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TECHNICAL REPORT
EP-114

PREDICTIVE METHODS IN TOPOGRAPHIC ANALYSIS
II. ESTIMATING RELIEF FROM WORLD AERONAUTICAL CHARTS

QUARTERMASTER RESEARCH & ENGINEERING CENTER
ENVIRONMENTAL PROTECTION RESEARCH DIVISION

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NATICK, MASSACHUSETTS

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PREDICTIVE METHODS IN TOPOGRAPHIC ANALYSIS

II. ESTIMATING RELIEF FROM WORLD AERONAUTICAL CHARTS

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The largest-scale map series which supplies world coverage is World Aeronautical Chart (scale 1:1,000,000). Estimates of relief h been made from these maps, and the accuracy of these estimates valid by comparing them with actual relief values read from 1:50,000- and 1:62,500-scale maps. It was thus demonstrated that this study has p duced a method for obtaining accurate estimates of relief from the 1:1,000,000 maps.

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ABSTRACT

A method ~~has been~~ developed for obtaining an estimate of relief of an area from the World Aeronautical Charts (WAC) (scale 1:1,000,000). This method consists of determining ~~a~~ values for the lowest elevation and ~~a value for~~ the highest elevation of an area; relief of the area is the difference between these two values. ~~The~~ technique for determining lowest elevations is based on an assumed geometric progression of elevations along a stream; the technique for determining highest elevations depends on an arithmetic progression of elevations on a land surface.

The accuracy of these methods was tested on 197 areas (each 160 ± mi) ~~160~~-square-mile ~~areas~~ in the United States. Correlation of relief values at a scale of 1:1,000,000 with values for the same areas at a scale of 1:62,500 resulted in a coefficient of correlation of .9952. For the most part, relief from the 1:1,000,000-scale maps was within 200 feet of error. A series of regression equations ~~has been~~ devised which can be applied to improve these estimated values.

Since ~~Since it has~~ been demonstrated that, it is possible to obtain a realistic relief figure from the World ~~Aeronautical Charts~~, rather serious limitations to quantitative terrain analysis, imposed by inadequate map coverage, can be overcome.

PREDICTIVE METHODS IN TOPOGRAPHIC ANALYSIS:
II. ESTIMATING RELIEF FROM WORLD AERONAUTICAL CHARTS

1. Introduction

The first report of this series(3) described, quantitatively, the relationship of six geomorphic factors and included many regression equations for predicting one particular dimension of terrain from knowledge of other dimensions. The entire analysis was based on measurements taken from 200 U.S. topographic maps at scales of 1:50,000 or 1:62,500. Because the amount of detail shown on a map varies with different scales, the equations presented in the previous report have applicability only to maps of the scales cited. However, such maps are not available for many areas of the world.

The largest-scale map series having world coverage is the 1:1,000,000 World Aeronautical Chart (referred to hereafter as the WAC) produced by the U.S. Air Force Chart and Information Center. This is, therefore, the "minimum" map for any part of the world.* Although these charts have only a 1,000-foot contour interval, they are an important source of terrain data, a fact which perhaps even their producers do not fully realize. A good aeronautical chart must accurately reproduce, within the limits of the scale, such easily recognizable features as stream patterns. Also, surface elevations of many water bodies, heights of mountain peaks, and numerous elevations of prominent landmarks, airstrips, and towns will be indicated. Drawing upon all of this information, it is possible to make estimates of relief from the WAC which, for most practical purposes, may be considered as identical to relief data obtained from an inch-to-the-mile map.

This report will describe procedures and techniques that can be used to estimate relief of 160-square-mile areas when the only data source is a WAC chart. With this information, the equations presented in the first report(3) for using relief on 160-square-mile areas to predict relief, average slope, and slope direction changes of smaller areas, will have world-wide application. Methods have been developed for extracting information from the WAC which was previously thought to be available only on maps of a much larger scale. Thus a beginning has been made toward overcoming the limitations imposed by inadequate map coverage.

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* WAC coverage for Alaska and the United States is actually published by the U.S. Coast and Geodetic Survey but is distributed by the U.S. Air Force Chart and Information Center.

2. Procedure for obtaining an estimate of relief from the WAC

Relief is the difference between the highest and lowest elevations within a unit area. Therefore, the problem of estimating relief of an area becomes one of estimating realistic figures for the highest and lowest points within the area. A first glance at a WAC chart would give the impression that this is not feasible, except perhaps for areas of 1000 square miles or more. However, experiments with 197 sample areas in the United States resulted in a series of techniques for estimating both a lowest elevation and a highest elevation within a 160-square-mile area (delimited by a circle with a diameter of 0.9 inche) from the WAC charts. These methods are discussed below.

a. Lowest elevations

It is reasonable to assume that the lowest elevation of an area will be found along a stream, except in areas of interior drainage where it will be in the center of a basin. Hydrologists, working in relatively small areas, have found that the gradients of streams generally decrease geometrically with progress from origin to mouth.(1) Thus, if the elevations along a stream channel are plotted on a logarithmic Y axis and distance from source is plotted on an arithmetic X axis, the path of dots makes a relatively straight line.* The techniques for determining lowest elevations on the WAC are based on the geometric progression of stream elevations. Low elevations for 154 of the samples studied were determined in the following manner.

