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HEC-2 has recently been modified to accept input for a floating ice cover. Several techniques were evaluated in calibrating the model versus the measured field data for a steep, shallow river. The ice cover thickness, as expected, was the dominant parameter affecting the water levels and not the Manning's roughness coefficient of the ice cover. Excellent field data on ice cover thicknesses, water levels and flow discharges were available for calibration. The relatively shallow depths of less than 6 ft and ice covers of up to 3-ft thick created special problems in matching the water levels. The actual ice cover thicknesses measured in the field should be used as a guide for ice thickness input to the model for shallow streams. The transition of ice cover thickness from one section to the next in the model is extremely critical, otherwise there will be excessive head losses. Several methods for interpolating the ice thickness between the measured sections were attempted in trying to simulate the freeze-up, and ineffective flow areas were blocked off as well. The latter provided the most realistic simulation of flow velocities beneath the ice cover.

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PREFACE

This report was prepared by Darryl J. Calkins, Chief, Geological Sciences Branch, Research Division, and Mark D. Adley, former Civil Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by CWIS 31724.

This report was technically reviewed by Jon Zufelt and Steven Daly of CRREL.

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM Metric Practice Guide (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	by	To obtain
inch	25.4	millimetre
foot	0.3048	metre
foot^3 per second	0.02831685	metre^3 per second
mile^2	2,589,998	metre^2
degrees Fahrenheit	$t_{°C} = (t_{°F} - 32)/1.8$	degrees Celsius

CALIBRATING HEC-2 IN A SHALLOW, ICE-COVERED RIVER

by

Darryl J. Calkins and Mark D. Adley

INTRODUCTION

A part of any flood control program is predicting expected water levels and flows in affected rivers using mathematical models. There are several models available for computing water surface profiles in natural channels. One of the most widely used is HEC-2, developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC), which has been modified by HEC and CRREL to include the option for a floating ice cover.

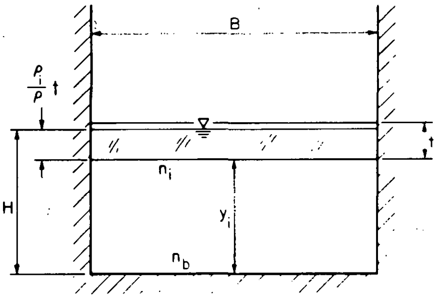
This report focuses on the use of HEC-2 to simulate the water surface profile of a steep, shallow river -- the Ottauquechee River in central Vermont -- with an ice cover formed during the freeze-up period. Field data on the discharge, ice cover thickness and water surface profiles exist for three winter seasons. Our main objective was to evaluate four possible methods of calibrating the model; we also intended to determine the effect of adjusting the roughness coefficients to match the observed water levels in a natural channel, i.e., to see how sensitive the model is to varying roughnesses.

We know of no documentation of the use of HEC-2 in shallow streams with a freeze-up ice cover. Keehan et al. (1982) report on the use of HEC-2 for analyzing freeze-up ice jams on the Peace River in Alberta, but the river is 20 ft deep or more and 1500 ft wide, a far cry from the Ottauquechee River, which is 6 ft deep and 150 ft wide. Calkins et al. (1982a) presented an example of using HEC-2 for a wide and deep ice-covered waterway that was rectangular, and showed the importance of a laterally growing ice cover on the backwater regime.

BACKGROUND

Uniform flow equation for a floating ice cover

A steep, shallow river is approximated by a rectangular section for ease in presenting the Manning's equation and flow under an ice cover. The



Open Channel Flow-Floating Ice Cover

Figure 1. Definition sketch of an ice-covered channel.

hydraulic radius in a wide river with a floating ice cover (Fig. 1) may be approximated by

$$R = \frac{A}{2B} \approx \frac{y_i}{2} \tag{1}$$

where A is the cross-sectional area, B is the width and y_i is the flow depth.

Since there are two resistant surfaces, the bed and ice cover underside, a means for computing a composite Manning's roughness coefficient is needed. A simple but highly successful relationship for the composite coefficient, verified by Carey (1967) and Uzuner (1975), is

$$n_c = \left[\frac{n_i^{3/2} + n_b^{3/2}}{2}\right]^{2/3} \tag{2}$$

where n_i and n_b are the underside ice cover and stream bed roughness coefficients (Fig. 1). The normal depth of flow beneath a floating ice cover for uniform flow using the Manning equation is

$$y_i = 1.32 \left[\frac{Q\, n_c}{1.49\, B\sqrt{S_o}}\right]^{3/5} \tag{3}$$

in which the factor 1.32 accounts for the change in the hydraulic radius being approximately $y_i/2$. Q is the flow discharge and S_o is the slope of the energy line. Thus, the total water depth in an ice-covered channel for uniform flow is

$$H = y_i + S_i t \tag{4}$$

where S_i is the ratio of freshwater ice to water density (0.92) and the t is the ice cover thickness.

Sensitivity analysis

A technique for estimating the sensitivity of certain parameters in an expression is to evaluate the relative error contribution from the various terms. This is especially helpful when measuring several physical parameters and the question of accuracy arises. However, we can also use this error analysis to assess the importance of accuracy for the parameters used in computing the total stage of a river with an ice cover present.

