CDOH-UCD-R-88-5

DEVELOPMENT OF A RISK COST METHODOLOGY FOR DETOUR CULVERT DESIGN

By

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in cooperation with
the Colorado Department of Highways
Denver, Colorado

in Fulfilment of
the Research Contract
Number 1503A Type B

December, 1987

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CDOH-UCD-R-88-5		

4. Title and Subtitle Development of a Risk-Cost Methodology for Detour Culvert Design	5. Report Date January, 1988
	6. Performing Organization Code 1503A
7. Author(s) Guo, James C. Y., PhD., P.E.	8. Performing Organization Report No. CDOH-UCD-R-88-5
9. Performing Organization Name and Address University of Colorado at Denver 1100 Fourteenth Street Denver, CO 80202	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. 1503A
12. Sponsoring Agency Name and Address Colorado Department of Highways 4201 East Arkansas Avenue Denver, CO 80222	13. Type of Report and Period Covered Final
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with FHWA, U. S. Department of Transportation

16. Abstract

A detour drainage structure is a temporary structure serving for several months. Many existing design guidelines are not applicable to determining the design capacity of a detour drain. In this study, a risk-cost methodology has been developed to assist the engineer in making decisions.

A non-dimensional linear cost-capacity function has been established through an extensive cost data analysis on concrete box culverts and corrugated metal pipes. It is found that the cost-capacity coefficient varies within a narrow range between 0.3 to 0.5. The method developed in this study also allows engineers to adjust their decisions with the different damage-cost ratios, depending upon the local situations. This capability further allows the engineer to take more factors into account in a decision-making process.

Implementation

The design models and methodologies described should be incorporated into the detour drainage design process.

17. Key Words	18. Distribution Statement
Drainage, Flood, Damage, Runoff	No restrictions: This report is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72)

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I. OBJECTIVE AND SCOPE

Any permanent hydraulic drainage structure such as a bridge or culvert requires a construction time of several months or even longer. During the construction, detour drainage facilities need to maintain the continuity of traffic flows and runoff flows. From the design point of view, the larger design flood used, the lower the risk of failure. In general, the design flood for a temporary detour structure should be less than that of a permanent structure. Engineers tasked with the design of detour structure must make the decision on the selection of design flood and, at the same time, keep the cost of this temporary structure economical.

In the assessment of risk cost involved in a drainage structure design, engineers have to look into the potential loss of life, property replacement, and the roadway service in terms of traffic delay (22). Most highway design manuals set forth the criteria for the selection of design flood frequency based upon the use and the importance of the highway under design. For instance, a 100-year flood is used for an urban freeway design while a 25-year flood is used for a 2-lane rural highway. However, these design criteria applied to permanent structures may be not suitable for a temporary detour drain. Preferable to rigid design guidelines is an approach in selecting a detour design flood frequency by achieving the optimal design using the risk-cost analysis. This approach has become increasingly important in recent years due to increased shortage of construction funds.

In 1985, the Colorado Department of Highways spent 261.7 million dollars on highway construction which was an increase of 68.5% since

1970 (3). On a national level in the past 10 years, approximately one dollar out of four was spent for drainage structures in highway construction (20). The fact that almost every drainage structure requires a detour structure during the construction, indicates the urgent need for the development of a detour drainage structure design methodology.

The risk-cost method has long been recommended as an effective means to make alternative design decisions. This concept minimizes the total expected risk cost with respect to decision factors (17). For instance, in the design of a structure, the total risk cost includes construction cost and expected failure damage. The decision factor is the design flood frequency. In practice, the engineer needs to determine the risk costs for all possible alternatives, and then plot the total risk cost against decision factors for different alternatives. As illustrated in Figure 1, the sum gives the lowest total risk cost which may be used in selecting the design.

In the case of detour culvert design, the temporary nature of the structure and the potential flooding risk make this task even more difficult. Due to its short service, the cost of a detour structure should be kept as economic as possible. However, the failure of an undersized detour may cause as much damage, in terms of traffic loss, as losing the permanent structure. The seriousness of any traffic delay is proportional to the highway site, traffic volume, availability of alternate routes and the overall importance of the route (25).

In this study, the assumption is that the service period of a detour structure is shorter than 12 months. A design methodology using the risk-cost analysis was developed for determining the design flood for detour drains. To establish the cost-capacity relationship between permanent and detour structures, an extensive cost data analysis was performed, based on concrete and corrugated metal culverts constructed in the State of Colorado from 1979 to 1985. Major factors found were service time of the detour drain, monthly rainfall or runoff distribution at the project site, damage-cost ratio and cost capacity coefficients. In this study, Gumbel distribution was used for the frequency analysis of local runoff data. The same approach can be applied to other statistical distributions such as Log-normal and Log-pearson type iii.

Subsequent to the development of the detour culvert design methodology, a design chart for determining the design flood frequency and a personal computer software, RADCD, were developed to assist engineers in the use of this method.

II. DEVELOPMENT OF RISK-COST METHODOLOGY

An extensive literature review did not provide any easy solution for temporal drainage structure design such as detour culvert design. Both Hydraulic Engineering Circular No. 17 (1981) and FHWA Report No. FHWA-RD-74-11 (1970) address the approach of using risk and risk-cost analysis in the design of drainage structures. However, almost all studies related to this subject were only concerned with permanent structures and present lengthy and detailed approaches to risk or risk-cost analysis. It is difficult to obtain the many economic data and factors required by these methods. Based on the fact that the cost and capacity of a drainage structure increases with respect to the size we may conclude

culvert capacity α size of culvert

and

culvert installation cost α size of culvert

Mathematically, the cost of installing a drainage culvert, C_d, may be expressed as a function of its capacity, q. Thus, for a detour drain, we may write

$$C_d = F_1(q) \tag{1}$$

in which $F_1(q)$ = a functional relationship.

Similarly, the cost of installing a permanent structure, C_p, may be expressed as a function of its capacity, Q, as well.

$$C_p = F_1(Q) \tag{2}$$

in which $F_1(Q)$ = a functional relationship.

Combining Eq's 1 and 2, we may develop a functional relationship between cost ratio and capacity ratio for any two drainage structures.

Therefore, the cost ratio of a detour culvert to its permanent structure may then be expressed as their flow capacity ratio; namely:

$$C_d/C_p = f(q/Q) \tag{3}$$

in which C_d = cost of detour structure. C_p = cost of permanent structure, q = detour culvert capacity, Q = capacity of permanent structure, f(q/Q) = a functional relationship.

The functional relationship in Eq. 3 needs to be further determined by cost data. Often, detour drains serve for a period of time shorter than 12 months. From an economic point of view, the design flood frequency for a detour culvert is expected not to exceed a ten-year flood. For such a narrow solution domain, this functional relationship may be further assumed to be linear.

$$\frac{C_d}{C_p} = a(q/Q) \tag{4}$$

in which a = cost-capacity coefficient to be determined by cost data.

One of the primary drawbacks to most risk-cost analysis procedures is the degree of difficulty in determining the damages resulted from a drainage structure failure. As far as the losses due to the discontinuity of traffic is concerned, we may consider that the failure of a detour structure may result in the same amount of damages as that incurred in the failure of a permanent structure. In this study, it is suggested that the total loss of losing a detour structure versus that of a permanent structure differs only in the cost of the structures themselves.

The chance of failure of a detour drain can be assessed by the joint probability that includes:

(1) the probability of having a flood exceeding the design capacity of the detour culvert. For a period of 12 months, this probability is 1/T in which T is the return period of the design flood.

(2) the probability of having this flood occur during the service period of the detour drain. The value of this probability may be estimated by the monthly rainfall or runoff distribution at the project site.

With the assumptions that detour culvert will fail when a flood exceeds the design capacity and the two events mentioned above are independent, the expected damage associated with the failure of a detour drain can be written as follows:

$$C_r = (P/T) \cdot D_p \tag{5}$$

in which C_r = expected damage due to the failure of a detour structure, D_p = damage caused by the permanent drainage structure failure, T = return period of the design flood for detour drain, P = probability of having a flood exceeding the detour drain capacity during its service.

By definition, the total risk cost of a detour drain can then be written as follows:

$$C_T = C_d + C_r \tag{6}$$

in which CT = total risk cost for a detour drain.

Substituting Eq's (4) and (5) into Eq. (6) yields

$$C_T = (aq/Q)C_P + (P/T)D_P \tag{7}$$

The objective is to minimize the total risk cost in terms of selecting the return period ,T, to determine the detour drain capacity, q, in Eq. 7. Taking the first derivative of Eq. 7 with respect to the return period, T, and setting the resulting equation equal to zero yields

$$\frac{dq}{d_T} = \frac{PQ}{aT^2}\,\frac{D_p}{C_p} \tag{8}$$

In flood frequency analysis, the magnitude of a flood variable, q, with a return period, T, can be related to its mean and standard deviation.

$$q = \overline{Q} + K_T \cdot S \tag{9}$$

in which $\overline{Q}$ = mean of flood variable, S = standard deviation of flood variable. K_T = frequency factor of flood variable.

Values of $\overline{Q}$ and S may be determined by the frequency analysis on the observed runoff near or at the project site. If field data are not available, flood prediction methods may be used to estimate flood magnitudes. With any two known flood magnitudes, Eq. 9 can be simultaneously solved for mean and standard deviation. Computation procedures can be found in many standard hydrology textbooks; it will not be repeated here.

Taking the first derivative of Eq. 9 with respect to the variable T yields

$$\frac{dq}{dT} = S\,\frac{dK_T}{dT} \tag{10}$$

Substituting Eq. 10 into Eq. 8 yields

$$\frac{dK_T}{dT} = \frac{pQ}{aS}\,\frac{q}{T^2}\cdot\frac{Dp}{C_p} \tag{11}$$

Eq. 11 applies to any probability model as long as it fits runoff data observed at the project site (14).

Frequency factor is determined by the runoff probabilistic distribution. When considering Gumbel distribution, the frequency factor is computed by the following equation.

$$K_T = \frac{\sqrt{6}}{\pi}\left\{ 0.5772 + \ln\ln\left[\frac{T}{(T-1)}\right]\right\} \tag{12}$$

in which π = a constant equal to 3.1416. and ln = natural logarithm function.

Taking the first derivative of Eq. 12 with respect to T yields

$$dK/dT = \frac{\sqrt{6}}{\pi} \left[\frac{1}{\ln\left[\frac{T}{(T-1)}\right] \cdot (T-1) \cdot T} \right] \tag{13}$$

Substituting Eq. 13 into Eq. 11 yields

$$\frac{P}{T} = B \left\{ \frac{1}{\ln\left[\frac{T}{(T-1)}\right] \cdot (T-1)} \right\} \frac{D_p}{C_p} \tag{14}$$

in which $B = \frac{a\sqrt{6}}{\pi} \left(\frac{S}{Q} \right) \frac{D_p}{C_p}$ (15)

In highway drainage design, a 100-year flood is often used to design permanent structures under an urban highway and a 25 or 50-year flood is generally used for a rural highway. These design criteria have been achieved based on experience. From an economic point of view, we may consider that this kind of guideline attempts to give the most economic design that is to achieve a damage to cost ratio of about unity. With this assumption, Eq. 14 may further be simplified to

$$\frac{P}{T} = B \frac{1}{\ln\left[\frac{T}{T-1}\right] \cdot (T-1)} \tag{16}$$

The probability, P, of having a flood exceed the capacity of a detour drain during its service, may be estimated by either the monthly rainfall distribution (normalized by its annual total precipitation) or the monthly runoff distribution (normalized by its annual total runoff). With the normalization, the area under monthly rainfall or runoff distribution curves becomes unity. For instance, when the detour drain will be installed to serve from the i-th month to j-th month in a year, the probability, P, may be estimated as follows:

$$P = \sum_{m=i}^{m=j} (Pm/Pa) \tag{17}$$

in which Pm = average monthly precipitation in m-th month, $1 <= m <= 12$.

