Report No. K-TRAN: KU-04-3
FINAL REPORT

STORAGE EFFECTS AT CULVERTS

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DECEMBER 2005

K-TRAN

A COOPERATIVE TRANSPORTATION RESEARCH PROGRAM BETWEEN:
KANSAS DEPARTMENT OF TRANSPORTATION
KANSAS STATE UNIVERSITY
THE UNIVERSITY OF KANSAS

1 Report No. K-TRAN: KU-04-3	2 Government Accession No.	3 Recipient Catalog No.
4 Title and Subtitle STORAGE EFFECTS AT CULVERTS		5 Report Date December 2005
		6 Performing Organization Code
7 Author(s) Bruce M. McEnroe and Scott A. Gonzalez		8 Performing Organization Report No.
9 Performing Organization Name and Address University of Kansas Civil, Environmental & Architectural Engineering Department 1530 West 15th Street, Room 2150D Lawrence, Kansas 66045-7609		10 Work Unit No. (TRAIS)
		11 Contract or Grant No. C1409
12 Sponsoring Agency Name and Address Kansas Department of Transportation Bureau of Materials and Research 700 SW Harrison Street Topeka, Kansas 66603-3754		13 Type of Report and Period Covered Final Report July 2003 – April 2005
		14 Sponsoring Agency Code RE-0346-01
15 Supplementary Notes For more information write to address in block 9.		

16 Abstract

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This report presents new methods for quickly estimating the effects of detention storage on the performance of existing culverts and the sizing of new culverts. These methods, which do not require hydrograph routing, are applicable to pipe and box culverts operating under inlet control with no overtopping of the roadway. Peak discharges can be computed by the Rational method, USGS regression equations or any other appropriate method. Water-surface areas at two or more stages are needed to define an approximate depth-area relationship. The required areas can be estimated from existing topographic maps or measured in the field by one person with a rotating laser level and a GPS unit.

Analyses of seven pipe-culvert sites in Johnson County showed that detention-storage design would reduce the required pipe diameter by at least one increment at five of the seven sites, and by two or more increments at three of the sites. Similar analyses of ten box-culvert sites showed that detention-storage design would reduce the required span by more than 10% at three of the ten sites. Our test results indicate that storage effects are less likely to be significant for large culverts than for small culverts.

The design of a culvert for detention storage rather than peak flow generally requires another survey, extra design effort and the purchase of additional right-of-way or a drainage easement for the storage area. Detention-storage design is economically justifiable only if cost savings on the culvert exceeds these added costs. In locations where storage effects are significant but detention-storage design is not economically justifiable, the culvert should be designed for peak flow.

17 Key Words Culvert, Design, Discharge, Drainage, Storage and Topography,		18 Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19 Security Classification (of this report) Unclassified	20 Security Classification (of this page) Unclassified	21 No. of pages 93	22 Price

Form DOT F 1700.7 (8-72)

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A Report on Research Sponsored By

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
LAWRENCE, KANSAS

December 2005

PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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saving on the culvert exceeds these added costs. In locations where storage effects are significant but detention-storage design is not economically justifiable, the culvert should be designed for peak flow.

ACKNOWLEDGMENTS

This project was supported by the Kansas Department of Transportation (KDOT) through the Kansas Transportation Research and New Developments (K-TRAN) Program. James R. Richardson, P.E., of KDOT served as project monitor. M. Wayne Blackbourn, L.S., of KDOT provided guidance on survey methods. Kent Lage, P.E., and Chet Belcher, P.E., of the Johnson County Public Works Department provided the digital planimetric data. The authors sincerely appreciate these contributions of these individuals.

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A	inundated area (acres)
A_1	inundated area at headwater depth h_1 (acres)
A_2	inundated area at headwater depth h_2 (acres)
A_a	inundated area at allowable headwater depth (acres)
A_d	inundated area at headwater depth $h = d$ (acres)
A_{ref}	headwater depth at reference headwater depth, h_{ref} (acres)
B	total span of box culvert (sum of spans for all cells) (feet)
B^*	B/d or B/h_a (dimensionless)
B_o	required total span for no storage effect (feet)
B_o^*	B_o/h_a (dimensionless)
c	constant in depth-area relationship (equation 2-16)
C_I	storage factor, defined by equation 3-8, 4-6, 5-7 or 6-8 (dimensionless)
C_S	discharge factor, defined by equation 3-7, 4-5, 5-6 or 6-7 (dimensionless)
d	culvert diameter or rise (feet)
d^*	d/h_a (dimensionless)
d_o	required pipe diameter for no storage effect (feet)
d_o^*	d_o/h_a (dimensionless)
f_I	shape function for inflow hydrograph
f_Q	discharge function for culvert
g	gravitational constant (32.2 ft/s^2 or 9.81 m/s^2)
h	headwater depth (feet)
h_a	allowable headwater depth (feet)
h_p	peak headwater depth (feet)
h_p^*	h_p/d or h_p/h_a (dimensionless)
h_{po}	peak headwater depth for no storage effect (feet)
h_{po}^*	h_{po}/d (dimensionless)
h_1	any headwater depth at which inundated area is known (feet)
h_2	any headwater depth at which inundated area is known (feet)
h^*	h/d or h/h_a (dimensionless)
I	inflow (discharge into storage)
I_p	peak discharge on inflow hydrograph (ft^3/s)
m	exponent in depth-area relationship (equation 2-16)
N	number of identical pipes or box sections in parallel
Q	outflow (discharge out of storage through culvert) (ft^3/s)
S	volume of water in storage (acre-feet)
t	time from start of inflow (hours)
t_p	time-to-peak on inflow hydrograph (hours)
t^*	t/t_p (dimensionless)
V	flood volume (acre-feet)
W	drainage area (mi^2)

CHAPTER 1

INTRODUCTION

The temporary ponding of water on the upstream side of a culvert serves to reduce the peak discharge that the culvert must convey. In many cases the discharge reduction resulting from this detention storage is insignificant and can be neglected in design. However, in some cases the storage effect is substantial and accounting for it may result in a more economical design.

The design of a culvert for detention storage requires more effort than design for peak flow. A culvert may be designed for detention storage where significant cost savings would result. Storage effects should not be considered in design if the storage site could be filled in or developed in the future. In certain locations, the potential cost savings from detention-storage design may justify the purchase of additional right-of-way or a drainage easement to protect the storage site.

Hydrologic models for floodplain mapping studies should include reservoir routing at culverts where storage effects are significant. Reservoir routing may be omitted at culverts where these effects are negligible. Experience has shown that storage effects tend to be negligible at most culverts but can be substantial at certain installations.

This report presents new methods for quickly estimating the effects of storage on the performance of existing culverts and the sizing of new culverts. These methods apply to both pipe culverts and box culverts and do not require flood hydrograph simulation or reservoir routing. These new methods are used to investigate the potential benefits of detention-storage design at seventeen sites in Johnson County.

CHAPTER 2

PRELIMINARIES

2.1 Reservoir Routing

Detention storage effects at culverts can be analyzed by standard reservoir routing. The inputs to the reservoir routing calculation are a depth-storage or depth-area relationship for the detention site, a depth-discharge relationship (rating curve) for the culvert, and an inflow hydrograph. The outputs are outflow hydrograph and the record of headwater level versus time. The peak outflow is compared with the peak inflow, and the peak headwater level from the routing calculation is compared with the headwater level required to pass the peak inflow with no storage.

The standard statement of continuity for reservoir routing is

$$\frac{dS}{dt} = I - Q \tag{2-1}$$

in which S = volume of water in storage above a specified datum, t = time, I = inflow (discharge into storage), and Q = outflow (discharge out of storage). The rate of change in storage can be expressed in terms of the water-surface area and the rate of change in the water level as

$$\frac{dS}{dt} = \frac{dS}{dh}\frac{dh}{dt} = A\frac{dh}{dt} \tag{2-2}$$

in which A = water-surface area, and h = water level. In this analysis, the relevant water level is the headwater depth upstream of the culvert, measured above the flowline elevation at the culvert entrance. The continuity equation can be written in terms of the headwater depth and the water-surface area as

$$A \frac{dh}{dt} = I - Q \qquad (2\text{-}3)$$

2.2 Inflow Hydrograph

2.2.1 Hydrograph Shape

The inflow hydrograph is assumed to have a characteristic shape that relates I/I_p to t/t_p, where I_p is the peak inflow and t_p is the time-to-peak; i.e.,

$$I = I_p \, f_I\left(\frac{t}{t_p}\right) \qquad (2\text{-}4)$$

in which f_I is the hydrograph shape function. In this analysis, the inflow hydrograph is assumed to have the shape shown in Figure 2-1. The shape function for this dimensionless hydrograph is

$$f_I\left(\frac{t}{t_p}\right) = \left(\frac{t}{t_p}\right)^4 \exp\left[-4\left(\frac{t}{t_p} - 1\right)\right] \qquad (2\text{-}5)$$

This shape is similar to the shape of the NRCS dimensionless unit hydrograph.

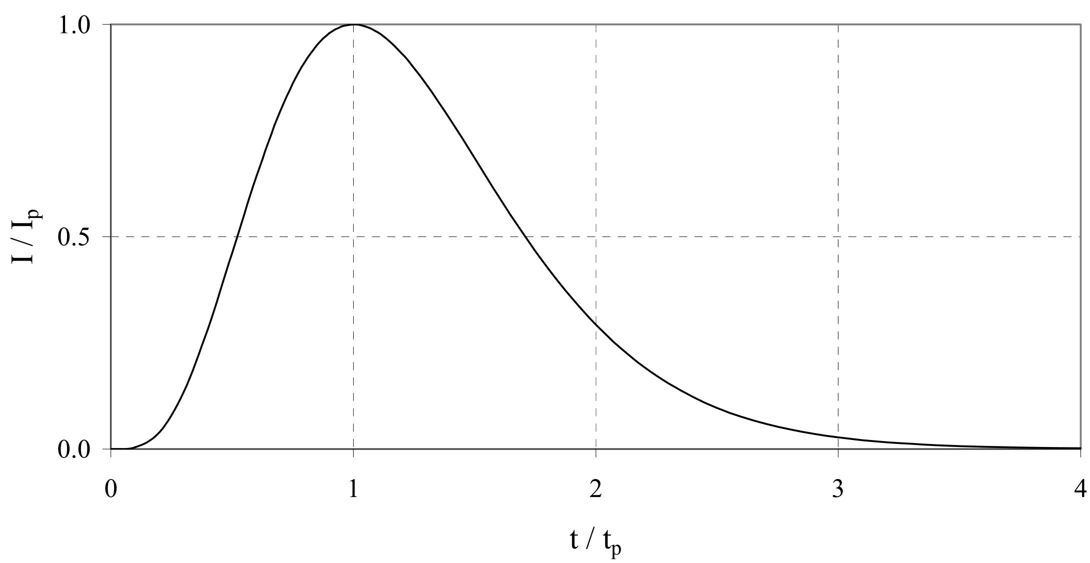

Figure 2-1. Dimensionless Inflow Hydrograph

2.2.2 Determination of Time to Peak

The flood volume, V, depends on the peak inflow, the time-to-peak and the shape function. The relationship for the selected shape function (equation 2-5) is

$$V = 1.280\, I_p\, t_p \tag{2-6}$$

The constant in equation 2-6 is dimensionless; the units of V are determined by the units of I_p and t_p.

The simplified methods developed in this report requires I_p and t_p as inputs. The peak inflow can be computed by any method that would be acceptable for routine design. The time-to-peak can be computed from the peak inflow and a reasonable estimate of the flood volume with the relationship

$$t_p = 9.45 \frac{V}{I_p} \tag{2-7}$$

in which t_p is in hours, I_p is in cubic feet per second and V is in acre-feet. Equation 2-7 follows directly from equation 2-6.

The flood volume in equation 2-7 can be obtained from the regression equations in Table 2-1, provided that (1) the watershed is located in Kansas, (2) the drainage area is under 20 square miles, and (3) the recurrence interval is not less than 10 years and not more than 100 years. We fitted these equations to the results of flood hydrograph simulations for the 66 gaged watersheds listed in Table 2. Figure 2-3 shows the locations of these USGS streamflow gages. These watersheds are the same ones investigated in a previous study of design-storm durations and antecedent moisture conditions (McEnroe and Gonzalez, 2003). Floods with recurrence intervals of 10, 25, 50 and 100 years were simulated as directed in the 2004 draft revisions to the Hydrology section of the KDOT Design Manual.

Table 2-1. Regression Equations for Volume of Design Flood

Hydrologic Region of Kansas	Recurrence Interval (years)	Equation	Standard Error (%)	Equation number
East	10	$V = 14.2\ W^{0.774}\ I_p^{0.332}$	11	2-8
East	25	$V = 48.2\ W^{0.851}\ I_p^{0.212}$	10	2-9
East	50	$V = 100.6\ W^{0.901}\ I_p^{0.135}$	9	2-10
East	100	$V = 192.8\ W^{0.774}\ I_p^{0.332}$	7	2-11
West	10	$V = 3.92\ W^{0.752}\ I_p^{0.409}$	15	2-12
West	25	$V = 6.18\ W^{0.758}\ I_p^{0.405}$	14	2-13
West	50	$V = 9.01\ W^{0.779}\ I_p^{0.368}$	13	2-14
West	100	$V = 17.26\ W^{0.809}\ I_p^{0.319}$	13	2-15

Note: V = volume in ac-ft, W = drainage area in mi^2, I_p = peak discharge in cfs

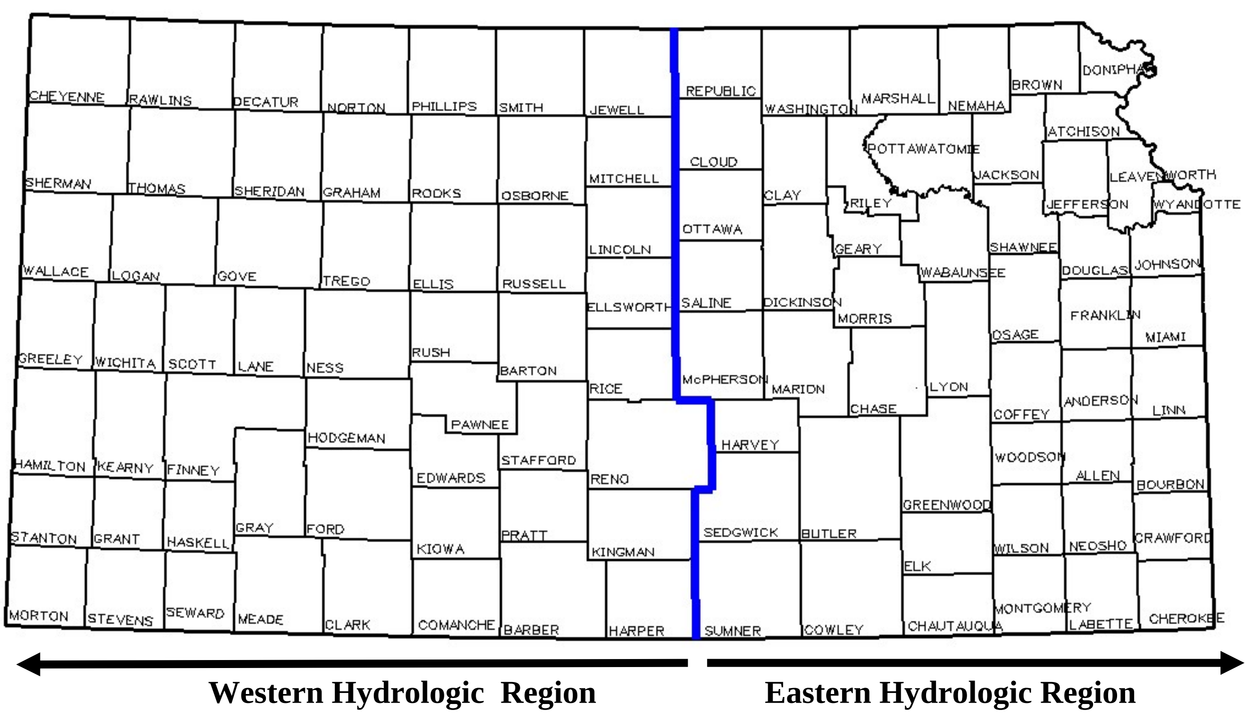

Figure 2-2. Eastern and Western Hydrologic Regions of Kansas

Table 2-2. Selected USGS Streamflow Gages

Station ID	Station Name	County	Drainage Area (km^2)	Years of record
6813700	Tennessee Creek tributary near Seneca	Nemaha	2.32	33
6815700	Buttermilk Creek near Willis	Brown	9.57	40
6818260	White Clay Creek at Atchison	Atchison	33.40	25
6846200	Beaver Creek tributary near Ludell	Rawlins	27.32	33
6847600	Prairie Dog Creek tributary at Colby	Thomas	20.28	41
6848200	Prairie Dog Creek tributary near Norton	Norton	2.75	35
6856800	Moll Creek near Green	Clay	10.32	34
6863400	Big Creek tributary near Ogallah	Trego	12.45	41
6863700	Big Creek tributary near Hays	Ellis	15.79	39
6864300	Smoky Hill River tributary at Dorrance	Russell	14.16	41
6864700	Spring Creek near Kanopolis	Ellsworth	24.84	33
6866800	Saline River tributary at Collyer	Trego	8.85	33
6867800	Cedar Creek tributary near Bunker Hill	Russell	2.79	21
6868300	Coon Creek tributary near Luray	Osborne	16.76	41
6868900	Bullfoot Creek tributary near Lincoln	Lincoln	7.52	31
6872600	Oak Creek at Bellaire	Smith	13.92	33
6873300	Ash Creek tributary near Stockton	Rooks	2.27	39
6873800	Kill Creek tributary near Bloomington	Osborne	3.72	21
6876200	Middle Pipe Creek near Miltonvale	Cloud	25.49	21
6877400	Turkey Creek tributary near Elmo	Dickinson	6.43	21
6879700	Wildcat Creek at Riley	Riley	35.06	21
6884100	Mulberry Creek tributary near Haddam	Washington	4.18	32
6884300	Mill Creek tributary near Washington	Washington	7.50	41
6887200	Cedar Creek near Manhattan	Pottawatomie	36.27	32
6888600	Dry Creek near Maple Hill	Wabaunsee	40.70	21
6889100	Soldier Creek near Goff	Nemaha	5.36	23
6889120	Soldier Creek near Bancroft	Nemaha	27.29	24
6889140	Soldier Creek near Soldier	Nemaha	43.59	33
6889600	South Branch Shunganunga Creek near Pauline	Shawnee	9.95	21
6890700	Slough Creek tributary near Oskaloosa	Jefferson	2.18	21
6891050	Stone House Creek at Williamstown	Jefferson	33.81	26
6912300	Dragoon Creek tributary near Lyndon	Osage	9.44	34
6913600	Rock Creek near Ottawa	Franklin	25.90	21
6914250	South Fork Pottawatomie Creek trib. near Garnett	Anderson	0.95	34
6916700	Middle Creek near Kincaid	Anderson	5.38	34
6917100	Marmaton River tributary near Bronson	Allen	2.30	34
6917400	Marmaton River tributary near Fort Scott	Bourbon	7.28	41
7139700	Arkansas River tributary near Dodge City	Ford	24.24	39
7141400	South Fork Walnut Creek tributary near Dighton	Lane	2.24	21
7141800	Otter Creek near Rush Center, Kansas	Rush	44.54	33
7142100	Rattlesnake Creek tributary near Mullinville	Kiowa	25.86	33
7143100	Little Cheyenne Creek tributary near Claflin	Barton	3.81	41
7143200	Plum Creek near Holyrood	Ellsworth	49.07	20
7144900	South Fork Ninnescah River tributary near Pratt	Pratt	3.79	32
7145300	Clear Creek near Garden Plain	Sedgwick	13.11	33

Table 2-2. Selected USGS Streamflow Gages (continued)