The total increment theorem applied to the river stage where $H=f(y_i,t)$ leads to

$$\frac{\Delta H}{H} = \frac{1}{f(y_i,t)} \left(\left| \frac{\partial H}{\partial y_i} \Delta y_i \right| + \left| \frac{\partial H}{\partial t} \Delta t \right| \right) \quad . \tag{5}$$

Simplifying to incremental values yields

$$\frac{\Delta H}{H} = \frac{\Delta y_i + S_i \Delta t}{y_i + S_i t} \quad . \tag{6}$$

To calculate the individual error terms, Δy_i and Δt, they must be expanded separately. The expression for the contribution of relative errors in computing the flow depth beneath the ice cover, based on Manning's equation (eq 3), is

$$\frac{\Delta y_i}{y_i} = \left[\frac{0.3}{\frac{n_i^{3/2}}{2} + \frac{n_b^{3/2}}{2}}\right] \left[n_i^{1/2}\, \Delta n_i + n_b^{1/2}\, \Delta n_b\right] + 0.3\, \frac{\Delta S_o}{S_o} + 0.6 \left[\frac{\Delta Q}{Q} + \frac{\Delta B}{B}\right] . \tag{7}$$

For example, if $\Delta S_o = \Delta Q = \Delta B \approx 0$ and $n_i = n_b = 0.04$, with the roughness coefficients accurate to within only $\pm$ 0.005 (a reasonable assumption), what error does this represent compared to the total stage if the ice thickness $t = 3$ ft, $\Delta t = 0.5$ ft, $S_i = 0.92$ and the flow depth is 5 ft? By use of eq 7 to find Δy_i, the total relative errors and percent error from eq 6 is

$$\frac{\Delta H}{H} = \frac{0.168 + 0.46}{2.24 + 2.76} = \frac{0.168 + 0.46}{5.0} = 3.4\% + 9.2\% \quad . \tag{8}$$

This computation indicates an error in the ice thickness of 0.5 ft overwhelms the error introduced by not knowing the roughness coefficient to within 0.005 by a factor of almost 3 when the total stage is computed. Consequently, according to the above analysis, the accuracy of predicting the water elevation in a steep, shallow stream that can accumulate a thick floating cover will be governed primarily by its thickness and not by our inability to precisely determine the bed and ice roughness coefficients. The simulation of the Ottauquechee River freeze-up data that follows confirms this analysis.

HEC-2 ice cover option

The modifications of HEC-2 to compute water surface profiles in a partially ice-covered or fully closed section are based upon the change in hydraulic radius attributed to the increase in wetted perimeter caused by the ice, the change in the flow area to account for the presence of the ice, and the composite roughness coefficient from eq 2.

The required input is entered on a new card called the IC. The IC cards precede the X1 cards for each channel cross section (see Hydrologic Engineering Center 1981). The information coded for an IC card includes the ice thickness for the right and left overbank and the channel sections, which can be different, and the ice cover roughness coefficient, which is the same for the channel and overbank regions.

Once the ice cover thickness and roughness coefficient are coded for a particular section, the program will continue to use these values for all subsequent sections until a new IC card is read. The ice cover is assumed to be floating in all sections, i.e., no pressure flow.

TEST SITE

The river that we selected to evaluate the ice cover option was the Ottauquechee in Quechee, Vermont (Fig. 2). The Ottauquechee River, a tributary of the Connecticut River, has a drainage area of roughly 200 mi^2 above the measurement site. The river is relatively steep, with an average bed slope of $2x10^{-3}$ and alternating ripples and pools during ice-free conditions. The bed material is classified as cobbles, with an average size of 6 in.

The river has an average width of roughly 135 to 160 ft with bankfull depths of 6 to 12 ft. The average annual stream flow is 390 ft^3/s. The ice cover forms as a result of upstream frazil ice production and lateral ice cover growth. The maximum freeze-up ice thickness is 6 ft, depending on the location, but generally it averages 3 to 4 ft. Typical values for

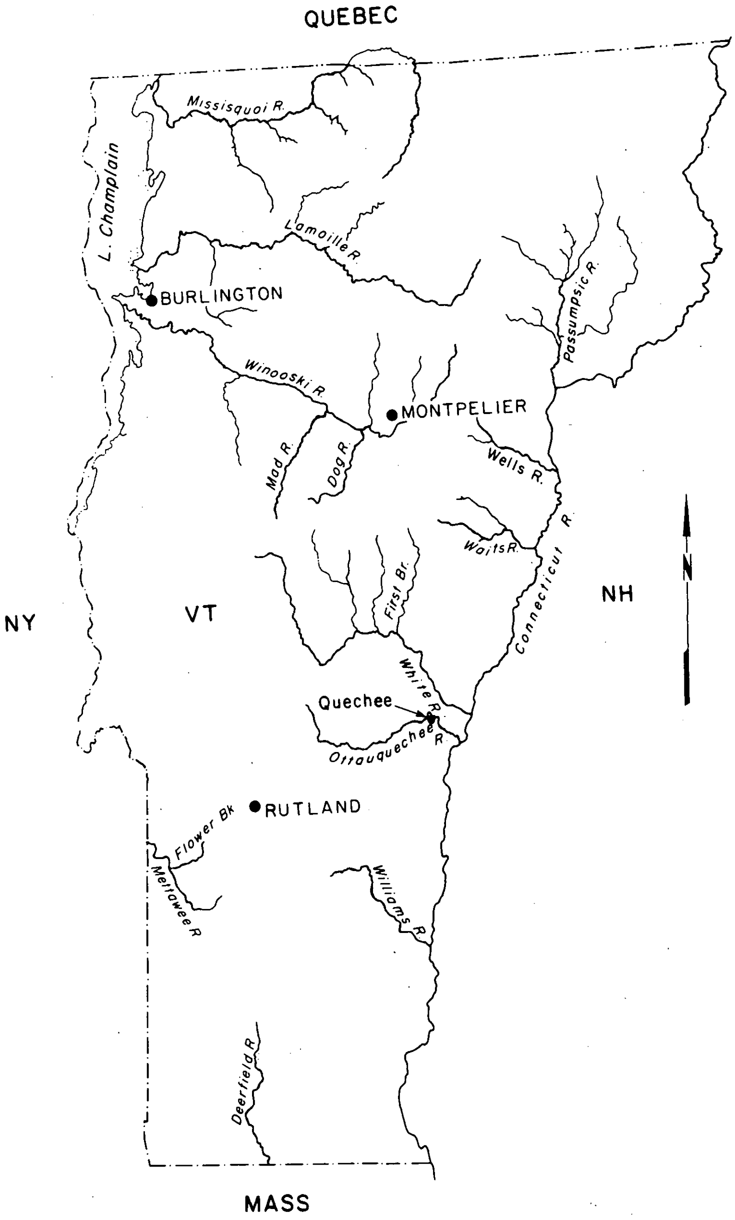


Figure 2. Ottauquechee River in east-central Vermont (the Downer's Mill Dam is in Quechee).

the ice cover roughness coefficient are Manning's n = 0.015 to 0.035 (Calkins et al. 1982b). The Ottauquechee River bed has a Manning's roughness coefficient of approximately 0.035 for low flows.

