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ACCURACY OF COMPUTED WATER SURFACE PROFILES[*]

By Michael W. Burnham and Darryl W. Davis[**]

ABSTRACT

Research was performed that investigated the effect of survey technology and accuracy and reliability of hydraulic roughness estimates on the accuracy of computed water surface profiles. The survey technologies studied include field surveys, aerial surveys, and topographic maps as data sources for stream geometry cross-sectional definition. A Monte Carlo simulation strategy was applied to develop an array of computed profile errors for the survey technologies and selected accuracies, and Manning's coefficient reliability. Ninety-eight natural stream data sets provided the basic data for the study. Comparison of computed base condition profiles and Monte Carlo simulation profiles enabled calculation of mean absolute and maximum absolute errors for each stream reach and error condition. Regression equations were derived for predicting profile errors as a function of survey technology, selected accuracy, Manning's roughness coefficient, and stream hydraulic properties.

The findings enable direct estimation of the accuracy of a computed profile for a given study, development of data collection strategies to assure predictable accuracies of computed profiles, and cost effective decisions to be made for determining an appropriate survey method. The significant findings are: 1) stream cross-sectional geometry obtained from aerial surveys (spot elevations) and topographic maps are more accurate than generally perceived; 2) aerial spot elevations are significantly more accurate than topographic maps; 3) the reliability of the estimation of Manning's coefficient has a major effect on the computed profile accuracy; and 4) significant errors exist in many profile computations due to inaccurate numeric integration of the energy loss - distance relationship as commonly used in water surface profile computations.

This paper describes the goals of the study, the investigative strategy employed, data collection, Monte Carlo simulation results, and findings and conclusions. The error prediction equations as published in the final technical report are presented and described.

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[*] Presented at the January 1987 Annual Meeting of the Transportation Research Board, Washington D.C.

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INTRODUCTION

Water surface profiles are computed for a variety of technical uses. Profiles are computed for flood insurance studies, flood hazard mitigation investigations, drainage crossing analysis, and other similar design needs. Tens of thousands of profile analyses are performed each year. The accuracy of the resulting computed profiles has profound implications. In the case of flood insurance studies, the computed profile is the determining factor of the acceptability of parcels of land for development. For flood control projects, the water surface elevation is important in planning and design of project features and in determining the economic feasibility of proposed solutions. For highway stream crossings, the computed profile can affect bridge design and is the mechanism for determining the effect of a bridge crossing on upstream water levels. The accuracy of computed profiles is thus of major interest to the water resources community. Similarly, with the large number of studies performed each year, the cost of acquiring essential data, such as cross-sectional geometry is significant. The relationship between mapping accuracy and resultant computed profile accuracy is therefore of major interest to engineers responsible for providing cost-effective technical analysis.

The water surface profile for the significant majority of streams can be computed using the step-profile (standard-step) method for steady flow. The method is based on solving the steady flow equations using a cross section to cross section, step by step procedure. Errors associated with computing water surface profiles with the step-profile method can be classified as technique applicability, computation, and data estimation errors (McBean 1984). The applicability of the technique is the responsibility of the professional engineer and much experience is available to assist in making an appropriate applicability decision. Computation errors include numerical round-off and numerical solution errors. The former is negligible using today's modern computers and the latter can be minimized by employing readily available mathematical solution techniques. Data estimation errors may result from incomplete or inaccurate data collection and inaccurate data estimation. The sources of data estimation errors are the accuracy of the stream geometry and the accuracy of the method used and data needed for the energy loss calculations. The accuracy in stream geometry as it affects accuracy of computed profiles is therefore of importance. The accuracy of energy loss calculations depends on the validity of the energy loss equation employed and the accuracy of the energy loss coefficients. The Manning equation is the most commonly used open channel flow equation and Manning's n-value is the coefficient measuring boundary friction.

This investigation focuses on determining the relationship between:

- survey technology and accuracy employed for determining cross-sectional geometry,
- degree of confidence in Manning's coefficient, and
- the resulting accuracy of the computed water surface profile.

A second component of the study developed equations that may be used to estimate the upstream and downstream study limits needed for data collection and analysis to ensure that accurate profile analysis is performed in the vicinity of a highway stream crossing. The HEC-2 Water Surface Profiles computer program (Hydrologic Engineering Center 1982) is used as the computational tool to compute the profiles for the investigation.

INVESTIGATION STRATEGY

The strategy adopted for the investigation was to assemble an array of existing HEC-2 data sets and adjust the data sets in a carefully controlled manner and observe the error effects. The error effects are determined by comparing the profiles computed for the adjusted data sets with the profiles computed for the original data set. The data adjustment strategy is that of Monte Carlo simulation, which incorporates within its methodology the interaction among the several sources of error. Probability density functions are derived that define the error distributions for survey cross-sectional measurements and Manning's roughness coefficients. Error analyses are performed for conventional field surveys, and 2-, 5-, and 10-foot contour interval aerial spot elevation survey and topographic maps. Three levels of reliability of Manning's roughness coefficient are studied, varying from n-values selected through professional judgment to accurately calibrated n-values based on observed historical profiles.

Comparison of computed base condition profiles and Monte Carlo simulation profiles enables calculation of mean absolute and maximum absolute errors for each stream reach and error condition. Regression equations are derived for predicting profile error as a function of survey technology, selected accuracy, Manning's roughness coefficient and stream hydraulic properties. Regression equations are also developed for estimating the upstream and downstream distances from a highway stream crossing that are needed for data collection and water surface profile analysis. Profile calculation data are needed downstream to assure that any initial profile error does not impact on the profile at the crossing. Profile calculation data are needed upstream a distance equal to the estimated convergence location of the profile resulting from stream crossing structure headloss.

Several important study bounds were adopted to ensure consistency in decisions involving data processing and analysis strategy, and to confine the investigation to a manageable set of issues. The study bounds are:

1. The discharge (flow rate) corresponding to the 1-percent chance flow is used and errors in discharge values are not considered,

2. The HEC-2 Water Surface Profiles computer program is used for all water surface profile computations. The program is applicable for natural stream geometry, one-dimensional, gradually varied, rigid boundary, steady flow conditions,

3. Only subcritical flow conditions are considered,

4. The incremental increase in error caused by local features such as bridges, culverts, dams, and radical bends are not considered.

Monte Carlo analysis provides a way to estimate the statistical properties of outputs (profile errors) of numerical models when one or more of inputs (surveyed cross section and Manning's coefficient errors) are random variables. The input variables used in a water surface profile calculation model differ from the true values because they are derived from measured data. Since the errors in these inputs are unknown, the evaluation of their effect on the profile is also unknown. A way to deal with this problem is to acknowledge that the inputs are samples drawn at random from a population of likely data sets. This approach allows probabilistic statements to be made regarding the relationship between input errors and output (profile) errors.

The adopted Monte Carlo simulation strategy is shown schematically in Figure 3.1. HEC-2 data sets obtained from Corps field offices are assembled in a data file for analysis (step 1 of Figure 3.1). The data sets are subsequently edited (step 2) to produce consistent data sets. This process eliminates all but the 1- and 10-percent chance discharge values, removes all bridge data and non-surveyed cross sections, and edits all data sets to the same expansion and contraction loss coefficients. The data sets are subsequently evaluated to define appropriate reach lengths and to assure that all profiles are subcritical. Of the 140 original data sets, 98 are retained for the profile accuracy analysis after editing.

The edited data sets are further modified to develop the base condition data sets. Interpolated cross sections are added to minimize numerical integration error (step 3). Comparison of profiles computed from the several commonly used friction loss approximation techniques of; average friction slope, average conveyance, and geometric and harmonic mean friction slope shows significant differences, more than a foot, in reaches of many streams. A significant number of the original data sets underestimate the profiles as compared to those calculated with more accurate integration of the energy loss-distance function made possible by using closer-spaced cross sections. The cross sections are linearly interpolated at 500 foot spacings from the surveyed cross sections (step 3). These cross sections are not required for better definition of physical and hydraulic changes along the stream but only for increasing the number of computation steps. The original data sets adequately define the geometric variations.

The edited data sets with the interpolated cross sections become the base HEC-2 data sets (step 4) used to generate the base water surface profile (step 5). Figure 4.4 contains several charts that illustrate the range of stream characteristics represented by the adopted data sets. A base profile is calculated for each of the 98 data sets and subsequently compared with the profiles computed for the adjusted HEC-2 data sets.