Station ID	Station Name	County	Drainage Area (km^2)	Years of record
7145800	Antelope Creek tributary near Dalton	Sumner	1.03	33
7146700	West Branch Walnut River tributary near Degraff	Butler	26.45	21
7147020	Whitewater River tributary near Towanda	Butler	0.45	34
7147200	Dry Creek tributary near Augusta	Butler	2.28	21
7147990	Cedar Creek tributary near Cambridge	Cowley	6.48	35
7148700	Dog Creek near Deerhead, Kansas	Barber	12.99	21
7148800	Medicine Lodge River trib. near Medicine Lodge	Barber	5.53	21
7151600	Rush Creek near Harper	Harper	30.33	33
7156700	Cimarron River tributary near Satanta	Seward	10.43	38
7157400	Crooked Creek tributary at Meade	Meade	17.42	33
7166200	Sandy Creek near Yates Center	Woodson	17.64	41
7169200	Salt Creek near Severy	Greenwood	19.48	21
7169700	Snake Creek near Howard	Elk	4.67	21
7170600	Cherry Creek near Cherryvale	Labette	38.82	21
7170800	Mud Creek near Mound Valle	Labette	11.11	34
7171700	Spring Branch near Cedar Vale	Chautauqua	7.99	38
7171800	Cedar Creek tributary near Hooser	Cowley	1.39	34
7171900	Grant Creek near Wauneta	Chautauqua	49.89	21
7180300	Spring Creek tributary near Florence	Marion	1.50	34
7182520	Rock Creek at Burlington	Coffey	21.42	21
7183800	Limestone Creek near Beulah	Crawford	33.97	33

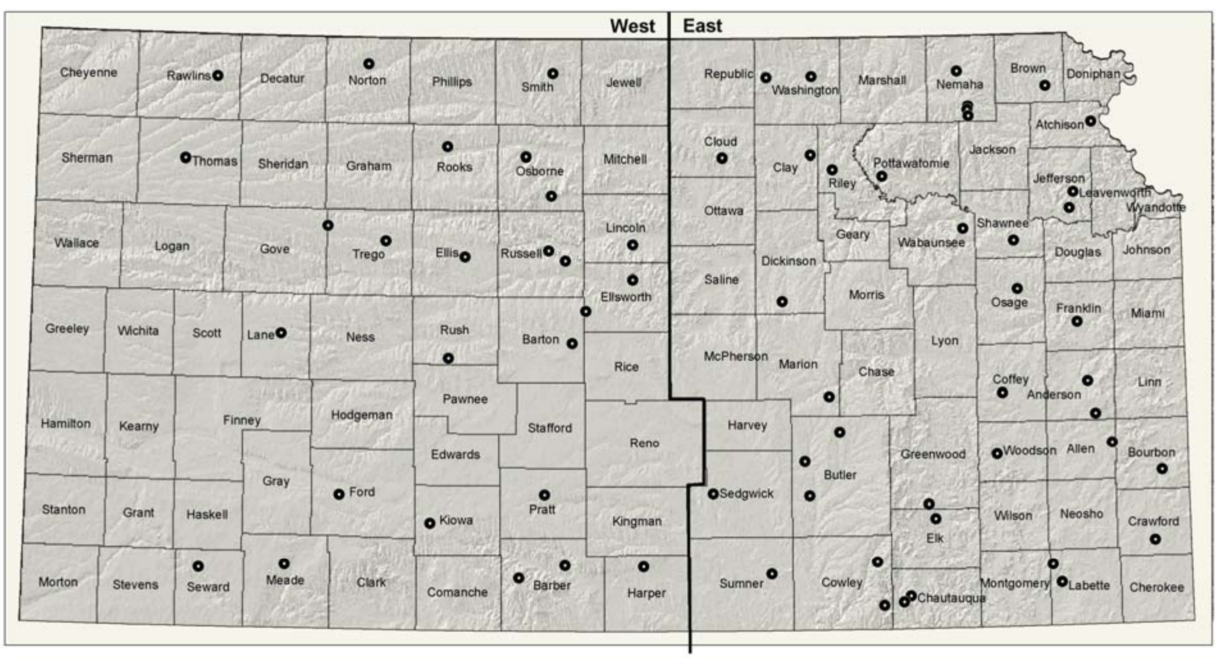

Figure 2-3. Locations of Selected USGS Streamflow Gages

2.3 Depth-Area Relationship

2.3.1 General Form

To determine an appropriate functional form for a generalized depth-area relationship, we analyzed stage-area data for 25 culvert sites on highways K-7, US-69, I-35 and K-10 in Johnson County. The Johnson County Stormwater Management Program provided digital two-foot elevation contours for these sites. We used ArcView GIS to find the area enclosed by each contour. The flowline at the culvert entrance was assumed to be two feet below the lowest contour upstream of the culvert. We found that the depth-area relationships at these sites could be approximated satisfactorily with equations of the form

$$A = c\,h^m \tag{2-16}$$

in which c and m are constants for the site. The values of c and m for each site were determined by linear regression with log(h) as the independent variable and log(A) as the dependent variable. The m values for the 25 sites range from 1.66 to 4.33 with a median value of 2.58, a mean value of 2.70 and a standard deviation of 0.74.

Eq. 2-16 can be written in terms of the inundated area at a reference headwater depth as

$$A = A_{ref}\left(\frac{h}{h_{ref}}\right)^m \tag{2-17}$$

in which A_{ref} is the inundated area at headwater depth h_{ref}. This report addresses both the analysis of existing culverts and the sizing of new culverts. The appropriate reference depth for culvert analysis is the culvert diameter or rise, d; the corresponding depth-area relationship for culvert analysis is

$$A = A_d \left(\frac{h}{d} \right)^m \tag{2-18}$$

in which A_d is the inundated area at h = d. The appropriate reference depth for culvert sizing is the allowable headwater depth, h_a; the corresponding depth-area relationship for culvert sizing is

$$A = A_a \left(\frac{h}{h_a} \right)^m \tag{2-19}$$

in which A_a is the inundated area at $h = h_a$.

2.3.2 Determination of Depth-Area Constants

The simplified analysis and design methods require values of m and either A_d or A_a as inputs. These values can be determined from measured (or estimated) areas of ponding at two or more headwater depths. Section 2.3.3 suggests a simple method for acquiring these data by survey where they cannot be estimated reliably from existing maps or survey data.

The values of constants m, A_d and A_a can be computed from the two data points with the equations 2-20 through 2-22.

$$m = \frac{\log\left(\frac{A_2}{A_1} \right)}{\log\left(\frac{h_2}{h_1} \right)} \tag{2-20}$$

$$A_d = A_1 \left(\frac{d}{h_1} \right)^m \tag{2-21}$$

$$A_a = A_1 \left(\frac{h_a}{h_1} \right)^m \tag{2-22}$$

in which A_1 is the area at depth h_1 and A_2 is the area at depth h_2.

The volume of water in storage at any headwater depth can be estimated with the equation

$$S = \frac{A_1\, h_1}{m+1}\left(\frac{h}{h_1}\right)^m \tag{2-23}$$

in which S is the storage at depth h and A_{ref} is the known area at any reference depth h_{ref}. Equation 2-23 yields S in acre-feet for A_1 in acres and h_1 and h in feet.

2.3.3 Recommended Method for Depth-Area Survey

The area that would be inundated at a given headwater depth can be determined with sufficient accuracy by one person with a rotating laser level and sensor, a level rod, some survey flags and a GPS unit. The GPS unit should be capable of calculating the area of a polygon. The procedure is as follows:

1. Set up the rotating laser level a few feet above the desired headwater level. Locate the laser level so that the laser beam has an unobstructed line to a sufficient number of points on the perimeter of the area to be measured.

2. Set the level rod at the flowline of the culvert entrance and position the sensor on the rod at the level of the laser beam. If the laser level is too high above the flowline, measure the height to the top of the pipe or headwall, then set the rod on top of the pipe or headwall and position the sensor at the level of the laser beam. Determine the height of the laser beam above the flowline by reading the height of the sensor on the rod and, if necessary, adding the height of the rod above the flowline. Reposition the sensor on rod so that the height of the sensor above the base of the rod equals the height of the laser level above the desired headwater level. For example, if the laser beam is 8.52 ft above the flowline and the desired headwater level is 4.00 ft, the sensor should be set at 4.52 feet (8.52 ft minus 4.00 ft) on the rod.

3. Use the level rod with the sensor to identify points on the perimeter of the area that would be inundated at the specified headwater level. Mark these points with survey flags. Mark enough points to adequately define the boundary.

4. Use the GPS unit to measure the area within the perimeter marked by the survey flags. The procedure varies with the make and model of the GPS unit.

2.4 Depth-Discharge Relationship

The depth-discharge relationship for a culvert operating under inlet control depends only on the size and design of the inlet. If the culvert is operating under outlet control, the depth-discharge relationship depends on the length, slope and roughness of the culvert and the tailwater rating curve as well as the inlet characteristics. In this analysis, the culvert is assumed to operate under inlet control at all times. A second key assumption is that the flow does not overtop the roadway. These assumptions greatly simplify the analysis but also may limit the applicability of the results.

2.4.1 Pipe Culverts

For a pipe culvert operating under inlet control, dimensional analysis leads to the relationship

$$Q = N\sqrt{g\,d^5}\; f_Q\left(\frac{h}{d}\right) \tag{2-24}$$

in which d is the pipe diameter, N is the number of identical pipes in parallel, g is the gravitational constant, and f_Q is a discharge function that depends on the design of the inlet. In this analysis, pipe culverts are assumed to have concrete Type I end sections. The discharge function for concrete Type I end sections is

$$f_Q\left(\frac{h}{d}\right) = \begin{cases} 0.462\left(\frac{h}{d}\right)^{1.82}, & h/d \le 0.95 \\ 0.469\left(\frac{h}{d} - 0.055\right), & 0.95 < h/d \le 1.50 \\ 0.30 + 0.20\sqrt{2.25 + 10\left(\frac{h}{d} - 1.37\right)}, & h/d > 1.50 \end{cases} \qquad (2\text{-}25)$$

Equation 2-25 was fitted to experimental data from a hydraulic model studies conducted at the University of Kansas (McEnroe and Johnson, 1993; McEnroe, 1994).

2.4.2 Box Culverts

The general discharge relationship for a box culvert operating under inlet control is

$$Q = B\sqrt{g\,d^3}\; f_Q\left(\frac{h}{d}\right) \qquad (2\text{-}26)$$

in which d is the rise, B is the total span (the sum of the spans for all cells), and f_Q is a discharge function that depends on the design of the entrance. In this analysis, the box culvert is assumed to have wingwalls, either 45° or straight, and the top edge of the inlet is assumed to be either rounded or beveled. The discharge function for this type of entrance is

$$f_Q\left(\frac{h}{d}\right) = \begin{cases} 0.484\left(\frac{h}{d}\right)^{1.5}, & h/d \le 1.25 \\ 1.003\sqrt{\frac{h}{d} - 0.795}, & h/d > 1.25 \end{cases} \qquad (2\text{-}27)$$

Equation 2-27 was developed from equations published in the Federal Highway Administration's *Hydraulic Design Series No. 5* (FHWA, 1985).

CHAPTER 3

ANALYSIS OF EXISTING PIPE CULVERTS

3.1 Objectives

The objectives of this analysis are to estimate the effects of detention storage on the peak headwater depth, h_p, and the peak discharge, Q_p, for an existing pipe culvert. The detention-storage effects are indicated by the ratios h_p/h_{po} and Q_p/I_p, in which h_{po} is the peak headwater depth for no storage effect (the headwater depth required to discharge the peak inflow).

3.2 Problem Formulation

The replacement of A, I and Q in equation 2-3 with the right-hand sides of equations 2-18, 2-4 and 2-24 yields

$$A_d \left(\frac{h}{d}\right)^m \frac{dh}{dt} = I_p \, f_I\left(\frac{t}{t_p}\right) - N\sqrt{g\,d^5}\; f_Q\left(\frac{h}{d}\right) \tag{3-1}$$

The initial condition for equation 3-1 is h = 0 at t = 0. Equation 3-1 can be written in terms of dimensionless variables as

$$C_S\,(h^*)^m \frac{dh^*}{dt^*} = C_I\; f_I(t^*) - f_Q(h^*) \tag{3-2}$$

in which

$$t^* = \frac{t}{t_p} \tag{3-3}$$

$$h^* = \frac{h}{d} \tag{3-4}$$

$$C_S = \frac{A_d}{t_p N \sqrt{g d^3}} \tag{3-5}$$

$$C_I = \frac{I_p}{N \sqrt{g d^5}} \tag{3-6}$$

The initial condition for equation 3-2 is $h^* = 0$ at $t^* = 0$.

The quantities C_S and C_I are termed the storage factor and the discharge factor. These quantities are dimensionless, which means that the units of the variables on the right-hand sides of equations 3-5 and 3-6 must cancel. Equivalent definitions for these variables in customary U. S. units are

$$C_S = 2.13 \frac{A_d}{t_p N d^{1.5}} \tag{3-7}$$

$$C_I = 0.176 \frac{I_p}{N d^{2.5}} \tag{3-8}$$

for A_d in acres, t_p in hours, d in feet and I_p in cfs. The definitions of C_S and C_I in equations 3-5 through 3-8 apply only to pipe-culvert analysis; different definitions apply to the box-culvert analysis, pipe-culvert sizing and box-culvert sizing.

This initial-value problem is solved numerically to find the peak value of h_p^* (= h_p/d). The corresponding value of h_{po}^* (= h_{po}/d) is found by solving equation 3-9 by trial and error. Finally, equations 3-10 and 3-11 yield the desired ratios h_p/h_{po} and Q_p/I_p.

$$C_I = f_Q\left(h_{po}^*\right) \tag{3-9}$$

$$\frac{h_p}{h_{po}} = \frac{h_p^*}{h_{po}^*} \tag{3-10}$$

$$\frac{Q_p}{I_p} = \frac{f_Q\left(h_p^*\right)}{f_Q\left(h_{po}^*\right)} \tag{3-11}$$

3.3 Numerical Results

The problem formulated in Section 3.2, with f_I and f_Q defined by equations 2-5 and 2-25, was solved for all possible combinations of five values of m, 11 values of C_I and 23 values of C_S. The selected values of these inputs span the ranges of practical interest. Equation 3-2 was solved numerically by a fourth-order Runge-Kutta method. The results for h_p/h_{po} are presented in Tables 3-1 through 3-5. The results for Q_p/I_p are presented in Tables 3-6 through 3-10. Figures 3-1 and 3-2 shows that the larger the values of storage and discharge factors, the greater the storage effect (the smaller the values of h_p/h_{po} and Q_p/I_p).

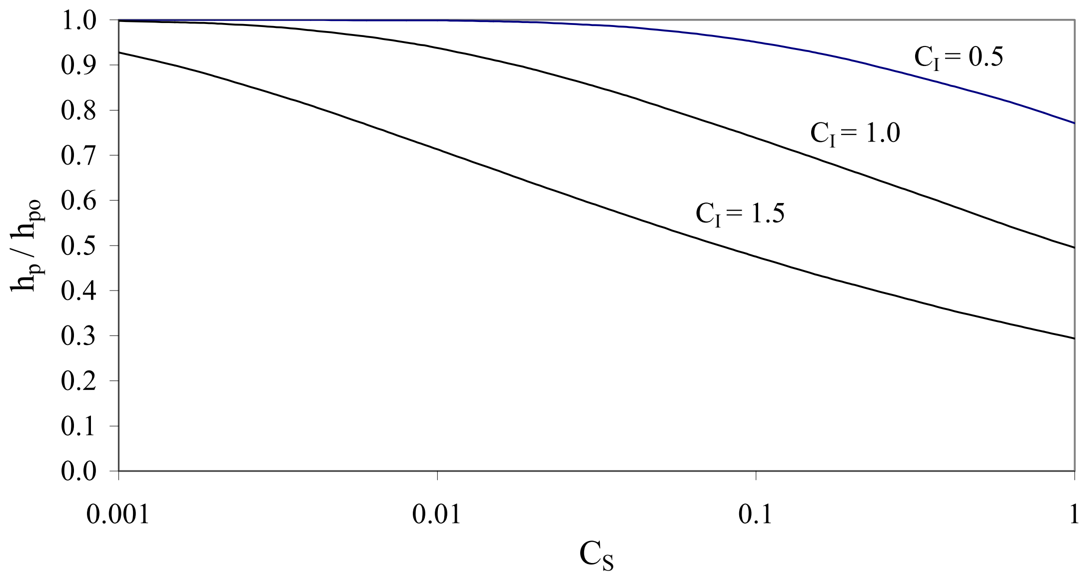

Figure 3-1. Effect of Storage on Peak Headwater Depth for Pipe Culverts, m = 2.5

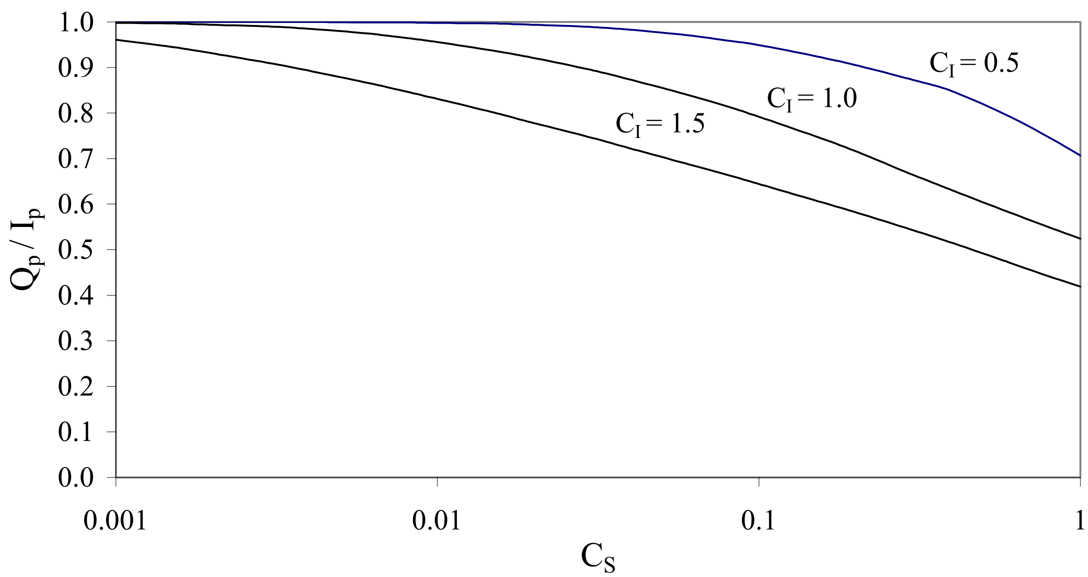

Figure 3-2. Effect of Storage on Peak Discharge for Pipe Culverts, m = 2.5

Table 3-1. Effect of Storage on Peak Headwater Depth for Pipe Culverts, m = 1.5

C_S	h_p/h_{po} = (Peak headwater depth with storage)/(Peak headwater depth without storage)										
	C_I = 0.5	C_I = 0.6	C_I = 0.7	C_I = 0.8	C_I = 0.9	C_I = 1.0	C_I = 1.1	C_I = 1.2	C_I = 1.3	C_I = 1.4	C_I = 1.5
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.996	0.993	0.988
0.0015	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.996	0.992	0.986	0.978
0.0020	1.000	1.000	1.000	1.000	0.999	0.998	0.996	0.993	0.987	0.979	0.968
0.0030	1.000	1.000	1.000	0.999	0.998	0.996	0.992	0.985	0.976	0.963	0.947
0.0040	1.000	1.000	1.000	0.999	0.997	0.993	0.987	0.978	0.964	0.948	0.927
0.0060	1.000	0.999	0.999	0.997	0.994	0.987	0.977	0.962	0.942	0.919	0.893
0.0080	0.999	0.999	0.998	0.996	0.990	0.980	0.966	0.946	0.922	0.895	0.865
0.0100	0.999	0.998	0.997	0.993	0.986	0.973	0.955	0.932	0.904	0.874	0.841
0.0150	0.997	0.996	0.994	0.987	0.974	0.955	0.930	0.899	0.866	0.830	0.793
0.0200	0.995	0.992	0.990	0.980	0.963	0.938	0.908	0.873	0.835	0.796	0.757
0.0300	0.991	0.985	0.981	0.966	0.941	0.909	0.871	0.830	0.788	0.745	0.704
0.0400	0.985	0.977	0.970	0.952	0.921	0.883	0.841	0.797	0.752	0.708	0.666
0.0600	0.973	0.959	0.948	0.925	0.887	0.843	0.795	0.747	0.700	0.655	0.612
0.0800	0.962	0.943	0.927	0.901	0.859	0.811	0.760	0.710	0.662	0.617	0.575
0.1000	0.950	0.927	0.908	0.880	0.835	0.785	0.732	0.681	0.633	0.588	0.546
0.1500	0.925	0.892	0.867	0.836	0.788	0.734	0.680	0.629	0.580	0.536	0.496
0.2000	0.902	0.863	0.834	0.800	0.752	0.697	0.643	0.592	0.544	0.501	0.462
0.3000	0.864	0.817	0.782	0.746	0.697	0.644	0.591	0.540	0.495	0.453	0.416
0.4000	0.836	0.780	0.743	0.705	0.657	0.605	0.554	0.505	0.461	0.421	0.386
0.6000	0.790	0.727	0.686	0.647	0.599	0.550	0.501	0.456	0.415	0.378	0.346
0.8000	0.753	0.690	0.645	0.605	0.559	0.511	0.465	0.423	0.384	0.349	0.319
1.0000	0.722	0.661	0.614	0.574	0.529	0.482	0.438	0.397	0.361	0.328	0.299