Pa = annual total precipitation.

$$Pa = \sum_{m=i}^{m=12} Pm \tag{18}$$

The same concept may be applied to monthly runoff data if they are available at the site. In comparison, the monthly runoff distribution may give more direct estimate of the probability of flood occurrence than monthly rainfall. However, it is often found that the monthly rainfall distribution is easier to obtain than monthly runoff.
As indicated in Appendix F, a monthly rainfall distribution diagram prepared by the Colorado State Planning Commission, Weather Bureau, gives statewide rainfall information that can be incorporated into Eq's 17 and 18.

As shown in Eq. 16, the solution of the design flood for a detour structure depends on the variables of P and B. The cost-capacity functional relationship described in Eq. 4, so far, remain undecided. The next section presents cost data analysis for the development of this functional relationship.

III. COST DATA ANALYSIS AND DETERMINATION OF COST-CAPACITY FUNCTION

In order to develop the cost-capacity functional relationship described in Eq. 4, a large amount of cost records of highway drainage structures constructed in the State of Colorado from 1981 to 1985 were examined and then analyzed. Reviewing cost data ((7) to (13)) indicates that many major drainage structures were constructed with reinforced concrete box culverts (CBC) and detour drains were corrugated metal pipes (CMP). As a result, in this study, cost and capacity analysis is performed between concrete box culverts (CBC) and metal pipes including aluminum and steel pipes. The detailed data reduction process and analysis are explained in the next sections.

3.1 Determination of Detour Culvert Pipe Cost

In general, the Colorado Department of Highways (CDOH) does not specify a particular type of drainage pipe (21) for detour culverts. The choice of detour culvert sise and type are normally addressed in the Project Special Provisions of a particular project. This practice encourages the most economic installation by allowing contractors to select their own type of pipe as long as an equivalent pipe capacity is provided.

Equivalent diameter pipes for detour drain may be selected from corrugated steel or aluminum pipe, pipe arch, and reinforced concrete pipe (21) (CDOH Standard Specifications). Based on Colorado Standard Plans (4), diameters of pipes may range from 12 inches to 120 inches.

For the purpose of this study, however, only pipes of 18 inches in diameter or larger were considered because the CDOH Roadway Design Manual (5) specifies that this diameter is the minimum size for culverts crossing under Colorado highways due to debris and maintenance considerations. Although this design criteria is aimed at permanent structures, detour culverts are still subject to clogging from debris and silt.

Examination of cost data reveals that only certain diameters of pipe have been commonly used. Their costs per linear foot are shown in Appendix C. Costs considered are an average cost per linear foot of steel and aluminum pipes used in each year.

3.2 Determination of Concrete Box Culvert Costs

Cost data analyzed in this study indicate that numerous types of CBC's have been used. Precast structures and special CBC's with non-standard cell widths or heights have been used as well. However, standard concrete box culverts are still dominant in use. For this reason only CBC's with standard sizes were used for the cost analysis. Costs for concrete box culverts were determined in much the same manner as used for culvert pipes. Standard sizes for cast-in-place concrete box culverts (CBC's) were obtained from the Standard Plans (4) and listed in Table 1.

Records of the drainage culverts built from 1979 through 1985 also indicate that a wide variety of inlet treatments were used with CBC's. Due to the fact that price ranges on inlets varied significantly from one project to another, in this study only the barrel of the culvert was considered in determining its cost. Unlike the cost used for the culvert pipe, costs for the CBC's were not an average, but was based on the actual bid price per linear foot of culvert barrel for the structure that was built.

Thickness of individual box culverts may vary depending on the height of fill that structure will be expected to carry. However in this analysis, thickness was not considered as an important factor in the overall cost of the structure. Cost used in analysis was based on the cost of linear foot of concrete barrel. Results are listed in Appendix D.

3.3 Determination of Culvert Pipe and CBC Capacity

Studies have shown that the headwater depth, inlet configurations, tailwater depth and pipe roughness determine the capacity of a culvert (15). When evaluating the allowable headwater depth upstream of a culvert, the engineer must take into consideration the amount of debris or detritus that needs to pass through the culvert, the effects of a headwater pool upstream, and flow velocities at the inlet (15). For the purposes of this study, the ratios of headwater depth to diameter of culvert presented in Table 2 are used to estimate the capacity of those culverts installed in the State of Colorado from 1981 to 1985.

Capacity determination for each culvert was made using the design charts for inlet control recommended in the Hydraulic

Engineering Circular Number 5 (HEC-5) (15). Nomographs presented in HEC-5 allow the engineer to determine the capacity of most commonly used pipes utilizing a known diameter and headwater to diameter ratio.

In this study, the design chart for round corrugated metal pipes (CMP's) was used to determine the capacity of culverts. Round pipe is the most commonly manufactured shape of culvert (1) and is available from suppliers at a lower cost than other shapes (22).

A final factor in determining the capacity for a culvert with an inlet control was the configurations of the inlet. The type of end treatment must be known when using the design nomographs. For this study it was assumed that pipe detour culverts would be installed with no special end treatments, namely the barrel would be projecting from the fill. This assumption is based on the temporary nature of detour culvert. Special end treatment would not be justified due to the additional cost of construction.

Determination of capacity for the CBC's was done much in the same way as that used for the detour culvert. Inlet control was assumed to be the controlling condition, headwater to depth ratios were based on those presented in Table 2, and the design charts in HEC-5 (15) for CBC's were used to determine the capacity. The capacity of CBC were estimated using headwall and wing walls as the Design Manual of the Colorado Department of Highways (15) specifics this type end treatment for all CBC's.

A final CBC end treatment assumption was that the wingwalls were configured with a flare of 30° to 75° relative to the center-line of the structure. Although it is not the most efficient layout from a hydraulic standpoint, this configuration is most commonly used, based on experience.

3.4 <u>Determination of Cost-Capacity Function</u>

As discussed previously, a linear relationship was assumed to exist for the cost-capacity function. The cost-capacity coefficient, a, was introduced to Eq. 3. To determine this coefficient, cost ratios were plotted against capacity ratios for all possible combinations among the pipes and CBC's analyzed. The detailed data reductions are presented in Appendix D for cost ratios and Appendix E for capacity ratios. Results are presented in Figures 2 through 4 for the cost data from 1983 through 1985. Although data points are scattered, an obvious linear relationship may be observed. This conclusion agrees with the assumption made on the cost-capacity functional relationship. Based on 1983 to 1985 cost data, the range of the cost-capacity coefficient is found to be 0.3 to 0.5.

V. APPLICATION OF THE DEVELOPED METHODOLOGY

According to Eq. 16, the determination of design flood for a detour culvert depends on the values of B and P. The value B involves the standard deviation of runoff variability at the site, the capacity of the permanent structure, the damage-cost ratio and the cost-capacity coefficient.

When there is a gage station near the project site with a record of 10 or more years, the standard deviation of runoff variable may be determined by frequency analysis. The detailed procedures can be found in the Bulletin 17B published by the American Water Resources Council (2).

Often, there is not a gage station near the project site. The magnitude of a design flood must then be estimated by empirical methods. Using Eq. 9, the unknown standard deviation, (S), and mean value of runoff variability (Q), may be obtained with any two known floods predicted by the regional runoff prediction methods.

As found in this study, the range of the cost-capacity coefficient, a, varies between 0.3 to 0.5. When a and S are known for the site, the engineer may consider different construction periods in a year as alternatives. For each period, the engineer needs to find the probability, P, from either monthly runoff or rainfall distribution and then substituting the values of variable B and P into Eq. 16. The solution for the design return period T can then be obtained by a trial and error iterative scheme.

A graphic solution chart is developed for Eq. 16 and presented in Figure 5. The use of this design chart will be further explained in the design example.

VI. DESIGN EXAMPLE

The existing bridge, Number N-10-C, is located at State Highway 160 and South Fork River near Crede, Colorado. The length of the bridge is 165 feet and it has a skew angle of 32 degree to the centerline of the river. This bridge was built in the early 1930's. It is planned to replace this bridge with concrete culverts. As a four-lane highway in a rural area, the replacement bridge is designed to survive a 50-year flood.

During the construction, a detour culvert will serve for a period of three months: July, August and September. The task is to find the proper design flood for this detour culvert.

Hydrology at the Site

The drainage area is found from the USGS topographic map to be 216 squared miles. The average basin elevation is 10500 feet above mean sea level. It is covered by woods and pasture. A few ponds and lakes are scattered in the upper part of the basin.

From the USGS Water Resources Data, it is found that there is a stream gage station, Gage 08219500, located a mile upstream of the project site. The annual peak runoff has been recorded from 1949 to 1977. Applying Gumbel distribution for flood frequency analysis to the observed peak runoff flow rates, we can compute runoff statistics. In this study, the software package, FREQ, developed by the University of Colorado at Denver, is used and results are shown in Appendix A. The mean and standard deviation of runoff at the site are 1516.6 cfs and 754.4 cfs respectively. The magnitude of a 50-year flood is determined to be 3472 cfs.

Development of Monthly Flood Occurrence Probability Distribution

The next step is to determine the monthly flood occurrence probability distribution. As mentioned previously, it may be approximated by either monthly runoff or rainfall distribution normalized by its annual amount. For the purpose of comparison, both runoff data and rainfall statistics from Appendix F are used to develop the monthly flood occurrence probability.

A. Using Monthly Precipitation Distribution

From the monthly precipitation distribution diagram prepared by the Colorado State Planning Commission, Weather Bureau, the monthly average rainfall distribution near the city of Creede is listed as follows:

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Inches	0.9	1.3	1.0	1.3	1.0	1.1	2.4	2.5	2.1	1.8	1.0	0.9	17.3
Normalized in percent	5.2	7.5	5.8	7.5	5.8	6.4	13.9	14.5	12.1	10.4	5.8	5.2	100.00

The total annual precipitation is 17.3 inches. Dividing each monthly average precepitation depth by this total annual precipitation, we get the normalized percentage which may be used to approximate flood occurrence probability. For instance, the probability of a flood occurring in June is 6.4% or 0.064.

B. Using Monthly Runoff Distribution

The USGS Water Resources Data provides monthly peak runoff for 12 months a year. In this example, data gathered from 1961 through 1977 are used to calculate the average monthly peak runoff. Results are listed as follows:

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Runoff cfs	56	62	153	574	1550	1470	770	375	284	198	89	75	5656
Normalized in Percent	1.0	1.1	2.7	10.1	27.4	26.0	13.6	6.6	5.0	3.5	1.6	1.3	100.0

The sum of these monthly peaks is 5656 cfs which is used to normalize each monthly runoff to get its percentage, as shown in the above table.

It can seen that monthly runoff distribution does not agree to monthly precipitation distribution. This may indicate that the basin has a delay time for rainfall to be converted to runoff. In this case, snowmelt in early Spring may contribute more significant runoff than rainfall. As a result, the highest monthly runoff occurs in May that is two months earlier than the highest monthly rainfall.

For the purpose of runoff prediction, monthly runoff distribution should provide more direct and reliable prediction than monthly precipatation. In this study, the normalized monthly runoff distribution is selected to approximate the flood occurrence probability for any given month.