The adjusted HEC-2 data sets are developed using the Monte Carlo simulation approach to randomly adjust survey cross-sectional coordinate points and Manning's coefficients for errors associated with these parameters. Analysis conditions are specified (step 6) and measurement error statistics are used to randomly adjust each coordinate point and Manning's coefficient in the data set (step 7). No adjustments are made for field surveys since they are considered to be without error. Cross-sectional adjustments are performed for aerial spot elevations and topographic maps for 2-, 5-, and 10-foot contour intervals. The probability density functions (PDF) of errors for these conditions are obtained from published mapping standards. Manning's coefficient analyses are performed for three levels of reliability of the estimates ranging from professional judgment based on field observations to precisely calibrated estimates.

The various combinations of survey and Manning's coefficient conditions result in 21 different error evaluation situations for each of the 98 edited data sets. The adjusted data sets (step 8) are then processed by HEC-2 to yield the error condition predicted water surface profiles (step 9). Each of the adjusted profiles is compared with the base condition profile (step 10) to determine the mean absolute reach error (average error over the stream reach) and absolute maximum reach error.

The profile computed for the adjusted HEC-2 data set for a specified survey and Manning's coefficient represents one of a set of possible profiles based on the PDF's of the two error sources. It is therefore necessary to generate sufficient replicates of each condition analyzed to develop a reliable set of the error statistics of the mean absolute and maximum absolute reach errors. The resulting mean absolute reach error values and maximum absolute reach error values were subsequently used to

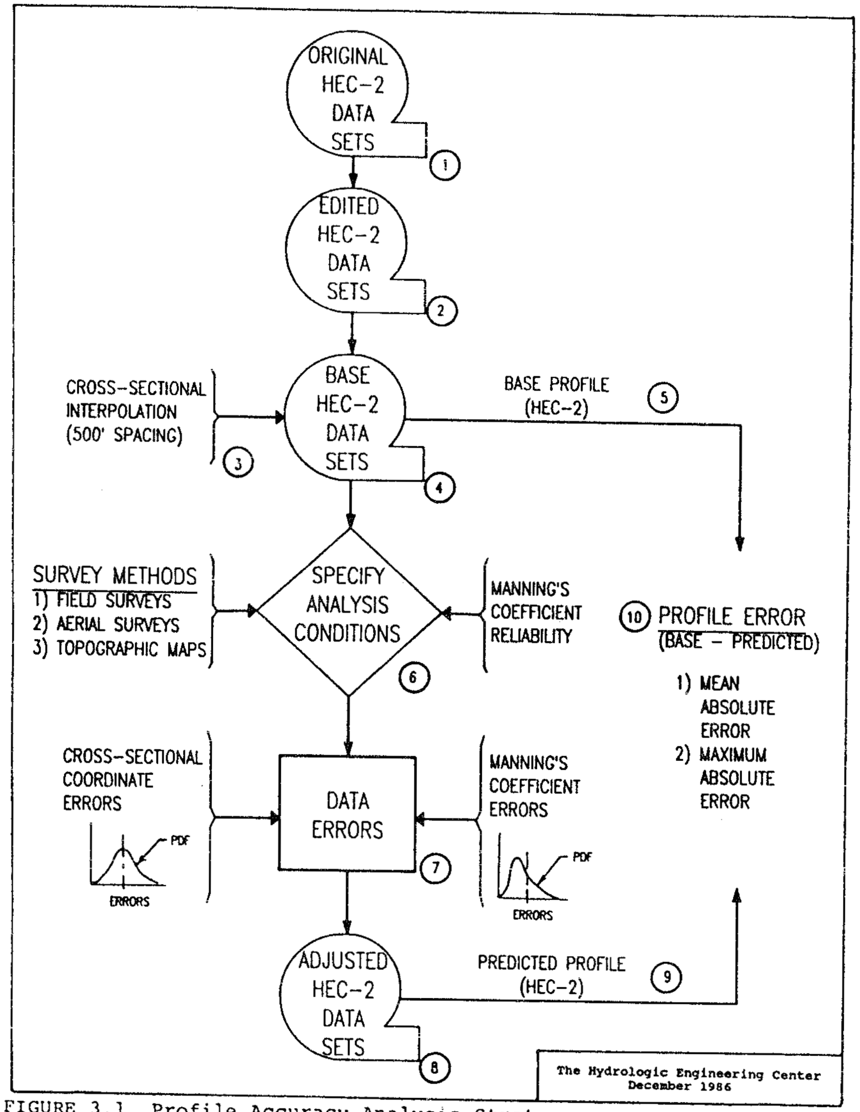

FIGURE 3.1 Profile Accuracy Analysis Strategy

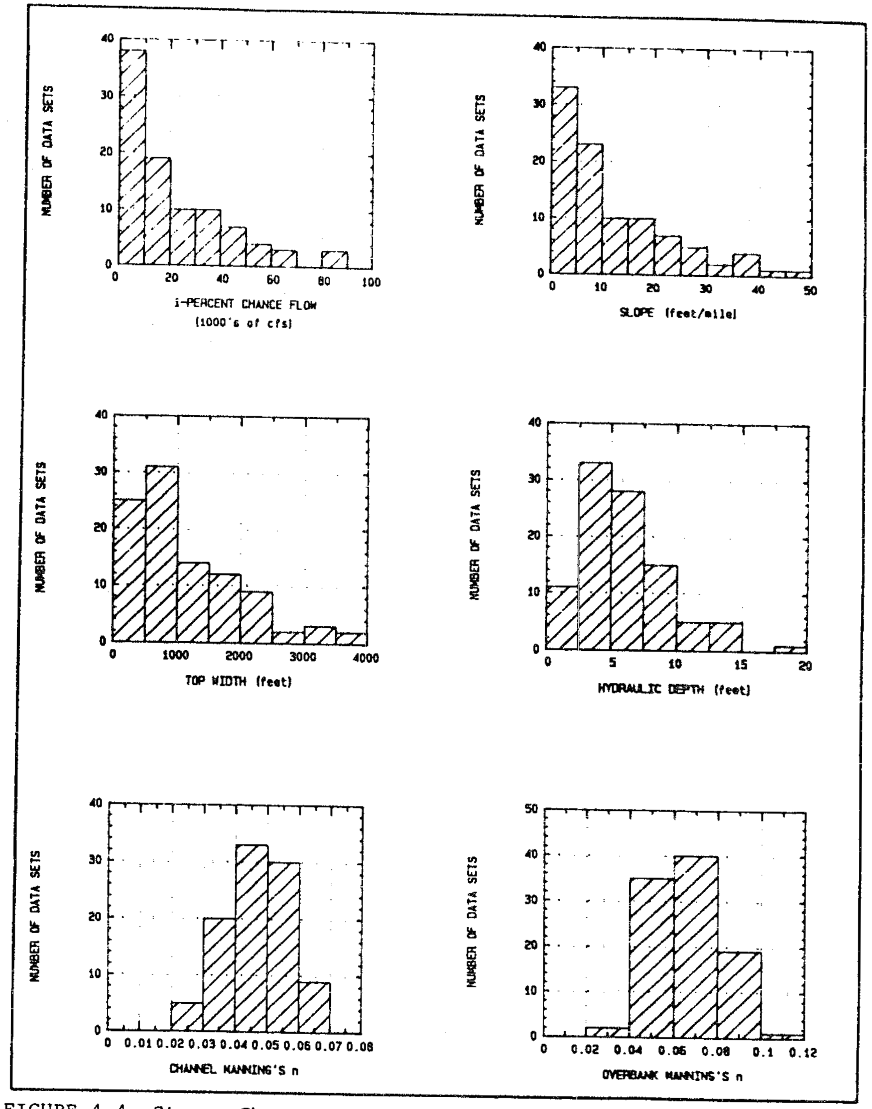

FIGURE 4.4 Stream Characteristics of Base Data Sets

derive regression equations for predicting water surface profile errors for specified survey accuracy and Manning's coefficient reliability conditions.

SURVEY METHODS AND ACCURACY

A stream cross section is a vertical section through the surface of the ground taken perpendicular to the flow. The cross section is defined by distance and elevation coordinates taken at changes in topography along the cross-sectional alignment.