Table 3-2. Effect of Storage on Peak Headwater Depth for Pipe Culverts, m = 2.0

C_S	h_p/h_{po} = (Peak headwater depth with storage)/(Peak headwater depth without storage)										
	C_I = 0.5	C_I = 0.6	C_I = 0.7	C_I = 0.8	C_I = 0.9	C_I = 1.0	C_I = 1.1	C_I = 1.2	C_I = 1.3	C_I = 1.4	C_I = 1.5
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	1.000	0.999	0.997	0.994	0.988	0.979	0.966
0.0015	1.000	1.000	1.000	1.000	0.999	0.998	0.994	0.988	0.979	0.965	0.946
0.0020	1.000	1.000	1.000	0.999	0.998	0.996	0.991	0.982	0.969	0.951	0.928
0.0030	1.000	1.000	1.000	0.999	0.997	0.992	0.983	0.969	0.950	0.925	0.897
0.0040	1.000	1.000	0.999	0.998	0.994	0.987	0.975	0.956	0.932	0.903	0.871
0.0060	1.000	0.999	0.999	0.996	0.989	0.977	0.958	0.933	0.902	0.867	0.830
0.0080	0.999	0.998	0.997	0.993	0.983	0.967	0.943	0.913	0.877	0.839	0.799
0.0100	0.999	0.997	0.996	0.990	0.977	0.957	0.929	0.895	0.856	0.816	0.774
0.0150	0.997	0.994	0.992	0.982	0.962	0.934	0.899	0.858	0.815	0.771	0.727
0.0200	0.995	0.991	0.987	0.973	0.948	0.915	0.874	0.830	0.784	0.737	0.692
0.0300	0.990	0.982	0.975	0.956	0.923	0.882	0.836	0.787	0.737	0.690	0.644
0.0400	0.984	0.973	0.963	0.939	0.902	0.856	0.806	0.754	0.704	0.655	0.610
0.0600	0.973	0.955	0.939	0.911	0.867	0.816	0.762	0.708	0.656	0.608	0.563
0.0800	0.962	0.938	0.918	0.887	0.839	0.785	0.729	0.674	0.623	0.575	0.531
0.1000	0.951	0.923	0.899	0.867	0.816	0.760	0.703	0.648	0.597	0.550	0.506
0.1500	0.927	0.890	0.860	0.824	0.772	0.714	0.656	0.602	0.551	0.505	0.464
0.2000	0.907	0.864	0.829	0.791	0.739	0.680	0.623	0.569	0.520	0.475	0.435
0.3000	0.873	0.822	0.783	0.742	0.689	0.633	0.577	0.524	0.477	0.435	0.397
0.4000	0.847	0.790	0.748	0.705	0.653	0.598	0.544	0.494	0.448	0.407	0.371
0.6000	0.809	0.742	0.697	0.654	0.603	0.550	0.499	0.451	0.409	0.371	0.337
0.8000	0.777	0.709	0.661	0.617	0.567	0.516	0.467	0.422	0.382	0.346	0.314
1.0000	0.751	0.684	0.633	0.589	0.540	0.491	0.443	0.400	0.361	0.327	0.297

Table 3-3. Effect of Storage on Peak Headwater Depth for Pipe Culverts, m = 2.5

C_S	h_p/h_{po} = (Peak headwater depth with storage)/(Peak headwater depth without storage)										
	C_I = 0.5	C_I = 0.6	C_I = 0.7	C_I = 0.8	C_I = 0.9	C_I = 1.0	C_I = 1.1	C_I = 1.2	C_I = 1.3	C_I = 1.4	C_I = 1.5
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	0.999	0.998	0.994	0.986	0.972	0.953	0.928
0.0015	1.000	1.000	1.000	0.999	0.998	0.995	0.988	0.975	0.955	0.930	0.899
0.0020	1.000	1.000	1.000	0.999	0.997	0.992	0.981	0.964	0.940	0.910	0.875
0.0030	1.000	1.000	0.999	0.998	0.994	0.985	0.969	0.945	0.914	0.877	0.838
0.0040	1.000	0.999	0.999	0.997	0.990	0.977	0.956	0.927	0.892	0.852	0.810
0.0060	0.999	0.999	0.998	0.993	0.982	0.963	0.935	0.898	0.857	0.813	0.768
0.0080	0.999	0.998	0.996	0.989	0.974	0.950	0.916	0.875	0.830	0.784	0.737
0.0100	0.999	0.997	0.994	0.985	0.966	0.938	0.900	0.856	0.808	0.760	0.713
0.0150	0.997	0.993	0.989	0.974	0.948	0.911	0.867	0.818	0.767	0.717	0.669
0.0200	0.995	0.989	0.982	0.964	0.932	0.890	0.841	0.789	0.737	0.686	0.638
0.0300	0.989	0.979	0.968	0.944	0.905	0.856	0.802	0.747	0.694	0.642	0.595
0.0400	0.984	0.970	0.955	0.927	0.882	0.830	0.774	0.717	0.663	0.612	0.565
0.0600	0.972	0.951	0.930	0.898	0.847	0.790	0.732	0.674	0.620	0.570	0.524
0.0800	0.961	0.934	0.909	0.874	0.820	0.761	0.701	0.644	0.590	0.541	0.496
0.1000	0.951	0.920	0.891	0.853	0.799	0.738	0.678	0.620	0.567	0.519	0.475
0.1500	0.929	0.888	0.853	0.813	0.757	0.696	0.635	0.579	0.527	0.480	0.438
0.2000	0.910	0.863	0.825	0.782	0.726	0.665	0.605	0.550	0.499	0.454	0.414
0.3000	0.879	0.825	0.782	0.737	0.681	0.622	0.564	0.510	0.462	0.419	0.381
0.4000	0.856	0.796	0.750	0.704	0.648	0.591	0.535	0.483	0.436	0.395	0.358
0.6000	0.822	0.753	0.704	0.657	0.603	0.547	0.494	0.446	0.402	0.363	0.329
0.8000	0.794	0.722	0.672	0.625	0.571	0.517	0.466	0.420	0.378	0.341	0.309
1.0000	0.771	0.699	0.647	0.600	0.547	0.495	0.445	0.400	0.360	0.325	0.294

Table 3-4. Effect of Storage on Peak Headwater Depth for Pipe Culverts, m = 3.0

C_S	h_p/h_{po} = (Peak headwater depth with storage)/(Peak headwater depth without storage)										
	C_I = 0.5	C_I = 0.6	C_I = 0.7	C_I = 0.8	C_I = 0.9	C_I = 1.0	C_I = 1.1	C_I = 1.2	C_I = 1.3	C_I = 1.4	C_I = 1.5
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	0.998	0.995	0.986	0.970	0.946	0.915	0.878
0.0015	1.000	1.000	1.000	0.999	0.997	0.990	0.976	0.954	0.923	0.886	0.844
0.0020	1.000	1.000	1.000	0.998	0.994	0.985	0.967	0.939	0.903	0.862	0.818
0.0030	1.000	1.000	0.999	0.997	0.989	0.974	0.949	0.914	0.872	0.827	0.780
0.0040	1.000	0.999	0.999	0.995	0.984	0.964	0.933	0.894	0.848	0.800	0.751
0.0060	0.999	0.998	0.997	0.990	0.973	0.946	0.907	0.862	0.812	0.761	0.711
0.0080	0.999	0.997	0.995	0.984	0.963	0.930	0.887	0.837	0.785	0.733	0.682
0.0100	0.998	0.996	0.992	0.979	0.954	0.916	0.869	0.817	0.764	0.711	0.660
0.0150	0.997	0.991	0.985	0.966	0.932	0.888	0.835	0.780	0.724	0.670	0.620
0.0200	0.994	0.986	0.977	0.954	0.915	0.865	0.810	0.752	0.696	0.642	0.592
0.0300	0.989	0.976	0.961	0.932	0.886	0.831	0.772	0.713	0.656	0.603	0.554
0.0400	0.983	0.966	0.947	0.914	0.864	0.805	0.745	0.685	0.628	0.576	0.528
0.0600	0.972	0.947	0.921	0.884	0.829	0.768	0.705	0.645	0.589	0.538	0.492
0.0800	0.961	0.930	0.900	0.861	0.803	0.740	0.678	0.618	0.563	0.513	0.468
0.1000	0.951	0.916	0.882	0.841	0.782	0.719	0.656	0.597	0.542	0.493	0.449
0.1500	0.930	0.886	0.847	0.802	0.743	0.679	0.617	0.559	0.507	0.459	0.418
0.2000	0.912	0.862	0.820	0.773	0.714	0.651	0.590	0.533	0.482	0.436	0.396
0.3000	0.884	0.827	0.780	0.731	0.673	0.612	0.553	0.498	0.449	0.405	0.367
0.4000	0.862	0.800	0.751	0.701	0.643	0.583	0.526	0.474	0.426	0.384	0.348
0.6000	0.831	0.760	0.709	0.659	0.602	0.544	0.490	0.440	0.395	0.356	0.322
0.8000	0.807	0.732	0.679	0.629	0.573	0.517	0.465	0.417	0.374	0.337	0.304
1.0000	0.786	0.711	0.656	0.606	0.551	0.497	0.446	0.400	0.358	0.322	0.291

Table 3-5. Effect of Storage on Peak Headwater Depth for Pipe Culverts, m = 3.5

C_S	h_p/h_{po} = (Peak headwater depth with storage)/(Peak headwater depth without storage)										
	C_I = 0.5	C_I = 0.6	C_I = 0.7	C_I = 0.8	C_I = 0.9	C_I = 1.0	C_I = 1.1	C_I = 1.2	C_I = 1.3	C_I = 1.4	C_I = 1.5
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	0.999	0.997	0.990	0.974	0.949	0.913	0.871	0.825
0.0015	1.000	1.000	1.000	0.998	0.994	0.982	0.960	0.927	0.885	0.838	0.789
0.0020	1.000	1.000	0.999	0.997	0.990	0.975	0.947	0.909	0.863	0.814	0.763
0.0030	1.000	0.999	0.999	0.995	0.983	0.960	0.925	0.880	0.830	0.778	0.726
0.0040	1.000	0.999	0.998	0.992	0.976	0.948	0.907	0.858	0.805	0.751	0.699
0.0060	0.999	0.998	0.995	0.985	0.962	0.926	0.879	0.825	0.769	0.714	0.661
0.0080	0.999	0.996	0.992	0.978	0.950	0.908	0.857	0.801	0.743	0.688	0.635
0.0100	0.998	0.995	0.989	0.972	0.939	0.893	0.839	0.781	0.723	0.667	0.615
0.0150	0.996	0.990	0.980	0.956	0.916	0.864	0.805	0.745	0.686	0.631	0.579
0.0200	0.994	0.984	0.971	0.943	0.897	0.841	0.780	0.719	0.660	0.605	0.554
0.0300	0.988	0.973	0.954	0.920	0.868	0.808	0.744	0.682	0.624	0.570	0.521
0.0400	0.982	0.962	0.938	0.901	0.846	0.783	0.719	0.656	0.598	0.545	0.497
0.0600	0.971	0.943	0.913	0.872	0.812	0.747	0.682	0.620	0.564	0.512	0.466
0.0800	0.961	0.927	0.892	0.848	0.787	0.721	0.656	0.595	0.540	0.489	0.444
0.1000	0.951	0.912	0.874	0.829	0.768	0.701	0.637	0.576	0.521	0.472	0.428
0.1500	0.931	0.884	0.841	0.792	0.731	0.665	0.601	0.542	0.489	0.442	0.400
0.2000	0.914	0.861	0.815	0.765	0.704	0.639	0.577	0.519	0.467	0.422	0.381
0.3000	0.888	0.828	0.778	0.726	0.665	0.602	0.542	0.487	0.438	0.394	0.356
0.4000	0.868	0.802	0.750	0.698	0.638	0.577	0.518	0.465	0.417	0.375	0.338
0.6000	0.838	0.766	0.712	0.659	0.600	0.541	0.485	0.434	0.389	0.350	0.315
0.8000	0.817	0.740	0.684	0.632	0.574	0.516	0.462	0.414	0.370	0.332	0.299
1.0000	0.798	0.720	0.663	0.611	0.554	0.498	0.445	0.398	0.356	0.319	0.287

Table 3-6. Effect of Storage on Peak Discharge for Pipe Culverts, m = 1.5

C_S	Q_p/I_p = (Peak discharge with storage)/(Peak discharge without storage)										
	C_I = 0.5	C_I = 0.6	C_I = 0.7	C_I = 0.8	C_I = 0.9	C_I = 1.0	C_I = 1.1	C_I = 1.2	C_I = 1.3	C_I = 1.4	C_I = 1.5
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.996	0.994
0.0015	1.000	1.000	1.000	1.000	1.000	0.999	0.999	0.997	0.995	0.993	0.989
0.0020	1.000	1.000	1.000	1.000	0.999	0.999	0.998	0.996	0.993	0.988	0.983
0.0030	1.000	1.000	1.000	0.999	0.999	0.997	0.995	0.991	0.986	0.980	0.971
0.0040	1.000	1.000	1.000	0.999	0.998	0.996	0.992	0.987	0.980	0.971	0.961
0.0060	1.000	0.999	0.999	0.998	0.995	0.991	0.985	0.977	0.967	0.955	0.942
0.0080	0.999	0.999	0.998	0.996	0.992	0.986	0.978	0.968	0.955	0.941	0.925
0.0100	0.999	0.998	0.997	0.994	0.989	0.981	0.971	0.959	0.944	0.928	0.911
0.0150	0.997	0.995	0.994	0.989	0.980	0.969	0.955	0.939	0.921	0.902	0.882
0.0200	0.995	0.992	0.989	0.982	0.971	0.957	0.940	0.921	0.901	0.881	0.860
0.0300	0.990	0.984	0.978	0.969	0.954	0.935	0.914	0.893	0.870	0.847	0.825
0.0400	0.984	0.976	0.966	0.956	0.937	0.916	0.893	0.869	0.845	0.822	0.799
0.0600	0.972	0.958	0.943	0.930	0.908	0.884	0.859	0.833	0.808	0.783	0.759
0.0800	0.960	0.940	0.922	0.906	0.883	0.858	0.831	0.805	0.779	0.754	0.730
0.1000	0.948	0.924	0.902	0.883	0.861	0.835	0.808	0.781	0.755	0.731	0.707
0.1500	0.921	0.888	0.860	0.835	0.814	0.788	0.762	0.736	0.710	0.686	0.664
0.2000	0.897	0.857	0.825	0.798	0.774	0.751	0.726	0.701	0.677	0.653	0.632
0.3000	0.857	0.809	0.772	0.741	0.714	0.691	0.670	0.648	0.626	0.605	0.585
0.4000	0.819	0.771	0.731	0.699	0.671	0.646	0.625	0.606	0.587	0.568	0.550
0.6000	0.739	0.715	0.672	0.638	0.610	0.585	0.563	0.544	0.527	0.512	0.497
0.8000	0.677	0.661	0.630	0.595	0.567	0.542	0.521	0.502	0.485	0.470	0.456
1.0000	0.626	0.611	0.598	0.563	0.534	0.510	0.489	0.471	0.454	0.440	0.426

Table 3-7. Effect of Storage on Peak Discharge for Pipe Culverts, m = 2.0

C_S	Q_p/I_p = (Peak discharge with storage)/(Peak discharge without storage)										
	C_I = 0.5	C_I = 0.6	C_I = 0.7	C_I = 0.8	C_I = 0.9	C_I = 1.0	C_I = 1.1	C_I = 1.2	C_I = 1.3	C_I = 1.4	C_I = 1.5
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.997	0.993	0.989	0.982
0.0015	1.000	1.000	1.000	1.000	0.999	0.998	0.996	0.993	0.988	0.981	0.971
0.0020	1.000	1.000	1.000	1.000	0.999	0.997	0.994	0.989	0.982	0.973	0.961
0.0030	1.000	1.000	1.000	0.999	0.997	0.994	0.989	0.982	0.971	0.958	0.944
0.0040	1.000	1.000	0.999	0.998	0.996	0.991	0.984	0.974	0.961	0.946	0.929
0.0060	0.999	0.999	0.998	0.996	0.992	0.984	0.973	0.960	0.943	0.925	0.905
0.0080	0.999	0.998	0.997	0.994	0.987	0.977	0.964	0.947	0.928	0.907	0.886
0.0100	0.999	0.997	0.996	0.991	0.983	0.970	0.954	0.936	0.915	0.893	0.870
0.0150	0.997	0.994	0.991	0.983	0.971	0.954	0.934	0.912	0.888	0.864	0.840
0.0200	0.995	0.990	0.985	0.975	0.960	0.940	0.917	0.893	0.867	0.842	0.817
0.0300	0.990	0.982	0.972	0.959	0.939	0.915	0.889	0.862	0.835	0.809	0.783
0.0400	0.984	0.972	0.959	0.944	0.921	0.895	0.867	0.839	0.811	0.784	0.758
0.0600	0.971	0.953	0.934	0.916	0.890	0.862	0.832	0.803	0.774	0.747	0.721
0.0800	0.960	0.936	0.912	0.891	0.865	0.835	0.805	0.775	0.747	0.720	0.694
0.1000	0.948	0.920	0.893	0.868	0.842	0.813	0.783	0.753	0.725	0.698	0.673
0.1500	0.923	0.886	0.853	0.822	0.796	0.768	0.739	0.711	0.683	0.658	0.634
0.2000	0.902	0.858	0.821	0.788	0.759	0.733	0.705	0.678	0.652	0.628	0.605
0.3000	0.867	0.814	0.773	0.737	0.705	0.677	0.654	0.630	0.606	0.584	0.563
0.4000	0.839	0.781	0.736	0.699	0.667	0.639	0.613	0.592	0.571	0.551	0.531
0.6000	0.771	0.731	0.684	0.646	0.613	0.585	0.560	0.538	0.518	0.501	0.485
0.8000	0.717	0.694	0.647	0.608	0.575	0.548	0.523	0.502	0.482	0.465	0.449
1.0000	0.673	0.650	0.618	0.579	0.547	0.519	0.495	0.474	0.456	0.439	0.423