As a result, the value of P in Eq 17, is the sum of occurrence probabilities from July through September namely:

$$P = 13.6\% + 6.6\% + 5.0\% = 25.21\%$$

It means that on the average, a flood has a 25.21 % chance of occurring within these three months.

Determination of Damage-Cost Ratio and Cost-Capacity Coefficient

In this study, the value of the cost-capacity coefficient, shown in Eq 4, is found to vary between 0.3 to 0.5. For simplicity, the average value of 0.4 is used for this example. The damage-cost ratio defined in Eq 14, may be considered to be unity. Substituting these two variables into Eq 15, we have

$$B = 0.068$$

Using the values of B and P, the design flood for the detour culvert can be graphically determined with Figure 5. The solution is that a 3-year flood shall be used for design.

Sensitivity Study

The value of the cost-capacity coefficient, in equation 4 represents the slope of the linear relationship between cost ratio and culvert capacity ratio. The higher the value of the cost-capacity coefficient, a, the smaller the detour culvert suggested by the risk-cost method.

On the contrary, as Eq 14 indicates, the detour culvert size is a function of damage-cost ratio. The higher the damage-cost ratio the larger the detour culvert should be. Using this example, a sensitivity study on the values of cost-capacity coefficient and damage-cost ratio is further performed.

Using the cost-capacity coefficient equal to 0.4, the variation of design flood for a detour culvert with respect to damage-cost ratio is listed as follows:

Variable Dp/Cp in Eq 15	Design Return Period in Year	Magnitude of Design Flood in CFS
0.5	1.1	660
1.0	3.1	1720
2.0	6.9	2270

In comparison, the ratio of Dp/Cp=0.5, which is less than unity, tends to discourage the engineer from using a larger detour culvert because this ratio implies that a one dollar investment returns only one-half dollar in damage prevention. This condition may be considered for a detour drain in a rural area. On the other hand, when loss of traffic will cause severe damage, the damage-cost ratio may be raised to two, suggesting that higher design flood be used. This implies that the engineer should consider a larger detour culvert because of a higher expected return from the detour investment.

Using the damage-cost ratio equal to unity, the variation of the design flood for a detour drain with respect to the cost-capacity coefficient is shown as below:

Variable a in Eq 4	Design Return Period in Year	Magnitude of Design Flood in CFS
0.3	8.6	2410
0.4	3.1	1720
0.5	2.2	1460

Based on Eq 4, it can be expected that the higher the value of the cost-coefficient, a, the larger the detour culvert.

Discussion

Using this example, we have seen the effects of the cost-capacity coeficient and the damage-cost ratio on detour culvert design. It may appear complicated for an engineer to select those variables. As a matter of fact, when a risk-cost analysis is used for design, the engineer's decision is more than just determinating the magnitude of a single event. Instead, the engineer needs to compare different alternatives on the same basis such as a selected damage-cost ratio used for all alternatives. Alternatives in detour culvert design, as far as this example is concerned, may be the selection of which three consecutive months should be the construction period.

In most cases, the damage-cost ratio shall be equal to unity and the cost-capacity coefficient varies in a small range. If engineer can not get better information, the average value of 0.4 is recommended.

VII. DESIGN COMPUTER SOFTWARE - RADCD

A personal computer software, RISK ANALYSIS FOR DETOUR CULVERT DESIGN (RADCD) has been developed for assisting the engineer in using this method. RADCD was written in BASIC computer language for the use of an IBM personal computer or compatible. It is menu driven and user interactive. The program requires 256K computer memory and can be run on a floppy or hard disk system with a black/white or color monitor. The printout can be produced by a standard dot matrix printer.

Capability of RADCD

RADCD includes a data editor which has the capability of full screen data editing and creation. The computation program executes iterative computations and tabulates results for all possible alternatives in terms of the selection of detour culvert service periods. For instance, after the user specifies the service period of a detour culvert to be three months, the program will start from

January and use every three consecutive months as a possible service period to compute the corresponding design flood. The tabulated results give the engineer a basis for decision making and alternative selection.

The program provides the user an option of graphically displaying monthly rainfall/runoff distribution, the distributions of design frequency and design flood magnitude for different service periods.

Installation of RADCD

RADCD is delivered on a 5-1/4 inch floppy diskette. The user shall make a working copy and save the original in a safe place. Making a copy can be done by the Copy Command of Disk Operation System (DOS). If the user likes to run this package on a hard disk system, it is suggested to make a sub-direstory and copy this package onto this sub-directory. The detailed procedures can be found in the DOS user's manual.

How to Run the Software

If the screen graphic display is intended to be printed out on a printer, the user must execute the PC DOS command, GRAPHIC.COM before running this package. To do so, the user types, after the DOS prompt.

GRAPHICS

This execution allows the user to transfer the screen graphic image to a dot matrix printer by pressing the print-screen key on the computer key board.

The user must make sure that the computer is logged to the disk drive or sub-directory which contains the software package and then types in

RADCD

This command invokes the program to provide the main menu on the screen. The user follow the menu on the screen to complete each run. The program always provides the default value or the last input on the screen. The user can simply press the return key on the key board to accept it, or type in new data to replace it. To select the option from the menu, the user enters a letter "Y" representing (Y)es or a letter "N" representing (N)o to ignore. After entering either data values or selecting an option, the user must press the return key to signal the computer to execute the user's decision.

Input Data Requirements

RADCD requires the user to provide

a. Project Title

b. Runoff Statistics

The user can either provide mean and standard deviation of runoff at the site or enter two known flood magnitudes with their return periods. Since the solution for a detour culvert is in the range of low floods, it is suggested to use 2-year and 5-year floods as known floods to calculate the corresponding mean and standard deviation.

c. Rainfall/Runoff Monthly Distribution

There is no default values for these 12 variables.

d. Damage-Cost Ratio and Cost-Capacity Coefficient.

The default values are 1 and 0.4 respectively.

e. The Design Flood Magnitude for the Permanent Structure in CFS.

f. Length of Service Period in Months.

The default length is three months.

By following the menu on the screen, the user will be able to complete data input and save data files on a diskette.

Output File and Printout

RADCD summarizes all the input data and tabulates the design flood frequency and magnitude for each possible service period for the detour culvert under design. The user also has the option of plotting monthly rainfall/runoff distribution, and design flood frequencies and magnitudes for different service periods. All screen graphs can be sent to a dot matrix printer as long as the DOS command. GRAPHICS.COM has been invoked.

Design Example

Using the previous example, an input data file, DSIZE.DAT, is created by the data editor of RADCD. Printout from RADCD for this example is presented in Appendix B.

VIII. CONCULSIONS

A detour drainage structure is a temporary structure generally serving for several months. Many existing design guidelines are not applicable for determining the design capacity of a detour drain. In this study, a risk-cost methodology has been developed to assist the engineer in making decisions. To demonstrate the usefulness of the method, a practical design problem using Gumbel distribution is used to determine flood distribution and prediction. However, the method developed in this study can be extended to any probability distribution as long as it fits local runoff observed near the project site.

In this study, a non-dimensional linear cost-capacity function has been established through an extensive cost data analysis on concrete box culverts and corrugated metal pipes. It is found that the cost-capacity coefficient varies within a narrow range bewteen 0.3 to 0.5. This method allows engineers to adjust their decisions with the different damage-cost ratios, depending upon the local situations. This capability further allows the engineer to take more factors into account in a decision making process.

As a non-dimensional approach, all costs are expressed as cost ratios, permanent structure cost to detour culvert cost. This ratio relationship is not effected by the present worth and interest rate used in many economic studies.

Associated with the development of design methodology, a software, RISK ANALYSIS FOR DETOUR CULVERT DESIGN, RADCD, is also developed to assist the engineer to process the lengthy computations involved in computing alternatives and to make comparisons for decision making.

It is believed that RADCD will further help the engineer in the use of the method developed in this study.

IX. NOTATIONS

C	=	Cost
Q	=	design runoff for a permanent structure
q	=	design runoff for a detour structure
P	=	probability of having a flood exceeding the detour drain capacity
T	=	return period
K_T	=	frequency factor
S	=	standard deviation of flood
$\bar{Q}$	=	mean of flood
P_m	=	monthly precipitation
P_a	=	annual total precipitation

<u>Subscript</u>

d	=	detour structure
p	=	permanent structure
r	=	expected damage

X. ACKNOWLEDGMENT

This project was supported by the Federal Highway Administration through the State Department of Highways. The author would like to express his deep appreciation to Mr. Del Roupp and Mr. Gary Johnson, Colorado Department of Highways for their valuable suggestions.

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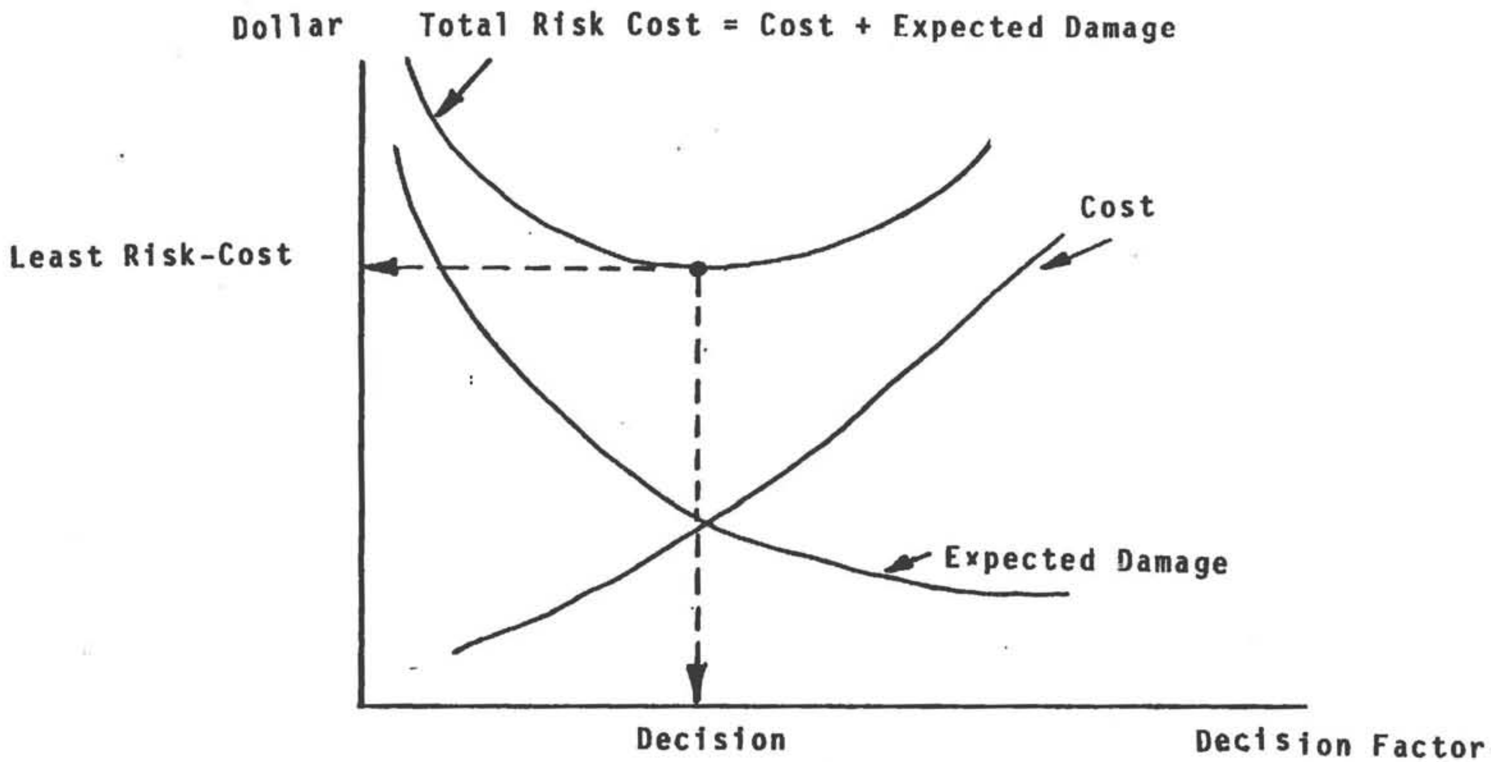


Fiaure 1. Illustration of Risk-Cost Analysis.