The number of cross sections that are taken vary with study requirements and stream characteristics. Survey methods used to measure cross-sectional coordinates include field surveys performed with land surveying instruments, aerial spot elevations developed from aerial stereo models, topographic maps generated from aerial photography procedures, and hydrographic surveys that are needed when the size and depth of streams prevent measurement by other means. Measurement errors for these methods are a function of industry adopted accuracy standards, equipment, terrain, and land surface cover.

Aerial photogrammetry is an increasingly used technology for determining cross-sectional coordinate data. The data can be easily processed to the desired formats for direct computer application. Two distinct products are spot elevations along the alignment of the cross sections and topographic maps from which the cross sections are subsequently taken. Both techniques are derived from basic photogrammetry technology.

The accuracy of aerial technology for generating cross-sectional coordinate data are governed by mapping industry standards. Table 5.2 is a summary of relevant accuracy standards. Cross sections obtained from contours of topographic maps developed by photogrammetric methods are not as accurate as those generated from spot elevations. The elevation errors of aerial spot elevations and points on the topographic map are spatially uncorrelated and random (Hydrologic Engineering Center 1985). Therefore, measurement errors for adjacent cross-sectional coordinate points obtained from either procedure are not correlated.

The study was performed based on the following adopted survey accuracy statements.

1. Field surveys are considered to produce precise, exact replication of the base condition cross-sectional geometry with no errors. This represents the lower, no measurement error bound on the computed profile accuracy analysis,

2. Aerial spot elevation and topographic map cross-sectional measurement errors are based on the mapping industry accuracy standards shown in Table 5.2. Only

TABLE 5.2

Aerial Survey Procedures Vertical (Elevation) Accuracy*

Aerial survey map accuracy for spot elevations and topographic maps is defined by the mapping industry standard. Standard Map Accuracy is described by the following criteria:

1. The plotted position of all coordinate grid ticks and monuments, except benchmarks, will be within 0.01 inch from their calculated positions.

2. At least 90 percent of all well-defined planimetric features shall be within 0.033 inch of their true positions, and all shall be within 0.066 inch of their true positions.

3. At least 90 percent of all contours shall be within one-half contour of true elevations, and all contours shall be within one contour interval of true elevation, except as follows:

   For mapping at scales of 1" = 100' or larger in areas where the ground is completely obscured by dense brush or timber, 90 percent of all contours shall be within one contour interval or one-half the average height of the ground cover, whichever is the greater, of true elevation. All contours shall be within two contour intervals or the average height of the groundcover, whichever is the greater, of true elevation. Contours in such areas shall be indicated by dashed lines.

   Any contour which can be brought within the specified vertical tolerance by shifting its plotter position .033 inch shall be accepted as correctly plotted.

   At least 90 percent of all spot elevations shall be within one-fourth the specified contour interval of their true elevation, and all spot elevations shall be within one-half the contour interval of their true elevation, except that for 5-foot contours 90 percent shall be within 1.0 foot and all shall be within 2.0 feet.

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*Source: Brochure from Cartwright Aerial Surveys Inc., Sacramento, California.

vertical (elevation) errors are analyzed. Errors in horizontal cross-sectional coordinates are not considered significant,

3. The accuracy of hydrographic surveys for channel cross sections is taken to be the same as that used for the overbank or floodplain portions of the cross sections,

4. The magnitude and frequency of errors due to human mistakes in measurements or calculations (blunders), are not readily definable and are not considered. Blunders are largely negated through normal verification of measurements with other sources of data.

The probability density function for the aerial survey spot elevations and topographic maps may be estimated from the values specified in Table 5.2. Table 5.3 is a tabulation of the standard deviations for the selected contour intervals for both aerial spot elevations and topographic maps.

TABLE 5.3

Standard Deviations
Aerial Spot Elevations and Topographic Maps
(feet)

Contour Interval	Standard Deviation Aerial Spot Elevations	Standard Deviation Topographic Maps
2	0.30	0.60
5	0.60	1.50
10	1.50	3.00

Adjusting cross-sectional coordinate values for the Monte Carlo simulation for aerial spot elevation surveys is performed as follows:

1. Determine the standard deviation for the contour interval being evaluated (Table 5.3),

2. Calculate the standard normal deviate by first generating a uniform distribution of random numbers varying from 0 to 1. Transform the values to represent the normal (Gaussian) distribution,

3. Calculate the random error for the cross-sectional coordinate elevation using the generated standard normal deviate and the standard deviation for the survey method and accuracy standard for the specified contour interval,

4. Add the random error to the base coordinate point elevation value,

5. Repeat 2. through 4. for all coordinate points and cross sections in the HEC-2 data set.

A similar process is followed for adjusting cross-sectional coordinate values associated with reading points from topographic maps. The difference is the addition of steps to simulate being able to read the map only at contour lines. Figure 5.4 contains cross-sectional adjustment examples.

MANNING'S COEFFICIENT ERRORS

Accurate estimation of Manning's coefficients is hampered by lack of observable field attributes and spatial variation along the stream. Reliable estimates of Manning's coefficients are difficult even with use of documented procedures, field reconnaissance, and calibration methods (Chow 1959 and Federal Highway Administration 1984).

Statistical information on Manning's coefficient estimation errors is largely nonexistent. Therefore, an experiment is devised to obtain the error probability density functions required for the Monte Carlo simulation. Staff of the Hydrologic Engineering Center and participants in two training courses attended by experienced Corps of Engineers hydraulic engineers are asked to estimate the Manning's coefficient associated with the 1-percent chance flow for 10 widely different stream reaches. The participants are given a photograph and description of each stream and a method for estimating Manning's coefficients from Open Channel Hydraulics (Chow 1959). Study experience significantly influenced the estimates of some participants, while others rely primarily on comparisons of photographs and descriptions provided in reference materials.

The experiment, though approximate in nature, provides insight into the variations possible in estimating Manning's coefficient. A few outliers are deleted and histograms of the estimations constructed for each of the 10 reaches. Figure 5.5 contains plots for five of the stream reaches illustrating the variability of the estimates. The log-normal distribution provides the best fit to the histogram data and is therefore adopted to represent the probability density function of errors associated with estimating Manning's coefficient. The mean of the estimates of each of the 10 histograms is taken as the true coefficient value.

Review of the histograms indicates a greater variance of estimates for higher Manning's coefficient values than for lower coefficient values. Estimates of Manning's coefficient for concrete channels, for example, have less variance than those for a densely vegetated stream as one would expect since the range of possibilities is larger. A simple linear regression analysis developed a relationship for the standard deviation of errors as

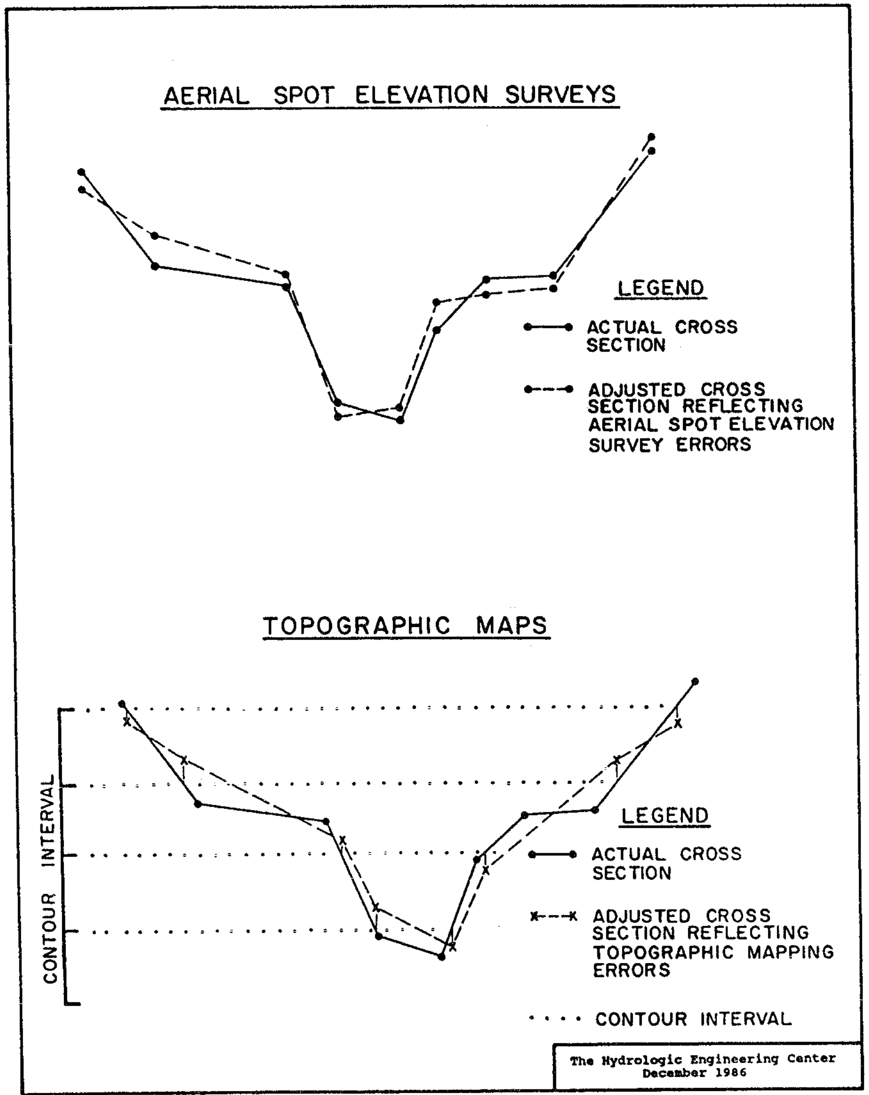

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FIGURE 5.4 Cross Section Adjustment Examples