River cross sections were taken every 200 ft in 1975 beginning at Downer's Mill Dam and the floodplain topography was added to the cross sections in 1981. A total of about 40 natural cross sections, spaced 200 ft apart, were used in the following calibrations.

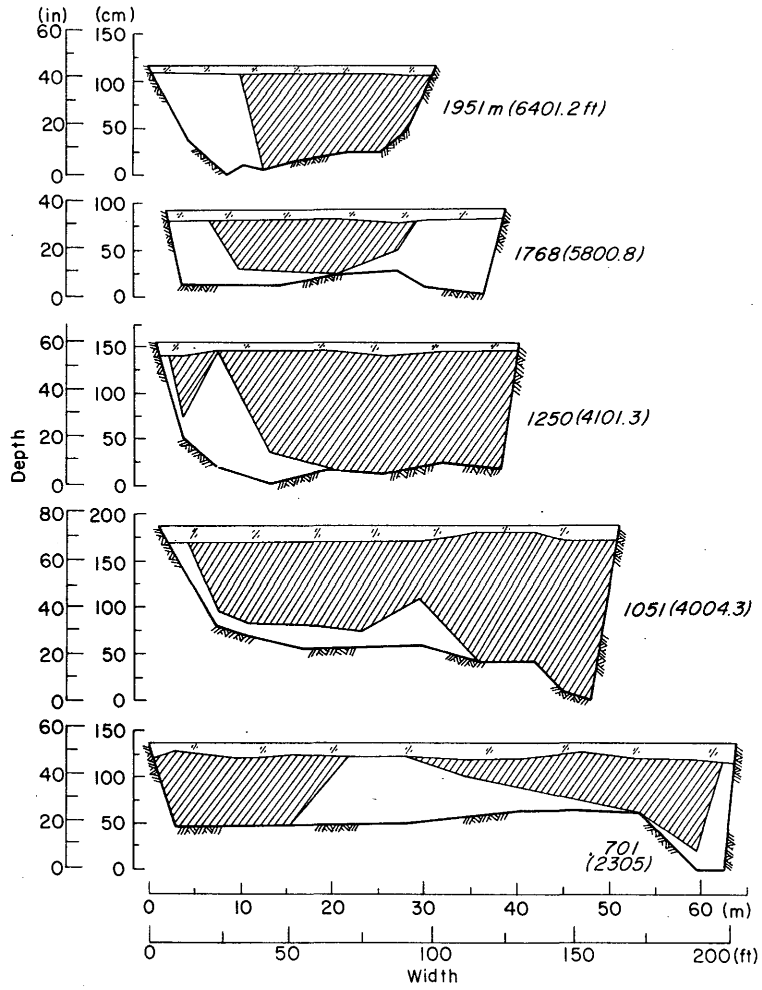


Figure 3. Ice thickness distributions at selected cross sections, 21 December 1981.

The freeze-up of the river in this region is the result of frazil ice being generated in the open water reaches and transported downstream until an ice bridge forms above the dam at Downer's Mill in Quechee. Once the ice bridge forms just above the dam, the ice cover progresses upstream by several processes until the ice discharge is reduced by the loss of open water area and the leading edge blends into the laterally growing ice from the banks.

The ice cover thickens from mechanical shoving until it reaches an equilibrium stable thickness and then continues to thicken by deposition of frazil slush ice beneath the already stable ice cover. Figure 3 shows five typical ice-filled cross sections during the 1981 freeze-up; at least 65% of the total cross section is filled with frazil ice, with the solid ice

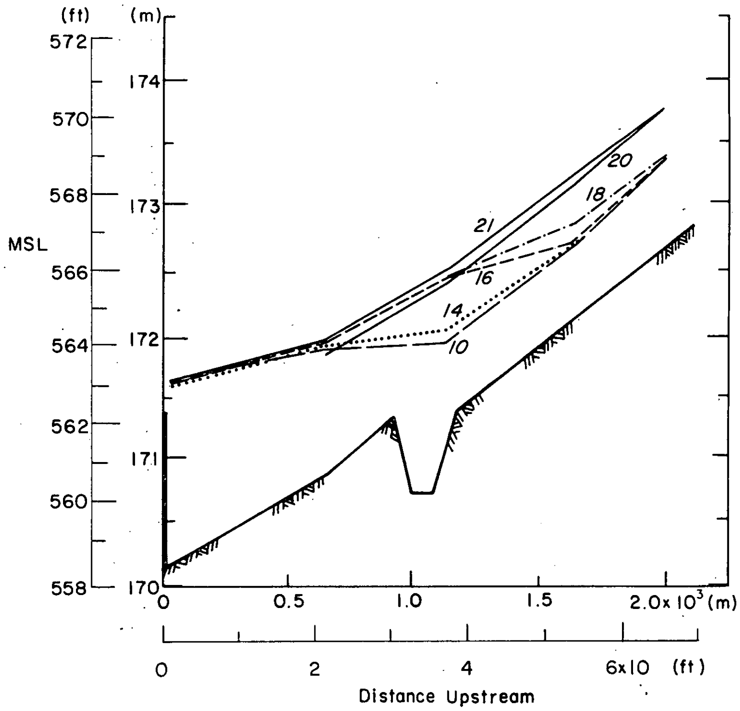


Figure 4. Freeze-up water surface profiles for various days in December 1981.

cover just beginning to develop. The ice cover thickness measurements (four to eight holes per section) were made at roughly 7 to 10 sections during the various years over the entire length of the river being simulated, i.e., ≈ 6500 ft.

A typical time history of the water surface profile during freeze-up is given in Figure 4. As the leading edge moves upstream, the water level rises anywhere from 1.5 to 2.5 ft. Higher flow discharges and only moderately low temperatures (10-20°F), or both, have actually created higher water levels for this same reach in other years.

