the study as well as certain other functions which are performed for each snow survey. The 3 set-up steps may be briefly described as follows:

(1) A 10 km x 10 km grid was applied to the study area, the elevation of the south-west corner of each square was recorded, and various physiographic characteristics were determined for each grid square (east-west or I coordinate, north-south or J coordinate, average elevation, slope and slope orientation).

(2) Corresponding physiographic characteristics were determined for each snow survey station.

(3) Corresponding average physiographic characteristics were determined for each watershed.

The following steps were subsequently performed for each historic snow survey, and are currently performed as each new set of snow survey observations becomes available.

(1) For each snow survey, a linear regression equation is determined to relate the water equivalent of snow cover observed at a station to the physiographic characteristics of the station (or suitable transformations thereof).

(2) These regression equations and the physiographic characteristics of each grid square can be used to estimate the water equivalent snow cover of each grid square.

(3) The regression equations and the average physiographic characteristics of each watershed can be used to estimate the average water equivalent snow cover of each watershed.

Square grid techniques have often been used for the spatial interpolation of hydrometeorological variables and other problems of applied hydrology (Solomon et al.,1968; Solomon and Cadou,1975; U.S. Army Corps of Engineers, Hydrologic Engineering Center,1978), although the authors are not aware of any other attempts to use the technique for spatial interpolation of snow cover. The grid interval is generally a function of the size of the study area, the detail of the available data, the desired accuracy of the study, and computer limitations with respect to core storage, peripheral storage and execution time. The 10 km by 10 km grid chosen as a basis for the current study is shown on the 1:250000 scale Universal Transverse Mercator (UTM) maps available from the Surveys and Mapping Branch of Energy, Mines and Resources Canada. One limitation of the UTM grid is that a discontinuity occurs between each zone, a zone covering 6^{o} of longitude. The study area in question is split almost down the centre by the 72^{o} meridian which is the division between UTM zones 18 and

19. In order to overcome problems associated with this discontinuity, the UTM grid was used directly for that portion of the study area east of the 72° meridian, and this grid was then extended westward into the portion of the total watershed west of the 72° meridian.

Numerous transformations of the basic physiographic data were investigated for possible inclusion as independent variables in the regression equations. The following independent variables were then chosen as potential explanatory variables for each snow survey:

(1) the east-west coordinate, I
(2) the north-south coordinate, J
(3) the average elevation, E
(4) the slope, S
(5) the orientation of the slope, O
(6) I^2
(7) J^2
(8) $(I^2 + J^2)^{1/2}$
(9) S^2
(10) O^2

The maximum number of independent variables accepted in any given regression is restricted to a maximum of one quarter the number of observations available (i.e., the number of snow survey stations reporting for a given survey).

RESULTS

The independent variable which showed up most often as a significant explanatory variable for snow cover was elevation, and it appeared in 30 out of 75 of the historic snow surveys (January, February and March, 1955-1979). The independent variable which proved least useful was slope, appearing in only 9 cases.

An F test was used to determine the goodness of fit between snow cover and physiographic characteristics. At the 90% level of significance, 81.4% of the relationships were acceptable. This rate of acceptance was slightly lower than hoped for in view of the physical relationship which is believed to exist between snow cover and physiographic characteristics. These results may be accounted for to some extent by the quality and timing of the snow cover measurements.

A snow survey network and snow cover measurement techniques are in a continual state of evolution. For the Alcan snow survey network, the last major impetus on the quality of measurements was made in 1972, and it involved better location and maintenance of snow survey lines as well as some additional training of technicians making the measurements. Furthermore, during the period since 1972, the technical personnel taking the snow cover measurements has not changed. The improved quality of the observations appears to be reflected by the fact that 22 of 24 or 92% of the relationships between snow cover and physiographic characteristics for the 1972-1979 period proved significant at the 90% level. Thus, it appears that the technique used for the spatial interpolation of snow cover will be increasingly valid as the quality of observations improves. However, it is important to note that, for one of the two cases which were not significant at the 90% level (March 1979), the quality of measurements was somewhat reduced by abnormally high temperatures which made it difficult to contain the snow in the sampling instrument. This illustrates the fact that the quality of the spatial interpolation will always be limited by the quality of the original snow cover measurements.