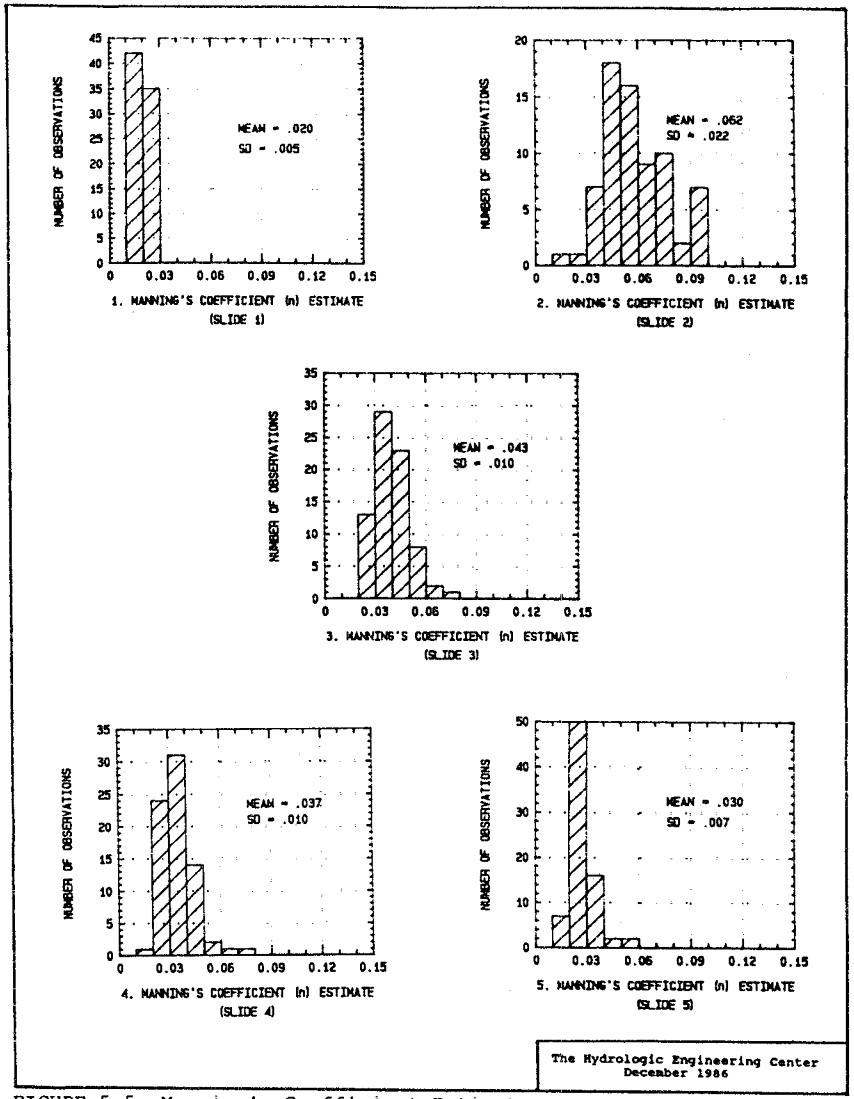

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FIGURE 5.5 Manning's Coefficient Estimates a function of the magnitude of the roughness coefficient.

The relationship represents an n-value estimate that would be representative of minimum effort based on professional judgment. It reflects estimates derived from photographs of a stream, a limited set of background and descriptive information, and made without interaction with other professionals. The other extreme is perfect knowledge of Manning's coefficient - no estimation error and no need for adjustment of the base coefficient values in the Monte Carlo simulation. This condition can be approached by skilled and experienced analysts using reliable calibration data. Most estimates used in practice for profile computations fall somewhere between these bounds.

A reliability coefficient (Nr) is postulated to enable numerical analysis of the error in Manning's n-value. Nr ranges from 0 to 1, where

Nr = 0, when the n-value is known exactly. This represents perfect confidence in the estimated value.

Nr = .5, when reasonable efforts are made to substantiate the estimate, but detailed, intensive calibration is not successful. Moderate confidence exists in the estimated value.

Nr = 1.0, when an approach similar to that tested in the experiment is used to estimate the coefficient. Modest confidence exists in estimated value.

The derived Manning's n-value error equation can be multiplied by the reliability coefficient to reflect the confidence of an n-value estimate. The procedure for randomly adjusting Manning's coefficient for the Monte Carlo simulation is:

1. The overbank and channel Manning's coefficients are retrieved from the base conditions HEC-2 data files (they are contained on NC records),

2. The natural logarithms of the values are determined,

3. The reliability level (Nr) is selected and the associated Manning's coefficient standard deviation is computed,

4. A random normal standard deviate is generated. A single deviate is used to adjust the channel and overbank n-values simultaneously to simulate the likelihood of the estimates in practice to be consistently high or low at a specific location,

5. The adjusted Manning's coefficients are calculated by adding the product of the normal deviate and standard

deviation to the base condition n-value,

6. The adjusted Manning's coefficient is obtained by taking the antilog of the value calculated in 5. above,

7. Steps 1 through 6 are repeated for each set of Manning's coefficients in the data file (HEC-2 NC records).

COMPUTED PROFILE ERRORS

The specific error conditions analyzed are documented in Table 6.1. A total of 21 survey and Nr combination error conditions are analyzed for each of the 98 data sets. Processing these error conditions with the number of replicates needed to yield stable error statistics resulted in about 50,000 HEC-2 executions.

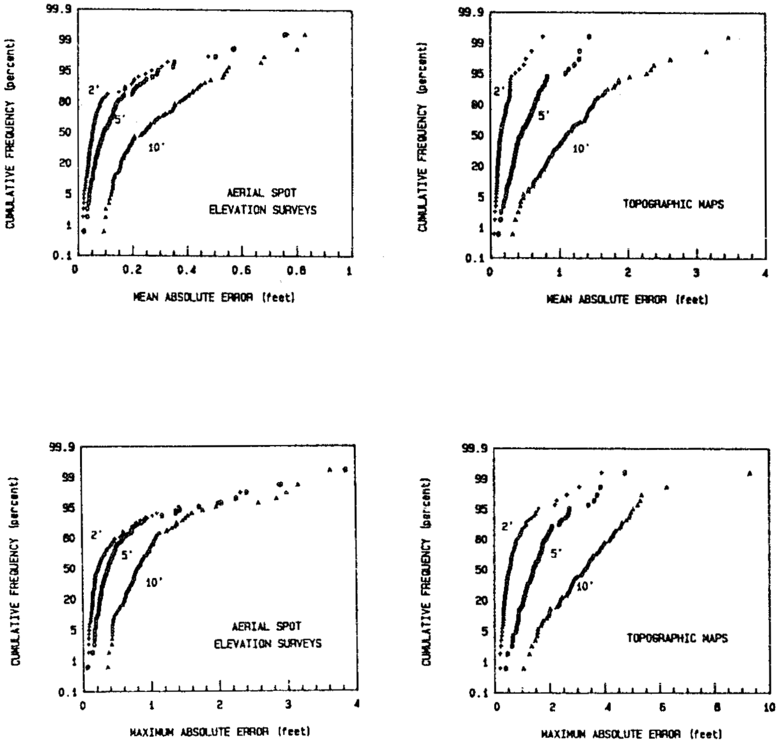
TABLE 6.1

Survey and Manning's
Coefficient Error Conditions

Contour Interval (feet)	Reliability of Manning's Coefficient (Nr) Field Surveys	 Aerial Spot Elevations	 Topographic Maps
No Error	0,.5,1.0	N.A.	N.A.
2	N.A.	0,.5,1.0	0,.5,1.0
5	N.A.	0,.5,1.0	0,.5,1.0
10	N.A.	0,.5,1.0	0,.5,1.0

Profile errors are computed as the absolute difference (in feet) between the base data set computed profiles and the adjusted data set computed profiles. The error calculations are made at the 500 foot interpolated cross section spacing. The reach mean absolute error is the sum of the absolute differences divided by the number of locations. The reach maximum absolute error is the largest absolute difference that occurs within the stream reach.