Method 1

TO FIND A VALUE FOR THE LOWEST ELEVATION OF AN AREA WHEN A STREAM CROSSES THE AREA BETWEEN TWO POINTS OF KNOWN ELEVATIONS (Fig. 1)

1. Locate the lowest elevations within the area, which is assumed to be where the boundary of the sample crosses the stream on the downstream edge. (If more than one stream crosses the area, choose the one which appears to be carrying the most water.)

2. With dividers set at a standard interval (5 miles was found to be adequate), measure the stream between the two contours flanking the low spot. Also, note the

---

* To test this assumption, estimates were made of elevations along 25 widely different streams. The correlation of the estimated and actual elevations yielded a coefficient of correlation of 0.9936.

distance between the lowest contour and the lowest point of the sample.

WITH SEMI-LOG PAPER:	or	WITH SLIDE RULE OR LOG TABLES:
3. Plot the distance between contours at their proper elevations. (Distance on the arithmetic X axis and elevations on the logarithmic Y axis.) Connect the two points with a straight line.		3. Subtract the logarithm of the lower contour from the logarithm of of the higher.
4. Locate the position of the sample low point on this line and read the elevation of this point on the scale.		4. Multiply the remainder, obtained in 3 above, by a fraction whose numerator is the distance from the lower-numbered contour to the lowest point in the sample and whose denominator is the total distance between contours.
		5. Add the product to the logarithm of the lower-numbered contour. This sum will be the antilogarithm of the estimated low elevations for the sample.

The remaining 43 samples did not contain a stream which extended to points of known elevation. These samples were from regions of interior drainage or the coastal plain. It was impossible to use Method 1 to determine the lowest elevation for these cases, so another method was developed. Method 2 is the most impartial of all methods tried for obtaining an estimate; however, the results are not as accurate as those produced by Method 1.

Method 2

TO FIND A VALUE FOR THE LOWEST ELEVATION OF AN AREA WHEN A STREAM DOES NOT CROSS THE AREA BETWEEN TWO POINTS OF KNOWN ELEVATIONS (Fig. 2)

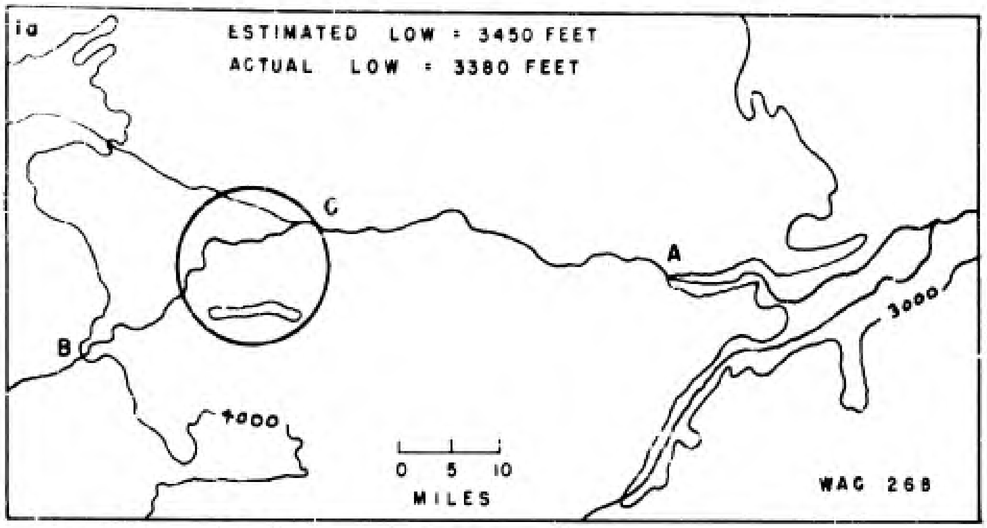
1. Establish limits within which the lowest elevation must occur. (That is, for each case, it is possible to say that the lowest elevation will be higher than one figure and lower than another.) The narrower these limits are, the better the results will be. The following are possible situations for which limits can be established:
    a. The contour interval may be the only indication of the limits (Fig. 2a)
    b. A stream, along which elevations can be determined, may lie a few miles outside the area (Fig. 2b).
    c. A high elevation in or near the sample may be known (Fig. 2c).
    d. A short stream may drain into a lake whose surface elevation is marked (Fig. 2d).

WITH SEMI-LOG PAPER:	or	WITH SLIDE RULE OR LOG TABLES:
2. Plot the high and low limit at any assumed distance apart (Figure 2e).		2. $\frac{\log H + \log L}{2} = \log E$; where log H is the logarithm of the upper limit of the lowest elevation in the sample, log L is the logarithm of the lower limit, and log E is the logarithm of the estimated lowest elevation.
3. At half this distance, read a value for elevation on the scale.		3. For cases where the lowest limit is zero, take 0.4 of the highest limit.* For example, Figure 2a: Highest limit = 1000 feet x .4