A second point to be considered in accounting for the results is the timing of the measurements. The sampling of snow cover at the 13 stations accessible by road is spread out over at least 3 days, and any significant snowfall or melt during this period would obviously invalidate the implicit assumption that the observations are concurrent in time. Weather conditions unsuitable for landing on isolated lakes may further delay the sampling of the northern stations. For example, in March of 1978, the southern stations were sampled on 28-31 March, while the northern stations were sampled on 3 April. A major snow storm passed through the region on 1 April. This may explain why the relationship between snow cover and physiographic characteristics was not significant at the 90% level for this particular survey.

SECTIONS OF HYDROMETEOROLOGICAL INFORMATION SYSTEM DEALING WITH SPATIAL INTERPOLATION OF SNOW COVER

The basic theme behind Alcan's Hydrometeorological Information System is that the various hydrometeorological measurements and data can be of greater benefit in the operation of a water resources system if a conscientious effort is made to forward this data to operational management in the most appropriate form and in reasonable time delays. In fact, in the development of this information system, the term "information" has been restricted to mean data which have been placed in context and presented to the appropriate decision-maker such that it will have a bearing on the decision process (Radford,1973). An outline of the components of Alcan's HIS is given in Figure 2, and a more detailed description is available from Thompstone et al. (1978). The present paper will discuss only those sections of the HIS which deal with spatial interpolation of snow cover, as shown in Figure 3.

There are a total of 6 data banks in the common data base of the HIS which are relevant to the spatial interpolation of snow cover. Three of these are static, while 3 are dynamic in the sense that they are updated for each new snow survey. The 3 static data banks correspond to the 3 set-up steps discussed in the previous section, and they contain:

(1) physiographic characteristics by grid squares,
(2) physiographic characteristics by snow survey stations, and
(3) physiographic characteristics by watershed.

The physiographic data by snow survey station were derived by placing a 10 km x 10 km square such that the station was at the center of the square. The physiographic characteristics by watershed data bank is used to directly estimate snow cover by watershed using the regression equations rather than following the relatively expensive procedure of averaging the estimates for each complete or partial grid square in the watershed. Note that, in order to do this, the data bank must contain averages of transformed physiographic data as well as averages of the raw physiographic data.

The 3 dynamic data banks are updated following each snow survey. They contain:

(4) snow cover by snow survey station,
(5) snow cover regression equations (relating snow cover to physiographic characteristics), and
(6) snow cover estimates by watershed.

The snow cover by snow survey station data bank contains 3 groups of data. The first group contains only historic observations from 1955 up to and including the most recent survey. Missing data is indicated by an entry of "-999." as an observation. In the second group, missing data have been replaced by estimates from the regression equations, while in the third group, all data are estimates from the regression equations. The initial records of the data banks for snow cover by survey station and snow cover by watershed contain long-term statistics for each watershed or station for January, February and March. These records include the long-term mean, standard deviation, coefficient of skewness, kirtosis, minimum and maximum, as well as the number of years for which observations were available to compute the statistics. These long-term statistics are used to quickly determine if any given station has abnormally high or low snow cover.

There are 2 main programs in the data management system of the HIS which are relevant to the spatial interpolation of snow cover. The first, "NEIGE1", is run after each snow survey (January, February and March), and the second, "NEIGE2", is run each year after the 3 snow surveys have been completed. The program NEIGE1 takes snow cover observations which are punched on a CRT or typewriter terminal and enters them in the data bank for snow cover observations by station. Any missing observations are entered as "-999.". It then develops a relationship between snow cover and physiographic characteristics using as dependent variables the snow cover observations and as independent variables the physiographic characteristics (and transformations thereof) extracted from the data bank for physiographic data by station. The resulting relationship is then written in the data bank for snow cover regression equations. The data bank for physiographic characteristics by grid squares is read and snow cover is estimated for each grid square. The data bank for