Cumulative frequency plots for the mean errors resulting from the Monte Carlo simulations for the 98 data sets were developed to display the range of errors generated in the analysis. Figures 6.2 and 6.3 present the frequency plots for both the mean absolute errors and maximum absolute errors at the extremes of Manning's coefficient reliability. Note that the errors are grouped in bands corresponding to the survey contour intervals. This indicates that the profile errors vary distinctly in magnitude with the 2-, 5-, and 10-foot contour intervals. Note also that as Manning's n-value becomes less reliable, the



Monte Carlo simulation results - 98 data sets. Nr = 0.

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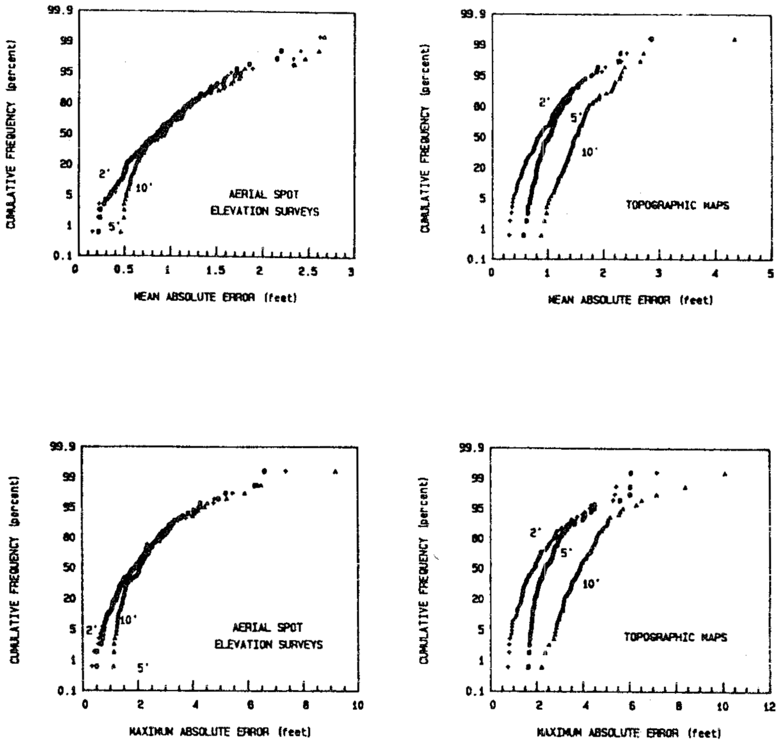
FIGURE 6.2 Frequency of Profile Errors - High Reliability of Manning's Coefficient



Monte Carlo simulation results - 98 data sets. Nr = 1.

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FIGURE 6.3 Frequency of Profile Errors - Low Reliability of Manning's Coefficient grouping into contour interval bands is less distinct.

Regression analyses are performed to develop equations for predicting the computed water surface profile error. The several hydraulic variables tested as explanatory variables include the 1-percent chance flow rate, Manning's coefficient, cross-sectional top width, hydraulic depth, and channel slope. Manning's coefficient, cross-sectional top width, and hydraulic depth are stream reach length weighted values. The dominant hydraulic variables are slope and hydraulic depth. A dimensionless term to account for joint variation in Manning's n-value confidence and contour interval is formulated for inclusion in the regression equation. Several combinations of dimensionless weighted coefficients are tested for this term and the best values selected.

The adopted regression equations derived for predicting computed profile errors for the three survey methods are tabulated below.

Field Surveys

$$Emean = .076*HD^{.60}*S^{.11}*(5*Nr)^{.65} \qquad \text{(Equation 6.3)}$$

and $$Emax = 2.1(Emean)^{.8} \qquad \text{(Equation 6.4)}$$

where: Emean = mean reach absolute profile error in feet,
Emax = absolute reach maximum profile error in feet,
HD = reach mean hydraulic depth in feet,
S = reach average channel slope in feet per mile,
Nr = reliability of estimation of Manning's coefficient on a scale of 0 to 1.0.

Aerial Spot Elevations

$$Emean = .076*HD^{.60}*S^{.11}*(5*Nr + Sn)^{.65} \qquad \text{(Equation 6.5)}$$

and $$Emax = 2.1*(Emean)^{.8} \qquad \text{(Equation 6.6)}$$

where: Sn = the standardized survey accuracy being analyzed - the contour interval 2-, 5-, 10-feet divided by 10; and other variables are as previously defined.

For the special case of Manning's coefficient being precisely known (Nr = 0),

$$Emean = .0731*S^{.49}*Sn^{.83} \qquad \text{(Equation 6.7)}$$

Topographic Maps

$$Emean = .45*HD^{.35}*S^{.13}*(Nr + Sn) \qquad \text{(Equation 6.8)}$$

and $Emax = 2.6*(Emean)^{.8}$ (Equation 6.9)

For the special case of Manning's coefficient being precisely known (Nr = 0),

$$Emean = .632*S^{.23}*Sn^{1.18} \quad \text{(Equation 6.10)}$$

The goodness-of-fit of the regression equations can be expressed using the coefficient of determination and the standard error of regression. The coefficient of determination defines the proportion of the total variation of a dependent variable explained by the independent variables. For example, a value of 0.90 indicates that 90 percent of the variation is accounted for by the independent variables. The standard error of regression is the root-mean-square error. Table 6.2 summarizes the goodness-of-fit statistics for the adopted regression equations. Table 6.3 shows standard error values for selected profile accuracies.

The regression equations were adapted to nomographs to facilitate ease of use. Figures 6.5, and 6.7 are nomographs for aerial spot elevation survey and corresponding topographic map accuracies for Manning coefficient estimation reliabilities (Nr) of 0 and 1.0, respectively.

TABLE 6.2

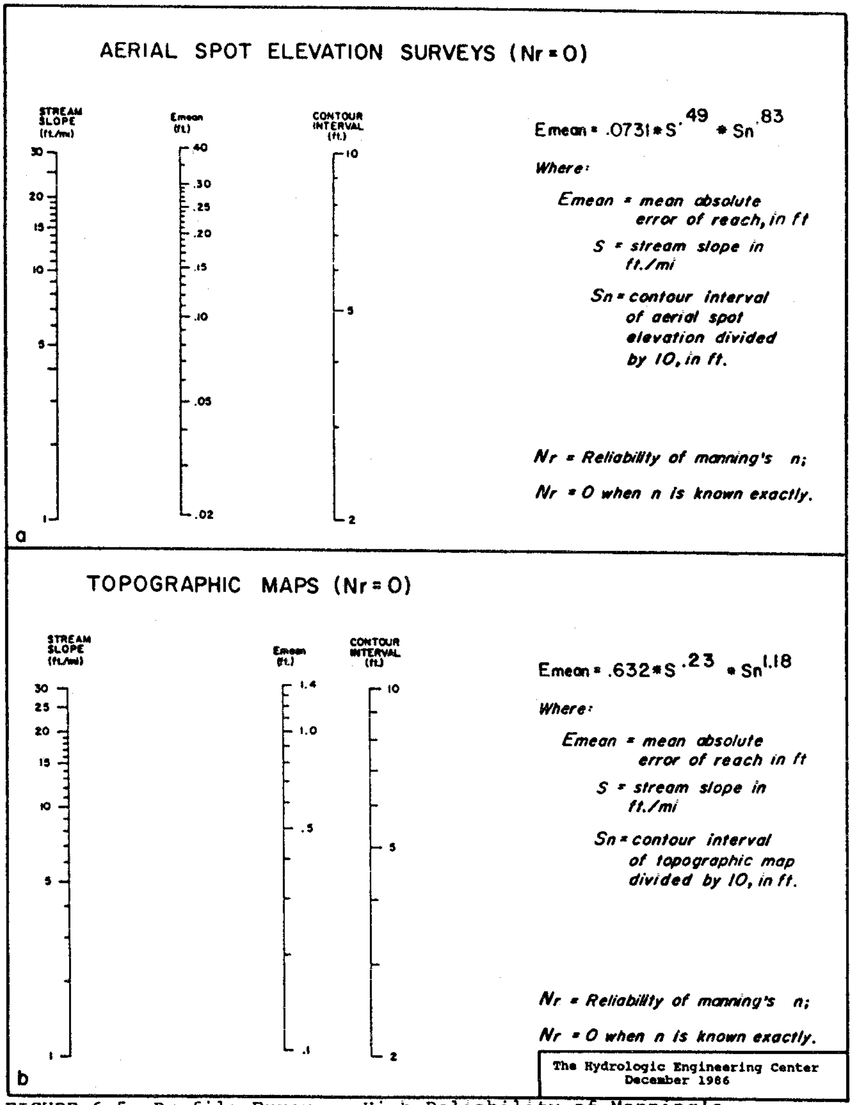
Regression Analysis
Goodness-of-Fit Statistics