CALIBRATION WITH OPEN WATER

The Manning's roughness coefficients for the various reaches of the Ottauquechee River were determined for five flows, ranging from 343 to 4162 ft^3/s. The downstream control was an Ogee type spillway with free overfall at Downer's Mill Dam. For discharges up to 1000 ft^3/s, wading in the river was possible to determine the velocity and subsequently the discharge. The discharge of the higher flows was calculated from the spillway rating curve.

Table 1. Measured water surface profiles on the Ottauquechee River (ft above m.s.l.) - open water.

	Flow discharge (ft^3/s)				
Section	343	426	890	2040	4162
12	563.15	563.3	563.9	565.04	566.41
21	563.4	563.62	564.26	565.53	567.09
29	564.03	564.25	564.96	566.37	567.86
38	566.21	566.54	567.32	568.96	--
45	568.85	569.26	569.99	571.7	573.69
49	571.87	572.0	572.47	--	574.37
53	572.30	572.54	513.43	--	577.33

Table 1 documents the measured water surface profiles used for the calibration runs. Table 2 gives the results of the HEC-2 runs where the Manning's roughness coefficient, n, for the bed has been adjusted to match the observed water levels within 0.1 ft. The river was broken down into reaches, essentially made up of the areas between the water level recording stations and the fixed measurement sites. The general trend of the bed hydraulic roughness coefficients was to decrease with increasing flow discharge except for the reach made up of sections 49 to 54, which increased. The only explanation we find is that the reach has a very large rock outcrop along the right bank that extends at least 300 ft, or almost one-third the length of the reach. The high values for the roughness coefficients at the low flows for the reach made up of sections 44 to 49 can be explained by the steep gradient through this section -- i.e., it is a riffle section.

The n values were adjusted on a reach basis, i.e., between water level measuring sites. All sections within the reach were given the same n value for a trial run.

The model was also calibrated section by section, but we used a limited number of cross sections for a few runs. However, the range of roughness coefficients obtained was similar to that which we would have obtained if we were to use the full compliment of cross sections.

Table 2. Computed bed roughness coefficient values for open water calibration.

	Flow discharge (ft^3/s)				
Sections	343	426	890	2044	4162
12 to 21	0.042	0.042	0.037	0.030	0.025
21 to 29	0.045	0.045	0.037	0.032	0.023
29 to 38	0.025	0.025	0.033	0.036	0.023
38 to 44	0.042	0.042	0.035	0.036	0.037
44 to 49	0.065	0.065	0.040	0.030	0.017
49 to 54	0.023	0.023	0.030	0.035	0.040

CALIBRATION WITH ICE COVER

The calibration of HEC-2 to the observed water levels with an ice cover presents some interesting problems in deciding on how to input the ice thickness data. HEC-2 could not handle a complicated flow-ice delineation, such as given in Figure 3.

As stated earlier, we tried four methods of calibrating HEC-2 to the observed water levels. Each method used a different combination of the roughness and ice thickenss variables, with the goal of seeing which combination of input variables would quickly and accurately simulate the observed water levels to within 0.1 ft. The bed roughness coefficients for the flow of 343 ft^3/s were used during the ice cover simulation for all runs. The downstream control was Downer's Mill Dam. Table 3 presents the measured water surface elevations for the freeze-up ice conditions.

Table 3. Measured water surface elevations (ft above m.s.l.) when the Ottauquechee River is ice-covered.

	Flow discharge (ft^3/s)				
Section	145	215	230	284	335
12	-	-	-	563.76	-
15	562.7	563.9	562.9	564.09	563.05
18	-	-	-	564.47	-
21	563.6	564.0	564.0	-	-
26	-	-	-	565.85	-
27	-	-	-	566.24	566.65
29	567.7	565.8	566.25	-	-
30	-	-	-	566.65	-
37	-	-	-	568.30	-
38	569.1	568.2	-	-	-
44	570.9	570.0	-	570.45	-
45	-	-	-	-	571.25
49	-	-	-	573.30	-
53	-	-	-	574.50	-

Method 1 -- Adjusting the ice cover roughness coefficient

We first distributed the ice thickness over the width of each measured cross section and arrived at some average section value. The ice cover thickness was input starting with that average ice cover thickness for the first measured section, using it until the next section with a measured ice thickness was encountered. The new value would be used until the next measured value at an upstream section was reached, and so on.

We attempted to simulate the observed water surface profiles by adjusting only the ice cover roughness coefficients, n_i, along the river, keeping the bed roughness values constant. Many problems arose during our attempt to calibrate: 1) a critical depth with a floating ice cover (which is physically impossible) would be computed when the input ice thickness was too large compared to the total flow depth, 2) the values for the roughness coefficient were too high or too low for some reaches (in light of previous work by Calkins et al. [1982b]) and 3) the computed mean channel velocities were far too low compared to field data obtained from velocity profile measurements.

Table 4. Final results for ice cover calibration.

Section reaches	Input Manning's coefficient for bed n_b	"Calibrated" Manning's coefficient for ice n_i	Known and interpolated water surface elevation (ft)†	Water surface elevations from HEC-2 (ft)†	Difference	Measured input ice thicknesses* (ft)
			145 ft^3/s			
12-15	0.042	0.010	562.70	562.7	0	1.42
15-21	0.045	0.040	563.60	563.6	0	1.83
21-26	0.045	0.200	564.91	565.0	0.09	0.77
26-29	0.025	0.250	565.70	565.3	-0.40	0.30
29-31	0.025	0.090	566.6	565.6	-0.86	2.86
31-38	0.042	0.065	569.10	569.0	-0.10	2.88
38-40	0.042	0.040	569.70	569.8	0.10	2.71
			215 ft^3/s			
12-15	0.042	0.090	562.91	562.9	-0.01	0.74
15-22	0.045	0.070	564.18	564.2	0.02	1.58
22-28	0.045	0.060	565.56	565.5	-0.06	3.18
28-31	0.025	0.020	566.33	566.3	-0.03	3.15
31-34	0.025	0.050	567.13	567.2	0.07	2.36
34-36	0.025	0.080	567.67	567.7	0.03	1.44
36-38	0.042	0.048	568.20	568.2	0	1.64
38-40	0.042	0.030	568.80	568.8	0	1.14
40-43	0.042	0.030	569.70	569.7	0	2.17
			335 ft^3/s			
12-15	0.042	0.020	563.03	563.01	-0.02	2.79
15-21	0.045	0.020	564.83	565.47	0.64	2.26
21-25	0.045	0.070	566.03	565.98	-0.05	2.30
25-27	0.045	0.020	566.63	566.75	0.12	5.48
27-29	0.025	0.020	567.14	567.82	0.68	5.25
29-31	0.025	0.020	567.65	568.19	0.54	5.02
31-33	0.025	0.090	568.17	568.62	0.45	2.30
33-37	0.025	0.020	569.19	569.22	0.03	2.30
37-45	0.065	0.020	571.24	571.96	0.72	2.30

* Section averaged values.
† Above m.s.l.