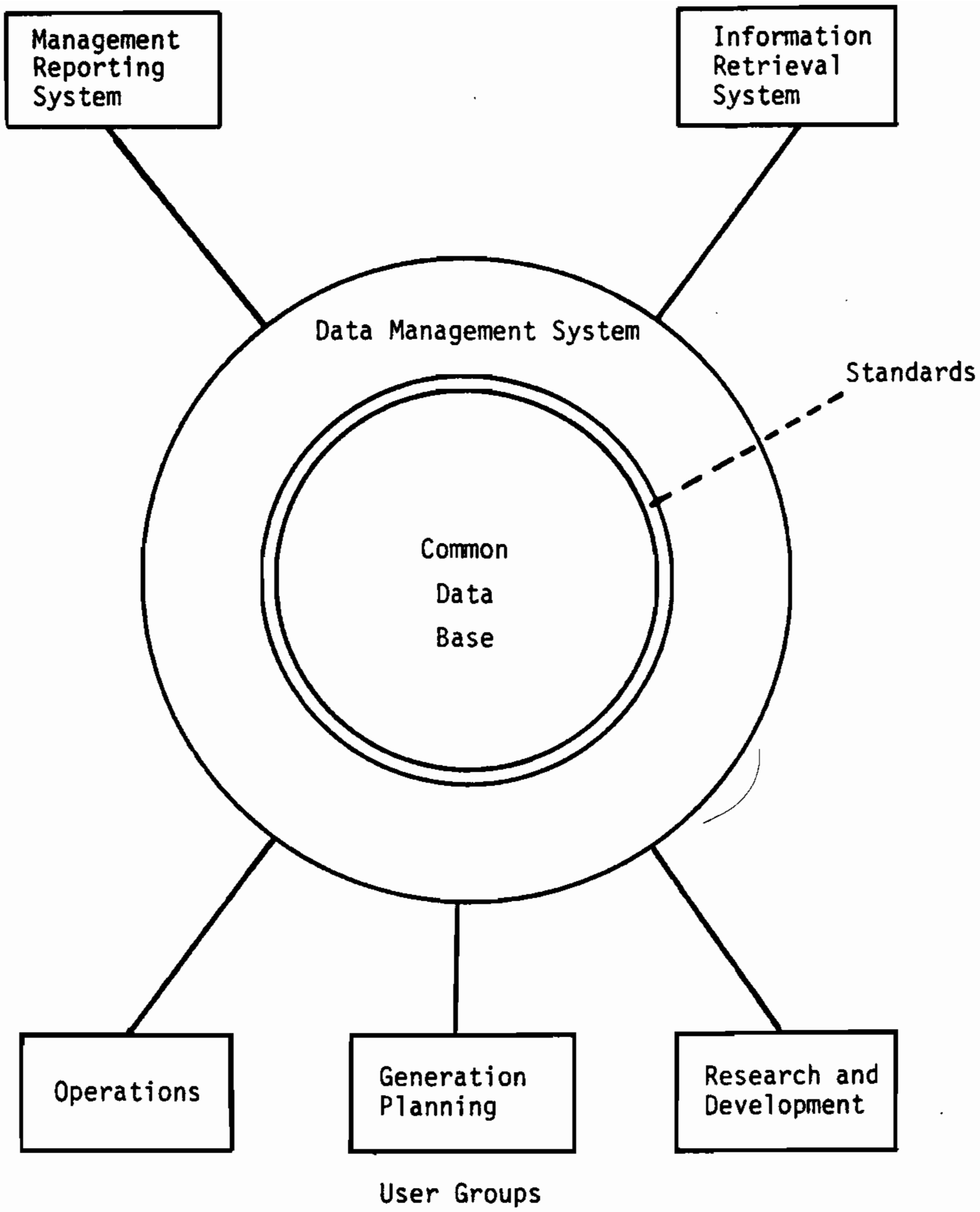

Figure 2: Components of the Hydrometeorological Information System

Ref.: after Radford's generic design of an information system (Radford, 1973)