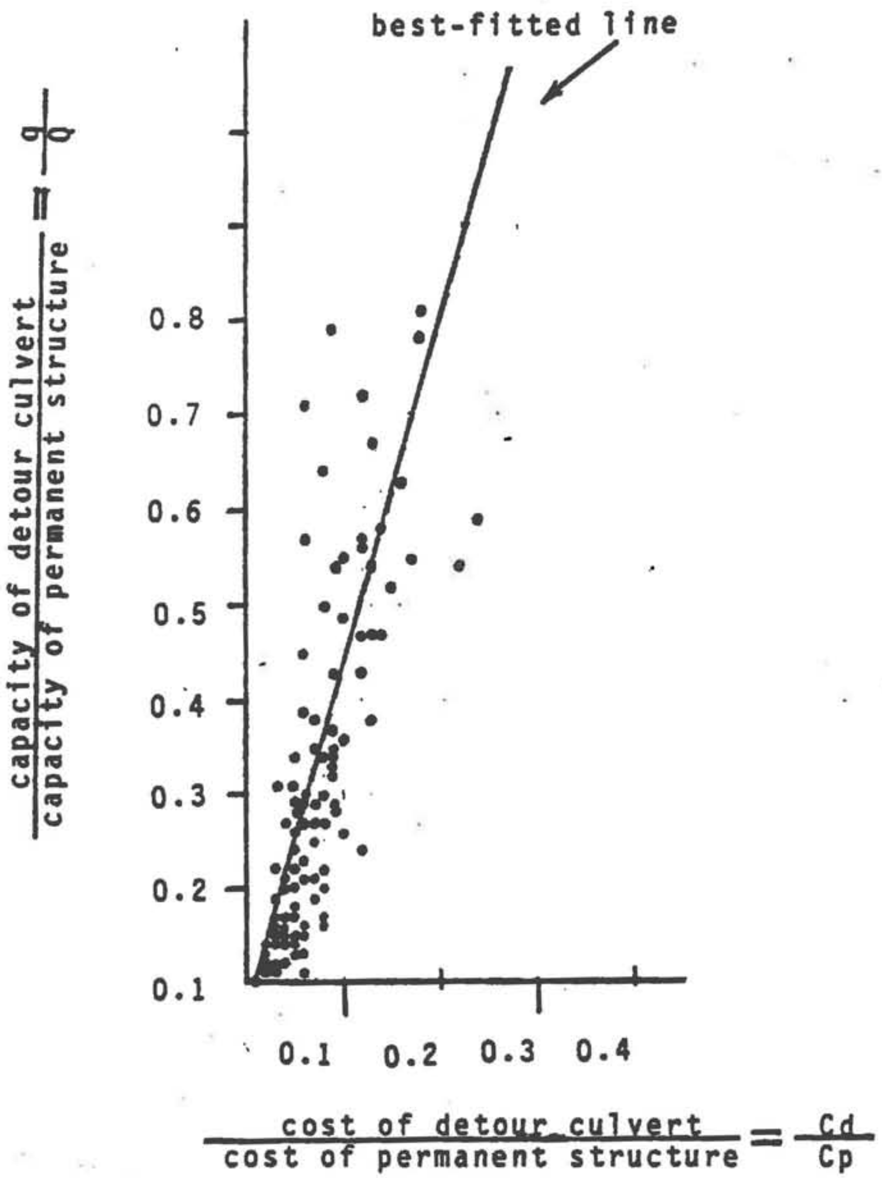


Figure 2. Cost-Capacity Data Analysis for the Year of 1983. The cost-capacity coefficient is found to be 0.23.

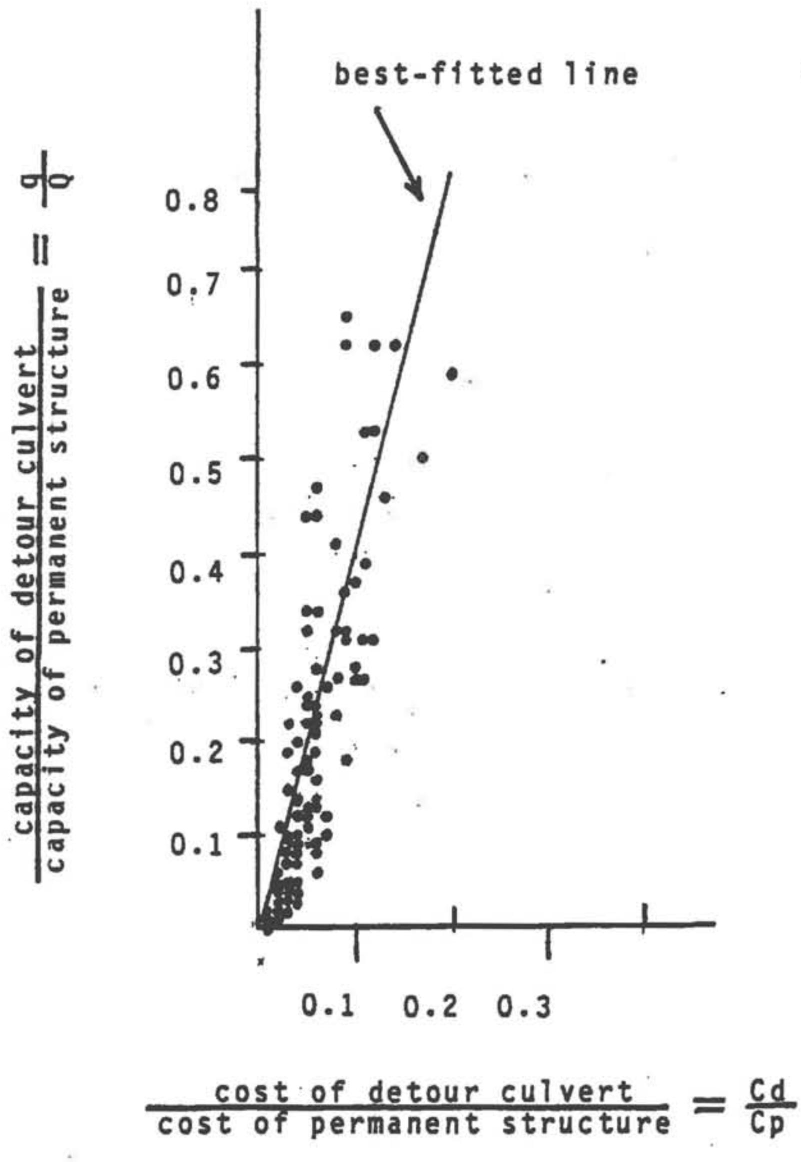


Figure 3. Cost-Capacity Data Analysis for the Year of 1984. The cost-capacity coefficient is found to be 0.25.

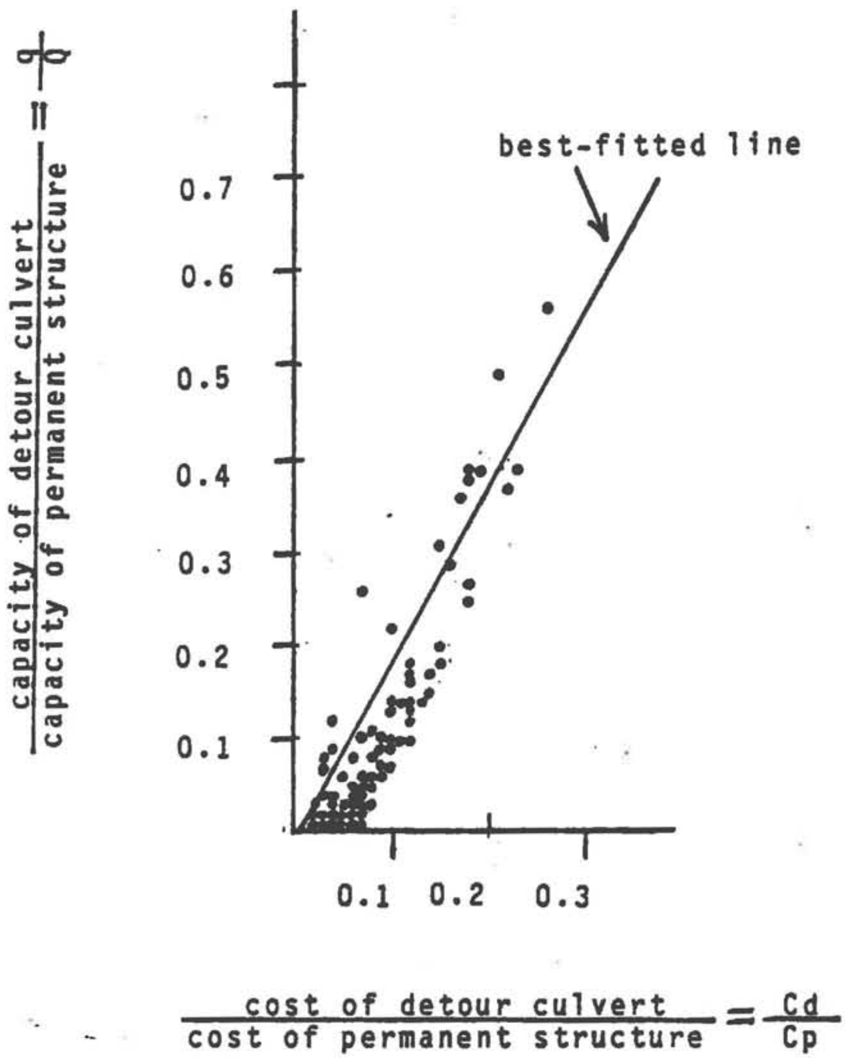


Figure 4. Cost-Capacity Data Analysis for the Year of 1985.
The cost-capacity coefficient is found to be 0.5.