Table 4 presents the final results of our attempt to calibrate the water level data obtained from HEC-2 with the field data by adjusting only the ice roughness coefficient. This method was abandoned because the roughness coefficients would have been too high or too low to make the model match the measured water surface profiles for many of the reaches.

Method 2 -- Adjusting both boundary roughness coefficients and linearly interpolating the ice thickness between sections

This technique used a combination of variable inputs. The measured ice thicknesses at the various cross sections were retained, but linear interpolations for ice thickness between these sections were input. Both the bed and ice cover roughness coefficients were changed to produce suitable composite values.

These approaches did not solve the problem. Unrealistic values for the roughness coefficients were still being used to balance the energy losses, even using interpolated ice thicknesses. Table 5 is a summary of the final runs for all the freeze-up flows.

Table 5. Calibration results from varying both the ice and bed roughness coefficients and using interpolated ice cover thicknesses between the averaged section values.

Section reaches	Calibrated Manning's coefficient for bed n_b	"Calibrated" Manning's coefficient for ice n_i	Known and interpolated water surface elevation (ft)*	Water surface elevations from HEC-2 (ft)*	Difference	Calibrated input ice thicknesses (ft)
			145 ft^3/s			
15	0.040	0.020	562.7	562.7	0	1.42
21	0.070	0.060	563.60	563.8	0.20	1.83
26	0.070	0.090	564.91	564.9	-0.01	0.77
27	0.070	0.090	565.17	565.0	-0.17	1.47
28	0.070	0.090	565.44	565.1	-0.34	2.17
29	0.070	0.090	565.70	565.3	-0.40	2.86
30	0.070	0.090	566.07	565.9	-0.17	2.86
31	0.070	0.090	566.46	566.1	-0.36	2.86
38	0.042	0.050	569.10	569.10	0	2.88
40	0.042	0.045	569.70	569.7	0	2.71
44	0.065	0.020	570.90	570.9	0	2.10
49	0.023	0.020	572.40	573.1	0.7	0.39
54	0.023	0.020	573.90	574.2	0.7	1.71
			215 ft^3/s			
12	0.040	0.010	562.90	562.9	0	2.38
17	0.042	0.010	563.27	563.6	0.33	2.38
18	0.042	0.010	563.45	563.8	0.35	1.87
19	0.042	0.010	563.64	564.0	0.36	1.37
20	0.042	0.010	563.82	564.0	0.18	0.87
21	0.045	0.090	564.0	564.1	0.10	0.36
26	0.045	0.100	564.78	564.6	-0.18	0.34
27	0.045	0.100	564.94	564.8	-0.14	1.2
28	0.045	0.090	565.09	565.0	-0.09	2.1
29	0.025	0.020	565.25	565.3	0.05	2.94
31	0.025	0.020	565.55	565.7	0.15	2.95
32	0.025	0.030	565.70	565.7	0	1.64
33	0.025	0.020	565.85	565.8	-0.05	0.33

Table 5 (Cont'd.)

Section reaches	Calibrated Manning's coefficient for bed n_b	"Calibrated" Manning's coefficient for ice n_i	Known and interpolated water surface elevation (ft)*	Water surface elevations from HEC-2 (ft)	Difference	Calibrated input ice thicknesses (ft)
230 ft^3/s						
12	0.020	0.015	562.90	562.9	0	2.38
17	0.020	0.015	563.27	563.3	0.03	2.38
18	0.020	0.015	563.45	563.4	-0.05	1.87
19	0.020	0.090	563.64	563.7	0.06	1.37
20	0.020	0.090	563.82	563.9	0.08	0.87
21	0.070	0.090	564.0	564.1	0.10	0.36
26	0.070	0.090	564.78	564.7	-0.08	0.34
27	0.070	0.090	564.94	564.9	-0.04	1.2
28	0.070	0.090	565.09	565.1	0.01	2.1
29	0.020	0.015	565.25	565.3	0.05	2.94
31	0.020	0.030	565.55	565.6	0.05	2.95
32	0.020	0.050	565.70	565.7	0	1.64
33	0.020	0.020	565.85	565.8	-0.05	0.33
284 ft^3/s						
12	0.040	0.015	563.76	563.8	0.04	3.42
15	0.020	0.015	564.09	564.0	-0.09	4.67
18	0.020	0.015	564.47	565.0	0.53	3.00
26	0.045	0.040	565.85	566.0	0.15	2.42
27	0.045	0.040	566.24	566.2	-0.04	3.50
30	0.020	0.035	566.65	566.7	0.05	3.33
37	0.020	0.015	568.30	568.3	0	2.75
44	0.020	0.015	570.45	571.0	0.55	3.00
49	0.023	0.050	573.30	573.6	0.30	2.33
53	0.023	0.015	574.50	574.5	0	2.67
63	0.020	0.015	578.60	578.7	0.10	
335 ft^3/s						
15	0.042	0.015	563.03	563.0	-0.03	2.79
21	0.045	0.015	564.83	565.2	0.37	2.26
25	0.045	0.015	566.03	565.8	-0.23	2.30
26	0.045	0.015	566.33	566.4	0.07	3.89
27	0.045	0.015	566.63	567.5	0.87	5.48
29	0.025	0.015	567.14	567.9	0.76	5.25
31	0.025	0.015	567.65	568.2	0.55	5.02
32	0.025	0.015	567.91	568.2	0.39	3.66
33	0.025	0.090	568.17	568.3	0.13	2.30
37	0.025	0.015	569.19	569.1	-0.09	2.30
45	0.065	0.015	571.24	571.9	0.66	2.30

* Above m.s.l.