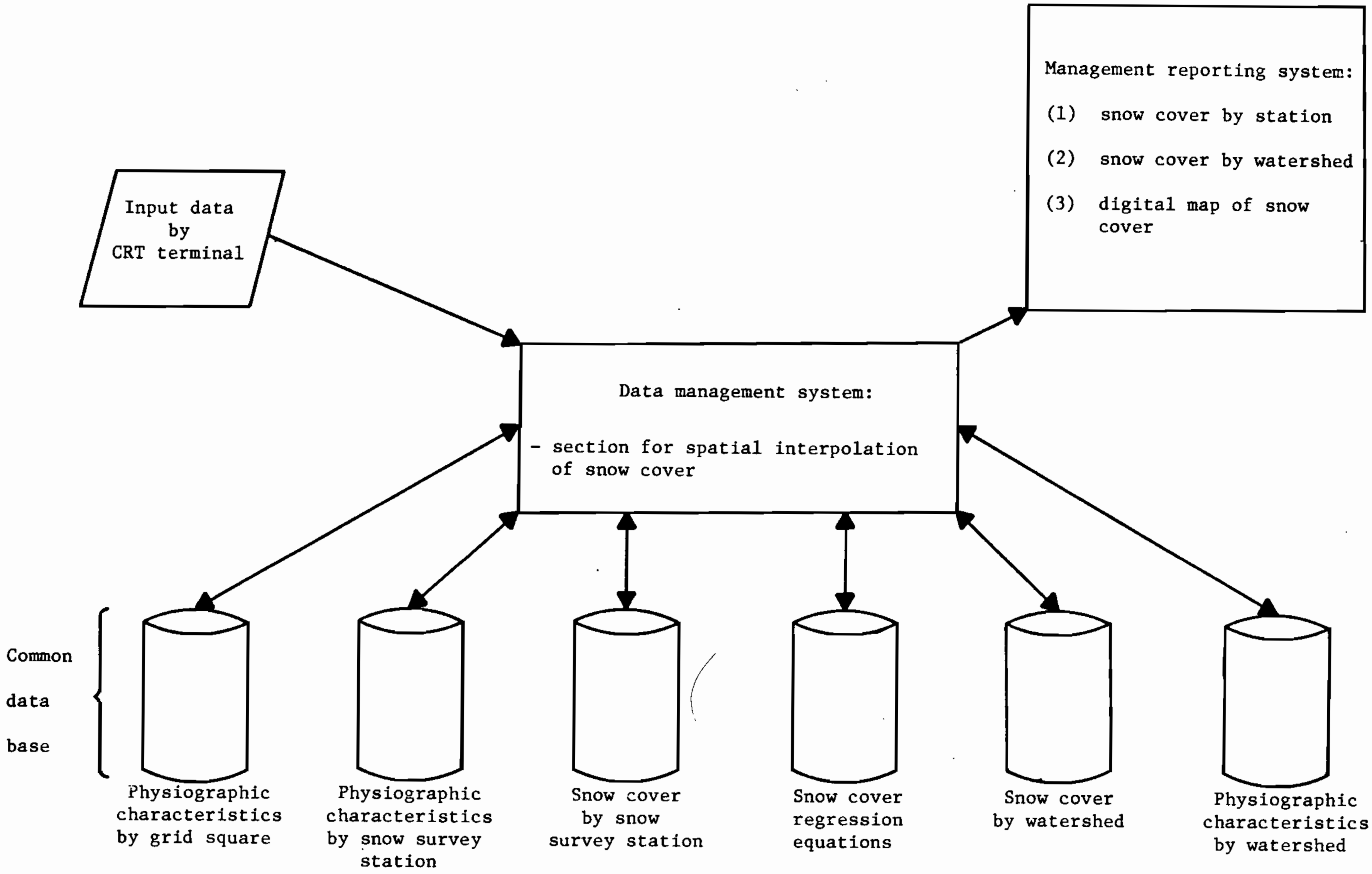

Figure 3: Sections of Hydrometeorological Information System dealing with spatial interpolation of snow cover.

physiographic characteristics by watershed is read, average snow cover is estimated for each watershed, and the results are written in the data bank for snow cover by watershed. As part of the management reporting system of the HIS, the following 3 items are output by NEIGE1:

(1) A table showing, for each station in the network, the current snow cover, the long-term average snow cover (for the month in question), the current snow cover expressed as a percentage of the long-term average, and 5 other long-term statistics: minimum, maximum, standard deviation, coefficient of skewness, and kirtosis.

(2) A similar table for each of the 8 watersheds described in Table 1.

(3) A digital map of snow cover (by grid square) for the total Saguenay-Lac St-Jean watershed.

By way of examples, Tables 2 and 3 of this paper show English-language translations of the above two types of tables for the most recent survey, March 1979. Figure 4 contains the digital map of snow cover for the same survey.

The data banks for snow cover observations by survey station and physiographic characteristics by survey station are dimensioned to allow for easy inclusion of data for any new survey stations. Similarly, the data banks for snow cover estimates by watershed and physiographic data by watershed contain storage space for any newly defined watershed which may become of interest. Since the snow cover regression equations are stored in a data bank, it is relatively easy to estimate a historic series of snow cover observations for any new survey station or watershed. Thus, it is possible to relate new observations or estimates to long-term averages and, thereby, determine if, for any given survey, the new station or watershed has an abnormally high or low snow cover.