Table 3-8. Effect of Storage on Peak Discharge for Pipe Culverts, m = 2.5

	Q_p/I_p = (Peak discharge with storage)/(Peak discharge without storage)										
C_S	C_I = 0.5	C_I = 0.6	C_I = 0.7	C_I = 0.8	C_I = 0.9	C_I = 1.0	C_I = 1.1	C_I = 1.2	C_I = 1.3	C_I = 1.4	C_I = 1.5
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	0.999	0.998	0.996	0.991	0.984	0.974	0.961
0.0015	1.000	1.000	1.000	1.000	0.999	0.997	0.992	0.985	0.975	0.961	0.945
0.0020	1.000	1.000	1.000	0.999	0.998	0.994	0.988	0.979	0.966	0.950	0.931
0.0030	1.000	1.000	0.999	0.998	0.995	0.990	0.980	0.967	0.950	0.931	0.910
0.0040	1.000	0.999	0.999	0.997	0.993	0.985	0.972	0.956	0.937	0.915	0.893
0.0060	0.999	0.999	0.998	0.994	0.987	0.975	0.958	0.938	0.915	0.891	0.867
0.0080	0.999	0.998	0.996	0.990	0.980	0.965	0.946	0.923	0.898	0.873	0.847
0.0100	0.998	0.996	0.994	0.987	0.974	0.956	0.935	0.910	0.884	0.857	0.831
0.0150	0.997	0.993	0.987	0.977	0.960	0.937	0.912	0.884	0.856	0.828	0.801
0.0200	0.994	0.988	0.980	0.967	0.946	0.921	0.893	0.864	0.835	0.806	0.778
0.0300	0.989	0.978	0.965	0.949	0.924	0.895	0.864	0.833	0.803	0.774	0.746
0.0400	0.983	0.968	0.950	0.932	0.904	0.873	0.842	0.810	0.779	0.750	0.722
0.0600	0.971	0.949	0.925	0.902	0.872	0.840	0.807	0.775	0.745	0.716	0.688
0.0800	0.959	0.932	0.903	0.876	0.847	0.814	0.781	0.749	0.719	0.690	0.664
0.1000	0.949	0.916	0.884	0.853	0.825	0.792	0.760	0.728	0.698	0.670	0.644
0.1500	0.925	0.884	0.846	0.811	0.780	0.749	0.718	0.688	0.660	0.633	0.608
0.2000	0.905	0.857	0.816	0.779	0.745	0.716	0.687	0.658	0.631	0.605	0.582
0.3000	0.873	0.817	0.771	0.732	0.696	0.665	0.638	0.613	0.588	0.565	0.543
0.4000	0.848	0.787	0.739	0.698	0.662	0.630	0.602	0.578	0.556	0.535	0.515
0.6000	0.793	0.742	0.691	0.649	0.614	0.582	0.555	0.531	0.509	0.489	0.472
0.8000	0.746	0.710	0.658	0.615	0.580	0.549	0.522	0.499	0.478	0.458	0.441
1.0000	0.707	0.677	0.632	0.589	0.554	0.524	0.498	0.475	0.454	0.436	0.419

Table 3-9. Effect of Storage on Peak Discharge for Pipe Culverts, m = 3.0

C_S	Q_p/I_p = (Peak discharge with storage)/(Peak discharge without storage)										
	C_I = 0.5	C_I = 0.6	C_I = 0.7	C_I = 0.8	C_I = 0.9	C_I = 1.0	C_I = 1.1	C_I = 1.2	C_I = 1.3	C_I = 1.4	C_I = 1.5
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	0.999	0.996	0.991	0.982	0.969	0.953	0.933
0.0015	1.000	1.000	1.000	0.999	0.997	0.993	0.985	0.972	0.956	0.935	0.913
0.0020	1.000	1.000	1.000	0.999	0.996	0.990	0.979	0.963	0.944	0.922	0.898
0.0030	1.000	1.000	0.999	0.997	0.992	0.982	0.967	0.948	0.925	0.900	0.874
0.0040	1.000	0.999	0.998	0.995	0.988	0.975	0.957	0.935	0.910	0.883	0.856
0.0060	0.999	0.998	0.996	0.991	0.980	0.962	0.940	0.914	0.886	0.858	0.830
0.0080	0.999	0.997	0.994	0.986	0.971	0.951	0.926	0.898	0.868	0.839	0.810
0.0100	0.998	0.995	0.991	0.981	0.964	0.941	0.913	0.884	0.854	0.824	0.794
0.0150	0.996	0.991	0.983	0.969	0.947	0.919	0.889	0.857	0.826	0.795	0.765
0.0200	0.994	0.986	0.974	0.958	0.932	0.902	0.870	0.837	0.805	0.774	0.744
0.0300	0.988	0.975	0.957	0.937	0.908	0.875	0.840	0.807	0.774	0.743	0.714
0.0400	0.982	0.964	0.942	0.919	0.887	0.853	0.818	0.784	0.751	0.721	0.692
0.0600	0.970	0.945	0.916	0.888	0.855	0.820	0.784	0.750	0.718	0.688	0.660
0.0800	0.959	0.927	0.894	0.862	0.829	0.794	0.759	0.726	0.694	0.665	0.637
0.1000	0.949	0.912	0.876	0.840	0.808	0.773	0.739	0.706	0.675	0.646	0.619
0.1500	0.926	0.881	0.839	0.800	0.764	0.732	0.699	0.668	0.639	0.611	0.586
0.2000	0.908	0.857	0.811	0.770	0.732	0.700	0.669	0.640	0.612	0.586	0.562
0.3000	0.878	0.819	0.770	0.726	0.688	0.654	0.624	0.598	0.572	0.549	0.526
0.4000	0.855	0.791	0.739	0.695	0.656	0.622	0.592	0.565	0.543	0.521	0.500
0.6000	0.810	0.750	0.696	0.651	0.613	0.579	0.550	0.524	0.500	0.479	0.461
0.8000	0.767	0.721	0.665	0.620	0.582	0.549	0.520	0.495	0.472	0.452	0.434
1.0000	0.733	0.697	0.642	0.596	0.559	0.526	0.498	0.474	0.452	0.432	0.414

Table 3-10. Effect of Storage on Peak Discharge for Pipe Culverts, m = 3.5

C_S	Q_p/I_p = (Peak discharge with storage)/(Peak discharge without storage)										
	C_I = 0.5	C_I = 0.6	C_I = 0.7	C_I = 0.8	C_I = 0.9	C_I = 1.0	C_I = 1.1	C_I = 1.2	C_I = 1.3	C_I = 1.4	C_I = 1.5
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	0.999	0.998	0.993	0.984	0.969	0.950	0.927	0.902
0.0015	1.000	1.000	1.000	0.999	0.995	0.988	0.975	0.956	0.933	0.907	0.880
0.0020	1.000	1.000	0.999	0.998	0.993	0.983	0.966	0.944	0.919	0.892	0.863
0.0030	1.000	0.999	0.999	0.995	0.987	0.973	0.952	0.926	0.898	0.869	0.839
0.0040	1.000	0.999	0.998	0.993	0.982	0.964	0.940	0.912	0.882	0.851	0.821
0.0060	0.999	0.998	0.995	0.987	0.971	0.948	0.920	0.889	0.858	0.826	0.795
0.0080	0.999	0.996	0.992	0.980	0.961	0.935	0.905	0.872	0.840	0.807	0.777
0.0100	0.998	0.994	0.988	0.974	0.952	0.924	0.892	0.858	0.825	0.793	0.762
0.0150	0.996	0.989	0.978	0.960	0.933	0.901	0.866	0.832	0.797	0.765	0.734
0.0200	0.993	0.983	0.967	0.947	0.917	0.883	0.847	0.812	0.777	0.745	0.714
0.0300	0.988	0.972	0.949	0.925	0.891	0.855	0.818	0.782	0.748	0.716	0.686
0.0400	0.982	0.960	0.934	0.906	0.871	0.833	0.796	0.760	0.726	0.695	0.665
0.0600	0.970	0.940	0.907	0.874	0.838	0.801	0.764	0.728	0.695	0.664	0.636
0.0800	0.959	0.923	0.886	0.847	0.813	0.776	0.739	0.704	0.672	0.642	0.614
0.1000	0.949	0.909	0.868	0.827	0.792	0.755	0.720	0.686	0.654	0.625	0.598
0.1500	0.927	0.879	0.832	0.789	0.750	0.716	0.682	0.650	0.620	0.592	0.567
0.2000	0.910	0.855	0.806	0.761	0.721	0.685	0.654	0.623	0.595	0.568	0.544
0.3000	0.882	0.820	0.767	0.721	0.680	0.643	0.611	0.584	0.558	0.534	0.511
0.4000	0.861	0.794	0.739	0.692	0.651	0.615	0.583	0.554	0.530	0.508	0.487
0.6000	0.823	0.756	0.699	0.651	0.611	0.575	0.544	0.517	0.492	0.470	0.451
0.8000	0.784	0.729	0.671	0.623	0.583	0.548	0.518	0.491	0.467	0.446	0.427
1.0000	0.753	0.708	0.649	0.601	0.561	0.527	0.498	0.472	0.448	0.428	0.409

3.4 Application Procedure

Use the following steps to determine the ratios h_p/h_{po} and Q_p/I_p for an existing pipe culvert.

1. Compute the peak inflow, I_p, by any acceptable method.
2. Compute the flood volume, V, with the appropriate regression equation from Table 2-1.
3. Compute the time-to-peak, t_p, with equation 2-7.
4. Compute the values of m and A_d as explained in Section 2.3.2.
5. Compute the storage factor, C_S, and the discharge factor, C_I, with equations 3-7 and 3-8.
6. Find the ratios h_p/h_{po} and Q_p/I_p by interpolation in the tables listed in Table 3-11.

Table 3-11. Where to Find h_p/h_{po} and Q_p/I_p

m	Find h_p/h_{po} in	Find Q_p/I_p in
m [1.75	Table 3-1	Table 3-6
1.75 < m [2.25	Table 3-2	Table 3-7
2.25 < m [2.75	Table 3-3	Table 3-8
2.75 < m [3.25	Table 3-4	Table 3-9
m > 3.25	Table 3-5	Table 3-10

3.5 Example

3.5.1 Problem

A 72-inch pipe culvert in rural Shawnee County operates under inlet control. The culvert must be evaluated for the 50-year flood. The 50-year discharge from the 160-acre watershed is 450 cfs. A headwater depth of 12.2 feet would be needed to pass the 50-year discharge through the culvert. However, the topography upstream of the culvert is such that a considerable amount of storage would need to be filled before the headwater could reach this level. At a headwater depth of 6.5 feet, 2.30 acres would be inundated; and at a headwater depth of 10.5 feet, 7.28

acres would be inundated. Estimate the impact of this detention storage on the peak headwater depth and the peak discharge through the culvert, following the procedure in Section 3.4.

3.5.2 Solution

Shawnee County is located in the eastern hydrologic region of Kansas, as defined by Figure 2-2. The 50-year flood volume is obtained from equation 2-10.

$$V = 100.6\ W^{0.901}\ I_p^{0.135} = 100.6\ (160/640)^{0.901}\ (450)^{0.135} = 65.8 \text{ acre-feet}$$

The time-to-peak is computed with equation 2-7.

$$t_p = 9.45\,\frac{V}{I_p} = 9.45\left(\frac{65.8}{450}\right) = 1.38 \text{ hours}$$

The values of m and A_d in the area-depth relationship are computed with equations 2-20 and 2-21.

$$m = \frac{\log\left(\frac{A_2}{A_1}\right)}{\log\left(\frac{h_2}{h_1}\right)} = \frac{\log\left(\frac{7.28}{2.30}\right)}{\log\left(\frac{10.5}{6.5}\right)} = 2.40$$

$$A_d = A_1\left(\frac{d}{h_1}\right)^m = 2.30\left(\frac{6.0}{6.5}\right)^{2.40} = 1.90 \text{ acres}$$

The storage and discharge factors are computed with equations 3-7 and 3-8.

$$C_S = 2.13\,\frac{A_d}{t_p\,N\,d^{1.5}} = 2.13\,\frac{1.90}{1.38\,(1)\,(6.0)^{1.5}} = 0.200$$

$$C_I = 0.176\,\frac{I_p}{N\,d^{2.5}} = 0.176\,\frac{450}{1\,(6.0)^{2.5}} = 0.898$$

The ratios h_p/h_{po} and Q_p/I_p are found by interpolation in Tables 3-3 and 3-8 for m = 2.5.

$h_p/h_{po} = 0.727$

$Q_p/I_p = 0.746$

The estimated peak headwater depth and peak discharge are

$h_p = 0.727\ h_{po} = 0.727\ (12.2) = 8.9$ feet

$Q_p = 0.727\ I_p = 0.746\ (450) = 336$ cfs

Detention storage reduces the peak headwater depth by approximately 27% and the peak discharge by approximately 25%.

CHAPTER 4

ANALYSIS OF EXISTING BOX CULVERTS

4.1 Objectives

The objectives of this analysis are to estimate the effects of detention storage on the peak headwater depth, h_p, and the peak discharge, Q_p, for an existing box culvert. The detention-storage effects are indicated by the ratios h_p/h_{po} and Q_p/I_p, in which h_{po} is the peak headwater depth for no storage effect (the headwater depth required to discharge the peak inflow).

4.2 Problem Formulation

The replacement of A, I and Q in equation 2-3 with the right-hand sides of equations 2-18, 2-4 and 2-19 yields

$$A_d \left(\frac{h}{d}\right)^m \frac{dh}{dt} = I_p\, f_I\left(\frac{t}{t_p}\right) - B\sqrt{g\,d^3}\; f_Q\left(\frac{h}{d}\right) \tag{4-1}$$

The initial condition for equation 4-1 is h = 0 at t = 0. Equation 4-1 can be written in terms of dimensionless variables as

$$C_S\,(h^*)^m \frac{dh^*}{dt^*} = C_I\; f_I(t^*) - f_Q(h^*) \tag{4-2}$$

in which

$$t^* = \frac{t}{t_p} \tag{4-3}$$

$$h^* = \frac{h}{d} \tag{4-4}$$

$$C_S = \frac{A_d}{t_p\, B \sqrt{g\, d}} \tag{4-5}$$

$$C_I = \frac{I_p}{B \sqrt{g\, d^3}} \tag{4-6}$$

The initial condition for equation 4-2 is $h^* = 0$ at $t^* = 0$.

The quantities C_S and C_I are termed the storage factor and the discharge factor. These quantities are dimensionless, which means that the units of the variables on the right-hand sides of equations 4-5 and 4-6 must cancel. Equivalent definitions for variables in customary U. S. units are

$$C_S = 2.13 \; \frac{A_d}{t_p\, B\, d^{0.5}} \tag{4-7}$$

$$C_I = 0.176 \; \frac{I_p}{B\, d^{1.5}} \tag{4-8}$$

for A_d in acres, t_p in hours, B in feet, d in feet and I_p in cfs. The definitions of C_S and C_I in equations 4-5 through 4-8 apply only to box-culvert analysis; different definitions apply to the pipe-culvert analysis, pipe-culvert sizing and box-culvert sizing.

This initial-value problem is solved numerically to find the peak value of h_p^* (= h_p/d). The corresponding value of h_{po}^* (= h_{po}/d) is found by solving equation 4-9 by trial. Finally, equations 4-10 and 4-11 yield the desired ratios h_p/h_{po} and Q_p/I_p.

$$C_I = f_Q\left(h_{po}^*\right) \tag{4-9}$$

$$\frac{h_p}{h_{po}} = \frac{h_p^*}{h_{po}^*} \tag{4-10}$$

$$\frac{Q_p}{I_p} = \frac{f_Q\left(h_p^*\right)}{f_Q\left(h_{po}^*\right)} \tag{4-11}$$

4.3 Numerical Results

The problem formulated in Section 4.2, with f_I and f_Q defined by equations 2-5 and 2-27, was solved for all possible combinations of five values of m, eight values of C_I and 23 values of C_S. The selected values of these inputs span the ranges of practical interest. Equation 4-2 was solved numerically by a fourth-order Runge-Kutta method. The results for h_p/h_{po} are presented in Tables 4-1 through 4-5. The results for Q_p/I_p are presented in Tables 4-6 through 4-10. Figures 4-1 and 4-2 show that the larger the values of storage and discharge factors, the greater the storage effect (the smaller the values of h_p/h_{po} and Q_p/I_p).

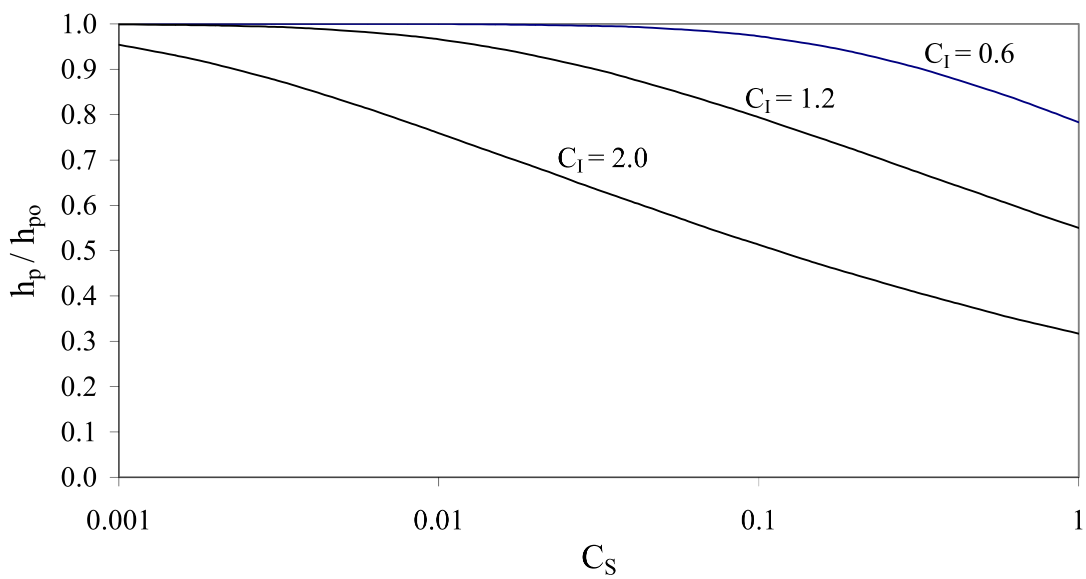

Figure 4-1. Effect of Storage on Peak Headwater Depth for Box Culverts, m = 2.5

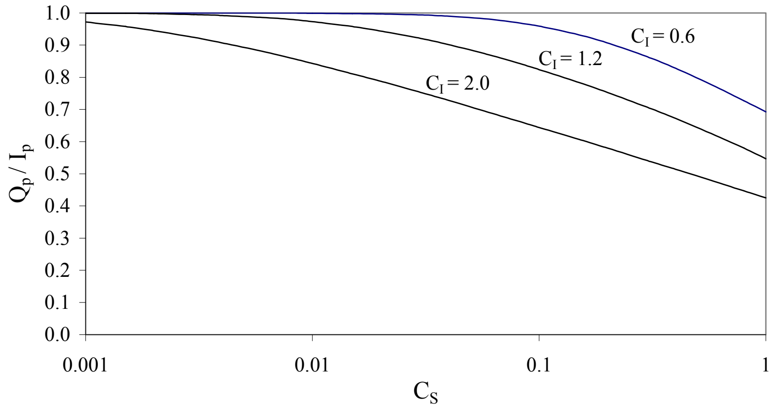

Figure 4-2. Effect of Storage on Peak Discharge for Box Culverts, m = 2.5

Table 4-1. Effect of Storage on Peak Headwater Depth for Box Culverts, m = 1.5

C_S	h_p/h_{po} = (Peak headwater depth with storage)/(Peak headwater depth without storage)							
	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	1.000	0.999	0.997	0.995
0.0015	1.000	1.000	1.000	1.000	0.999	0.998	0.995	0.989
0.0020	1.000	1.000	1.000	0.999	0.998	0.996	0.991	0.983
0.0030	1.000	1.000	1.000	0.999	0.996	0.991	0.983	0.970
0.0040	1.000	1.000	0.999	0.998	0.994	0.986	0.974	0.956
0.0060	1.000	1.000	0.998	0.995	0.987	0.974	0.955	0.931
0.0080	1.000	0.999	0.997	0.991	0.980	0.962	0.938	0.908
0.0100	1.000	0.999	0.995	0.988	0.973	0.951	0.922	0.888
0.0150	0.999	0.997	0.991	0.977	0.954	0.923	0.886	0.845
0.0200	0.999	0.995	0.985	0.966	0.937	0.899	0.857	0.812
0.0300	0.997	0.991	0.974	0.945	0.906	0.860	0.811	0.761
0.0400	0.995	0.985	0.962	0.926	0.879	0.828	0.775	0.723
0.0600	0.989	0.973	0.939	0.892	0.837	0.779	0.722	0.668
0.0800	0.982	0.961	0.919	0.864	0.804	0.743	0.684	0.629
0.1000	0.974	0.949	0.901	0.841	0.776	0.713	0.654	0.599
0.1500	0.954	0.921	0.862	0.794	0.725	0.659	0.599	0.546
0.2000	0.933	0.896	0.830	0.758	0.687	0.621	0.561	0.509
0.3000	0.896	0.854	0.781	0.705	0.632	0.567	0.509	0.459
0.4000	0.863	0.819	0.744	0.666	0.594	0.530	0.474	0.426
0.6000	0.810	0.764	0.689	0.611	0.541	0.479	0.426	0.381
0.8000	0.768	0.722	0.649	0.573	0.504	0.445	0.394	0.352
1.0000	0.734	0.687	0.616	0.543	0.477	0.419	0.371	0.330