For example, to calibrate for the flow of 145 ft^3/s, the roughness coefficients for both ice and bed would exceed 0.07 for sections 21 through 31, which is unrealistic in light of calculations made using velocity profile data (Calkins et al. 1982b). Conversely, for a flow of 230 ft^3/s, sections 12-18 required that the Manning's n for both ice and bed be reduced to 0.015 and 0.020, respectively (Tables 4 and 5).

The general trend that appeared when we tried to calibrate using this technique was that low ice roughness coefficients were needed, as well as much lower bed roughness coefficients than for the open channel flow, just to get the computed values of the water surface profile within 0.5 ft of the observed values. Another reason that this technique was abandoned was that computed flow velocities were lower than the measured values reported by Calkins et al. (1982b) and Calkins and Gooch (in press). In addition, there is no unique solution.

Method 3 -- Varying the ice thickness and maintaining constant channel and ice roughness coefficients

Field measurements of the thickness distribution of an ice cover formed from frazil ice take an incredible amount of time. The field data that were taken for this study were accurate, but because of the time required to obtain them, not all surveyed river sections have ice thickness data. It is safe to say that the ice thickness data were taken at an interval of 800-1000 ft or roughly five to seven times the river width.

This third technique first assumed that the bed roughness coefficients computed from the open water calibration of 343 ft^3/s were reasonable (Table 2). Based on previous computations of the Manning's roughness coefficient from velocity profiles for these same sections, the ice roughness coefficient was assumed to be 0.025 for the entire river. The only major input variable left that would significantly affect the water surface profile would be the ice thickness. Hence, the calibration proceeded along these lines; the field-surveyed ice thicknesses would be used as a guide for the input values for the cross sections and the input ice thickness to the model would be adjusted until the water levels were matched along the river.

The result of the calibration runs are given in Table 6. The water surface profiles were matched within 0.10 ft or better for all flows in about 6 to 8 trial runs. The data in these tables indicate the final values of ice thickness that were used to achieve calibration and the aver-

Table 6. Calibration of HEC-2 on the Ottauquechee River by varying the ice thickness; n_i = 0.025, n_b values for Q = 343 ft^3/s.

Section	Measured ice thickness* (ft)	Final input ice thickness (ft)†	Measured water levels (ft)†
a. Q = 145 ft^3/s, 9 runs for calibration			
12	--	1.40	562.7
13	--	1.40	--
14	--	1.40	--
15	1.42	1.40	--
16	--	1.40	--
17	--	1.40	--
18	--	1.40	--
19	--	1.40	--
20	--	1.40	--
21	1.83	1.40	563.6
22	--	1.70	--
23	--	2.00	--
24	--	2.00	--
25	--	2.00	--
26	0.77	2.0	--
27	--	2.73	--
28	--	3.47	--
29	0.30	4.20	565.7
30	--	4.20	--
31	2.86	4.20	--
32	--	4.20	--
33	--	4.20	--
34	--	4.20	--
35	--	4.20	--
36	--	4.20	--
37	--	3.76	--
38	2.88	3.3	569.1
39	--	2.90	--
40	2.71	--	--
41	--	--	--
42	--	--	--
43	--	--	--
44	2.10	2.90	570.9
45	--	2.23	--
46	--	1.56	--
47	--	0.90	--
48	--		--
49	0.39	0.90	--
50	--	0.90	--
51	--	0.90	--
52	--	0.90	--
53	--	0.90	--
54	1.71	0.90	--

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* Averaged section value.

† Above m.s.l.

Table 6 (cont'd). Calibration of HEC-2 on the Ottauquechee River by varying the ice thickness; $n_i = 0.025$, n_b values for Q = 343 ft^3/s.

Section	Measured ice thickness* (ft)	Final input ice thickness (ft)	Measured water levels (ft)†	Other ice** thickness (ft)
b. Q = 215 ft^3/s, 8 runs for calibration				
12	--	1.20	--	1.08
13	--	1.20	--	1.08
14	--	1.20	--	1.08
15	0.74	1.20	562.9	1.08
16	--	1.20	--	1.08
17	--	1.20	--	1.08
18	--	1.20	--	1.08
19	--	1.20	--	1.08
20	--	1.20	--	1.08
21	--	1.60	564.0	1.49
22	1.58	2.0	--	1.91
23	--	2.0	--	1.91
24	--	2.0	--	1.91
25	--	2.0	--	1.91
26	--	2.0	--	1.91
27	--	2.8	--	2.69
28	3.18	3.6	--	3.48
29	--	3.6	565.80	3.48
30	--	3.6	--	3.48
31	3.15	3.6	--	3.48
32	--	3.25	--	3.08
33	--	2.90	--	2.69
34	2.36	2.90	--	--
35	--	2.90	--	--
36	1.44	2.9	--	2.69
37	--	2.33	--	2.15
38	1.64	1.75	568.20	1.6
39	--	1.75	--	--
40	1.14	1.75	--	1.6
41	--	1.35	--	1.2
42	--	0.95	--	0.8
43	2.18	0.95	--	--
44	--	0.95	570.0	0.8

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* Averaged section value.

† Above m.s.l.

** Ice thickness generated when $n_i = 0.035$ to calibrate versus the measured water levels.

Table 6 (cont'd).

Section	Measured ice thickness* (ft)	Final input ice thickness (ft)	Measured water levels (ft)*
c. $Q = 230\ \text{ft}^3/\text{s}$, 5 runs for calibration			
12	--	1.70	--
13	--	1.70	--
14	--	1.70	--
15	--	1.70	562.9
16	--	1.70	--
17	2.38	1.70	--
18	--	1.70	--
19	--	1.45	--
20	--	1.20	--
21	0.36	1.20	564.0
22	--	1.20	--
23	--	1.20	--
24	--	1.20	--
25	--	1.20	--
26	0.25	1.20	--
27	--	2.1	--
28	--	3.0	--
29	2.94	3.0	565.25
30	--	3.0	--
31	2.95	1.6	--
32	--	1.4	--
33	--	--	--
34	--	--	--
35	--	--	--
36	--	--	--
37	--	--	--
38	(open water)		566.6

* Above m.s.l.