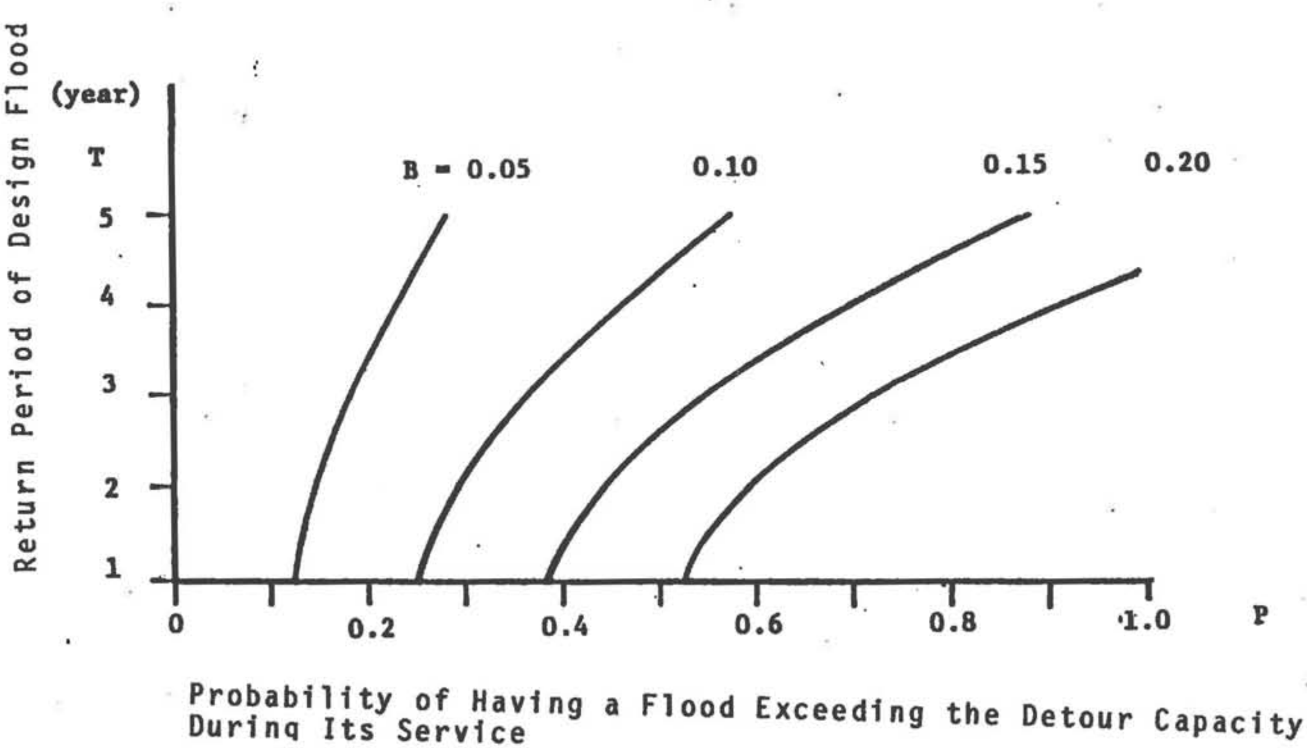


Figure 5. Design Chart for Determining the Design Flood Frequency for a Detour Culvert.

DIMENSIONS OF STANDARD CONCRETE BOX CULVERT

NUMBER OF CELLS	WIDTH OF EACH CELL (FT)	CELL HEIGHT (FT)
1	5	3 TO 5
1	6 or 7	4 to 7
1	8	4 to 8
1	9	5 to 9
1	10; 11; 12; 13 or 14	6 to 10
2	6 or 8	3 to 6
2	10	4 to 10
2	12 or 14	6 to 10
3	9-12-9	6; 8; 10
3	11-14-11	6; 8; 10

Table 1. Standard Sizes of Concrete Box Culverts.

MAXIMUM DESIGN HEAD WATER DEPTH

CULVERT DIAMETER	HEADWATER DEPTH/DIAMETER
LESS THAN 3'	1.5
3' TO 5'	1.3
5.5' TO 7'	1.2
MORE THAN 7'	1.0

Table 2. Headwater Depths Used in Estimation of Culvert Capacity.

Appendix A: Flood Frequency Analysis for Gage Station 8219500.

==

HYDROLOGIC FREQUENCY ANALYSIS DEVELOPED BY CU-DENVER
DATA ANALYSIS AND PREDICTIONS BY GUMBEL DISTRIBUTION
COLORADO STATE DEPARTMENT OF HIGHWAYS - DENVER COLORADO
ON DATE 12-15-1987 AT TIME 00:50:59

==

HYDROLOGIC FREQUENCY ANALYSIS FOR ANNUAL MAXIMUM SERIES

THE GAGE STATION NUMBER 8219500
THE LENGTH OF DATA RECORD 44 YEARS
THE PLOTTING FORMULA TR=(N+A)/(M+B); A = 1 ; B = 0

REPORT OF DATA ANALYSIS

YEAR	EVENT	TR	P(Q>=q)	FREQ K
1949	3420.0	45.00	0.02	2.509
1952	3310.0	22.50	0.04	1.960
1948	3080.0	15.00	0.07	1.635
1979	2690.0	11.25	0.09	1.401
1973	2640.0	9.00	0.11	1.218
1957	2580.0	7.50	0.13	1.066
1965	2430.0	6.43	0.16	0.936
1941	2220.0	5.63	0.18	0.822
1975	2070.0	5.00	0.20	0.719
1970	2010.0	4.50	0.22	0.627
1968	1960.0	4.09	0.24	0.542
1937	1950.0	3.75	0.27	0.463
1938	1920.0	3.46	0.29	0.389
1944	1800.0	3.21	0.31	0.320
1958	1760.0	3.00	0.33	0.254
1942	1730.0	2.81	0.36	0.191
1976	1690.0	2.65	0.38	0.131
1962	1670.0	2.50	0.40	0.074
1969	1440.0	2.37	0.42	0.018
1964	1410.0	2.25	0.44	-0.036
1936	1300.0	2.14	0.47	-0.088
1960	1280.0	2.05	0.49	-0.139
1945	1250.0	1.96	0.51	-0.189
1966	1230.0	1.88	0.53	-0.238
1956	1220.0	1.80	0.56	-0.287
1953	1140.0	1.73	0.58	-0.334
1961	1090.0	1.67	0.60	-0.382
1978	1090.0	1.61	0.62	-0.429
1951	1020.0	1.55	0.64	-0.476
1974	996.0	1.50	0.67	-0.523
1943	975.0	1.45	0.69	-0.571

1939	972.0	1.41	0.71	-0.619
1947	954.0	1.36	0.73	-0.668
1955	954.0	1.32	0.76	-0.717
1950	950.0	1.29	0.78	-0.768
1967	944.0	1.25	0.80	-0.821
1971	894.0	1.22	0.82	-0.876
1946	883.0	1.18	0.84	-0.934
1972	780.0	1.15	0.87	-0.996
1963	686.0	1.13	0.89	-1.064
1954	619.0	1.10	0.91	-1.139
1959	619.0	1.07	0.93	-1.227
1940	614.0	1.05	0.96	-1.336
1977	491.0	1.02	0.98	-1.492

REPORT OF DATA STATISTICS

MEAN OF DATA	1516.614
STANDARD DEVIATION OF DATA	754.427
SKEWNESS COEFFICIENT OF DATA	.9117323

THE BEST FITTED LINE IS:

PREDICTED Q = 1536.792 + FREQ K * 823.9307

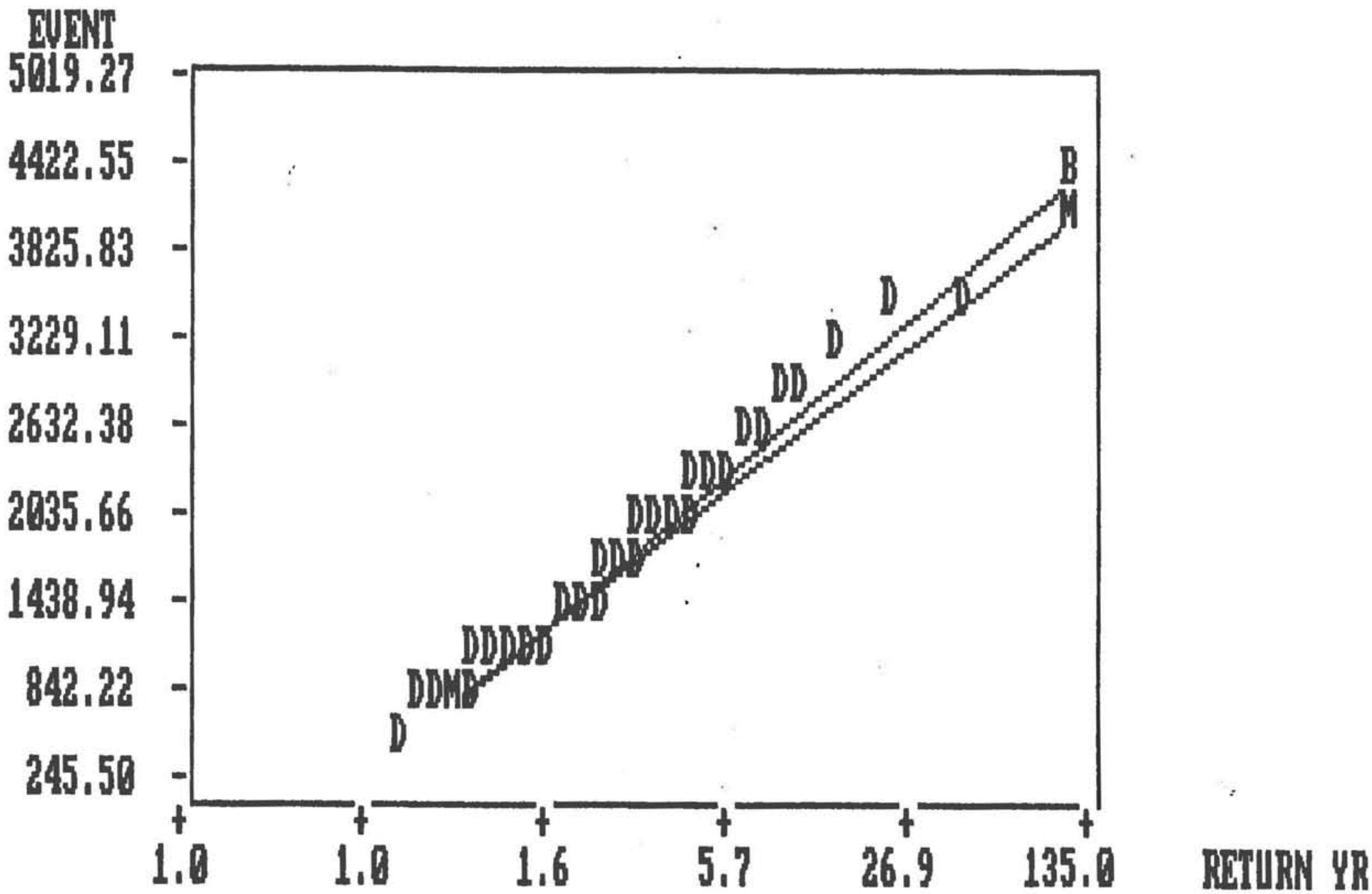
CORRELATION COEFFICIENT = .990489

REPORT OF PREDICTED MAGNITUDES

TR	FREQ K	P(Q<=q)	MODEL	BEST FIT
2.00	-0.16	0.500	1392.67	1401.43
5.00	0.72	0.200	2059.39	2129.57
10.00	1.30	0.100	2500.81	2611.66
25.00	2.04	0.040	3058.55	3220.78
50.00	2.59	0.020	3472.31	3672.66
100.00	3.14	0.010	3883.02	4121.21

REPORT OF 95 PERCENT CONFIDENCE LIMITS

TR	LOW BOUND	EVENT	HIGH BOUND
2	1199.19	1392.67	1607.86
10	2077.93	2500.81	2999.94
100	3022.73	3883.02	4962.59



D -DATA M -MODEL PREDICTION B -BEST FIT
PREDICTION BY GUMBEL DISTRIBUTION FOR GAGE 8219500

Appendix B: Example Printout from the Software- RADCD.