Table 4-2. Effect of Storage on Peak Headwater Depth for Box Culverts, m = 2.0

C_S	h_p/h_{po} = (Peak headwater depth with storage)/(Peak headwater depth without storage)							
	$C_I = 0.6$	$C_I = 0.8$	$C_I = 1.0$	$C_I = 1.2$	$C_I = 1.4$	$C_I = 1.6$	$C_I = 1.8$	$C_I = 2.0$
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	0.999	0.996	0.991	0.982
0.0015	1.000	1.000	1.000	0.999	0.997	0.993	0.984	0.969
0.0020	1.000	1.000	1.000	0.999	0.996	0.988	0.975	0.955
0.0030	1.000	1.000	0.999	0.997	0.991	0.979	0.959	0.931
0.0040	1.000	1.000	0.999	0.995	0.986	0.969	0.943	0.910
0.0060	1.000	0.999	0.997	0.990	0.975	0.949	0.915	0.875
0.0080	1.000	0.999	0.995	0.984	0.963	0.932	0.892	0.846
0.0100	1.000	0.998	0.993	0.978	0.953	0.916	0.872	0.823
0.0150	0.999	0.996	0.986	0.964	0.928	0.882	0.831	0.778
0.0200	0.998	0.994	0.979	0.949	0.907	0.855	0.800	0.744
0.0300	0.997	0.988	0.964	0.924	0.872	0.813	0.753	0.695
0.0400	0.994	0.982	0.950	0.902	0.844	0.781	0.719	0.660
0.0600	0.988	0.968	0.926	0.867	0.801	0.734	0.670	0.611
0.0800	0.981	0.955	0.904	0.839	0.769	0.700	0.635	0.577
0.1000	0.974	0.943	0.886	0.816	0.743	0.673	0.609	0.551
0.1500	0.954	0.916	0.848	0.772	0.696	0.625	0.561	0.505
0.2000	0.936	0.892	0.819	0.739	0.661	0.591	0.529	0.474
0.3000	0.903	0.854	0.774	0.691	0.613	0.544	0.484	0.432
0.4000	0.874	0.822	0.740	0.656	0.580	0.512	0.454	0.404
0.6000	0.828	0.774	0.691	0.608	0.533	0.469	0.414	0.367
0.8000	0.792	0.736	0.656	0.574	0.501	0.439	0.386	0.342
1.0000	0.763	0.706	0.628	0.548	0.477	0.417	0.366	0.323

Table 4-3. Effect of Storage on Peak Headwater Depth for Box Culverts, m = 2.5

C_S	h_p/h_{po} = (Peak headwater depth with storage)/(Peak headwater depth without storage)							
	$C_I = 0.6$	$C_I = 0.8$	$C_I = 1.0$	$C_I = 1.2$	$C_I = 1.4$	$C_I = 1.6$	$C_I = 1.8$	$C_I = 2.0$
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	0.999	0.997	0.990	0.977	0.954
0.0015	1.000	1.000	1.000	0.998	0.994	0.982	0.961	0.931
0.0020	1.000	1.000	0.999	0.997	0.990	0.974	0.947	0.911
0.0030	1.000	1.000	0.999	0.994	0.981	0.957	0.922	0.879
0.0040	1.000	1.000	0.998	0.990	0.973	0.942	0.901	0.853
0.0060	1.000	0.999	0.995	0.982	0.956	0.916	0.867	0.813
0.0080	1.000	0.998	0.992	0.974	0.941	0.895	0.840	0.783
0.0100	1.000	0.997	0.989	0.966	0.927	0.876	0.819	0.759
0.0150	0.999	0.995	0.980	0.947	0.898	0.839	0.777	0.715
0.0200	0.998	0.992	0.971	0.930	0.875	0.811	0.746	0.684
0.0300	0.996	0.985	0.953	0.902	0.838	0.769	0.702	0.639
0.0400	0.994	0.978	0.938	0.879	0.810	0.739	0.670	0.608
0.0600	0.987	0.963	0.912	0.843	0.768	0.695	0.626	0.565
0.0800	0.980	0.950	0.890	0.816	0.738	0.664	0.596	0.535
0.1000	0.973	0.937	0.872	0.794	0.714	0.639	0.572	0.513
0.1500	0.954	0.910	0.835	0.752	0.671	0.596	0.530	0.473
0.2000	0.937	0.888	0.807	0.722	0.640	0.566	0.502	0.447
0.3000	0.907	0.852	0.766	0.678	0.597	0.525	0.463	0.411
0.4000	0.881	0.823	0.735	0.647	0.567	0.497	0.437	0.387
0.6000	0.841	0.779	0.691	0.604	0.526	0.459	0.402	0.354
0.8000	0.809	0.746	0.659	0.573	0.497	0.433	0.378	0.333
1.0000	0.783	0.719	0.634	0.550	0.476	0.413	0.361	0.317

Table 4-4. Effect of Storage on Peak Headwater Depth for Box Culverts, m = 3.0

C_S	h_p/h_{po} = (Peak headwater depth with storage)/(Peak headwater depth without storage)							
	$C_I = 0.6$	$C_I = 0.8$	$C_I = 1.0$	$C_I = 1.2$	$C_I = 1.4$	$C_I = 1.6$	$C_I = 1.8$	$C_I = 2.0$
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	0.998	0.993	0.978	0.950	0.912
0.0015	1.000	1.000	0.999	0.996	0.986	0.964	0.928	0.881
0.0020	1.000	1.000	0.999	0.994	0.980	0.951	0.908	0.857
0.0030	1.000	1.000	0.998	0.989	0.967	0.928	0.878	0.821
0.0040	1.000	0.999	0.996	0.983	0.954	0.909	0.854	0.794
0.0060	1.000	0.999	0.992	0.972	0.933	0.879	0.817	0.754
0.0080	1.000	0.998	0.988	0.961	0.914	0.855	0.790	0.725
0.0100	0.999	0.997	0.983	0.951	0.899	0.835	0.768	0.702
0.0150	0.999	0.993	0.972	0.928	0.867	0.798	0.728	0.661
0.0200	0.998	0.989	0.961	0.910	0.843	0.770	0.699	0.632
0.0300	0.996	0.981	0.942	0.880	0.806	0.730	0.658	0.593
0.0400	0.993	0.973	0.925	0.856	0.779	0.701	0.629	0.565
0.0600	0.986	0.958	0.898	0.821	0.739	0.661	0.590	0.527
0.0800	0.979	0.944	0.877	0.795	0.711	0.632	0.562	0.501
0.1000	0.972	0.931	0.859	0.774	0.689	0.611	0.542	0.482
0.1500	0.954	0.905	0.823	0.734	0.649	0.572	0.505	0.447
0.2000	0.938	0.883	0.797	0.706	0.621	0.545	0.480	0.424
0.3000	0.910	0.849	0.758	0.666	0.582	0.509	0.446	0.393
0.4000	0.887	0.823	0.730	0.638	0.555	0.483	0.423	0.372
0.6000	0.850	0.782	0.690	0.599	0.518	0.449	0.392	0.344
0.8000	0.821	0.752	0.660	0.571	0.493	0.426	0.371	0.325
1.0000	0.798	0.728	0.638	0.550	0.474	0.409	0.355	0.311

Table 4-5. Effect of Storage on Peak Headwater Depth for Box Culverts, m = 3.5

C_S	h_p/h_{po} = (Peak headwater depth with storage)/(Peak headwater depth without storage)							
	$C_I = 0.6$	$C_I = 0.8$	$C_I = 1.0$	$C_I = 1.2$	$C_I = 1.4$	$C_I = 1.6$	$C_I = 1.8$	$C_I = 2.0$
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	0.999	0.997	0.985	0.958	0.915	0.861
0.0015	1.000	1.000	0.999	0.993	0.974	0.938	0.886	0.827
0.0020	1.000	1.000	0.998	0.989	0.965	0.921	0.864	0.802
0.0030	1.000	1.000	0.996	0.981	0.947	0.894	0.831	0.765
0.0040	1.000	0.999	0.994	0.973	0.931	0.873	0.806	0.738
0.0060	1.000	0.998	0.988	0.958	0.906	0.840	0.769	0.700
0.0080	1.000	0.997	0.982	0.945	0.886	0.815	0.743	0.674
0.0100	0.999	0.995	0.977	0.933	0.869	0.796	0.722	0.653
0.0150	0.999	0.991	0.963	0.908	0.836	0.759	0.684	0.615
0.0200	0.998	0.987	0.951	0.889	0.812	0.733	0.658	0.590
0.0300	0.995	0.978	0.930	0.858	0.776	0.695	0.621	0.554
0.0400	0.992	0.969	0.912	0.835	0.750	0.669	0.595	0.529
0.0600	0.985	0.952	0.885	0.800	0.713	0.632	0.559	0.496
0.0800	0.978	0.938	0.864	0.775	0.687	0.606	0.535	0.473
0.1000	0.971	0.926	0.846	0.755	0.666	0.586	0.516	0.456
0.1500	0.954	0.900	0.812	0.718	0.630	0.551	0.484	0.426
0.2000	0.939	0.879	0.787	0.692	0.604	0.527	0.461	0.406
0.3000	0.912	0.847	0.751	0.655	0.569	0.494	0.431	0.378
0.4000	0.891	0.822	0.725	0.629	0.544	0.472	0.411	0.360
0.6000	0.857	0.784	0.687	0.593	0.511	0.441	0.383	0.335
0.8000	0.831	0.756	0.661	0.568	0.488	0.420	0.364	0.318
1.0000	0.809	0.734	0.640	0.549	0.471	0.405	0.350	0.306

Table 4-6. Effect of Storage on Peak Discharge for Box Culverts, m = 1.5

C_S	Q_p/I_p = (Peak discharge with storage)/(Peak discharge without storage)							
	$C_I = 0.6$	$C_I = 0.8$	$C_I = 1.0$	$C_I = 1.2$	$C_I = 1.4$	$C_I = 1.6$	$C_I = 1.8$	$C_I = 2.0$
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	1.000	0.999	0.998	0.997
0.0015	1.000	1.000	1.000	1.000	0.999	0.998	0.997	0.994
0.0020	1.000	1.000	1.000	0.999	0.999	0.997	0.994	0.990
0.0030	1.000	1.000	1.000	0.999	0.997	0.994	0.989	0.982
0.0040	1.000	1.000	0.999	0.998	0.995	0.991	0.984	0.974
0.0060	1.000	0.999	0.998	0.996	0.991	0.983	0.972	0.958
0.0080	1.000	0.999	0.997	0.993	0.986	0.975	0.961	0.943
0.0100	0.999	0.999	0.996	0.990	0.981	0.967	0.950	0.930
0.0150	0.999	0.997	0.992	0.982	0.967	0.948	0.926	0.902
0.0200	0.998	0.995	0.987	0.973	0.955	0.932	0.906	0.880
0.0300	0.995	0.989	0.976	0.956	0.931	0.903	0.874	0.844
0.0400	0.992	0.983	0.965	0.940	0.911	0.880	0.848	0.817
0.0600	0.983	0.969	0.944	0.912	0.878	0.843	0.809	0.776
0.0800	0.973	0.955	0.924	0.888	0.851	0.814	0.778	0.745
0.1000	0.962	0.941	0.906	0.867	0.828	0.790	0.754	0.721
0.1500	0.931	0.907	0.867	0.824	0.783	0.744	0.707	0.674
0.2000	0.902	0.875	0.833	0.789	0.748	0.709	0.673	0.641
0.3000	0.848	0.818	0.779	0.735	0.695	0.657	0.623	0.593
0.4000	0.802	0.769	0.734	0.693	0.655	0.619	0.587	0.558
0.6000	0.729	0.692	0.663	0.629	0.595	0.563	0.534	0.507
0.8000	0.673	0.635	0.605	0.579	0.550	0.521	0.495	0.471
1.0000	0.629	0.591	0.561	0.537	0.513	0.488	0.464	0.443

Table 4-7. Effect of Storage on Peak Discharge for Box Culverts, m = 2.0

C_S	Q_p/I_p = (Peak discharge with storage)/(Peak discharge without storage)							
	$C_I = 0.6$	$C_I = 0.8$	$C_I = 1.0$	$C_I = 1.2$	$C_I = 1.4$	$C_I = 1.6$	$C_I = 1.8$	$C_I = 2.0$
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	1.000	0.999	0.998	0.995	0.989
0.0015	1.000	1.000	1.000	0.999	0.998	0.995	0.990	0.981
0.0020	1.000	1.000	1.000	0.999	0.997	0.992	0.984	0.973
0.0030	1.000	1.000	0.999	0.998	0.994	0.986	0.974	0.958
0.0040	1.000	1.000	0.999	0.996	0.990	0.979	0.964	0.944
0.0060	1.000	0.999	0.997	0.992	0.982	0.966	0.946	0.922
0.0080	1.000	0.999	0.995	0.988	0.974	0.954	0.930	0.903
0.0100	0.999	0.998	0.993	0.983	0.966	0.943	0.916	0.887
0.0150	0.999	0.996	0.987	0.971	0.948	0.920	0.888	0.856
0.0200	0.998	0.993	0.981	0.960	0.932	0.900	0.866	0.832
0.0300	0.995	0.986	0.967	0.939	0.905	0.869	0.832	0.796
0.0400	0.991	0.979	0.954	0.921	0.883	0.844	0.806	0.769
0.0600	0.982	0.964	0.931	0.891	0.849	0.807	0.767	0.730
0.0800	0.972	0.949	0.910	0.866	0.822	0.779	0.739	0.702
0.1000	0.961	0.934	0.892	0.845	0.799	0.756	0.716	0.679
0.1500	0.932	0.900	0.853	0.803	0.756	0.713	0.673	0.638
0.2000	0.905	0.870	0.821	0.771	0.724	0.681	0.642	0.608
0.3000	0.857	0.817	0.770	0.721	0.675	0.634	0.598	0.565
0.4000	0.817	0.773	0.730	0.683	0.639	0.600	0.565	0.534
0.6000	0.754	0.705	0.666	0.625	0.586	0.550	0.519	0.490
0.8000	0.705	0.655	0.615	0.581	0.546	0.514	0.485	0.459
1.0000	0.666	0.615	0.576	0.544	0.514	0.485	0.458	0.434

Table 4-8. Effect of Storage on Peak Discharge for Box Culverts, m = 2.5

C_S	Q_p/I_p = (Peak discharge with storage)/(Peak discharge without storage)							
	$C_I = 0.6$	$C_I = 0.8$	$C_I = 1.0$	$C_I = 1.2$	$C_I = 1.4$	$C_I = 1.6$	$C_I = 1.8$	$C_I = 2.0$
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	0.999	0.998	0.994	0.985	0.972
0.0015	1.000	1.000	1.000	0.999	0.995	0.988	0.976	0.958
0.0020	1.000	1.000	0.999	0.998	0.993	0.983	0.966	0.945
0.0030	1.000	1.000	0.999	0.995	0.987	0.972	0.950	0.924
0.0040	1.000	1.000	0.998	0.992	0.981	0.961	0.936	0.907
0.0060	1.000	0.999	0.996	0.986	0.969	0.944	0.913	0.881
0.0080	1.000	0.998	0.993	0.980	0.958	0.928	0.895	0.860
0.0100	0.999	0.997	0.990	0.973	0.947	0.915	0.880	0.843
0.0150	0.998	0.994	0.981	0.958	0.926	0.888	0.850	0.811
0.0200	0.997	0.991	0.973	0.944	0.907	0.867	0.827	0.788
0.0300	0.994	0.983	0.957	0.921	0.879	0.835	0.793	0.753
0.0400	0.990	0.974	0.943	0.901	0.856	0.811	0.768	0.728
0.0600	0.981	0.958	0.917	0.870	0.821	0.774	0.731	0.691
0.0800	0.970	0.942	0.896	0.845	0.795	0.747	0.704	0.665
0.1000	0.959	0.927	0.877	0.824	0.773	0.726	0.683	0.644
0.1500	0.932	0.893	0.839	0.784	0.732	0.686	0.644	0.607
0.2000	0.907	0.865	0.808	0.753	0.702	0.656	0.616	0.580
0.3000	0.864	0.815	0.761	0.707	0.657	0.614	0.575	0.541
0.4000	0.828	0.774	0.724	0.672	0.625	0.583	0.546	0.514
0.6000	0.771	0.712	0.666	0.619	0.576	0.538	0.505	0.475
0.8000	0.727	0.667	0.620	0.580	0.541	0.506	0.474	0.447
1.0000	0.693	0.632	0.585	0.547	0.512	0.480	0.451	0.425

Table 4-9. Effect of Storage on Peak Discharge for Box Culverts, m = 3.0

C_S	Q_p/I_p = (Peak discharge with storage)/(Peak discharge without storage)							
	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	0.999	0.995	0.985	0.969	0.946
0.0015	1.000	1.000	0.999	0.997	0.990	0.976	0.954	0.926
0.0020	1.000	1.000	0.999	0.995	0.986	0.967	0.941	0.910
0.0030	1.000	1.000	0.998	0.991	0.976	0.952	0.921	0.886
0.0040	1.000	0.999	0.996	0.987	0.967	0.939	0.904	0.867
0.0060	1.000	0.998	0.993	0.978	0.951	0.917	0.879	0.839
0.0080	0.999	0.997	0.989	0.969	0.938	0.900	0.859	0.818
0.0100	0.999	0.996	0.985	0.961	0.926	0.885	0.843	0.802
0.0150	0.998	0.992	0.974	0.943	0.902	0.857	0.813	0.770
0.0200	0.997	0.988	0.964	0.927	0.882	0.836	0.790	0.748
0.0300	0.994	0.979	0.946	0.902	0.852	0.804	0.757	0.715
0.0400	0.989	0.969	0.930	0.881	0.830	0.780	0.733	0.691
0.0600	0.980	0.951	0.904	0.850	0.796	0.745	0.699	0.658
0.0800	0.969	0.935	0.882	0.825	0.770	0.720	0.674	0.634
0.1000	0.958	0.920	0.863	0.805	0.750	0.699	0.655	0.615
0.1500	0.932	0.887	0.826	0.766	0.711	0.662	0.619	0.580
0.2000	0.909	0.859	0.797	0.737	0.683	0.635	0.593	0.556
0.3000	0.868	0.811	0.752	0.693	0.641	0.596	0.556	0.521
0.4000	0.835	0.773	0.717	0.661	0.611	0.568	0.530	0.497
0.6000	0.783	0.717	0.664	0.613	0.567	0.527	0.492	0.461
0.8000	0.744	0.676	0.622	0.577	0.535	0.497	0.465	0.436
1.0000	0.713	0.643	0.590	0.547	0.509	0.474	0.443	0.416

Table 4-10. Effect of Storage on Peak Discharge for Box Culverts, m = 3.5

C_S	Q_p/I_p = (Peak discharge with storage)/(Peak discharge without storage)							
	$C_I = 0.6$	$C_I = 0.8$	$C_I = 1.0$	$C_I = 1.2$	$C_I = 1.4$	$C_I = 1.6$	$C_I = 1.8$	$C_I = 2.0$
0.0000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.0010	1.000	1.000	1.000	0.997	0.989	0.972	0.945	0.913
0.0015	1.000	1.000	0.999	0.995	0.982	0.958	0.927	0.890
0.0020	1.000	1.000	0.998	0.992	0.975	0.947	0.912	0.873
0.0030	1.000	0.999	0.996	0.985	0.962	0.928	0.888	0.847
0.0040	1.000	0.999	0.994	0.979	0.950	0.913	0.871	0.828
0.0060	1.000	0.998	0.989	0.967	0.932	0.889	0.844	0.800
0.0080	0.999	0.996	0.984	0.956	0.916	0.871	0.824	0.780
0.0100	0.999	0.995	0.979	0.947	0.903	0.856	0.808	0.764
0.0150	0.998	0.990	0.966	0.926	0.877	0.827	0.779	0.734
0.0200	0.997	0.985	0.955	0.909	0.857	0.806	0.757	0.712
0.0300	0.993	0.974	0.935	0.883	0.828	0.775	0.726	0.682
0.0400	0.988	0.964	0.918	0.862	0.805	0.752	0.703	0.660
0.0600	0.978	0.945	0.891	0.830	0.772	0.719	0.671	0.629
0.0800	0.968	0.928	0.869	0.806	0.748	0.695	0.648	0.607
0.1000	0.957	0.913	0.850	0.787	0.728	0.676	0.630	0.589
0.1500	0.932	0.880	0.814	0.750	0.692	0.641	0.597	0.558
0.2000	0.909	0.853	0.786	0.722	0.665	0.616	0.573	0.536
0.3000	0.871	0.807	0.743	0.681	0.627	0.580	0.539	0.504
0.4000	0.841	0.772	0.711	0.651	0.599	0.554	0.515	0.481
0.6000	0.793	0.720	0.660	0.607	0.558	0.517	0.481	0.449
0.8000	0.757	0.682	0.622	0.573	0.529	0.490	0.456	0.426
1.0000	0.728	0.652	0.593	0.546	0.505	0.468	0.436	0.408

4.4 Application Procedure

Use the following steps to determine the ratios h_p/h_{po} and Q_p/I_p for an existing box culvert.