Estimated lowest elevation = 400.0 feet

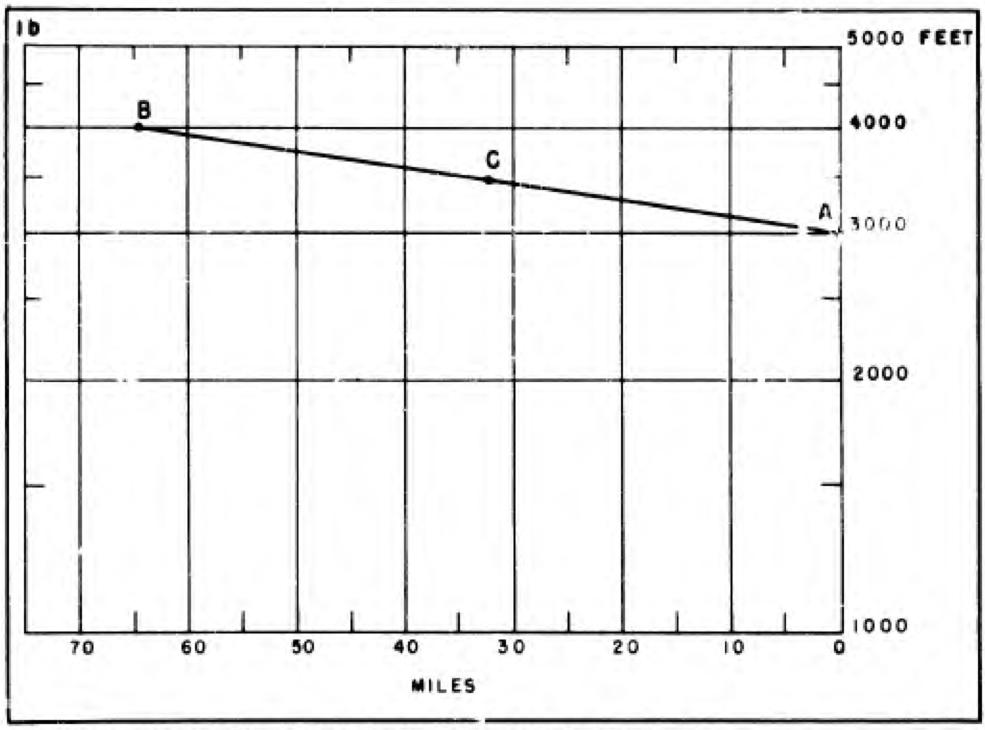
---

* Since a zero quantity cannot be placed on the logarithmic scale, it would be impossible to use the log technique described above to make estimates for cases where the lowest limit is zero. Therefore, it was necessary to decide what value would most closely approximate a value for elevation at half the distance between two points were one able to reach zero on the log scale; 0.4 of the highest limit was found to satisfy this.



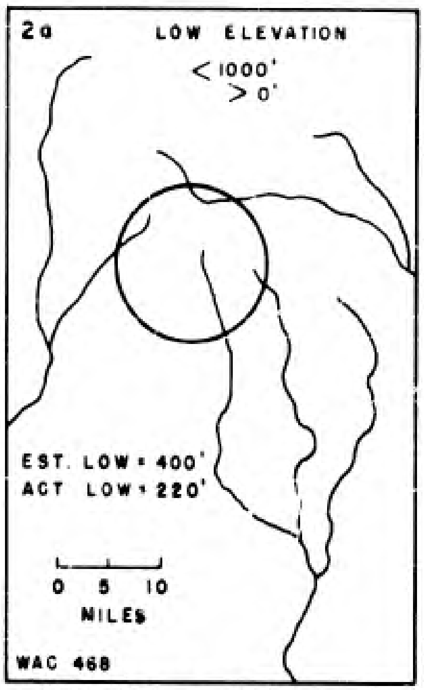
C = lowest elevation

A - C = 33 miles A - B = 65 miles

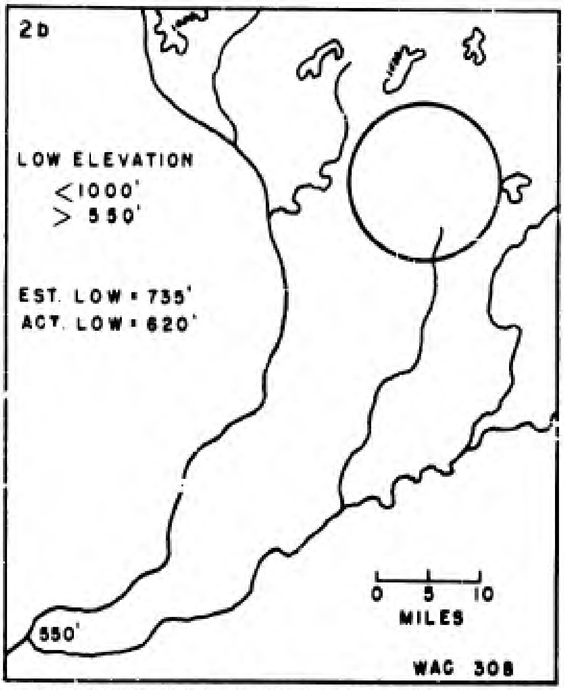


STREAM DISTANCES PLOTTED ON SEMI-LOG GRAPH PAPER

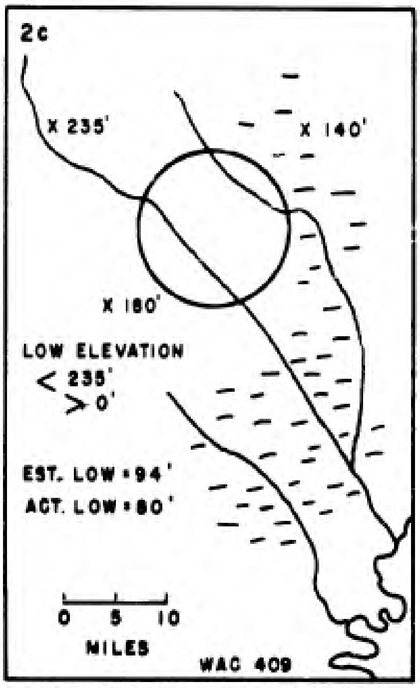
Fig. 1 The lowest elevation of an area (C) may be found on a stream crossing the area between two points of known elevation (A & B).