Table 6 (cont'd). Calibration of HEC-2 on the Ottauquechee River by varying the ice thickness; n_i = 0.025, n_b values for Q = 343 ft^3/s.

Section	Measured ice thickness (ft)	Final input ice thickness	Measured water levels (ft)*	Dif. computed-observed water levels†
	d. Q = 284 ft^3/s, 8 runs for calibration			
12	3.42	3.20	563.76	+0.04
13	--	3.20	--	--
14	--	3.20	--	--
15	4.6	3.20	564.09	-0.19
16	--	2.8	--	--
17	--	2.40	--	--
18	3.00	--	564.47	+0.43
19	--	2.40	--	--
20	--	2.40	--	--
21	--	2.40	--	--
22	--	2.40	--	--
23	--	2.40	--	--
24	--	2.40	--	--
25	--	2.40	--	--
26	2.42	2.40	565.85	+0.65
27	3.50	3.1	566.24	+0.36
28	--	3.8	--	--
29	--	--	--	--
30	3.33	--	566.65	+0.05
31	--	--	--	--
32	--	--	--	--
33	--	--	--	--
34	--	3.8	--	--
35	--	2.7	--	--
36	--	1.6	--	--
37	2.75	--	568.30	0.00
38	--	--	--	--
39	--	--	--	--
40	--	--	--	--
41	--	--	--	--
42	--	--	--	--
43	--	--	--	--
44	3.00	--	--	--
45	--	--	570.45	+1.25
46	--	--	--	--
47	--	--	--	--
48	--	--	--	+1.20
49	2.33	1.60	573.30	--
50	--	2.4	--	--
51	--	3.2	--	--
52	--	--	--	--
53	2.67	3.2	574.50	+0.3

* Above m.s.l.

† Difference between computed and observed water levels using an ice cover 3-ft thick for entire river reach.

Table 6 (cont'd).

Section	Measured ice thickness (ft)	Final input ice thickness (ft)	Measured water levels (ft)*
e. $Q = 335\ \mathrm{ft}^3/\mathrm{s}$, 9 runs for calibration			
12	--	1.60	--
13	2.79	--	--
14	--	--	--
15	2.79	--	563.03
16	--	--	--
17	--	--	--
18	--	--	--
19	--	1.60	--
20	--	2.0	--
21	2.26	2.4	--
22	--	--	--
23	--	--	--
24	--	2.4	--
25	2.30	2.95	--
26	--	3.4	--
27	5.48	3.4	566.63
28	--	4.2	--
29	--	5.0	--
30	--	5.0	--
31	5.02	5.0	--
32	--	4.3	--
33	2.30	3.6	--
34	--	3.6	--
35	--	3.6	--
36	--	3.6	--
37	2.30	3.6	--
38	--	2.5	--
39	--	1.4	--
40	--	1.4	--
41	--	1.4	--
42	--	1.4	--
43	--	1.4	--
44	--	1.4	--
45	2.30	1.4	571.24

* Above m.s.l.

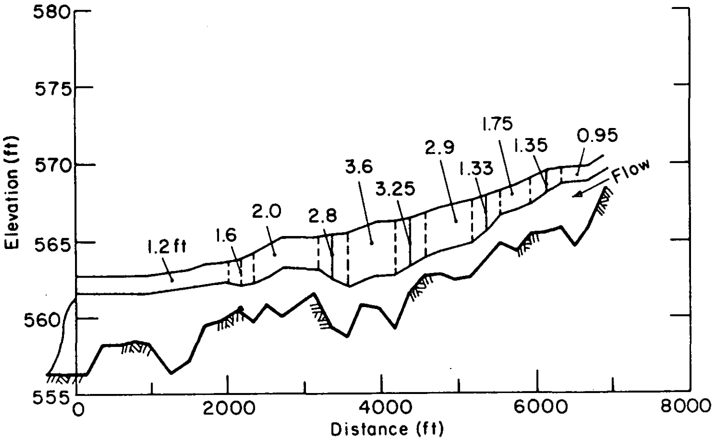

Figure 5. Calibrated ice thicknesses input to HEC-2 for the 215-ft^3/s flow.

age values of the ice thicknesses actually measured at the cross sections. Figure 5 shows the calibrated ice thickness input for the flow of 215 ft^3/s.

By fixing the roughness of the ice cover to 0.025 over the entire reach, are the results restricted? A calibration run using an ice cover roughness coefficient of 0.035 was compared with the values obtained using 0.025 for the discharge of 215 ft^3/s. Increasing the value of the ice cover roughness coefficient from 0.01 to 0.035 required that the ice thickness needed to achieve a calibrated water surface profile decrease by only 0.15 feet!

For the flow of 284 ft^3/s, the ice cover thickness over the entire river reach was approximately 3.0 ft. A run was conducted using this value of ice thickness for the entire reach and the difference between the computed and observed water levels is given in Table 6d. The trend was for an overprediction of water levels ranging of about 0.5 to 1.25 ft.

This method works well for matching the water levels as it required only a few trial runs to achieve calibration. Field data on the flow velocities beneath the cover had also been taken and the mean velocities were generally known. Based on the measured flow velocities presented by Calkins et al. (1982b), the flow velocities being computed with HEC-2 were low by as much as 1.0 ft^3/s, but generally by 0.5 ft^3/s over the entire river reach.

Method 4 -- Ineffective flow areas

The best set of ice thickness measurements was made in 1981 when the flow was 215 ft^3/s. Nine cross sections were surveyed with an average of nine thickness measurements across the river per cross section. Figure 3 shows the details of the ice accumulation. One can see the problem of converting these plugged sections, with ice attached to the river bottom, into a representative single layer ice thickness to be input to the program.

An option in HEC-2 allows ineffective flow areas to be designated within the channel. Since major portions of the cross sections were blocked to the bed with ice, both left and right channel blockages were used. The ice thickness for the channel section was then taken as 0.50 ft, roughly the solid ice growth for that time. The roughness coefficients were maintained at 0.025 for the ice cover and the bed values used were from the 343 ft^3/s open channel flow calibration.