1. Compute the peak inflow, I_p, by any acceptable method.
2. Compute the flood volume, V, with the appropriate regression equation from Table 2-1.
3. Compute the time-to-peak, t_p, with equation 2-7.
4. Compute the values of m and A_d as explained in Section 2.3.2.
5. Compute the storage factor, C_S, and the discharge factor, C_I, with equations 4-7 and 4-8.
6. Find the ratios h_p/h_{po} and Q_p/I_p by interpolation in the tables listed in Table 4-11.

Table 4-11. Where to Find h_p/h_{po} and Q_p/I_p

m	Find h_p/h_{po} in	Find Q_p/I_p in
$m \leq 1.75$	Table 4-1	Table 4-6
$1.75 < m \leq 2.25$	Table 4-2	Table 4-7
$2.25 < m \leq 2.75$	Table 4-3	Table 4-8
$2.75 < m \leq 3.25$	Table 4-4	Table 4-9
$m > 3.25$	Table 4-5	Table 4-10

4.5 Example

4.5.1 Problem

A double 6 ft x 6 ft box culvert in rural Shawnee County operates under inlet control. The culvert must be evaluated for the 50-year flood. The 50-year discharge from the 605-acre watershed is 1220 cfs. A headwater depth of 13.6 feet would be needed to pass the 50-year discharge through the culvert. However, the topography upstream of the culvert is such that a considerable amount of storage would need to be filled before the headwater could reach this level. At a headwater depth of 5.6 feet, 2.19 acres would be inundated; and at a headwater depth of 7.6 feet, 5.31 acres would be inundated. Estimate the impact of this detention storage on the peak headwater depth and the peak discharge through the culvert, following the procedure in Section 4.4.

4.5.2 Solution

Shawnee County is located in the eastern hydrologic region of Kansas, as defined by Figure 2-2. The 50-year flood volume is obtained from equation 2-10.

$$V = 100.6\ W^{0.901}\ I_p^{\ 0.135} = 100.6\ (605/640)^{0.901}\ (1220)^{0.135} = 250 \text{ acre-feet}$$

The time-to-peak is computed with equation 2-7.

$$t_p = 9.45\,\frac{V}{I_p} = 9.45\left(\frac{250}{1220}\right) = 1.94 \text{ hours}$$

The values of m and A_d in the area-depth relationship are computed with equations 2-20 and 2-21.

$$m = \frac{\log\left(\dfrac{A_2}{A_1}\right)}{\log\left(\dfrac{h_2}{h_1}\right)} = \frac{\log\left(\dfrac{5.31}{2.19}\right)}{\log\left(\dfrac{10.5}{6.5}\right)} = 2.90$$

$$A_d = A_1\left(\frac{d}{h_1}\right)^m = 2.19\ \left(\frac{6.0}{5.6}\right)^{2.40} = 2.68 \text{ acres}$$

The storage and discharge factors are computed with equations 4-7 and 4-8.

$$C_S = 2.13\ \frac{A_d}{t_p\,B\,d^{0.5}} = 2.13\ \frac{2.68}{1.94\,(12)\,(6.0)^{0.5}} = 0.100$$

$$C_I = 0.176\ \frac{I_p}{B\,d^{1.5}} = 0.176\ \frac{1220}{12\ (6.0)^{1.5}} = 1.217$$

The ratios h_p/h_{po} and Q_p/I_p are found by interpolation in Tables 4-4 and 4-9 for m = 3.0.

$h_p/h_{po} = 0.767$

$Q_p/I_p = 0.800$

The estimated peak headwater depth and peak discharge are

$h_p = 0.767\ h_{po} = 0.767\ (13.6) = 10.4$ feet

$Q_p = 0.800\ I_p = 0.800\ (1220) = 980$ cfs

Detention storage reduces the peak headwater depth by approximately 23% and the peak discharge by approximately 20%.

CHAPTER 5

SIZING OF PIPE CULVERTS

5.1 Objective

The objective of this analysis is to estimate the effect of detention storage on the required diameter, d, for a new pipe culvert. The detention-storage effect is indicated by the ratio d/d_o, in which d_o is the required pipe diameter for no storage effect (the pipe diameter required to pass the peak inflow at the allowable headwater depth).

5.2 Problem Formulation

The replacement of A, I and Q in equation 2-3 with the right-hand sides of equations 2-18, 2-4 and 2-24 yields

$$A_d \left(\frac{h}{d}\right)^m \frac{dh}{dt} = I_p \, f_I\!\left(\frac{t}{t_p}\right) - N\sqrt{g\,d^5}\; f_Q\!\left(\frac{h}{d}\right) \tag{5-1}$$

The initial condition for equation 5-1 is h = 0 at t = 0. Equation 5-1 can be written in terms of dimensionless variables as

$$C_S \,(h^*)^m \frac{dh^*}{dt^*} = C_I \; f_I(t^*) - (d^*)^{2.5} \, f_Q\!\left(\frac{h^*}{d^*}\right) \tag{5-2}$$

in which

$$t^* = \frac{t}{t_p} \tag{5-3}$$

$$h^* = \frac{h}{h_a} \tag{5-4}$$

$$d^* = \frac{d}{h_a} \tag{5-5}$$

$$C_S = \frac{A_a}{t_p N \sqrt{g h_a^3}} \tag{5-6}$$

$$C_I = \frac{I_p}{N \sqrt{g h_a^5}} \tag{5-7}$$

The initial condition for equation 5-2 is $h^* = 0$ at $t^* = 0$.

The quantities C_S and C_I are termed the storage factor and the discharge factor. These quantities are dimensionless, which means that the units of the variables on the right-hand sides of equations 5-6 and 5-7 must cancel. Equivalent definitions for variables in customary U. S. units are

$$C_S = 2.13 \, \frac{A_a}{t_p N h_a^{1.5}} \tag{5-8}$$

$$C_I = 0.176 \, \frac{I_p}{N h_a^{2.5}} \tag{5-9}$$

for A_a in acres, t_p in hours, h_a in feet and I_p in cfs. The definitions of C_S and C_I in equations 5-6 through 5-9 apply only to pipe-culvert sizing; different definitions apply to the pipe-culvert analysis, box-culvert analysis and box-culvert sizing.

The objective is to find the pipe size for which the peak headwater depth equals the allowable headwater depth, or in dimensionless terms, the value of d^* for which $h_p^* = 1$ ($h_p^* = h_p/h_a$). This value of d^* is found by trial. The initial-value problem is solved numerically to find the value of h_p^* for each trial value of d^*. The value of d_o^* (= d_o/h_a) is found by solving equation 5-10 by trial. Finally, equation 5-11 yields the desired ratio d/d_o.

$$C_I = (d_o^*)^{5/2} f_Q\left(\frac{1}{d_o^*}\right) \tag{5-10}$$

$$\frac{d}{d_o} = \frac{d^*}{d_o^*} \tag{5-11}$$

5.3 Numerical Results

The problem formulated in Section 5.2, with f_I and f_Q defined by equations 2-5 and 2-25, was solved for all possible combinations of five values of m, eight values of C_I and 21 values of C_S. The selected values of these inputs span the ranges of practical interest. Equation 5-2 was solved numerically by a fourth-order Runge-Kutta method. The results for d/d_o are presented in Tables 5-1 through 5-5. Figure 5-1 shows that the larger the values of storage and discharge factors, the greater the storage effect (the smaller the value of d/d_o).

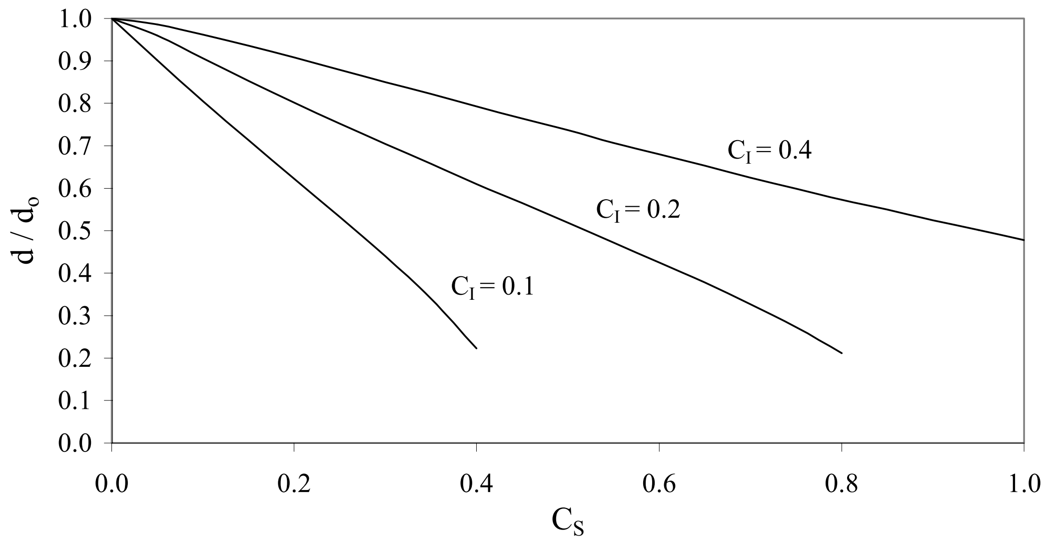

Figure 5-1. Effect of Storage on Required Diameter for Pipe Culverts, m = 2.5

Table 5-1. Effect of Storage on Required Diameter for Pipe Culverts, m = 1.5

C_S	d/d_o = (Required pipe diameter with storage)/(Required pipe diameter without storage)							
	C_I = 0.05	C_I = 0.10	C_I = 0.15	C_I = 0.20	C_I = 0.25	C_I = 0.30	C_I = 0.35	C_I = 0.40
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.05	0.755	0.880	0.928	0.954	0.965	0.974	0.979	0.985
0.10	0.500	0.751	0.840	0.886	0.909	0.931	0.945	0.958
0.15	0.170	0.624	0.751	0.816	0.851	0.882	0.906	0.924
0.20		0.492	0.664	0.748	0.793	0.831	0.863	0.889
0.25		0.350	0.576	0.680	0.736	0.780	0.820	0.851
0.30		0.168	0.488	0.614	0.681	0.730	0.776	0.812
0.35			0.394	0.546	0.626	0.683	0.731	0.773
0.40			0.292	0.479	0.572	0.636	0.686	0.735
0.45			0.164	0.410	0.519	0.590	0.644	0.695
0.50				0.337	0.465	0.545	0.602	0.655
0.55				0.256	0.412	0.499	0.563	0.617
0.60				0.159	0.355	0.455	0.523	0.579
0.65					0.296	0.409	0.485	0.544
0.70					0.230	0.363	0.446	0.509
0.75					0.154	0.317	0.407	0.474
0.80					0.012	0.266	0.368	0.441
0.85						0.212	0.329	0.406
0.90						0.148	0.287	0.371
0.95						0.056	0.244	0.338
1.00							0.198	0.302

Table 5-2. Effect of Storage on Required Diameter for Pipe Culverts, m = 2.0

C_S	d/d_o = (Required pipe diameter with storage)/(Required pipe diameter without storage)							
	C_I = 0.05	C_I = 0.10	C_I = 0.15	C_I = 0.20	C_I = 0.25	C_I = 0.30	C_I = 0.35	C_I = 0.40
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.05	0.787	0.892	0.935	0.957	0.967	0.976	0.980	0.986
0.10	0.578	0.782	0.858	0.898	0.917	0.936	0.949	0.960
0.15	0.351	0.676	0.783	0.838	0.867	0.894	0.914	0.931
0.20		0.570	0.709	0.779	0.817	0.850	0.877	0.900
0.25		0.463	0.638	0.723	0.768	0.807	0.840	0.868
0.30		0.345	0.566	0.667	0.722	0.763	0.802	0.835
0.35		0.200	0.494	0.612	0.675	0.723	0.766	0.802
0.40			0.418	0.558	0.630	0.683	0.728	0.768
0.45			0.338	0.503	0.587	0.643	0.691	0.736
0.50			0.248	0.449	0.543	0.606	0.655	0.703
0.55			0.136	0.391	0.500	0.569	0.622	0.669
0.60				0.331	0.455	0.532	0.589	0.638
0.65				0.266	0.412	0.496	0.556	0.607
0.70				0.192	0.367	0.459	0.524	0.577
0.75				0.088	0.319	0.423	0.492	0.548
0.80					0.270	0.386	0.461	0.518
0.85					0.214	0.349	0.430	0.491
0.90					0.151	0.309	0.399	0.463
0.95					0.058	0.271	0.368	0.435
1.00						0.228	0.336	0.407

Table 5-3. Effect of Storage on Required Diameter for Pipe Culverts, m = 2.5

	d/d_o = (Required pipe diameter with storage)/(Required pipe diameter without storage)							
C_S	C_I = 0.05	C_I = 0.10	C_I = 0.15	C_I = 0.20	C_I = 0.25	C_I = 0.30	C_I = 0.35	C_I = 0.40
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.05	0.810	0.902	0.940	0.960	0.970	0.977	0.982	0.986
0.10	0.630	0.805	0.871	0.906	0.924	0.941	0.952	0.962
0.15	0.449	0.713	0.805	0.853	0.878	0.903	0.921	0.936
0.20	0.228	0.623	0.741	0.802	0.833	0.864	0.887	0.908
0.25		0.532	0.680	0.752	0.791	0.825	0.855	0.879
0.30		0.440	0.618	0.704	0.749	0.788	0.822	0.850
0.35		0.340	0.558	0.658	0.710	0.751	0.790	0.822
0.40		0.223	0.496	0.610	0.671	0.716	0.756	0.793
0.45			0.434	0.565	0.633	0.682	0.724	0.764
0.50			0.368	0.519	0.596	0.648	0.693	0.737
0.55			0.298	0.472	0.559	0.616	0.663	0.707
0.60			0.216	0.425	0.522	0.584	0.634	0.680
0.65			0.112	0.378	0.486	0.554	0.605	0.653
0.70				0.327	0.449	0.523	0.577	0.625
0.75				0.273	0.412	0.492	0.549	0.599
0.80				0.212	0.374	0.463	0.524	0.573
0.85				0.138	0.336	0.432	0.497	0.550
0.90					0.296	0.402	0.471	0.525
0.95					0.252	0.371	0.444	0.502
1.00					0.203	0.338	0.418	0.478

Table 5-4. Effect of Storage on Required Diameter for Pipe Culverts, m = 3.0

C_S	d/d_o = (Required pipe diameter with storage)/(Required pipe diameter without storage)							
	C_I = 0.05	C_I = 0.10	C_I = 0.15	C_I = 0.20	C_I = 0.25	C_I = 0.30	C_I = 0.35	C_I = 0.40
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.05	0.827	0.909	0.944	0.963	0.971	0.978	0.982	0.986
0.10	0.670	0.822	0.881	0.913	0.929	0.945	0.955	0.964
0.15	0.514	0.740	0.822	0.865	0.887	0.909	0.925	0.939
0.20	0.344	0.661	0.765	0.820	0.846	0.875	0.895	0.914
0.25		0.584	0.710	0.775	0.809	0.840	0.867	0.888
0.30		0.505	0.657	0.732	0.771	0.806	0.837	0.863
0.35		0.425	0.604	0.690	0.736	0.772	0.808	0.836
0.40		0.338	0.552	0.649	0.701	0.742	0.779	0.810
0.45		0.235	0.500	0.609	0.667	0.711	0.749	0.785
0.50			0.446	0.570	0.635	0.680	0.722	0.760
0.55			0.390	0.530	0.601	0.652	0.694	0.735
0.60			0.332	0.491	0.570	0.624	0.668	0.711
0.65			0.268	0.450	0.539	0.596	0.643	0.686
0.70			0.192	0.410	0.507	0.569	0.617	0.661
0.75				0.368	0.475	0.542	0.593	0.638
0.80				0.324	0.443	0.517	0.569	0.615
0.85				0.277	0.412	0.490	0.545	0.592
0.90				0.226	0.380	0.463	0.522	0.571
0.95				0.169	0.346	0.437	0.499	0.550
1.00					0.313	0.412	0.477	0.529

Table 5-5. Effect of Storage on Required Diameter for Pipe Culverts, m = 3.5

C_S	d/d_o = (Required pipe diameter with storage)/(Required pipe diameter without storage)							
	C_I = 0.05	C_I = 0.10	C_I = 0.15	C_I = 0.20	C_I = 0.25	C_I = 0.30	C_I = 0.35	C_I = 0.40
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.05	0.841	0.915	0.947	0.965	0.972	0.979	0.983	0.987
0.10	0.699	0.835	0.890	0.919	0.933	0.948	0.957	0.965
0.15	0.563	0.761	0.835	0.875	0.894	0.916	0.930	0.942
0.20	0.420	0.691	0.784	0.833	0.858	0.884	0.902	0.919
0.25	0.254	0.623	0.735	0.793	0.822	0.852	0.875	0.895
0.30		0.554	0.687	0.754	0.788	0.821	0.848	0.871
0.35		0.485	0.640	0.717	0.757	0.790	0.822	0.848
0.40		0.412	0.594	0.680	0.725	0.761	0.795	0.825
0.45		0.335	0.548	0.644	0.694	0.733	0.770	0.802
0.50		0.247	0.500	0.609	0.664	0.706	0.745	0.779
0.55			0.454	0.573	0.635	0.680	0.720	0.757
0.60			0.406	0.538	0.606	0.655	0.694	0.735
0.65			0.356	0.503	0.578	0.629	0.671	0.712
0.70			0.300	0.469	0.551	0.605	0.648	0.690
0.75			0.244	0.433	0.522	0.581	0.626	0.669
0.80			0.176	0.398	0.496	0.558	0.605	0.648
0.85				0.361	0.467	0.535	0.584	0.627
0.90				0.320	0.441	0.512	0.563	0.607
0.95				0.280	0.412	0.488	0.543	0.588
1.00				0.236	0.383	0.465	0.522	0.569

5.4 Application Procedure

Use the following steps to determine the ratio d/d_o for a new pipe culvert.

1. Compute the peak inflow, I_p, by any acceptable method.
2. Compute the flood volume, V, with the appropriate regression equation from Table 2-1.
3. Compute the time-to-peak, t_p, with equation 2-7.
4. Compute the values of m and A_a as explained in Section 2.3.2.
5. Compute the storage factor, C_S, and the discharge factor, C_I, with equations 5-8 and 5-9.
6. Find the ratio d/d_o by interpolation in the table listed in Table 5-6.