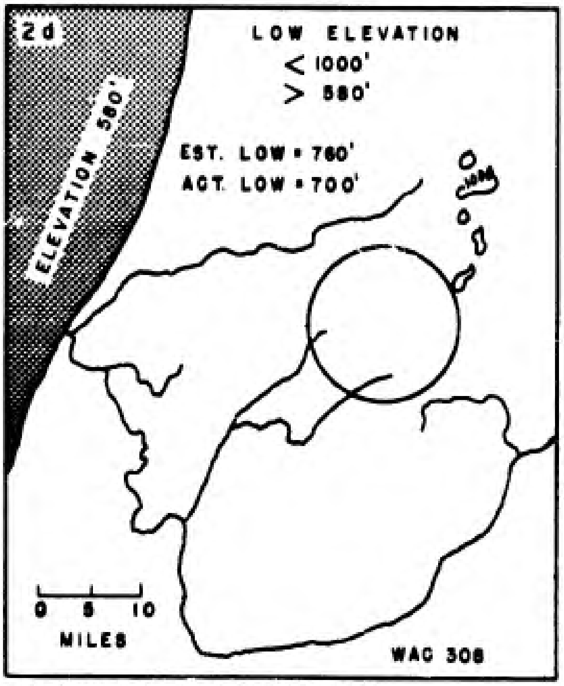
LIMITS SET BY CONTOUR INTERVAL



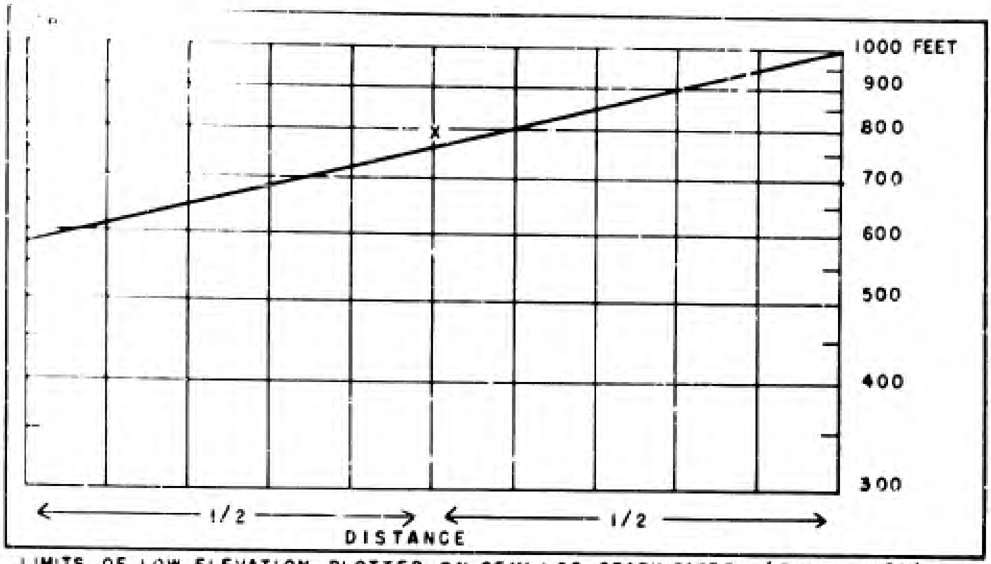
ELEVATION OF STREAM OUTSIDE AREA KNOWN



HIGH ELEVATION KNOWN



ELEVATION OF LAKE KNOWN



LIMITS OF LOW ELEVATION PLOTTED ON SEMI-LOG GRAPH PAPER (EXAMPLE: 2b)

Fig. 2: Reliable estimates of low elevations may be determined by setting limits within which the elevation must occur. Fig. 2a-2d indicate possible means of establishing these limits.

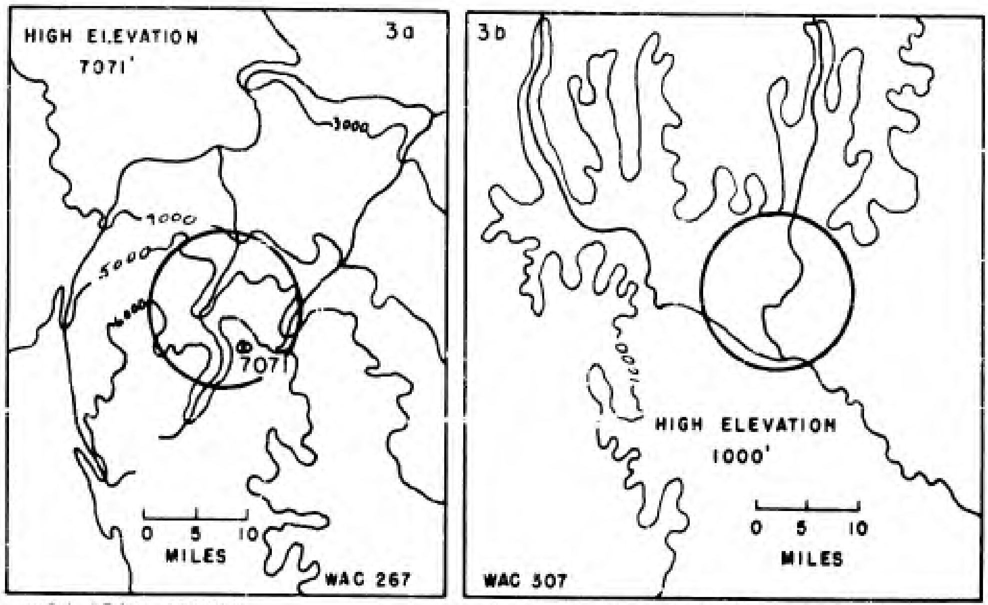
b. Highest elevation

To obtain a value for the highest elevations, no difficulty was encountered when a peak within the area was marked, or the boundary of the area touched a contour line. Of the total sample, highest elevations for 69 cases were determined in this manner (Method 1).