Statistic	Field and Aerial Spot Elevation Survey		Topographic Map	
	Nr = 0	Nr > 0	Nr = 0	Nr > 0
Coeff. of Determination	.67	.68	.77	.64
Standard Error (Se) (log units, base 10)	.21	.17	.19	.20

TABLE 6.3

Profile Accuracy Prediction Reliability*
Aerial Spot Elevations Surveys

Predicted Error (ft)	+1Se (ft)	-1Se (ft)	+2Se (ft)	-2Se (ft)
.10	.15	.07	.21	.05
.30	.44	.20	.64	.14
.50	.73	.34	1.07	.23



AERIAL SPOT ELEVATION SURVEYS (Nr = 0)

$Emean = .0731 * S^{.49} * Sn^{.83}$

Where:

Emean = mean absolute error of reach, in ft

S = stream slope in ft./mi

Sn = contour interval of aerial spot elevation divided by 10, in ft.

Nr = Reliability of manning's n;

Nr = 0 when n is known exactly.

TOPOGRAPHIC MAPS (Nr = 0)

$Emean = .632 * S^{.23} * Sn^{1.18}$

Where:

Emean = mean absolute error of reach in ft

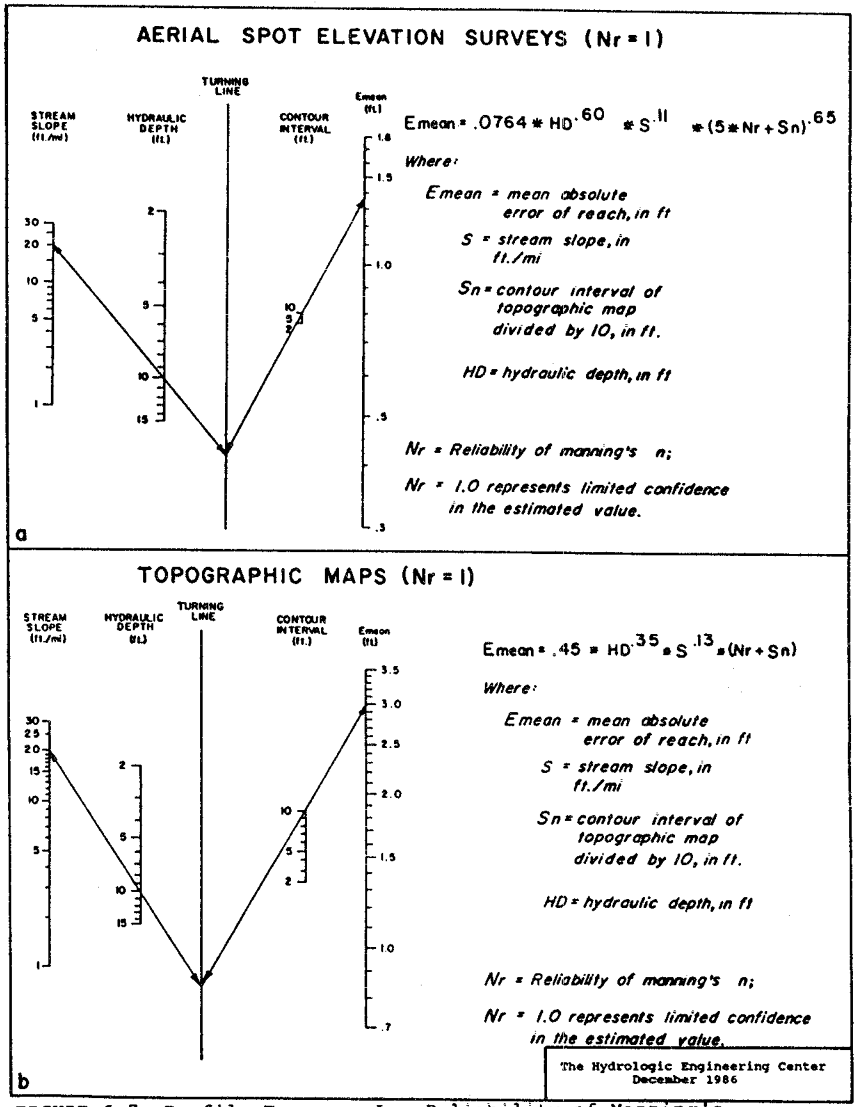
S = stream slope in ft./mi

Sn = contour interval of topographic map divided by 10, in ft.

Nr = Reliability of manning's n;

Nr = 0 when n is known exactly.

FIGURE 6.5 Profile Errors - High Reliability of Manning's Coefficients



AERIAL SPOT ELEVATION SURVEYS (Nr = 1)

$Emean = .0764 * HD^{.60} * S^{.11} * (5 * Nr + Sn)^{.65}$

Where:

Emean = mean absolute error of reach, in ft

S = stream slope, in ft./mi

Sn = contour interval of topographic map divided by 10, in ft.

HD = hydraulic depth, in ft

Nr = Reliability of manning's n;

Nr = 1.0 represents limited confidence in the estimated value.

TOPOGRAPHIC MAPS (Nr = 1)

$Emean = .45 * HD^{.35} * S^{.13} * (Nr + Sn)$

Where:

Emean = mean absolute error of reach, in ft

S = stream slope, in ft./mi

Sn = contour interval of topographic map divided by 10, in ft.

HD = hydraulic depth, in ft

Nr = Reliability of manning's n;

Nr = 1.0 represents limited confidence in the estimated value.

FIGURE 6.7 Profile Errors - Low Reliability of Manning's Coefficients

TABLE 6.3 cntd

Topographic Maps

Predicted Error (ft)	+1Se (ft)	-1Se (ft)	+2Se (ft)	-2Se (ft)
.50	.79	.32	1.26	.20
1.00	1.58	.63	2.51	.40
1.50	2.38	.95	3.77	.60

* The values are the plus and minus limits.

SUMMARY OF PROFILE ERROR RESULTS

Profile errors resulting from use of commonly applied field survey methods of obtaining cross-sectional coordinate data are a function only of Manning's coefficient reliability. Computed profile error is relatively small even for rough estimates of Manning's coefficient. For example, for hydraulic depth of 5 feet and stream slope of 10 feet per mile, the predicted mean errors are 0, .47, and .74 feet for reliability of Manning's n-value of 0, .5, and 1 respectively.

Profile errors resulting from use of aerial spot elevation surveys for obtaining cross-sectional coordinate data varies with the contour interval and reliability of Manning's n-value. For example, for hydraulic depth of 5 feet and stream slope of 10 feet per mile, the predicted mean errors for precisely known Manning's n-value is .06, .13, and .22 feet for contour intervals of 2-, 5-, and 10-feet respectively. Similarly, the predicted mean errors for low reliability of Manning's n-value (Nr = 1) are 0.75, 0.78, and 0.83 feet, respectively.

The relatively small profile error for the aerial spot elevation survey method is due to the high accuracy of aerial spot elevation surveys and the randomness of the measurement errors at the individual coordinate points. The latter results in compensating errors along the cross-sectional alignment. For the error prediction determined from the regression equations to be valid, eight or more cross-sectional coordinate points are needed to ensure that the randomness and thus compensatory error process has occurred.