CONCLUSION

The problem of the spatial interpolation of snow cover is recognized to be very complex and challenging (United States National Committee for the International Hydrological Decade, Working Group on Snow and Ice Hydrology,1976). The methodology described in this paper appears to represent a reasonable approach to performing such spatial interpolation for the study area in question. It takes into account some of the physiographic conditions which are believed to influence the accumulation and melt of snow. Techniques such as Thiessen polygons perform areal averaging, but do not take into account physiographic characteristics and do not provide an explicit estimate of missing data. Statistical techniques such as correlation with adjacent stations provide estimates of missing data only if there is a large enough sample of concurrent data at the stations, and these techniques do not, in general, treat the problem of areal averaging. Satellite techniques are being increasingly used to determine the presence or absence of snow cover, but are currently of limited use in determining the quantity of snow accumulated on the ground. Satellite images may, however, provide additional independent variables which could be used in estimating snow cover along the lines described in this paper.

At Alcan and elsewhere in the Province of Quebec, increasing emphasis is being placed on the quality of snow survey networks and the use of snow cover measurements for more accurate forecasting of spring inflow events and thus, better operation of reservoirs during the spring freshet (Morin et al.,1978; Thompstone et al.,1979; Thompstone and Poiré,1979; Paulin, 1979). The fully automated techniques programmed in Alcan's Hydrometeorological Information System allow the estimation of snow cover by watershed, snow cover by grid squares, snow cover at stations missed in any given survey, and historic snow cover for any newly defined watershed. It is felt that these procedures represent an effective means of transforming snow cover measurements into meaningful information which has a positive impact on reservoir management.

ACKNOWLEDGEMENTS

The authors are greatful to Réjeanne Bergeron and Alain Vallée for their assistance on computer aspects of this study and to Martin Buteau, Gaby Perron and Albert Poiré for background information on Alcan's procedures for snow surveys. The work described in this

Table 2: Snow Cover by Station - March 1979

Station	Snow Water Equivalent (cm)	Long-term mean snow depth	% of mean	Long-term min. (cm)	Long-term max. (cm)	S.D.	Skew	Kirt.
B. GERV.	18.29	23.43	78.07	12.70	32.51	4.66	-0.19	2.63
B. NORD	24.89	23.35	106.62	14.73	29.97	4.11	-0.26	2.15
B. SUD	27.43	24.02	114.19	14.48	32.00	5.45	-0.10	1.70
M. 22	20.32	24.43	83.19	13.21	33.53	4.52	-0.19	3.13
M. 41.3	19.81	23.61	83.91	13.21	33.78	4.81	-0.14	2.64
M. 55	15.24	24.26	62.81	11.18	40.04	6.17	0.22	3.45
L. ALEX	27.94	25.81	108.24	10.92	38.10	6.57	-0.40	3.04
L. BEN.	22.86	24.36	93.84	10.62	34.54	6.70	-0.23	1.97
L. CACHE	25.91	24.79	104.53	14.22	34.54	4.77	-0.17	2.76
L. CHIG.	20.83	22.37	93.12	11.94	32.00	5.80	-0.21	1.88
L.D. COMM.	22.86	23.14	98.81	15.75	35.05	4.70	0.83	2.96
L. D. CYG.	19.81	23.91	82.88	12.70	39.62	6.68	0.29	2.70
L. D. G. P.	28.96	26.05	111.17	8.38	37.08	5.69	-0.70	5.17
L. LONG	25.91	24.21	107.03	14.22	36.58	6.77	0.18	2.05
L. MACH.	24.89	26.18	95.08	14.22	37.08	5.99	-0.24	2.09
L. MANO.	22.86	25.77	88.71	16.26	36.32	5.64	0.34	2.02
L. PIAK.	25.91	24.76	104.63	14.76	33.77	5.40	0.20	2.06
PAS. DA.	23.88	27.38	87.21	20.83	39.12	4.82	0.99	3.46
RIV. SER.	27.43	26.86	102.13	14.73	39.12	5.77	0.51	2.76

Table 3: Snow Cover by Watershed - March 1979								
Basin	Snow Water Equivalent (cm)	Long-term mean snow depth	% of mean	Long-term min. (cm)	Long-term max. (cm)	S.D.	Skew	Kirt.
LM	25.29	25.97	97.39	17.07	36.88	5.41	0.34	2.44
CDP	25.26	25.36	99.60	14.14	36.23	5.69	-0.09	2.21
CD	24.27	26.13	92.87	16.31	37.34	4.56	0.23	3.23
CS	22.92	25.36	90.41	17.38	34.60	4.40	0.24	2.32
LSJ	23.99	24.39	98.35	17.15	33.18	4.31	0.31	2.15
AMNT	25.27	25.54	98.93	15.02	36.42	5.51	0.02	2.26
AVAL	24.02	24.71	97.18	17.88	33.92	4.14	0.43	2.41
TOT	24.29	24.90	97.57	18.13	34.48	4.18	0.53	2.57