Method 1

A HIGHEST ELEVATION MAY OFTEN BE READ DIRECTLY FROM THE MAP (Fig. 3)

When a high elevation could not be read directly from the map, the value was estimated by one of two methods. The most accurate measurements were produced by "approximation", a method which requires a particular topographic arrangement. Here, an elevation for a point lying between two known elevations (usually contour lines) was determined by arithmetic progression. This method is limited to those locations where it would be possible to walk directly up-slope or down-slope to a contour line without crossing a stream. In all, 28 cases were treated in this manner (Method 2), with results comparable to those cases where a value for highest elevation could be read directly from the map.



HIGH PEAK MARKED

SAMPLE EDGE TOUCHES CONTOUR

Fig. 3: A value for high elevation may be read directly from the map.

Method 2

TO "APPROXIMATE" A HIGHEST ELEVATION (Fig. 4)

1. Inspect the area to decide where the highest point logically ought to be. This is assumed to be where two contour lines bracket the sample and come closest to each other.

2. Draw a straight line, without crossing a stream, to connect the two contour lines at the points where the two lines come closest together.

3. Divide the straight line into equal units of measure to serve as a scale of elevations.

4. From this scale, read a value for the elevation of the highest point within the sample.

In 100 cases, no known high elevation fell within the sample area, nor could a realistic approximation be made by linear interpolation.

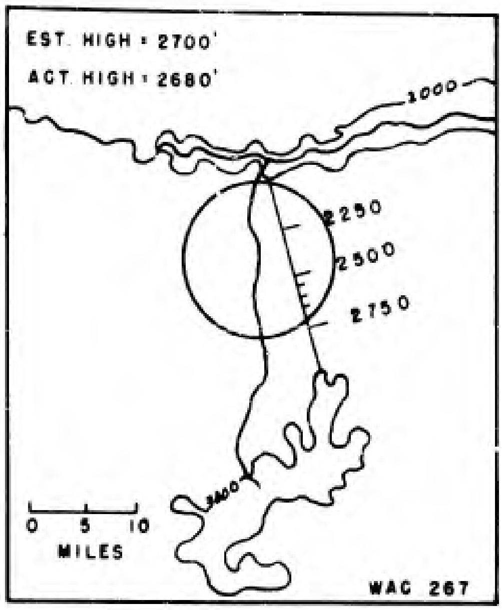


Fig. 4: A high elevation may be approximated by an arithmetic progression of elevation between two points of known elevation.

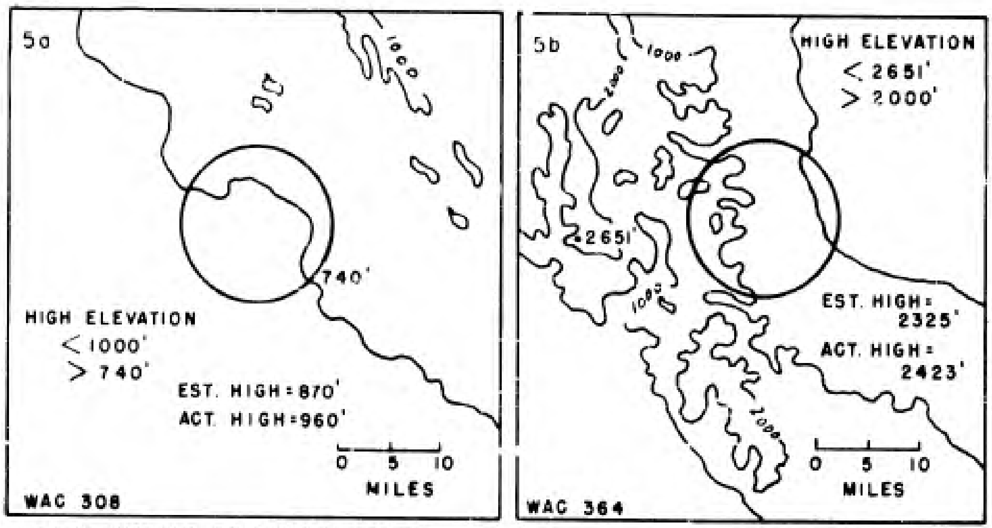
Therefore, these cases were treated in a manner similar to those where no reliable estimate could be made for lowest elevation; that is, limits were established within which the high point of the sample must occur. Again, the narrower the limits, the more reliable the estimate. Like the similarly estimated lowest elevation, values for highest elevations obtained in this manner were not as accurate as those obtained by Methods 1 and 2.