Table 5-6. Where to find d/d_o

m	Find d/d_o in
$m \leq 1.75$	Table 5-1
$1.75 < m \leq 2.25$	Table 5-2
$2.25 < m \leq 2.75$	Table 5-3
$2.75 < m \leq 3.25$	Table 5-4
$m > 3.25$	Table 5-5

5.5 Example

5.5.1 Problem

A new pipe culvert in Barber County must be sized for the 25-year flood. The drainage area is 325 acres, the 25-year discharge is 400 cfs, and the allowable headwater depth is 9.5 feet. The culvert would operate under inlet control. A pipe diameter of 78 inches would be required to pass the 25-year discharge at the allowable headwater. However, the topography upstream of the culvert is such that a considerable amount of storage would need to be filled before the headwater could reach this level. At a headwater depth of 6.0 feet, 1.63 acres would be inundated; and at a headwater depth of 9.0 feet, 4.69 acres would be inundated. Estimate the minimum pipe diameter required if detention storage is considered, following the procedure in Section 5.4.

5.5.2 Solution

Barber County is located in the western hydrologic region of Kansas, as defined by Figure 2-2. The 25-year flood volume is obtained from equation 2-13:

$$V = 6.18\ W^{0.758}\ I_p^{0.405} = 6.18\ (325/640)^{0.758}\ (400)^{0.405} = 41.9 \text{ acre-feet}$$

The time-to-peak is computed with equation 2-7.

$$t_p = 9.45\ \frac{V}{I_p} = 9.45 \left(\frac{41.9}{400} \right) = 0.99 \text{ hours}$$

The values of m and A_a in the area-depth relationship are computed with equations 2-20 and 2-22.

$$m = \frac{\log\left(\frac{A_2}{A_1}\right)}{\log\left(\frac{h_2}{h_1}\right)} = \frac{\log\left(\frac{4.69}{1.63}\right)}{\log\left(\frac{9.0}{6.0}\right)} = 2.61$$

$$A_a = A_1 \left(\frac{h_a}{h_1} \right)^m = 1.63 \left(\frac{9.5}{6.0} \right)^{2.61} = 5.41 \text{ acres}$$

The storage and discharge factors are computed with equations 5-8 and 5-9.

$$C_S = 2.13\ \frac{A_a}{t_p\ N\ h_a^{1.5}} = 2.13\ \frac{5.41}{0.99\ (1)\ (9.5)^{1.5}} = 0.398$$

$$C_I = 0.176\ \frac{I_p}{N\ h_a^{2.5}} = 0.176\ \frac{400}{1\ (9.5)^{2.5}} = 0.253$$

The ratio d/d_o is found by interpolation in Table 5-3 for m = 2.5.

$d/d_o = 0.676$

The minimum pipe size is

$d = 0.676\ d_o = 0.676\ (6.5) = 4.39$ feet = 52.7 in.

This approximate analysis indicates that a pipe culvert with a diameter of 54 inches or larger would prevent the allowable headwater depth from being exceeded in a 25-year flood.

CHAPTER 6

SIZING OF BOX CULVERTS

6.1 Objective

The objective of this analysis is to estimate the effect of detention storage on the required span, B, for a new box culvert with a specified rise, d. The detention-storage effect is indicated by the ratio B/B_o, in which B_o is the required span for no storage effect (the required to pass the peak inflow at the allowable headwater depth).

6.2 Problem Formulation

The replacement of A, I and Q in equation 2-3 with the right-hand sides of equations 2-19, 2-4 and 2-26 yields

$$A_a \left(\frac{h}{h_a}\right)^m \frac{dh}{dt} = I_p\, f_I\!\left(\frac{t}{t_p}\right) - B\sqrt{g\,d^3}\; f_Q\!\left(\frac{h}{d}\right) \tag{6-1}$$

The initial condition for equation 6-2 is h = 0 at t = 0. Equation 6-2 can be written in terms of dimensionless variables as

$$C_S\,(h^*)^m \frac{dh^*}{dt^*} = C_I\; f_I(t^*) - B^*(d^*)^{1.5}\, f_Q\!\left(\frac{h^*}{d^*}\right) \tag{6-2}$$

in which

$$t^* = \frac{t}{t_p} \tag{6-3}$$

$$h^* = \frac{h}{h_a} \tag{6-4}$$

$$d^* = \frac{d}{h_a} \tag{6-5}$$

$$B^* = \frac{B}{h_a} \tag{6-6}$$

$$C_S = \frac{A_a}{t_p \sqrt{g h_a^3}} \tag{6-7}$$

$$C_I = \frac{I_p}{\sqrt{g h_a^5}} \tag{6-8}$$

The initial condition for equation 6-2 is $h^* = 0$ at $t^* = 0$.

The quantities C_S and C_I are termed the storage factor and the discharge factor. These quantities are dimensionless, which means that the units of the variables on the right-hand sides of equations 6-7 and 6-8 must cancel. Equivalent definitions for variables in customary U. S. units are

$$C_S = 2.13 \frac{A_a}{t_p h_a^{1.5}} \tag{6-9}$$

$$C_I = 0.176 \frac{I_p}{h_a^{2.5}} \tag{6-10}$$

for A_a in acres, t_p in hours, h_a in feet and I_p in cfs. The definitions of C_S and C_I in equations 6-7 through 6-10 apply only to box-culvert sizing; different definitions apply to pipe-culvert analysis, box-culvert analysis and pipe-culvert sizing.

The objective is to find the culvert span (for a specified rise) for which the peak headwater depth equals the allowable headwater depth, or in dimensionless terms, the value of B^* for which $h_p^* = 1$ ($h_p^* = h_p/h_a$). This value of B^* is found by trial. The initial-value problem is solved numerically to find the value of h_p^* for each trial value of B^*. Equation 6-11 yields the value of B_o^* (= B_o/h_a), and equation 6-12 yields the desired ratio B/B_o.

$$B_o^* = \frac{C_I}{(d^*)^{1.5} f_Q\left(\frac{1}{d^*}\right)} \tag{6-11}$$

$$\frac{B}{B_o} = \frac{B^*}{B_o^*} \tag{6-12}$$

6.3 Numerical Results

The problem formulated in Section 6.2, with f_I and f_Q defined by equations 2-5 and 2-27, was solved for all possible combinations of two values of d^*, five values of m, eight values of C_I and 21 values of C_S. Equation 6-2 was solved numerically by a fourth-order Runge-Kutta method. The values of B/B_o for $d/h_a = 0.6$ are presented in Tables 6-1 through 6-5, and the results for $d/h_a = 0.8$ are presented in Tables 6-6 through 6-10, Figure 6.1 shows that the larger the values of storage and discharge factors, the greater the storage effect (the smaller the value of B/B_o). The ratio B/B_o is not very sensitive to the value of d/h_a within the range of practical interest.

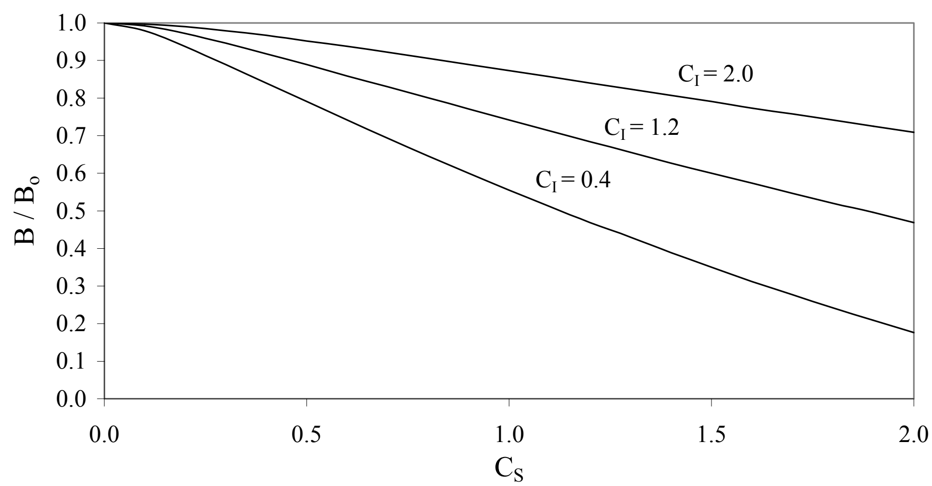

Figure 6-1. Effect of Storage on Required Span for Box Culverts, d/h_a = 0.8, m = 2.5

Table 6-1. Effect of Storage on Required Span for Box Culverts, $d/h_a = 0.6$, $m = 1.5$

C_S	B/B_o = (Required span with storage)/(Required span without storage)								
	C_I = 0.4	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.934	0.963	0.976	0.983	0.987	0.990	0.992	0.994	0.995
0.2	0.837	0.902	0.934	0.951	0.963	0.971	0.976	0.980	0.983
0.3	0.738	0.837	0.887	0.915	0.934	0.946	0.955	0.963	0.968
0.4	0.641	0.771	0.837	0.877	0.902	0.920	0.934	0.943	0.951
0.5	0.547	0.705	0.787	0.837	0.870	0.893	0.910	0.923	0.934
0.6	0.458	0.641	0.738	0.797	0.837	0.865	0.887	0.902	0.915
0.7	0.373	0.578	0.689	0.758	0.805	0.837	0.861	0.881	0.896
0.8	0.293	0.518	0.641	0.719	0.771	0.809	0.837	0.859	0.877
0.9	0.219	0.458	0.594	0.680	0.738	0.780	0.813	0.837	0.857
1.0	0.150	0.400	0.547	0.641	0.705	0.752	0.787	0.814	0.837
1.1	0.088	0.346	0.502	0.604	0.674	0.725	0.763	0.793	0.817
1.2		0.293	0.458	0.566	0.641	0.696	0.738	0.771	0.797
1.3		0.244	0.415	0.529	0.609	0.668	0.713	0.749	0.777
1.4		0.195	0.373	0.494	0.578	0.641	0.689	0.727	0.758
1.5		0.150	0.332	0.458	0.547	0.613	0.665	0.705	0.738
1.6		0.107	0.293	0.424	0.518	0.587	0.641	0.684	0.719
1.7		0.068	0.256	0.391	0.487	0.561	0.617	0.662	0.699
1.8			0.219	0.357	0.458	0.535	0.594	0.641	0.680
1.9			0.184	0.324	0.430	0.508	0.570	0.619	0.660
2.0			0.150	0.293	0.400	0.482	0.547	0.600	0.641

Table 6-2. Effect of Storage on Required Span for Box Culverts, $d/h_a = 0.6$, $m = 2.0$

C_S	B/B_o = (Required span with storage)/(Required span without storage)								
	C_I = 0.4	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.938	0.965	0.977	0.983	0.988	0.990	0.992	0.994	0.995
0.2	0.853	0.910	0.938	0.954	0.965	0.972	0.977	0.980	0.983
0.3	0.768	0.853	0.896	0.922	0.938	0.949	0.958	0.965	0.970
0.4	0.684	0.795	0.853	0.887	0.910	0.926	0.938	0.947	0.954
0.5	0.604	0.738	0.810	0.853	0.881	0.902	0.917	0.929	0.938
0.6	0.527	0.684	0.768	0.818	0.853	0.877	0.896	0.910	0.922
0.7	0.455	0.630	0.725	0.783	0.824	0.853	0.874	0.891	0.904
0.8	0.385	0.578	0.684	0.750	0.795	0.828	0.853	0.872	0.887
0.9	0.318	0.527	0.643	0.717	0.768	0.803	0.831	0.853	0.870
1.0	0.258	0.479	0.604	0.684	0.738	0.779	0.810	0.834	0.853
1.1	0.199	0.430	0.564	0.650	0.711	0.755	0.788	0.814	0.836
1.2	0.145	0.385	0.527	0.619	0.684	0.730	0.768	0.795	0.818
1.3	0.094	0.340	0.490	0.588	0.656	0.707	0.746	0.776	0.801
1.4		0.297	0.455	0.557	0.630	0.684	0.725	0.758	0.783
1.5		0.258	0.420	0.527	0.604	0.660	0.704	0.738	0.768
1.6		0.217	0.385	0.498	0.578	0.637	0.684	0.721	0.750
1.7		0.180	0.352	0.469	0.553	0.615	0.664	0.701	0.732
1.8		0.145	0.318	0.439	0.527	0.592	0.643	0.684	0.717
1.9		0.109	0.287	0.412	0.502	0.570	0.623	0.666	0.699
2.0		0.078	0.258	0.385	0.479	0.549	0.604	0.648	0.684

Table 6-3. Effect of Storage on Required Span for Box Culverts, $d/h_a = 0.6$, $m = 2.5$

C_S	B/B_o = (Required span with storage)/(Required span without storage)								
	C_I = 0.4	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.941	0.967	0.978	0.984	0.988	0.991	0.993	0.994	0.995
0.2	0.864	0.916	0.941	0.957	0.967	0.973	0.978	0.981	0.984
0.3	0.787	0.864	0.903	0.926	0.941	0.952	0.960	0.967	0.971
0.4	0.714	0.813	0.864	0.896	0.916	0.931	0.941	0.950	0.957
0.5	0.643	0.763	0.826	0.864	0.891	0.908	0.922	0.934	0.941
0.6	0.576	0.714	0.787	0.834	0.864	0.887	0.903	0.916	0.926
0.7	0.512	0.666	0.750	0.803	0.838	0.864	0.884	0.898	0.911
0.8	0.449	0.621	0.714	0.773	0.813	0.842	0.864	0.881	0.896
0.9	0.391	0.576	0.678	0.742	0.787	0.820	0.845	0.864	0.880
1.0	0.336	0.533	0.643	0.714	0.763	0.799	0.826	0.848	0.864
1.1	0.281	0.490	0.609	0.686	0.738	0.777	0.807	0.830	0.849
1.2	0.232	0.449	0.576	0.657	0.714	0.756	0.787	0.813	0.834
1.3	0.184	0.410	0.543	0.629	0.689	0.734	0.770	0.796	0.818
1.4	0.139	0.373	0.512	0.602	0.666	0.714	0.750	0.779	0.803
1.5	0.098	0.336	0.480	0.576	0.643	0.693	0.732	0.763	0.787
1.6		0.301	0.449	0.551	0.621	0.674	0.714	0.746	0.773
1.7		0.266	0.420	0.523	0.598	0.652	0.695	0.730	0.758
1.8		0.232	0.391	0.500	0.576	0.633	0.678	0.714	0.742
1.9		0.199	0.363	0.475	0.555	0.613	0.660	0.697	0.729
2.0		0.168	0.336	0.449	0.533	0.596	0.643	0.682	0.714

Table 6-4. Effect of Storage on Required Span for Box Culverts, d/h_a = 0.6, m = 3.0

C_S	B/B_o = (Required span with storage)/(Required span without storage)								
	C_I = 0.4	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.944	0.968	0.979	0.984	0.988	0.991	0.993	0.994	0.995
0.2	0.873	0.921	0.944	0.959	0.968	0.975	0.979	0.982	0.984
0.3	0.803	0.873	0.909	0.931	0.944	0.955	0.962	0.968	0.973
0.4	0.736	0.826	0.873	0.902	0.921	0.935	0.944	0.952	0.959
0.5	0.674	0.781	0.838	0.873	0.896	0.914	0.927	0.937	0.944
0.6	0.613	0.736	0.803	0.846	0.873	0.894	0.909	0.921	0.931
0.7	0.555	0.693	0.770	0.817	0.850	0.873	0.891	0.904	0.916
0.8	0.500	0.652	0.736	0.790	0.826	0.854	0.873	0.889	0.902
0.9	0.445	0.613	0.705	0.764	0.803	0.833	0.855	0.873	0.887
1.0	0.395	0.574	0.674	0.736	0.781	0.813	0.838	0.857	0.873
1.1	0.348	0.535	0.643	0.711	0.759	0.794	0.820	0.842	0.859
1.2	0.301	0.500	0.613	0.686	0.736	0.775	0.803	0.826	0.846
1.3	0.256	0.463	0.584	0.660	0.715	0.756	0.787	0.811	0.831
1.4	0.215	0.430	0.555	0.637	0.693	0.736	0.770	0.796	0.817
1.5	0.174	0.395	0.527	0.613	0.674	0.719	0.754	0.781	0.803
1.6	0.137	0.363	0.500	0.590	0.652	0.701	0.736	0.766	0.790
1.7	0.100	0.332	0.473	0.566	0.633	0.682	0.721	0.752	0.777
1.8		0.301	0.445	0.543	0.613	0.664	0.705	0.736	0.764
1.9		0.270	0.420	0.521	0.594	0.646	0.689	0.723	0.750
2.0		0.242	0.395	0.500	0.574	0.629	0.674	0.709	0.736

Table 6-5. Effect of Storage on Required Span for Box Culverts, d/h_a = 0.6, m = 3.5

C_S	B/B_o = (Required span with storage)/(Required span without storage)								
	C_I = 0.4	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.947	0.969	0.979	0.985	0.989	0.991	0.993	0.994	0.995
0.2	0.881	0.925	0.947	0.961	0.969	0.975	0.979	0.982	0.985
0.3	0.816	0.881	0.914	0.934	0.947	0.957	0.964	0.969	0.974
0.4	0.756	0.838	0.881	0.907	0.925	0.938	0.947	0.955	0.961
0.5	0.697	0.795	0.848	0.881	0.902	0.918	0.931	0.939	0.947
0.6	0.641	0.756	0.816	0.854	0.881	0.899	0.914	0.925	0.934
0.7	0.588	0.717	0.785	0.828	0.859	0.881	0.896	0.910	0.920
0.8	0.537	0.678	0.756	0.805	0.838	0.861	0.881	0.896	0.907
0.9	0.488	0.641	0.727	0.779	0.816	0.844	0.864	0.881	0.894
1.0	0.441	0.605	0.697	0.756	0.795	0.826	0.848	0.866	0.881
1.1	0.398	0.570	0.668	0.732	0.775	0.807	0.832	0.852	0.867
1.2	0.355	0.537	0.641	0.709	0.756	0.789	0.816	0.838	0.854
1.3	0.313	0.504	0.615	0.686	0.736	0.771	0.801	0.823	0.842
1.4	0.273	0.473	0.588	0.664	0.717	0.756	0.785	0.809	0.828
1.5	0.236	0.441	0.563	0.641	0.697	0.738	0.770	0.795	0.816
1.6	0.199	0.412	0.537	0.621	0.678	0.721	0.756	0.781	0.805
1.7	0.164	0.383	0.514	0.600	0.660	0.705	0.740	0.769	0.791
1.8	0.133	0.355	0.488	0.578	0.641	0.689	0.727	0.756	0.779
1.9	0.102	0.328	0.465	0.559	0.623	0.672	0.711	0.742	0.768
2.0		0.301	0.441	0.537	0.605	0.656	0.697	0.729	0.756

Table 6-6. Effect of Storage on Required Span for Box Culverts, $d/h_a = 0.8$, $m = 1.5$

C_S	B/B_o = (Required span with storage)/(Required span without storage)								
	C_I = 0.4	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.05	0.953	0.977	0.986	0.991	0.994	0.996	0.996	0.997	0.998
0.10	0.865	0.926	0.953	0.969	0.977	0.982	0.986	0.989	0.991
0.15	0.768	0.865	0.912	0.938	0.953	0.965	0.972	0.977	0.980
0.20	0.668	0.801	0.865	0.902	0.926	0.941	0.953	0.962	0.969
0.25	0.572	0.734	0.816	0.865	0.896	0.918	0.934	0.945	0.953
0.30	0.479	0.668	0.768	0.826	0.865	0.893	0.912	0.926	0.938
0.35	0.391	0.604	0.717	0.787	0.832	0.865	0.889	0.906	0.920
0.40	0.307	0.541	0.668	0.747	0.801	0.838	0.865	0.887	0.902
0.45	0.229	0.479	0.619	0.707	0.768	0.809	0.840	0.865	0.884
0.50	0.156	0.420	0.572	0.668	0.734	0.781	0.816	0.844	0.865
0.55	0.092	0.361	0.525	0.629	0.701	0.752	0.791	0.822	0.846
0.60		0.307	0.479	0.590	0.668	0.725	0.768	0.801	0.826
0.65		0.254	0.434	0.553	0.635	0.695	0.742	0.777	0.807
0.70		0.205	0.391	0.516	0.604	0.668	0.717	0.756	0.787
0.75		0.156	0.348	0.479	0.572	0.641	0.693	0.734	0.768
0.80		0.113	0.307	0.443	0.541	0.613	0.668	0.711	0.747
0.85		0.072	0.268	0.408	0.510	0.586	0.645	0.689	0.727
0.90			0.229	0.373	0.479	0.559	0.619	0.668	0.707
0.95			0.191	0.340	0.449	0.531	0.596	0.646	0.687
1.00			0.156	0.307	0.420	0.506	0.572	0.625	0.668