Note also that the error in computed water surface profiles increase significantly with decreased reliability of Manning's coefficient. The profile errors resulting from less reliable estimates of Manning's coefficient are several times those resulting from survey measurement errors alone. Figure 6.7a readily shows the insignificant effect of survey contour intervals on the profile error when less reliable Manning's coefficients are used. For reliability of Manning's n-value of 1.0, the error in the computed water surface profiles will probably be greater than .75 feet for stream reaches with average slopes greater than 10 feet per mile regardless of the aerial spot survey contour interval.

There is significantly greater error for larger contour intervals for topographic maps than for aerial spot elevation surveys. Data from topographic maps are simply less accurate than data from spot elevation methods. Also, topographic map cross-sectional elevations can only be obtained at the contour intervals. For example, for the same values of hydraulic depth (5 feet), stream slope (10 feet per mile), and Manning's n-value reliability (0 and 1), respectively, the predicted mean errors are .16, 0.47, and 1.06 feet; and 1.28, 1.60, and 2.13 feet. Significant mean profile errors (greater than 2 feet) may be expected for analyses involving steep streams, large contour intervals, and unreliable estimates of Manning's coefficients.

TABLE 6.7

SURVEY ACCURACY REQUIREMENTS[1]
FOR SPECIFIED PROFILE ACCURACIES
(Hydraulic Depth is 5 Feet)

		Manning's n-value Reliability - Nr = 0		Manning's n-value Reliability - Nr = 1	
Stream Slope (ft./mi.)	Profile Accuracy Emean[2] (feet)	Aerial Survey Contour Interval	Topo Map Contour Interval	Aerial Survey Contour Interval	Topo Map Contour Interval
1	.1	10 foot	N.A.	N.A.	N.A.
1	.5	10 foot	5 foot	N.A.	N.A.
1	1.0	>10 foot	10 foot	10 foot	2 foot
1	1.5	>10 foot	10 foot	10 foot	5 foot
1	2.0	>10 foot	10 foot	>10 foot	10 foot
10	.1	2 foot	N.A.	N.A.	N.A.
10	.5	10 foot	5 foot	N.A.	N.A.
10	1.0	10 foot	5 foot	10 foot	N.A.
10	1.5	>10 foot	10 foot	10 foot	2 foot
10	2.0	>10 foot	10 foot	10 foot	5 foot
30	.1	2 foot	N.A.	N.A.	N.A.
30	.5	10 foot	2 foot	N.A.	N.A.
30	1.0	10 foot	5 foot	10 foot	N.A.
30	1.5	>10 foot	10 foot	10 foot	2 foot
30	2.0	>10 foot	10 foot	10 foot	5 foot

[1] Denotes maximum survey contour interval to produce desired accuracy.
[2] Emean is mean absolute reach error.

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The error prediction equations may be used to determine the mapping required to achieve a desired computed profile accuracy. Table 6.7 is an example for selected stream slopes and Nr values of 0 and 1.0, and for a hydraulic depth of 5 feet. The table shows that a 10 foot contour interval for aerial spot elevations is sufficient except for mean profile errors of less than .1 feet for steep streams. Similar tables for other conditions may be developed from the nomographs or equations .

UPSTREAM AND DOWNSTREAM STUDY LIMITS

Establishment of the upstream and downstream study boundaries for profile calculations are required to define limits of data collection and subsequent analysis. Calculations must be initiated sufficiently far downstream to assure accurate results at the structure, and continued sufficiently upstream to accurately determine the impact of the structure on upstream water surface profiles. Underestimation of the upstream and downstream study lengths may produce less than desired accuracy of results and eventually require additional survey data at higher costs than could be obtained with initial surveys. On the other hand, significant over-estimation of the required study length can result in greater survey, data processing, and analysis costs than necessary.

The downstream study length is governed by the effect of errors in the starting water surface elevation on the computed water surface elevations at the structure (see Figure 7.1). When possible, the analysis should start at a location where there is either a known (historically recorded) water surface elevation or a downstream control where the profile passes through critical depth. Observed downstream high water marks are relatively common for calibration of models to historical events, but are unlikely to be available for evaluations of hypothetical events such as the 1-percent chance event. Alternative starting elevations are needed for stream conditions where high water marks and control locations are nonexistent or are too far downstream to be applicable. Two commonly applied starting criteria are critical depth and normal depth. The starting location should be far enough downstream so that the computed profile converges to the base (existing condition) profile prior to the bridge location.

The upstream study length is the distance to where the profile resulting from a structure-created headloss converges with the profile for the undisturbed condition. The magnitude of profile change and the upstream extent of the structure-induced disturbance are two of the primary criteria used to evaluate the impacts of modified or new structures.

Regression analyses were performed to develop prediction equations for determining study limits. HEC-2 base data sets were run for a variety of starting conditions and structure headloss values. The results were then used in the regression analysis. The resulting equations and associated nomographs provide the capability for determining the extent of required survey and mapping and other hydraulic parameter data collection.

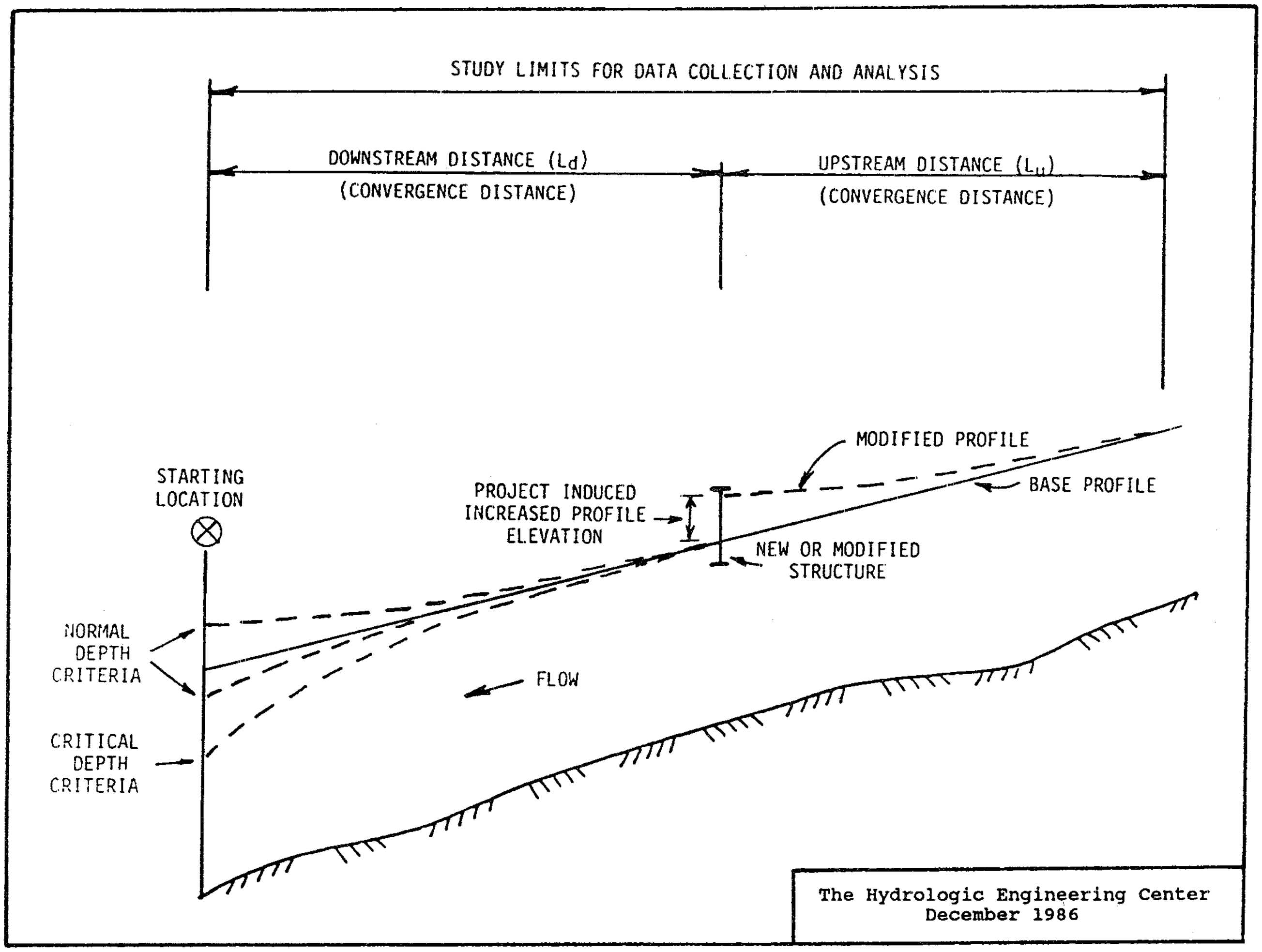


FIGURE 7.1 Profile Study Limits

The adopted regression equations are:

$Ldc = 6600*HD/S$ (Equation 7.1)

$Ldn = 8000*HD^{.8}/S$ (Equation 7.2)

$Lu = 10,000*HD^{.6}*HL^{.5}/S$ (Equation 7.3)

where: Ldc = downstream study length (along main channel) in feet for critical depth starting conditions,
Ldn = downstream study length (along main channel) in feet for normal depth starting conditions,
HD = average reach hydraulic depth (1-percent chance flow area divided by cross section top width) in feet,
S = average reach slope in feet per mile, and

HL = headloss between .5 and 5.0 feet at the channel crossing structure for the 1-percent chance flow.