Method 3

TO ESTABLISH A HIGHEST ELEVATION WHEN NO KNOWN ELEVATION IS AVAILABLE, OR WHEN APPROXIMATION IS NOT POSSIBLE (Fig. 5)

1. Establish limits of elevation within which the highest point must occur. (The lower limit might be the lowest elevation for the sample, or a contour line. The upper limit might be another contour line or a spot elevation lying in close proximity to the sample - within a radius of about 50 miles.)

2. Estimate the highest elevation by taking the average of these limits.
   For example, Fig. 5a: Highest limit = 1000 feet
   Lowest limit = 740 feet
   2/1740 feet
   Estimated highest elevation = 870 feet



LOW ELEVATION OF SAMPLE KNOWN

HIGH ELEVATION OUTSIDE SAMPLE KNOWN

Fig. 5: Reliable estimates of a high elevation may be determined by setting limits within which the high elevation must occur.

c. Relief

A highest and lowest elevation having been estimated from each sample, the relief was computed by subtracting the lowest from the highest. In this way an estimate of relief on 160 square miles at a scale of 1:1,000,000 (WAC) was made for 197 areas of the United States. The estimated relief values compared favorably with the actual relief values, previously computed from the 1:62,500 series, for the same areas.*

3. Evaluation of relief estimates

a. Improving the estimate by regression equations

The data pertaining to the statistical comparison of estimated and actual relief values for the 197 cases are given in Table I. Although the estimates of relief from the 1:1,000,000 series agreed well with the actual relief figures, these estimates may be improved by the following equation:

$$T = 100 + .9938\ X$$

---

* In general, the estimates were lower than the actual values and within 200 feet of error. The coefficient of correlation of estimated and actual values is .9952.

where T equals the revised estimate of relief and X equals the estimate of relief obtained by the methods described above for determining highest and lowest elevations.

TABLE I

Statistical Data for Total Sample

N	(Number of cases)	197
MY	(Mean Relief 1:62,500)	1356 feet
MX	(Mean Relief 1:1,000,000)	1264 feet
SDY	(Standard Deviation 1:62,500)	1531 feet
SDX	(Standard Deviation 1:1,000,000)	1533 feet
r	(Coefficient of correlation)	.9952
r^2	(Percentage of variance accounted for)	.9904
S	(Standard error of the estimate)	150 feet

Regression Equation $T = 100 + .9938X$

However, by treating all samples as one population, important variations among the estimated relief values are obscured. The estimates for highest and lowest elevations were necessarily made with varying degrees of reliability due to limitations of the WAC. Therefore, it is not realistic to treat a sample taken from an area where high elevations are marked, in the same manner as other samples where the highest and lowest elevations must be specified only as lying between rather broad limits. To refine the process of predicting relief and to reduce the margin of error as much as possible, the sample was divided into five groups. These groups were arranged according to the degree of certainty at which a relief figure could be estimated.

GROUP	NUMBER OF CASES	DEGREE OF CERTAINTY AT WHICH ELEVATION OBTAINED Lowest Elevation	Highest Elevation
I	62	Most certain (Method 1)	Most certain (Method 1)
II	26	Most certain (Method 1)	Approximated (Method 2)
III	66	Most certain (Method 1)	Least certain (Method 3)
IV	9	Least certain (Method 2)	Most certain (Method 1)
V	34	Least certain (Method 2)	Least certain (Method 3)

Table II gives the statistical data and equations for each of these groups.

TABLE II

Statistical Data for Five Groups of Cases

	GROUP I	GROUP II	GROUP III	GROUP IV	GROUP V
High Elevation:	Most Certain	Approximated	Least Certain	Most Certain	Least Certain
Low Elevation:	Most Certain	Most Certain	Most Certain	Least Certain	Least Certain
N	62	26	66	9	34
MY	2241 ft	929 ft	1283 ft	1030 ft	293 ft
MX	2152 ft	814 ft	1195 ft	860 ft	229 ft
SDY	1767 ft	1233 ft	1376 ft	1026 ft	211 ft
SDX	1800 ft	1250 ft	1342 ft	954 ft	262 ft
r	.9984	.9967	.9919	.9846	.7482
r^2	.9968	.9934	.9839	.9694	.5598
S	100 ft	100 ft	175 ft	179 ft	140 ft
Regression Equation	T=132+.9799X	T=129+.9828X	T=67+1.0173X	T=119+1.059X	T=155+.6029X
S/MY	.045	.108	.136	.139	.478

Analysis of these data reveals that:

1. If a high elevation is approximated (Method 2), the results are as good as if read directly from the map.

2. Where both factors are least certain (Group V), the estimates are the least reliable and the regression equation most different from the others.

3. Groups III and IV, where one or the other of the factors is least certain, exhibit a great deal of similarity.

4. There were too few samples in Group IV to yield a reliable regression equation.

5. The most accurate measurements can be made in mountainous areas at higher elevations where streams are short, contour lines are more frequent and closer spaced, and more elevations are marked.

6. In relative terms, the least accurate measurements are from areas of low elevation, particularly those lying below 1000 feet.

On the basis of this analysis, the data were arranged into three groups according to the similarity of prediction equations and three new equations devised. Table III presents the pertinent data and equations for these three groups.