==

DETOUR CULVERT SIZING
DEVELOPED BY
CIVIL ENGINEERING DEPARTMENT
UNIVERSITY OF COLORADO AT DENVER
IN COOPERATION WITH
THE COLORADO DEPARTMENT OF HIGHWAYS
TELEPHONE 303-556-2831 DR. JAMES C.Y. GUO

==

A. SUMMARY OF DESIGN INFORMATION

1. STATISTICS OF FLOOD AT SITE:
   MEAN = 1516.639 STANDARD DEVIATION = 754.4132
2. CAPACITY OF PERMANENT STRUCTURE = 3472 CFS
3. COST-CAPACITY COEFFICIENT = .4
4. DAMAGE-COST RATIO = 1
5. MONTHLY RAINFALL/RUNOFF DISTRIBUTION

JANUARY	FEBUARY	MARCH	APRIL	MAY	JUNE
56.00	62.00	153.00	574.00	1550.00	1470.00
JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
770.00	375.00	284.00	198.00	89.00	75.00

B. RETURN PERIODS OF DESIGN FLOOD FOR DIFFERENT CONSTRUCTION PERIODS

CONSTRUCTION PERIOD IN MONTHS = 3

START	END MONTH OF CONSTRUCTION											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
JAN	1.1	1.1	1.1									
FEB		1.1	1.1	1.1								
MAR			5.4	5.4	5.4							
APR				8.9	8.9	8.9						
MAY					9.4	9.4	9.4					
JUN						6.3	6.3	6.3				
JUL							3.1	3.1	3.1			
AUG								1.1	1.1	1.1		
SEP									1.1	1.1	1.1	
OCT										1.1	1.1	1.1
NOV	1.1										1.1	1.1
DEC	1.1	1.1										1.1

VALUES IN THE ABOVE TABLE SHOULD MUTIPLY BY 1
GUMBEL DISTRIBUTION CAN NOT BE USED FOR RETURN PERIOD<=ONE
1.1 REPRESENTS THAT ANALYTICAL SOLUTION IS LESS THAN ONE

C. MAGNITUDES OF DESIGN FLOOD FOR DIFFERENT CONSTRUCTION PERIODS

CONSTRUCTION PERIOD IN MONTHS = 3

START	END MONTH OF CONSTRUCTION											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
JAN	6.6	6.6	6.6									
FEB		6.6	6.6	6.6								
MAR			21.1	21.1	21.1							
APR				24.3	24.3	24.3						
MAY					24.6	24.6	24.6					
JUN						22.1	22.1	22.1				
JUL							17.2	17.2	17.2			
AUG								6.6	6.6	6.6		
SEP									6.6	6.6	6.6	
OCT										6.6	6.6	6.6
NOV	6.6										6.6	6.6
DEC	6.6	6.6										6.6

VALUES IN THE ABOVE TABLE SHOULD MUTIPLY BY 100
ZERO MEANS THAT THE PREDICTION OF FLOOD <=0
IT RESULTS FROM INADEQUATE REPRESENTATION OF MEAN AND SD FOR LOW FLOWS

Appendix C: Costs of Metal Pipes Used in Colorado.

EQUIVALENT PIPE DIAMETERS

USED IN COST ANALYSIS

OF DETOUR CULVERTS

	YEAR						
	1979	1980	1981	1982	1983	1984	1985
Pipe Dia	$ Pipe Cost/lin Ft						
18	14.92	20.53	20.39	16.49	7.92	8.12	19.79
24	17.12	22.92	26.13	19.69	11.62	11.45	21.79
30	26.10	29.00	26.46	24.99	11.78	11.04	23.04
36	26.15	36.36	31.61	27.77	15.07	18.73	27.69
42	29.84	90.00	45.00	27.51	12.02	18.72	28.57
48	37.56	83.00	45.97	36.44	19.03	17.83	38.13
54	50.00	86.00	-----	42.54	19.19	27.42	42.00
60	-----	50.00	68.65	48.33	20.45	25.00	49.26
72	-----	-----	-----	64.62	25.82	25.74	-----
78	-----	-----	-----	150.00	-----	24.00	-----
84	-----	-----	89.81	78.00	40.25	52.50	74.32
96	-----	-----	-----	81.05	65.00	60.00	-----

Appendix D: Data Reduction for Cost Ratios.

Year	Size of CBC Span * Rise (ft) (ft)	Cost CBC ($/ft)	Pipe Diameter in Inches Cost of Pipe/Foot / Cost of CBC/Foot = Cd/Cp						
			18	24	30	36	42	48	54
78	5X3	85.46	.1596	.1838	.3014	.24608			
78	6X7	118.22	.1153	.1328	.2178	.1778			
78	7X6	147.45	.0925	.1065	.1747	.1426			
78	8X6	168.52	.0809	.0932	.1528	.1247			
78	10X4	236.19	.0577	.0665	.1090	.0890			
78	10X10	314.5	.0433	.0499	.0819	.0668			
78	10X10	520.7	.0261	.0301	.0494	.0403			
78	10X10	339.09	.0402	.0463	.0759	.0620			
78	11X10	304.05	.0448	.0516	.0847	.0691			
78	12X3	252.3	.0540	.0622	.1021	.0833			
78	12X6	292.85	.0465	.0536	.0879	.0718			
78	12X6	471.25	.0289	.0333	.0546	.0446			
78	12X8	275.37	.0495	.0570	.0935	.07637			
78	14X5	369.82	.0368	.0424	.0696	.0568			
78	14X6	248.46	.0548	.0632	.1036	.0846			
78	16X10	584.03	.0233	.0268	.0441	.0360			
78	8-8X8	339.45	.0401	.0462	.0758	.0619			
78	10-10X6	604.01	.0225	.0260	.0426	.0348			
78	10-10X8	337.5	.0404	.0465	.0763	.0623			
78	10-10X12	653.16	.0208	.0240	.0394	.0321			
78	12-12X6	422.13	.0323	.0372	.0610	.0498			
78	12-12X6	525.67	.0259	.0298	.0490	.0400			
78	12-12X7	545.36	.0250	.0288	.0472	.0385			
78	14-14X6	566.68	.0240	.0277	.0454	.0371			
78	14-14X11	939.9	.0145	.0167	.0274	.0223			
78	9-12-9X10	547.7	.0249	.0286	.0470	.0383			
78	11-14-11X10	699.29	.0195	.0224	.0368	.0300			
78	13-16-13X7	1119.1	.0121	.0140	.0230	.0187			
78	13-16-13X8	700.07	.0194	.0224	.0367	.0300			
78	13-16-13X8	685.57	.0198	.0229	.0375	.0306			
78	13-16-13X9	709.01	.0192	.0221	.0363	.0296			
78	13-16-13X11	1758.45	.0077	.0089	.0146	.0119			
79	6X4	162.93	.0915	.1050	.1601	.1604	.1831	.2305	.3068
79	6X6	134.13	.1112	.1276	.1945	.1949	.2224	.2800	.3727
79	6X8	197.9	.0753	.0865	.1318	.1321	.1507	.1897	.2526
79	8X4	174.23	.0856	.0982	.1498	.1500	.1712	.2155	.2869
79	8X8	248.56	.0600	.0688	.1050	.1052	.1200	.1511	.2011
79	10X10	540.06	.0276	.0317	.0483	.0484	.0552	.0695	.0925
79	10X10	314.51	.0474	.0544	.0829	.0831	.0948	.1194	.1589
79	12X4	556.32	.0268	.0307	.0469	.0470	.0536	.0675	.0898
79	12X4	347.16	.0429	.0493	.0751	.0753	.0859	.1081	.1440
79	12X5	313.77	.0475	.0545	.0831	.0833	.0951	.1197	.1593
79	12X10	282.33	.0528	.0606	.0924	.0926	.1056	.1330	.1770
79	12X10	366.3	.0407	.0467	.0712	.0713	.0814	.1025	.1365
79	14X8	372.72	.0400	.0459	.0700	.0701	.0800	.1007	.1341
79	14X8	540.24	.0276	.0316	.0483	.0484	.0552	.0695	.0925
79	14X8	514.1	.0290	.0333	.0507	.0508	.0580	.0730	.0972

Year	Size of CBC Span * Rise (ft) (ft)	Cost CBC ($/ft)	Pipe Diameter in Inches $\frac{\text{Cost of Pipe/Foot}}{\text{Cost of CBC/Foot}} = \frac{Cd}{Cp}$								
			18	24	30	36	42	48	54	60	72
79	14-14X8	1228.62	.0121	.0139	.0212	.0212	.0242	.0305	.0406		
79	20-20X14	947.98	.0157	.0180	.0275	.0275	.0314	.0396	.0527		
79	11-14-11X10	771.35	.0193	.0221	.0338	.0339	.0386	.0486	.0648		
79	11-14-11X10	1279.98	.0116	.0133	.0203	.02043	.0233	.0293	.0390		
79	13-16-13X8	1120.64	.0133	.0152	.0232	.0233	.0266	.0335	.0446		
80	6X3	152.58	.1345	.1502	.1900	.2383	.5898	.5439	.5636	.3276	
80	7X3	170.92	.1201	.1340	.16967	.2127	.5265	.4856	.5031	.2925	
80	7X4	172	.1193	.1332	.1686	.2113	.5232	.4825	.5	.2906	
80	8X7	201.58	.1018	.1137	.1438	.1803	.4464	.4117	.4266	.2480	
80	8X8	204.1	.1005	.1122	.1420	.1781	.4409	.4066	.4213	.2449	
80	8X3	195.55	.1049	.1172	.1482	.1859	.4602	.4244	.4397	.2556	
80	10X10	274.7	.0747	.0834	.1055	.1323	.3276	.3021	.3130	.1820	
80	10X10	288.72	.0711	.0793	.1004	.1259	.3117	.2874	.2978	.1731	
80	10X6	309.01	.0664	.0741	.0938	.1176	.2912	.2685	.2783	.1618	
80	10X10	350.06	.0586	.0654	.0828	.1038	.2570	.2371	.2456	.1428	
80	10X10	462.16	.0444	.0495	.0627	.0786	.1947	.1795	.1860	.1081	
80	12X3	272.93	.0752	.0839	.1062	.1332	.3297	.3041	.3150	.1831	
80	14X8	427.78	.0479	.0535	.0677	.0849	.2103	.1940	.2010	.1168	
80	8-8X6	658.41	.0311	.0348	.0440	.0552	.1366	.1260	.1306	.0759	
80	9-9X5	770.72	.0266	.0297	.0376	.0471	.1167	.1076	.1115	.0648	
80	10-10X6	539.25	.0380	.0425	.0537	.0674	.1668	.1539	.1594	.0927	
80	10-10X6	564.84	.0363	.0405	.0513	.0643	.1593	.1469	.1522	.0885	
80	10-10X8	437.83	.0468	.0523	.0662	.0830	.2055	.1895	.1964	.1141	
80	10-10X8	505.21	.0406	.0453	.0574	.0719	.1781	.1642	.1702	.0989	
80	12-12X8	905.51	.0226	.0253	.0320	.0401	.0993	.0916	.0949	.0552	
80	12-12X10	618.08	.0332	.0370	.0469	.0588	.1456	.1342	.1391	.0808	
80	15-15X10	931.63	.0220	.0246	.0311	.0390	.0966	.0890	.0923	.0536	
80	9-12-9X8	632.06	.0324	.0362	.0458	.0575	.1423	.1313	.1360	.0791	
80	6-6-6X4	623.48	.0329	.0367	.0465	.0583	.1443	.1331	.1379	.0801	
80	9-12-9X10	674.01	.0304	.0340	.0430	.0539	.1335	.1231	.1275	.0741	
80	11-14-11X10	1529.94	.0134	.0149	.0189	.0237	.0588	.0542	.0562	.0326	
80	13-16-13X8	1018.2	.0201	.0225	.0284	.0357	.0883	.0815	.0844	.0491	
80	13-16-13X10	1113.08	.0184	.0205	.0260	.0326	.0808	.0745	.0772	.0449	
80	13-16-13X10	967.34	.0212	.0236	.0299	.0375	.0930	.0858	.0889	.0516	
81	5X3	112.06	.1819	.2331	.2361	.2820	.4015	.4102		.6126	.8014
81	6X4	168.92	.1207	.1546	.1566	.18713	.2663	.2721		.4064	.5316
81	6X7	227.19	.0897	.1150	.1164	.1391	.1980	.2023		.30217	.3953
81	7X7	283.02	.0720	.0923	.0934	.1116	.1589	.1624		.2425	.3173
81	8X4	148.48	.1373	.1759	.1782	.2128	.3030	.3096		.4623	.6048
81	8X7	223.13	.0913	.1171	.1185	.1416	.2016	.2060		.3076	.4025
81	8X8	215.89	.0944	.1210	.1225	.1464	.2084	.2129		.3179	.4160
81	8X8	201.3	.1012	.1298	.1314	.1570	.2235	.2283		.3410	.4461
81	10X5	348.39	.0585	.0750	.0759	.0907	.1291	.1319		.1970	.2577
81	10X8	306.47	.0665	.0852	.0863	.1031	.1468	.1499		.2240	.2930
81	10X10	248.56	.0820	.1051	.1064	.1271	.1810	.1849		.2761	.3613
81	10X10	480.9	.0423	.0543	.0550	.0657	.0935	.0955		.1427	.1867
81	12X8	379.44	.0537	.0688	.0697	.0833	.1185	.1211		.1809	.2366
81	14X5	524.57	.0388	.0498	.0504	.0602	.0857	.0876		.1308	.1712