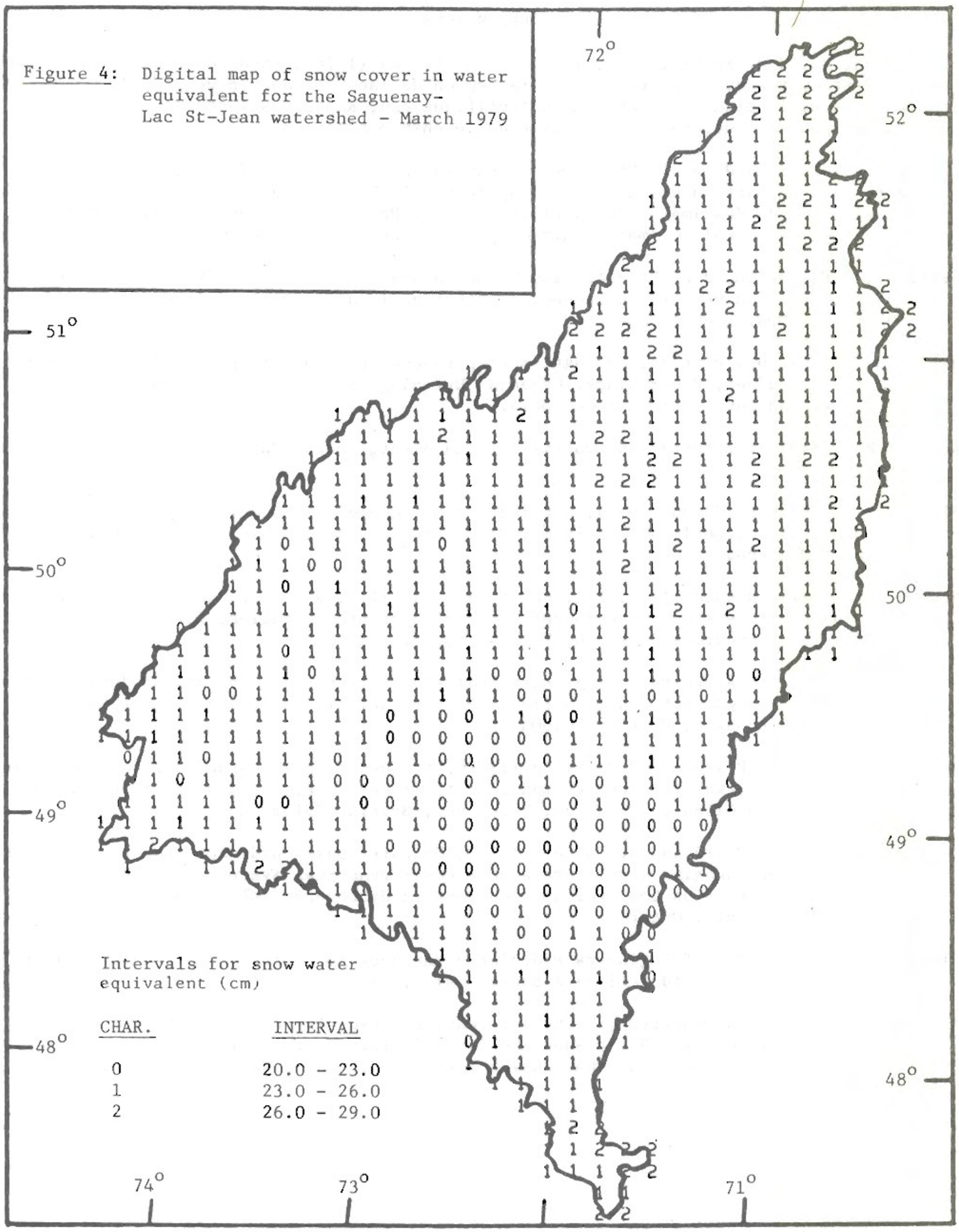

Figure 4: Digital map of snow cover in water equivalent for the Saguenay-Lac St-Jean watershed - March 1979

paper was financed in part by the Department of Industry, Trade and Commerce, Ottawa, Canada through the Program for the Advancement of Industrial Technology.

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