TABLE III

Statistical Data for Three Groups of Cases

	GROUP A* (Groups I & II)	GROUP B** (Groups III & IV)	GROUP C*** (Group V)
N	88	75	34
MY	1854 ft	1253 ft	293 ft
MX	1757 ft	1155 ft	229 ft
SDY	1734 ft	1342 ft	211 ft
SDX	1765 ft	1306 ft	262 ft
r	.9981	.9912	.7482
r^2	.9962	.9825	.5598
S	107 ft	178 ft	140 ft
Regression Equation	T=131+.9804X	T=77+1.0181X	T=155+.6029X
S/MY	.058	.142	.478

* Group A--Both high and low elevations most certain

** Group B--Either high or low elevations most certain; other factor least certain

*** Group C--Both high and low elevation least certain

Group A - Groups I and II combined. A low elevation can be obtained for all cases with certainty and a highest elevation can be read directly from the map or estimated by approximation. Table II has indicated that estimates of highest elevation by approximation are as good as values read directly. (88 cases)

Group B - Groups III and IV combined. In both instances only one factor has been estimated with certainty. Reliable prediction methods should not be based on a sample size of 9, so Group IV must be combined with some other group. Group III exhibits the most similarity to Group IV. (75 cases)

Group C - Group V was treated separately. Both factors are least certain, correlation is not high and the resulting equation shows considerably different characteristics than those of the other four groups. (34 cases)

b. Distribution of errors

The best estimates of relief, based on information from the WAC, will be made by using any of the equations presented in Table III which are appropriate for individual cases. The overall standard error of estimate (not corrected for sampling) to be expected when these equations are used is 140 feet. This figure was readily computed by obtaining the sums of the products (NS) for the three equations (Groups A, B, and C) and dividing by N:

$$\frac{(88 \times 107) + (75 \times 178) + (34 \times 140)}{197} = 140$$

The figure 140 is an overall improvement of only 10 feet over the standard error of estimate of that produced by the single equation (Table I). However, most of this improvement comes in the 34 cases of Group C, those cases where estimates of both highest and lowest elevations are least certain. The tabulation of errors is shown in Table IV and the distribution curve of actual errors, along with what would be a normal distribution curve for these cases, is represented in Figure 6. It will be seen that the actual distribution curve is skewed slightly to the right, but does not depart radically from the normal curve.

c. Special considerations

(1) Non-representative samples

The 197 cases cited in this report are contained within the 204-case sample orginally drawn for terrain study.(2) Seven of these original cases were eliminated because the topographic representation on the WAC was widely different from that indicated on the large-scale maps. Thus, relief figures for these cases were thought to be non-representative and too divergent from the actual relief to warrant their inclusion in the development of regression equations. However, the actual performance of the regression equations with these samples does show improvement of estimate (Table V). The fact that all seven of these cases are from areas of high relief, steep valleys, and crystalline bedrock suggests that a multiple regression equation incorporating independent variables other than relief might be developed for such special cases.

TABLE IV

Distribution of Errors*

(197 cases)

Error (In ft. Under Estimates)	No. of Cases	Cumulative No. of Cases	Error (In ft. Over Estimates)	No. of Cases	Cumulative No. of Cases
451-475	1	1	1- 25	14	105
426-450	1	2	26- 50	18	91
401-425	0	2	51- 75	17	73
376-400	1	3	76-100	10	56
351-375	2	5	101-125	13	46
326-350	0	5	126-150	6	33
301-325	1	6	151-175	6	27
276-300	1	7	176-200	8	21
251-275	2	9	201-225	2	13
226-250	3	12	226-250	3	11
201-225	3	15	251-275	1	8
176-200	8	23	276-300	1	7
151-175	3	26	301-325	0	6
126-150	3	29	326-350	1	6
101-125	6	35	351-375	0	5
76-100	8	43	376-400	1	5
51- 75	15	58	401-425	2	4
26- 50	11	69	426-450	0	2
1- 25	22	91	451-475	0	2
0	1	92	476-500	0	2
			501-525	0	2
			526-550	0	2
			551-575	0	2
			576-600	1	2
			601-625	1	1