Year	Size of CBC Span * Rise (ft) (ft)	Cost CBC ($/ft)	Pipe Diameter in Inches $\frac{\text{Cost of Pipe/Foot}}{\text{Cost of CBC/Foot}} = \frac{Cd}{Cp}$								
			18	24	30	36	42	48	54	60	72
81	5X3	112.06	.1819	.2331	.2361	.2820	.4015	.4102		.6126	.8014
81	6X4	168.92	.1207	.1546	.1566	.18713	.2663	.2721		.4064	.5316
81	6X7	227.19	.0897	.1150	.1164	.1391	.1980	.2023		.30217	.3953
81	7X7	283.02	.0720	.0923	.0934	.1116	.1589	.1624		.2425	.3173
81	8X4	148.48	.1373	.1759	.1782	.2128	.3030	.3096		.4623	.6048
81	8X7	223.13	.0913	.1171	.1185	.1416	.2016	.2060		.3076	.4025
81	8X8	215.89	.0944	.1210	.1225	.1464	.2084	.2129		.3179	.4160
81	8X8	201.3	.1012	.1298	.1314	.1570	.2235	.2283		.3410	.4461
81	10X5	348.39	.0585	.0750	.0759	.0907	.1291	.1319		.1970	.2577
81	10X8	306.47	.0665	.0852	.0863	.1031	.1468	.1499		.2240	.2930
81	10X10	248.56	.0820	.1051	.1064	.1271	.1810	.1849		.2761	.3613
81	10X10	480.9	.0423	.0543	.0550	.0657	.0935	.0955		.1427	.1867
81	12X8	379.44	.0537	.0688	.0697	.0833	.1185	.1211		.1809	.2366
81	14X5	524.57	.0388	.0498	.0504	.0602	.0857	.0876		.1308	.1712
81	14X8	540.24	.0377	.0483	.0489	.0585	.0832	.0850		.1270	.1662
81	14X10	594.38	.0343	.0439	.0445	.0531	.0757	.0773		.1154	.1511
81	14X14	526.6	.0387	.0496	.0502	.0600	.0854	.0872		.1303	.1705
81	18X5	576.68	.0353	.0453	.0458	.0548	.0780	.0797		.1190	.1557
81	20X8	614.58	.0331	.0425	.0430	.0514	.0732	.0747		.1117	.1461
81	10-10X10	589.23	.0346	.0443	.0449	.0536	.0763	.0780		.1165	.1524
81	12-12X10	563.72	.0361	.0463	.0469	.0560	.0798	.0815		.1217	.1593
81	12-12X10	688.53	.0296	.0379	.0384	.0459	.0653	.0667		.0997	.1304
81	9-12-9X6	561.54	.0363	.0465	.0471	.0562	.0801	.0818		.1222	.1599
81	14-14-14X10	942.33	.0216	.0277	.0280	.0335	.0477	.0487		.0728	.0953
82	8X3	276.3	.0596	.0712	.0904	.1005	.0995	.1318	.1539	.1749	.2823
82	8X8	232.22	.0710	.0847	.1076	.1195	.1184	.1569	.1831	.2081	.3358
82	8X8	260.07	.0634	.0757	.0960	.1067	.1057	.1401	.1635	.1858	.2999
82	9X6	258.8	.0637	.0760	.0965	.1073	.1062	.1408	.1643	.1867	.3013
82	9X6	350	.0471	.0562	.0714	.0793	.0786	.1041	.1215	.1380	.2228
82	20X7	773.66	.0213	.0254	.0323	.0358	.0355	.0471	.0549	.0624	.1008
82	20X8	601.85	.0273	.0327	.0415	.0461	.0457	.0605	.0706	.0803	.1296
82	6-6X4	236.35	.0697	.0833	.1057	.1174	.1163	.1541	.1799	.2044	.3300
82	8-8X4	308.87	.0533	.0637	.0809	.0899	.0890	.1179	.1377	.1564	.2525
82	8-8X6	385.72	.0427	.0510	.0647	.0719	.0713	.0944	.1102	.1252	.2022
82	8-8X6	349.02	.0472	.0564	.0716	.0795	.0788	.1044	.1218	.1384	.2234
82	9-9X6	365.28	.0451	.0539	.0684	.0760	.0753	.0997	.1164	.1323	.2135
82	9-9X6	426.75	.0386	.0461	.0585	.0650	.0644	.0853	.0996	.1132	.1827
82	10-10X6	476.51	.0346	.0413	.0524	.0582	.0577	.0764	.0892	.1014	.1636
82	10-10X6	542.87	.0303	.0362	.0460	.0511	.0506	.0671	.0783	.0890	.1436
82	10-10X6	394.3	.0418	.0499	.0633	.0704	.0697	.0924	.1078	.1225	.1978
82	10-10X8	401.27	.0410	.0490	.0622	.0692	.0685	.0908	.1060	.1204	.1943
82	10-10X10	446.2	.0369	.0441	.0560	.0622	.0616	.0816	.0953	.1083	.1748
82	10-10X10	488.52	.0337	.0403	.0511	.0568	.0563	.0745	.0870	.0989	.1596
82	12-12X6	529.25	.0311	.0372	.0472	.0524	.0519	.0688	.0803	.0913	.1473
82	9-12-9X10	793.92	.0207	.0248	.0314	.0349	.0346	.0458	.0535	.0608	.0982
82	12-12-12X12	791.33	.0208	.0248	.0315	.0350	.0347	.0460	.0537	.0610	.0985
82	13-16-13X6	883.81	.0186	.0222	.0282	.0314	.0311	.0412	.0481	.0546	.0882
82	13-16-13X6	817.36	.0201	.0240	.0305	.0339	.0336	.0445	.0520	.0591	.0954

Year	Size of CBC Span * Rise (ft) (ft)	Cost CBC ($/ft)	Pipe Diameter in Inches $\frac{\text{Cost of Pipe/Foot}}{\text{Cost of CBC/Foot}} = \frac{Cd}{Cp}$								
	--		18	24	30	36	42	48	54	60	72
83	5X7	149.38	.05	.08	.08	.10	.08	.13	.13	.14	.17
83	6X3	244.72	.03	.05	.05	.06	.05	.08	.08	.08	.11
83	6X4	163.48	.05	.07	.07	.09	.07	.12	.12	.13	.16
83	6X4	157.43	.05	.07	.07	.10	.08	.12	.12	.13	.16
83	6X5	153.31	.05	.08	.08	.10	.08	.12	.13	.13	.17
83	6X6	143.34	.06	.08	.08	.11	.08	.13	.13	.14	.18
83	7X4	234.00	.03	.05	.05	.06	.05	.08	.08	.09	.11
83	7X7	218.47	.04	.05	.05	.07	.06	.09	.09	.09	.12
83	8X4	344.67	.02	.03	.03	.04	.03	.06	.06	.06	.07
83	10X10	338.06	.02	.03	.03	.04	.04	.06	.06	.06	.08
83	10X10	295.29	.03	.04	.04	.05	.04	.06	.06	.07	.09
83	12X7	273.21	.03	.04	.04	.06	.04	.07	.07	.07	.09
83	12X8	406.41	.02	.03	.03	.04	.03	.05	.05	.05	.06
83	14X8	387.41	.02	.03	.03	.04	.03	.05	.05	.05	.07
83	7-7X10	357.24	.02	.03	.03	.04	.03	.05	.05	.06	.07
83	9-9X7	523.04	.02	.02	.02	.03	.02	.04	.04	.04	.05
83	10-10X10	689.64	.01	.02	.02	.02	.02	.03	.03	.03	.04
83	12-12X10	717.67	.01	.02	.02	.02	.02	.03	.03	.03	.04
83	14-14X8	731.85	.01	.02	.02	.02	.02	.03	.03	.03	.04
83	9-12-9X10	855.76	.01	.01	.01	.02	.01	.02	.02	.02	.03
83	12-12-12X12	972.75	.01	.01	.01	.02	.01	.02	.02	.02	.03
83	13-16-13X8	975.40	.01	.01	.01	.02	.01	.02	.02	.02	.03
84	6X4	296.70	.03	.04	.04	.06	.06	.06	.09	.08	.09
84	6X7	258.35	.03	.04	.04	.07	.07	.07	.11	.17	.10
84	6X7	290.80	.03	.04	.04	.06	.06	.06	.09		.09
84	8X6	275.37	.03	.04	.04	.07	.07	.06	.10		.09
84	10X7	303.42	.03	.04	.04	.06	.06	.06	.09	.16	.08
84	14X10	490.12	.02	.02	.02	.04	.04	.04	.06		.05
84	14X10	528.22	.02	.02	.02	.04	.04	.03	.05		.05
84	8-8X6	471.47	.02	.02	.02	.04	.04	.04	.06		.05
84	10-10X4	432.77	.02	.03	.03	.04	.04	.04	.06		.06
84	10-10X4	485.07	.02	.02	.02	.04	.04	.04	.06		.05
84	10-10X6	592.47	.01	.02	.02	.03	.03	.03	.05		.04
84	10-10X8	689.72	.01	.02	.02	.03	.03	.03	.04		.04
84	12-12X8	905.45	.01	.01	.01	.02	.02	.02	.03		.03
84	14-14X10	971.83	.01	.01	.01	.02	.02	.02	.03		.03
84	9-12-9X6	672.90	.01	.02	.02	.03	.03	.03	.04		.04
84	11-14-11X6	967.47	.01	.01	.01	.02	.02	.02	.03		.03
84	13-16-13X6	960.20	.01	.01	.01	.02	.02	.02	.03		.03
84	13-16-13X10	1257.32	.01	.01	.01	.01	.01	.01	.02		.02
85	6X7	132.68	.15	.16	.17	.21	.22	.29	.32		
85	7X5	234.45	.08	.09	.10	.12	.12	.16	.18		
85	9X7	280.90	.07	.08	.08	.10	.10	.14	.15		
85	10X10	343.17	.06	.06	.07	.08	.08	.11	.12		
85	14X7	427.33	.05	.05	.05	.06	.07	.09	.10		
85	14X8	417.51	.05	.05	.06	.07	.07	.09	.10		
85	14X10	417.95	.05	.05	.06	.07	.07	.09	.10		
85	5-5X3	471.38	.04	.05	.05	.06	.06	.08	.09		
85	8-8X6	394.52	.05	.06	.06	.07	.07	.10	.11		
85	8-8X6	327.91	.06	.07	.07	.08	.09	.12	.13		
85	10-10X6	499.93	.04	.04	.05	.06	.06	.08	.08		
85	12-12X4	635.48	.03	.03	.04	.04	.04	.06	.07		
85	12-12X6	1130.19	.02	.02	.02	.02	.03	.03	.04		
85	12-12X8	742.13	.03	.03	.03	.04	.04	.05	.06		