The equations were converted to nomographs to present the results in a convenient form. Figures 7.4 and 7.5 are the nomographs for downstream normal depth starting conditions and upstream reach length, respectively.

The goodness-of-fit of the regression equations can be expressed using the coefficient of determination and the standard error of regression. The coefficients of determination for equations 7.1, 7.2, and 7.3 are .89, .83, and .90 respectively. The standard errors of regression for the three equations are 0.26, 0.22, and 0.18 (in log units), respectively.

SUMMARY AND CONCLUSIONS

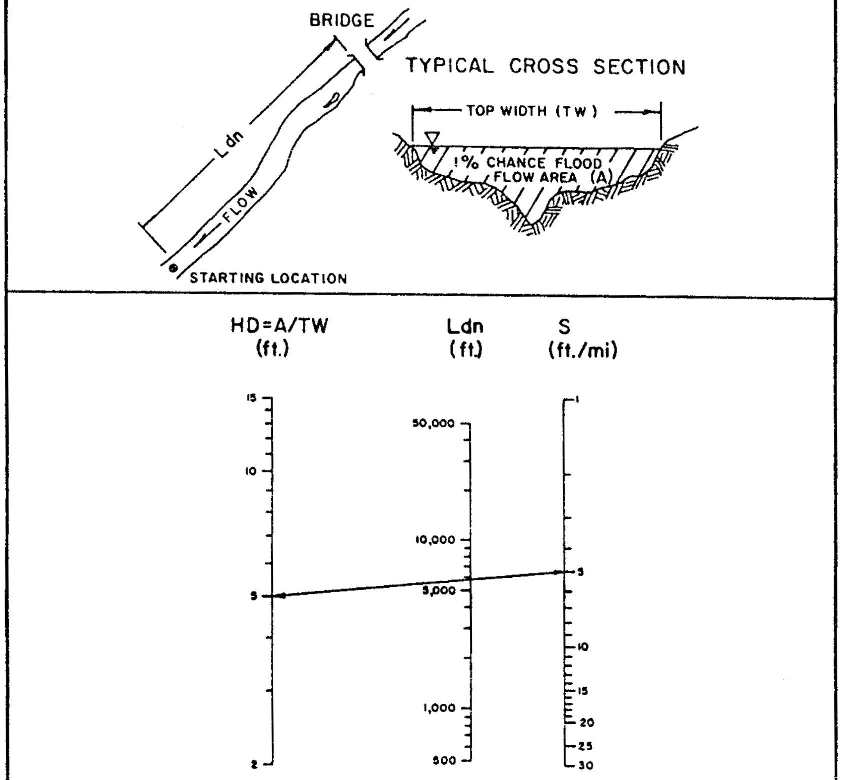
Aerial Survey and Topographic Map Accuracy. Stream cross-sectional geometry obtained from aerial surveys (aerial spot elevations and topographic maps) that conform to mapping industry standards are more accurate than is often recognized. Cross-sectional geometry obtained from the aerial spot elevation surveys is about twice as accurate as cross-sectional geometry obtained from topographic maps derived from aerial surveys for the same contour interval.

Profile Accuracy Prediction. The effect of aerial spot elevation survey or topographic mapping accuracy on the accuracy of computed water surface profiles can be predicted using the mapping industry accuracy standards, reliability of Mannings's coefficient, and stream hydraulic variables.

Manning's Coefficient Estimates. The reliability of the estimation of Manning's coefficient has a major impact on the accuracy of the computed water surface profile. Significant effort should be devoted to determining appropriate Manning's coefficients.

Additional Calculation Steps. Significant computational errors can result from using cross-sectional spacings that are often considered to be adequate. The errors are due to inaccurate integration of the energy loss-distance relationship that is the basis for profile computations. This error can be effectively eliminated by adding interpolated cross sections (more calculation steps) between surveyed sections.

Aerial Survey Procedures. Aerial spot elevation survey methods are generally more cost effective than field surveys when more than 15 survey cross sections are required. Use of aerial spot elevation survey technology permits additional coordinate points and cross sections to be obtained at small incremental cost. The coordinate points may be formatted for direct input to commonly used water surface profile computation computer programs.



Ldn = $8000 * HD^{.8}/S$ (Equation 7.2)

Where:

Ldn = Downstream study length – normal depth starting condition

HD = Average reach hydraulic depth (1-percent chance flow)

S = Average reach slope

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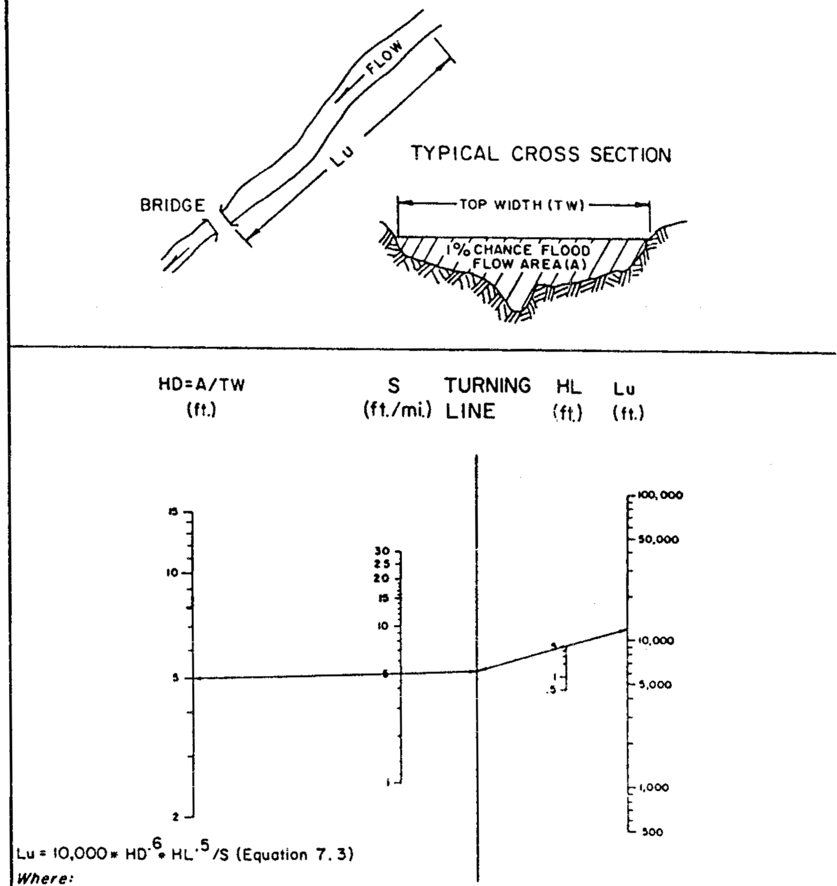
FIGURE 7.4 Downstream Reach Length Estimation - Normal Depth Criterion



Lu = $10{,}000 * HD^{.6} * HL^{.5}/S$ (Equation 7.3)

Where:

Lu = Upstream study length

HD = Average reach hydraulic depth (1-percent chance flow)

S = Average reach slope

HL = Headloss at the channel crossing structure for the 1-percent chance flow

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FIGURE 7.5 Upstream Reach Length Estimation

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