Table 6-7. Effect of Storage on Required Span for Box Culverts, $d/h_a = 0.8$, $m = 2.0$

C_S	B/B_o = (Required span with storage)/(Required span without storage)								
	C_I = 0.4	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.05	0.957	0.979	0.986	0.991	0.994	0.996	0.996	0.997	0.998
0.10	0.879	0.932	0.957	0.971	0.979	0.983	0.986	0.990	0.991
0.15	0.795	0.879	0.920	0.942	0.957	0.967	0.973	0.979	0.982
0.20	0.711	0.824	0.879	0.912	0.932	0.947	0.957	0.965	0.971
0.25	0.629	0.768	0.838	0.879	0.906	0.926	0.939	0.949	0.957
0.30	0.551	0.711	0.795	0.846	0.879	0.902	0.920	0.932	0.942
0.35	0.475	0.656	0.754	0.813	0.852	0.879	0.900	0.916	0.928
0.40	0.402	0.602	0.711	0.777	0.824	0.855	0.879	0.896	0.912
0.45	0.334	0.551	0.670	0.744	0.795	0.832	0.858	0.879	0.896
0.50	0.270	0.500	0.629	0.711	0.768	0.807	0.838	0.861	0.879
0.55	0.207	0.449	0.590	0.678	0.738	0.783	0.816	0.842	0.863
0.60	0.150	0.402	0.551	0.645	0.711	0.760	0.795	0.824	0.846
0.65	0.098	0.355	0.512	0.613	0.684	0.734	0.773	0.805	0.828
0.70		0.312	0.475	0.582	0.656	0.711	0.754	0.785	0.813
0.75		0.270	0.438	0.551	0.629	0.688	0.732	0.768	0.795
0.80		0.227	0.402	0.520	0.602	0.664	0.711	0.748	0.777
0.85		0.188	0.367	0.488	0.576	0.641	0.691	0.730	0.762
0.90		0.150	0.334	0.459	0.551	0.617	0.670	0.711	0.744
0.95		0.115	0.301	0.430	0.525	0.596	0.648	0.693	0.729
1.00		0.082	0.270	0.402	0.500	0.572	0.629	0.674	0.711

Table 6-8. Effect of Storage on Required Span for Box Culverts, $d/h_a = 0.8$, $m = 2.5$

C_S	B/B_o = (Required span with storage)/(Required span without storage)								
	C_I = 0.4	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.05	0.959	0.979	0.987	0.992	0.994	0.996	0.996	0.997	0.998
0.10	0.889	0.937	0.959	0.972	0.979	0.984	0.987	0.990	0.992
0.15	0.814	0.889	0.926	0.946	0.959	0.969	0.975	0.979	0.982
0.20	0.742	0.840	0.889	0.918	0.937	0.950	0.959	0.967	0.972
0.25	0.670	0.791	0.852	0.889	0.914	0.931	0.943	0.952	0.959
0.30	0.600	0.742	0.814	0.859	0.889	0.910	0.926	0.938	0.946
0.35	0.533	0.693	0.777	0.830	0.865	0.889	0.908	0.922	0.933
0.40	0.469	0.646	0.742	0.801	0.840	0.869	0.889	0.906	0.918
0.45	0.408	0.600	0.705	0.771	0.814	0.848	0.871	0.889	0.904
0.50	0.350	0.555	0.670	0.742	0.791	0.826	0.852	0.873	0.889
0.55	0.295	0.512	0.635	0.713	0.766	0.805	0.834	0.857	0.875
0.60	0.242	0.469	0.600	0.684	0.742	0.783	0.814	0.840	0.859
0.65	0.191	0.430	0.566	0.656	0.717	0.762	0.797	0.824	0.846
0.70	0.145	0.389	0.533	0.627	0.693	0.742	0.777	0.807	0.830
0.75	0.102	0.350	0.502	0.600	0.670	0.721	0.760	0.791	0.814
0.80		0.312	0.469	0.574	0.646	0.699	0.742	0.773	0.801
0.85		0.277	0.439	0.547	0.623	0.680	0.723	0.758	0.785
0.90		0.242	0.408	0.520	0.600	0.660	0.705	0.742	0.771
0.95		0.209	0.379	0.496	0.578	0.639	0.688	0.725	0.756
1.00		0.176	0.350	0.469	0.555	0.619	0.670	0.709	0.742

Table 6-9. Effect of Storage on Required Span for Box Culverts, $d/h_a = 0.8$, $m = 3.0$

C_S	B/B_o = (Required span with storage)/(Required span without storage)								
	C_I = 0.4	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.05	0.961	0.980	0.988	0.992	0.994	0.996	0.996	0.997	0.998
0.10	0.896	0.941	0.961	0.973	0.980	0.984	0.988	0.990	0.992
0.15	0.830	0.896	0.930	0.949	0.961	0.970	0.976	0.980	0.982
0.20	0.764	0.852	0.896	0.924	0.941	0.953	0.961	0.969	0.973
0.25	0.699	0.809	0.863	0.896	0.920	0.936	0.946	0.955	0.961
0.30	0.637	0.764	0.830	0.871	0.896	0.916	0.930	0.941	0.949
0.35	0.578	0.721	0.797	0.844	0.875	0.896	0.914	0.927	0.938
0.40	0.520	0.678	0.764	0.816	0.852	0.879	0.896	0.912	0.924
0.45	0.465	0.637	0.730	0.789	0.830	0.859	0.881	0.896	0.910
0.50	0.412	0.598	0.699	0.764	0.809	0.840	0.863	0.883	0.896
0.55	0.361	0.559	0.668	0.738	0.785	0.820	0.848	0.867	0.885
0.60	0.313	0.520	0.637	0.713	0.764	0.801	0.830	0.852	0.871
0.65	0.266	0.484	0.607	0.687	0.742	0.783	0.813	0.838	0.857
0.70	0.223	0.447	0.578	0.662	0.721	0.764	0.797	0.822	0.844
0.75	0.180	0.412	0.549	0.637	0.699	0.746	0.781	0.809	0.830
0.80	0.141	0.379	0.520	0.613	0.678	0.727	0.764	0.793	0.816
0.85	0.104	0.346	0.492	0.590	0.658	0.709	0.748	0.777	0.803
0.90		0.312	0.465	0.566	0.637	0.691	0.730	0.764	0.789
0.95		0.281	0.438	0.543	0.617	0.672	0.715	0.750	0.777
1.00		0.252	0.412	0.520	0.598	0.654	0.699	0.734	0.764

Table 6-10. Effect of Storage on Required Span for Box Culverts, $d/h_a = 0.8$, m = 3.5

C_S	B/B_o = (Required span with storage)/(Required span without storage)								
	C_I = 0.4	C_I = 0.6	C_I = 0.8	C_I = 1.0	C_I = 1.2	C_I = 1.4	C_I = 1.6	C_I = 1.8	C_I = 2.0
0.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.05	0.963	0.980	0.988	0.992	0.994	0.996	0.996	0.998	0.998
0.10	0.904	0.943	0.963	0.975	0.980	0.984	0.988	0.990	0.992
0.15	0.842	0.904	0.934	0.951	0.963	0.971	0.977	0.980	0.984
0.20	0.781	0.863	0.904	0.928	0.943	0.955	0.963	0.969	0.975
0.25	0.723	0.822	0.873	0.904	0.924	0.938	0.949	0.957	0.963
0.30	0.666	0.781	0.842	0.879	0.904	0.922	0.934	0.943	0.951
0.35	0.611	0.742	0.813	0.854	0.883	0.904	0.920	0.932	0.939
0.40	0.559	0.703	0.781	0.830	0.863	0.887	0.904	0.918	0.928
0.45	0.510	0.666	0.752	0.805	0.842	0.869	0.889	0.904	0.916
0.50	0.461	0.629	0.723	0.781	0.822	0.852	0.873	0.891	0.904
0.55	0.414	0.594	0.695	0.758	0.801	0.834	0.857	0.877	0.891
0.60	0.371	0.559	0.666	0.734	0.781	0.816	0.842	0.863	0.879
0.65	0.328	0.525	0.639	0.711	0.762	0.799	0.826	0.850	0.867
0.70	0.285	0.492	0.611	0.687	0.742	0.781	0.813	0.836	0.854
0.75	0.246	0.461	0.586	0.666	0.723	0.764	0.797	0.822	0.842
0.80	0.207	0.430	0.559	0.645	0.703	0.748	0.781	0.809	0.830
0.85	0.172	0.398	0.535	0.623	0.686	0.730	0.766	0.795	0.818
0.90	0.137	0.371	0.510	0.602	0.666	0.715	0.752	0.781	0.805
0.95	0.105	0.340	0.484	0.580	0.648	0.699	0.738	0.768	0.793
1.00		0.312	0.461	0.559	0.629	0.682	0.723	0.756	0.781

6.4 Application Procedure

Use the following steps to determine the ratio B/B_o for a new pipe culvert.

1. Compute the peak inflow, I_p, by any acceptable method.
2. Compute the flood volume, V, with the appropriate regression equation from Table 2-1.
3. Compute the time-to-peak, t_p, with equation 2-7.
4. Compute the values of m and A_a as explained in Section 2.3.2.
5. Compute the storage factor, C_S, and the discharge factor, C_I, with equations 6-9 and 6-10.
6. Find the ratio B/B_o by interpolation in the table listed in Table 6-11.

Table 6-11. Where to find B/B_o

d/h_a	m	Find B/B_o in
≤ 0.7	$m \leq 1.75$	Table 6-1
≤ 0.7	$1.75 < m \leq 2.25$	Table 6-2
≤ 0.7	$2.25 < m \leq 2.75$	Table 6-3
≤ 0.7	$2.75 < m \leq 3.25$	Table 6-4
≤ 0.7	$m > 3.25$	Table 6-5
> 0.7	$m \leq 1.75$	Table 6-6
> 0.7	$1.75 < m \leq 2.25$	Table 6-7
> 0.7	$2.25 < m \leq 2.75$	Table 6-8
> 0.7	$2.75 < m \leq 3.25$	Table 6-9
> 0.7	$m > 3.25$	Table 6-10

6.5 Example

6.5.1 Problem

A new box culvert in Barber County must be sized for the 25-year flood. The drainage area is 325 acres, the 25-year discharge is 400 cfs, and the allowable headwater depth is 8.0 feet. The culvert would operate under inlet control. The rise of the culvert is limited to 6.0 feet. A total span of 20 feet (i.e., two 10 ft x 6 ft cells) would be required to pass the 25-year discharge at the allowable headwater. However, the topography upstream of the culvert is such that a considerable amount of storage would need to be filled before the headwater could reach this level. At a headwater depth of 5.0 feet, 0.75 acres would be inundated; and at the allowable headwater depth of 8.0 feet, 2.05 acres would be inundated. The objective of this example is to estimate the minimum total span required if detention storage is considered, following the procedure in Section 6.4.

6.5.2 Solution

Barber County is located in the western hydrologic region of Kansas, as defined by Figure 2-2. The 25-year flood volume is obtained from equation 2-13:

$V = 6.18\ W^{0.758}\ I_p^{0.405} = 6.18\ (1120/640)^{0.758}\ (1220)^{0.405} = 168$ acre-feet

The time-to-peak is computed with equation 2-7.

$$t_p = 9.45\ \frac{V}{I_p} = 9.45 \left(\frac{168}{1220}\right) = 1.30 \text{ hours}$$

The exponent m in the area-depth relationship is computed with equation 2-20.

$$m = \frac{\log\left(\frac{A_2}{A_1}\right)}{\log\left(\frac{h_2}{h_1}\right)} = \frac{\log\left(\frac{2.05}{0.75}\right)}{\log\left(\frac{8.0}{6.0}\right)} = 2.14$$

The storage and discharge factors are computed with equations 6-9 and 6-10.

$$C_S = 2.13\ \frac{A_a}{t_p\ h_a^{1.5}} = 2.13\ \frac{2.05}{1.30\ (8.0)^{1.5}} = 0.148$$

$$C_I = 0.176\ \frac{I_p}{h_a^{2.5}} = 0.176\ \frac{1220}{(8.0)^{2.5}} = 1.186$$

The ratio B/B_o is found by interpolation in Table 6-7 for $d/h_a = 0.8$ and $m = 2.0$.

$B/B_o = 0.957$

The minimum total span is

$B = 0.957\ B_o = 0.957\ (20) = 19.1$ feet

This approximate analysis indicates that consideration of detention storage would reduce the required span by only 4%, an insignificant amount. This culvert should be sized for the peak flow without detention storage.

CHAPTER 7

STORAGE EFFECTS ON CULVERT SIZES AT SEVENTEEN SITES IN JOHNSON COUNTY

7.1 Methodology

The culvert-sizing procedures developed in Chapters 5 and 6 were used to investigate the significance of storage in culvert sizing at seventeen sites in Johnson County. These sites, all located on divided highways in rural areas, are a subset of the 25 sites for which stage-area relationships were developed (Section 2.3.1). Fifty-year design discharges (Q50) for these sites were computed by the procedures in the 2004 draft revisions to KDOT Design Manual (Volume I, Section 11). The design discharges for the seven sites with drainage areas under 640 acres were computed by the Rational method. These discharges were all less than 400 cfs. The design discharges for the ten sites with drainage areas over 640 acres were computed with the USGS regression equations. These discharges were all greater than 1000 cfs. The allowable headwater depth (the difference between the allowable water-surface elevation and the flowline elevation) for each site was estimated from the two-foot elevation contours. The allowable water surface was assumed to be two feet below the low point on the roadway profile, and the flowline elevation was assumed to be two feet below the lowest contour on the upstream side of the highway embankment. This calculation yielded allowable headwater depths for certain locations that were much larger than typical headwater depths for culverts. To keep the headwater depths within the typical range for culverts, an arbitrary upper limit of 12 feet was imposed on the allowable headwater depth.

The minimum culvert size required for each location was computed by two methods. First, the culvert was sized for the peak inflow by the procedure in the 2004 draft revisions to the KDOT Design Manual (Volume I, Section 14). Next, the culvert was resized for detention storage using the procedure in Chapter 5 (for a pipe culvert) or Chapter 6 (for a box culvert). The ratio of these two sizes indicates the significance of the storage effect. The dimensions of the existing culverts at these sites were not considered. Pipe culverts were sized for the seven sites with design discharges under 400 cfs. Box culverts were sized for the nine sites with design discharges over 1000 cfs. The rise of the box culvert was set to the whole-foot dimension nearest to eight-tenths of the allowable headwater depth. If the span required for this rise did not exceed the rise, the rise was reduced and the span was recalculated.

7.2 Results for Pipe-Culvert Sites

Table 7-1 shows the site data for the seven pipe-culvert sites. The allowable headwater depths range from 5 to 12 feet, and the inundated areas at the allowable headwater depths range from 0.58 to 6.10 acres. Table 7-2 compares the diameters of the pipe culverts sized for peak flow and detention storage. Column 2 shows the number of pipes needed at each site. Five sites require a single pipe, and two sites require two pipes. Column 3 shows the minimum diameters for peak-flow design, and Column 7 shows the minimum diameters for detention-storage design. The ratios d/d_o for these seven sites range from 0.39 to 0.97. Columns 8 and 9 compare the culvert diameters that would actually be specified (the smallest commercially available diameter that exceeds the minimum diameter) by the two methods. The differences between the specified pipe sizes for peak-flow design and detention-storage design range from zero to 27 inches. Sizing these seven pipe culverts for detention storage rather than peak flow makes no difference in two cases, a difference of one pipe size in two cases, and a difference of two or more pipe sizes in three cases.

Table 7-1. Site Data for Pipe-Culvert Sites

Site	Q50 (cfs)	t_p (hr)	h_a (ft)	A_a (ac)	m
1	290	1.16	11	1.37	2.35
2	379	1.42	10	6.10	2.37
3	145	0.87	8	0.74	3.56
4	127	0.96	12	2.98	2.39
5	216	1.09	12	1.50	2.19
6	156	1.05	5	0.58	4.33
7	320	1.15	6	1.32	4.23

Table 7-2. Results for Pipe-Culvert Sites

Site # (1)	n (2)	Min. d_o (in.) (3)	C_S (4)	C_I (5)	d/d_o (6)	Min. d (in.) (7)	Spec. d_o (in.) (8)	Spec. d (in.) (9)
1	1	58.8	0.069	0.127	0.891	52.4	60	54
2	1	72.0	0.290	0.211	0.726	52.3	72	54
3	1	45.2	0.079	0.141	0.906	41.0	48	42
4	1	37.0	0.158	0.045	0.386	14.3	42	15
5	1	48.6	0.071	0.076	0.775	37.7	54	42
6	2	40.1	0.053	0.245	0.969	38.8	42	42
7	2	57.5	0.084	0.319	0.961	55.2	60	60

7.3 Results for Box-Culvert Sites

Table 7-3 shows the site data for the ten box-culvert sites. The allowable headwater depths range from 7 to 12 feet, and the inundated areas at the allowable headwater depths range from 0.08 to 8.04 acres. Table 7-4 compares the minimum total spans for box culverts sized for peak flow and detention storage. The ratios B/B_o for these seven sites range from 0.77 to 1.00. The average value of B/B_o is 0.93; in other words, detention-storage design reduces the required span by an average of 7%. Detention-storage design reduces the required span by more than 10% in three of the ten cases.

Table 7-3. Site Data for Box-Culvert Sites

Site #	Q50 (cfs)	t_p (hr)	h_a (ft)	A_a (ac)	m
8	1019	1.03	11	6.67	3.13
9	1170	1.11	12	4.65	2.54
10	1479	1.27	12	4.16	3.04
11	1842	1.44	10	0.46	1.82
12	3416	2.05	9	8.04	1.71
13	3196	1.97	10	6.26	2.91
14	1740	1.39	9	2.61	3.29
15	2260	1.62	12	3.65	2.58
16	1946	1.48	7	0.08	1.66
17	2252	1.61	10	1.79	3.16

Table 7-4. Results for Box-Culvert Sites

Site #	d (ft)	C_S	C_I	B_o (ft)	B/B_o	B (ft)
8	6	0.379	0.447	11.9	0.770	9.2
9	7	0.215	0.413	11.6	0.856	9.9
10	10	0.168	0.522	13.0	0.851	11.1
11	8	0.021	1.025	21.2	0.996	21.1
12	7	0.310	2.474	46.3	0.970	44.9
13	8	0.214	1.779	36.8	0.964	35.5
14	7	0.148	1.260	23.6	0.966	22.8
15	10	0.116	0.797	19.8	0.948	18.8
16	6	0.006	2.642	38.3	1.000	38.3
17	8	0.075	1.253	25.9	0.988	25.6

CHAPTER 8

SUMMARY AND CONCLUSIONS

The relationships developed in this report are useful for estimating the magnitude of detention-storage effects at existing pipe and box culverts and for investigating the potential benefits of sizing culverts for detention storage rather than peak flow. The recommended procedures do not require hydrograph analysis or reservoir routing. Peak discharges can be computed by the Rational method, USGS regression equations or any other appropriate method. Water-surface areas at two or more stages are needed to define an approximate depth-area relationship. The required areas can be estimated from existing topographic maps or measured in the field by one person with a rotating laser level and a GPS unit.

Two limitations should be noted. First, the analysis and design procedures assume that the culvert operates under inlet control. Second, the analysis procedures are not applicable to floods that overtop the roadway.

Our analyses of seven pipe-culvert sites in Johnson County showed that detention-storage design would reduce the required pipe diameter by at least one increment at five of the seven sites, and by two or more increments at three of the sites. Similar analyses of ten box-culvert sites showed that detention-storage design would reduce the required span by more than 10% at three of the ten sites. Our test results indicate that storage effects are less likely to be significant for large culverts than for small culverts.

The design of a culvert for detention storage rather than peak flow generally requires another field survey and extra design effort, and may also require the purchase of additional right-of-way or a drainage easement for the storage area. Detention-storage design is economically justifiable only if cost savings on the culvert exceeds these added costs. In locations where storage effects are significant but detention-storage design is not economically justifiable, the culvert should be designed for peak flow.

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