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* See Figure 6

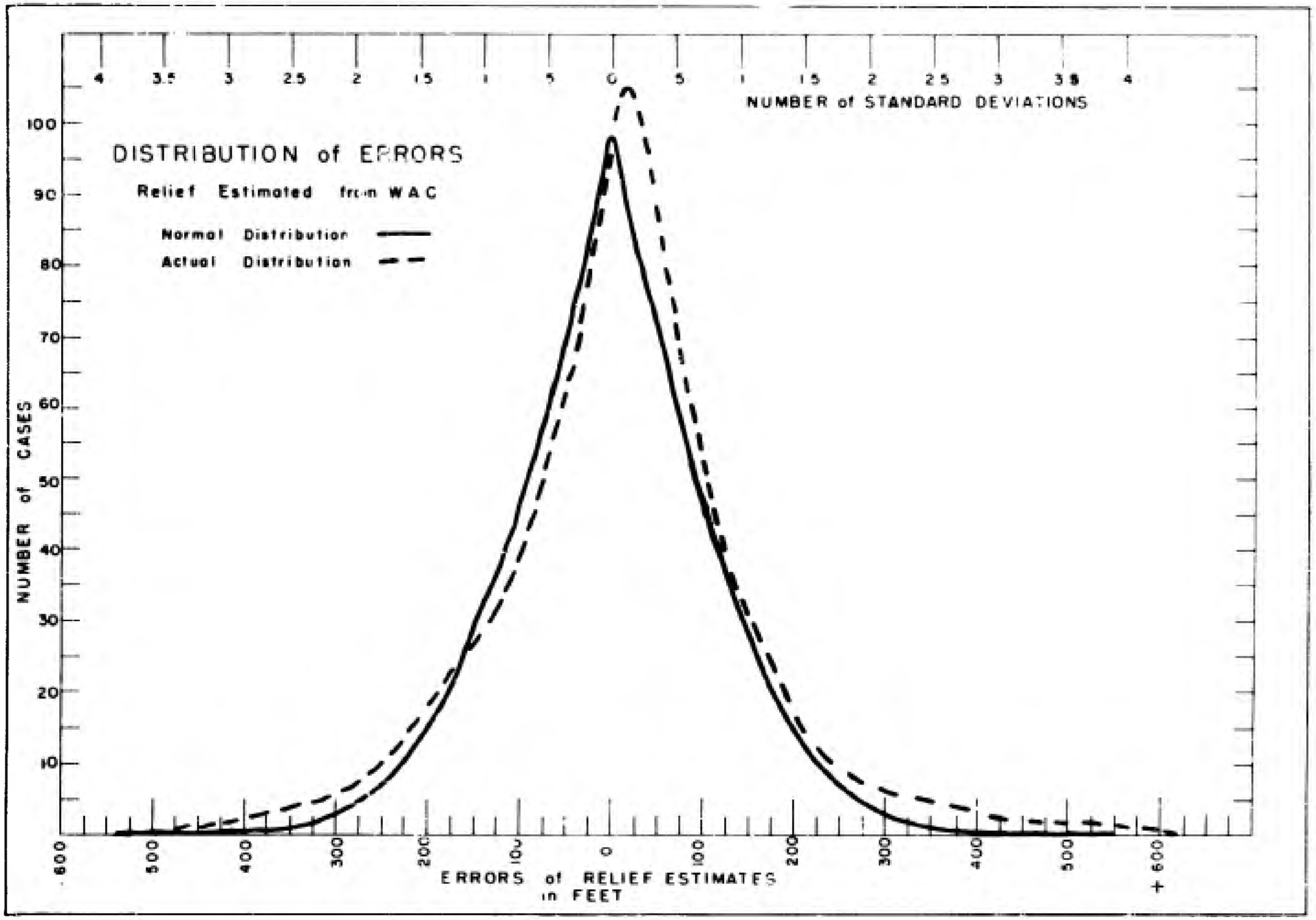

Fig. 6 Distribution of errors for relief values estimated from WAC, 197 cases.

TABLE V

Relief Data for Seven Samples not used in Development of Regression Equations

Sample Location	Highest Elevation (ft)		Lowest Elevation (ft)		Relief (ft)		Error (ft)	Regression Equation*	Relief (ft)	Error (ft)
	Actual (1:62,500)	Estimate (WAC)	Actual (1:62,500)	Estimate (WAC)	Actual (1:62,500)	Estimate (WAC)				
1. 37°52'30"N 120°7'30"W	5835	5500	850	1180	4980	4320	-560	B	4475	-505
2. 37°52'30"N 107°52'30"W	14250	14250	7900	8100	6350	6150	-200	A	6160	-190
3. 35°7'30"N 81°52'30"W	5837	5964	2150	2800	3687	3164	-523	A	3233	-454
4. 44°7'30"N 117°7'30"W	3447	4500	2200	2190	1227	2310	+1083	B	2429	+1202
5. 40°7'30"N 113°52'30"W	8465	7800	4500	4490	3965	3310	-665	B	3447	-518
6. 44°52'30"N 109°7'30"W	5675	7500	4020	4030	1655	3470	+1815	B	3610	+1955
7. 43°52'30"N 108°7'30"W	5500	5000	4100	4080	1400	920	-480	A	1033	-367

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* See Table III

(2) Areas smaller than 160 square miles

It would be desirable if relief on areas smaller than 160 square miles could also be estimated from the WAC with a high degree of certainty. Undoubtedly good to fair relief estimates could be made for smaller areas in regions of high relief (Tables II and III). However, good estimates are not obtained in areas of low relief (Table III, Group C); as successively smaller-sized areas are studied, relief values become lower. The result would be a rapidly increasing number of cases in the class for which good estimates cannot be made. Under the circumstances, it would be better to obtain a reliable estimate for the 160-square-mile area and to use this as the independent variable for predicting relief on smaller areas, as has been previously demonstrated.(3)

(3) World-wide applicability

The data, from which the foregoing techniques and equations were derived, are all from the United States, but these methods should have applicability in any part of the world. Accuracy of prediction would be limited only by the accuracy of the WAC. This should be evident since relief is merely a combination of geometric properties produced through the operation of physical processes shaping the physical earth.

(4) Individual map interpretation

The techniques which have been developed for estimating relief from the WAC are completely objective in approach, simple enough for quick measurements and uncomplicated, so that a minimum skill in map reading and arithmetic is all that is required to use them. However, there is no reason why a person with considerable map reading ability and knowledge of terrain could not use his own ingenuity to determine relief values from the WAC. Should a person wish to do this, a regression equation should not be employed. As a word of caution, it must be remembered that the prediction equations, together with the methods for estimating highest and lowest elevations, account for more than 99% of the variation among samples (Tables I, II, and III). Thus one should be confident of his powers of map interpretation before substituting any qualitative judgements.

4. Conclusion

Lack of maps at topographic scale need not limit the application of predictive terrain formulae which have been determined at detailed scales. It has now been shown that relief values estimated for 160-square-mile samples from the 1:1,000,000 WAC can be processed by a regression equation to increase their accuracy. These improved values can be used in terrain formulae developed in a previous study.(3)

5. References

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