The model was calibrated to the water surface profile by adjusting the amount of ineffective flow area at each section. This process took about 20 trials before the computed water surface profile matched the measured values. Table 7 is a comparison of the flow velocities that were calculated by method 3 and method 4. The ineffective flow area method consistently gave higher flow velocities, which was the result that we desired, that are now in the range of the measured values from the field (Calkins et al. 1982b; Calkins and Gooch, in press).

DISCUSSION

The HEC-2 backwater model could be calibrated to existing water levels in a shallow, ice-covered stream in many ways. The physical roughnesses of bed and ice as well as the ice thickness influence the total stage reached in a river, but with different magnitudes. The options available with HEC-2 allow a certain degree of flexibility in calibration.

The effect of the roughness coefficient in altering the water surface profile in a steep, shallow stream with a relatively thick ice cover was minor. In fact, the effect of changing both the ice cover and bed roughness coefficients by 0.005 (0.01 total) would only change the total stage by roughly 0.17 ft (see eq 8). This same magnitude was actually computed by HEC-2 for the change in the ice thickness over the entire river reach

Table 7. Comparison of computed flow velocities beneath the ice cover for the varying ice thickness technique and the ineffective flow area method, Q = 215 ft^3/s.

Section	Method 3	Method 4
15	0.52	0.44
16	0.76	0.70
17	0.68	1.30
18	1.23	2.09
19	0.89	1.08
20	0.79	0.54
21	1.19	0.84
22	1.10	1.05
23	1.48	2.25
24	0.81	1.60
25	0.65	1.53
26	0.94	1.17
27	0.86	0.78
28	1.05	0.67
29	2.45	2.32
30	1.10	2.73
31	1.16	2.29
32	2.10	3.75
33	1.51	3.64
34	1.73	3.59
35	1.84	2.83
36	1.49	2.74
37	1.60	2.49
38	1.49	2.05
39	1.39	1.71
40	1.85	1.70
41	1.47	1.98
42	1.04	1.60
43	0.88	1.80
44	1.08	1.90
45	2.04	2.22

(Table 6b) when the roughness coefficient was changed by 0.01 to maintain the same water surface profile.

The quality of the ice thickness data was excellent, but the quantity that could be physically gathered in any one time was limited. The ratio of ice sections surveyed to river sections was roughly 1 to 5. One problem that we encountered was trying to transform the measured ice thickness distribution to an equivalent rectangular-shaped section.

We judge the first two methods used for calibration inadequate because the most sensitive parameter to the total stage (ice thickness) was not being correctly represented. The roughness coefficients, as predicted in the Sensitivity Analysis section, did not significantly change the water surface elevation within the acceptable range of values normally used.

The third method of varying the ice cover thickness with no restrictions on the depth of ice was usable for calibrating the HEC-2 model to the observed water levels. This method employed a constant ice cover roughness coefficient of 0.025 and a bed roughness coefficient pattern along the river according to the 343 ft^3/s flow from the open water calibration and allowed the user the freedom of selecting the ice cover thickness to match the water level data. The solution converged rather quickly (although it was not unique) and the water levels were matched. The general trend was for thinner covers at the lower flows and slightly thicker covers at the higher flows of 284 and 335 ft^3/s. This trend was also observed in the ice cover thickness data from the field. The only drawback to this method was that the flow velocities computed were too low compared to actual measurements. To try and correct for the energy losses not being modeled correctly because of the presence of the ice cover, another option was evaluated.

The fourth and last method used an option in HEC-2 that allows the user to specify ineffective flow areas within the channel cross section. Since the ice cover actually grounded in a majority of sections measured, we felt this option would more nearly represent the actual shape of the section. Only one flow was evaluated and it took over 20 runs to get a balanced solution, but the velocity beneath the ice cover was more in line with measured values. This option deserves more attention. The limited data set did not allow for general statements to be made regarding the field versus model blockages of channel area.

CONCLUSIONS

1. Using HEC-2 to model the water surface profiles in a shallow, steep river that is ice covered was accomplished successfully by two techniques. Both used the bed roughness coefficients from the open channel flow that would be representative just prior to the freeze-up flow and a

constant ice cover roughness coefficient. The only difference was the type and distribution of the input ice cover thickness.

2. One technique allowed the user to adjust the ice thickness along the river using the field data as a guide. Calibration of water levels was achievable within a reasonable time, except that the computed flow velocities were low compared to the field measurements; i.e., energy losses were not correctly modeled. The second technique assumed a constant, relatively thin ice thickness for the flow area portion in the river and the model was calibrated by blocking out ineffective flow areas in the sections that corresponded to frazil blockage. This method took longer to calibrate but the computed flow velocities were more in line with the field measurements.

3. The need for accurate field measurements of total ice cover thicknesses in shallow rivers is important only in establishing the range of the values and the degree of frazil ice blockage. The field measurements over a 3-year period indicated a relatively consistent pattern; a maximum equilibrium velocity of roughly 3 ft/s would exist beneath the ice cover.

4. A drawback to using HEC-2 for improved channel conditions over the calibrated natural channel is that it requires the user to have knowledge of the ice processes such that the thicknesses input are realistic with the "modified channel." This is a difficult requirement because the equilibrium thickness of a floating, fragmented ice cover is directly related to the flow velocity.

5. This study points out the shortcomings of using HEC-2 with ice-covered rivers unless the user can predict the ice cover thickness distribution within the channel: a difficult task. A more sophisticated model combining the mechanical-hydraulic and thermal processes is needed.

SUMMARY

Four techniques for calibrating HEC-2 to the water surface profile with an ice cover in a steep, shallow stream were evaluated, and two were successful. Several flows were investigated where field data on the ice thickness distribution, flow velocities and water surface profile had been gathered. The error in not knowing precisely the Manning's ice cover roughness coefficient was shown theoretically and experimentally to be a minor contribution in determining the total stage reached in a steep, shallow, ice-covered river. The ice cover thickness was found to be the dominant parameter in determining the total stage.

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