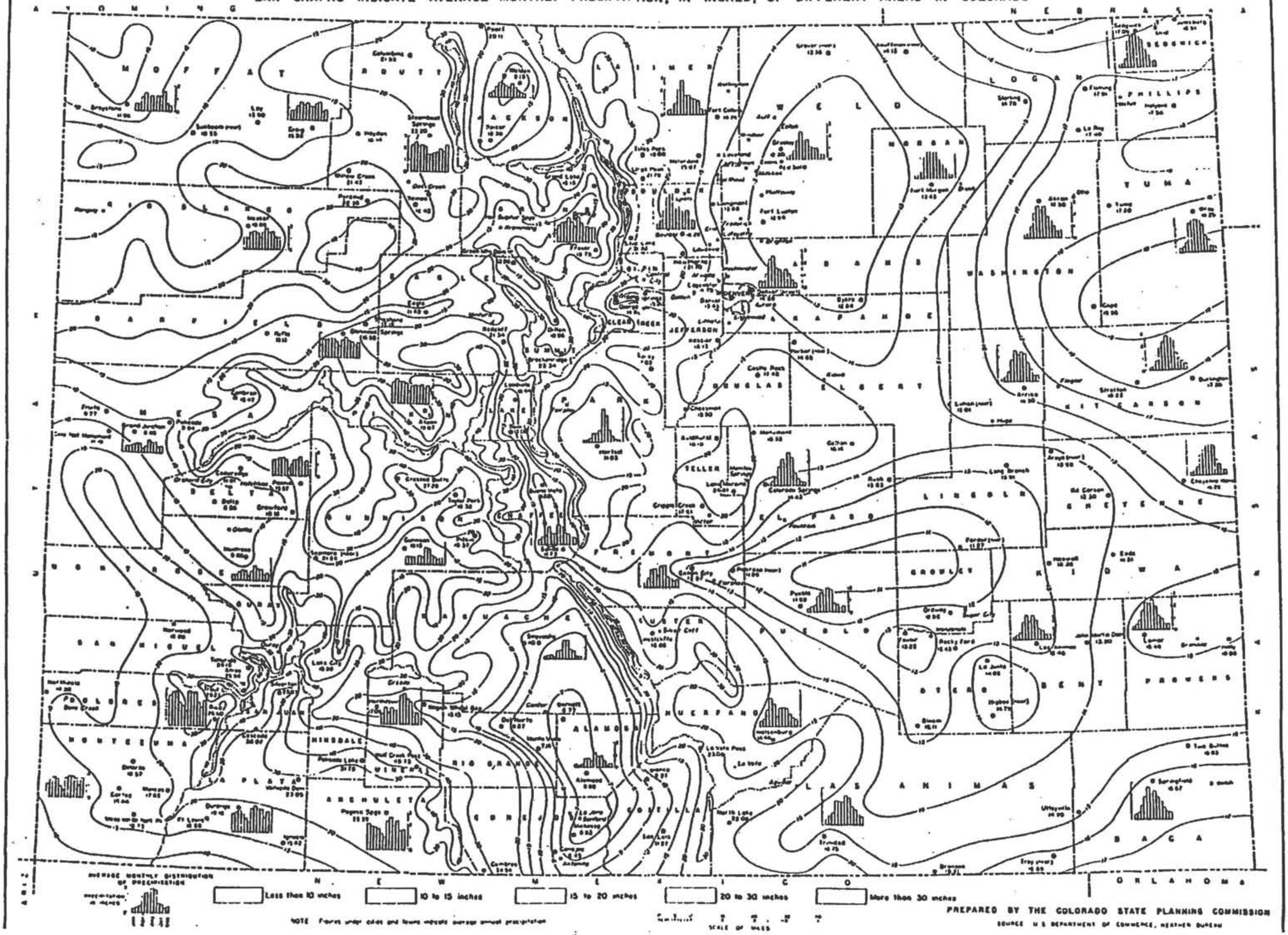
Appendix E: Data Reduction for Capacity Ratios.

Concrete Box Culvert Span (feet)	Concrete Box Culvert Rise (feet)	Capacity Q (cfs)	Pipe Diameter (inches) capacity of pipe / Capacity of CBC = q/Q: 18	24	30	36	42	48	54
5	3	100	.09	.18	.32	.44	.54	.90	
5	4	160	.06	.11	.20	.28	.34	.56	.75
5	5	225	.04	.08	.14	.20	.24	.40	.53
6	4	192	.05	.09	.17	.23	.28	.47	.62
6	5	270	.03	.07	.12	.16	.20	.33	.44
6	6	324	.03	.06	.10	.14	.17	.28	.37
7	4	224	.04	.08	.14	.20	.24	.40	.54
7	5	315	.03	.06	.10	.14	.17	.29	.38
7	6	378	.02	.05	.08	.12	.14	.24	.32
7	7	476	.02	.04	.07	.09	.11	.19	.25
8	4	256	.04	.07	.12	.17	.21	.35	.47
8	5	360	.03	.05	.09	.12	.15	.25	.33
8	6	432	.02	.04	.07	.10	.12	.21	.28
8	7	544	.02	.03	.06	.08	.10	.17	.22
8	8	504	.02	.04	.06	.09	.11	.18	.24
9	5	405	.02	.04	.08	.11	.13	.22	.30
9	6	486	.02	.04	.07	.09	.11	.19	.25
9	7	612	.01	.03	.05	.07	.09	.15	.20
9	8	567	.02	.03	.06	.08	.10	.16	.21
9	9	702	.01	.03	.05	.06	.08	.13	.17
10	6	540	.02	.03	.06	.08	.10	.17	.22
10	7	680	.01	.03	.05	.06	.08	.13	.18
10	8	630	.01	.03	.05	.07	.09	.14	.19
10	9	780	.01	.02	.04	.06	.07	.12	.15
10	10	910	.01	.02	.04	.05	.06	.10	.13
11	6	594	.02	.03	.05	.07	.09	.15	.20
11	7	748	.01	.02	.04	.06	.07	.12	.16
11	8	693	.01	.03	.05	.06	.08	.13	.17
11	9	858	.01	.02	.04	.05	.06	.10	.14
11	10	1001	.01	.02	.03	.04	.05	.09	.12
12	6	648	.01	.03	.05	.07	.08	.14	.19
12	7	816	.01	.02	.04	.05	.07	.11	.15
12	8	756	.01	.02	.04	.06	.07	.12	.16
12	9	936	.01	.02	.03	.05	.06	.10	.13
12	10	1092	.01	.02	.03	.04	.05	.08	.11
13	6	702	.01	.03	.05	.06	.08	.13	.17
13	7	884	.01	.02	.04	.05	.06	.10	.14
13	8	819	.01	.02	.04	.05	.07	.11	.15
13	9	1014	.01	.02	.03	.04	.05	.09	.12
13	10	1183	.01	.02	.03	.04	.05	.08	.10
14	6	756	.01	.02	.04	.06	.07	.12	.16
14	7	952	.01	.02	.03	.05	.06	.09	.13
14	8	882	.01	.02	.04	.05	.06	.10	.14
14	9	1092	.01	.02	.03	.04	.05	.08	.11
14	10	1274	.01	.01	.03	.03	.04	.07	.09

Concrete Box Culvert Span (feet)	Rise (feet)	Capacity Q (cfs)	Pipe Diameter (inches) capacity of pipe / Capacity of CBC = q / Q					
			54	60	72	78	84	96
5	3	100						
5	4	160	.75	.97				
5	5	225	.53	.69	.98			
6	4	192	.62	.81				
6	5	270	.44	.57	.81			
6	6	324	.37	.48	.68	.86		
7	4	224	.54	.69	.98			
7	5	315	.38	.49	.70	.89		
7	6	378	.32	.41	.58	.74	.90	
7	7	476	.25	.33	.46	.59	.71	.84
8	4	256	.47	.61	.86			
8	5	360	.33	.43	.61	.78	.94	
8	6	432	.28	.36	.51	.65	.79	.93
8	7	544	.22	.28	.40	.51	.62	.74
8	8	504	.24	.31	.44	.56	.67	.79
9	5	405	.30	.38	.54	.69	.84	.99
9	6	486	.25	.32	.45	.58	.70	.82
9	7	612	.20	.25	.36	.46	.56	.65
9	8	567	.21	.27	.39	.49	.60	.71
9	9	702	.17	.22	.31	.40	.48	.57
10	6	540	.22	.29	.41	.52	.63	.74
10	7	680	.18	.23	.32	.41	.50	.59
10	8	630	.19	.25	.35	.44	.54	.63
10	9	780	.15	.20	.28	.36	.44	.51
10	10	910	.13	.17	.24	.31	.37	.44
11	6	594	.20	.26	.37	.47	.57	.67
11	7	748	.16	.21	.29	.37	.45	.53
11	8	693	.17	.22	.32	.40	.49	.58
11	9	858	.14	.18	.26	.33	.40	.47
11	10	1001	.12	.15	.22	.28	.34	.40
12	6	648	.19	.24	.34	.43	.52	.62
12	7	816	.15	.19	.27	.34	.42	.49
12	8	756	.16	.21	.29	.37	.45	.53
12	9	936	.13	.17	.24	.30	.36	.43
12	10	1092	.11	.14	.20	.26	.31	.37
13	6	702	.17	.22	.31	.40	.48	.57
13	7	884	.14	.18	.25	.32	.38	.45
13	8	819	.15	.19	.27	.34	.42	.49
13	9	1014	.12	.15	.22	.28	.34	.39
13	10	1183	.10	.13	.19	.24	.29	.34
14	6	756	.16	.21	.29	.37	.45	.53
14	7	952	.13	.16	.23	.29	.36	.42
14	8	882	.14	.18	.25	.32	.39	.45
14	9	1092	.11	.14	.20	.26	.31	.37
14	10	1274	.09	.12	.17	.22	.27	.31

Appendix F: Diagram of Monthly Rainfall Distribution for the State of Colorado.

LINES WITH FIGURES INDICATE AREAS OF EQUAL AVERAGE ANNUAL PRECIPITATION, IN INCHES
BAR GRAPHS INDICATE AVERAGE MONTHLY PRECIPITATION, IN INCHES, OF DIFFERENT AREAS IN COLORADO



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