THE UNIVERSITY OF MANITOBA

THE HYDRAULIC BEHAVIOUR OF THE CITY OF WINNIPEG, STANDARD, STORM WATER, SUMP INLETS

by

Norman B. Brandson

A Thesis

Submitted to the Faculty of Graduate Studies

In Partial Fulfilment of the Requirements for the Degree

Of Master of Science in Civil Engineering

Winnipeg, Manitoba

October, 1971

ACKNOWLEDGEMENTS

As no project of this kind can be completed without the assistance of many individuals, so no acknowledgement can possibly give credit to all those to whom it is due. Special note must be taken, however, of major contributions without which this work would surely have floundered.

Dr. Kenneth Adam, whose patience with the author was inexhaustable, whose guidance was invaluable and whose encouragement was saving, is extended full credit and heartfelt thanks for his contributions.

The engineering staff of the City of Winnipeg, headed by City Engineer Mr. W. D. Hurst, not only laid open their technical resources to the author, but also supplied the actual storm water appurtenances which were the subject of this series of tests. Their extremely co-operative attitude and valuable assistance is gratefully acknowledged.

Finally, to the technical staff of the University of Manitoba Hydraulics Lab, particularly Mr. Stan Kaskuw, who suffered through many weeks of imparting their practical knowledge to the author, and supplemented his skills with their own, the author offers his humble gratitude.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE		PAGE

LIST OF SYMBOLS

SYMBOL	DEFINITION	DIMENSIONS
A	Area of the clear opening of an inlet	$Ft.^2$
A_o	Ratio of the normal gutter flow depth to the depth of water at the inlet mid-point	none
a	Depth of the local gutter depression	Ft.
b	Width of the deflectors for a deflector inlet	Ft.
C	A coefficient of discharge varying with the longitudinal gutter slope	none
C'	An expression representing $(0.45/1.12^M)$	
C_o	An expression representing $(8g\emptyset_o/f)^{1/2}$	
c	Clearance between the deflectors for a deflector inlet	Ft.
D	Normal gutter flow depth	Ft.
$d_{AV.}$	The average depth of flow over a gutter grade set on a continuous grade	Ft.
d_L	The normal gutter flow depth downstream of an inlet set on a continuous grade	Ft.
d_{MAX}	The depth of ponding in front of a depressed curb inlet set in a sump	Ft.
d_U	The normal gutter flow depth upstream of an inlet set on a continuous grade	Ft.
d_W	The depth of gutter flow a distance W from the curb	Ft.

SYMBOL	DEFINITION	DIMENSIONS
F	The force exerted on a falling body	Lbs.
F'	A symbol for the expression (V^2/gy)	none
Fr	Froude number of the gutter flow approaching the inlet	none
F_w	Froude number of the gutter flow approaching the inlet a distance W from the curb	none
f	The D'arcy friction factor	none
g	The gravitational acceleration	Ft./Sec.^{2}
h	The depth of ponded water in front of an inlet	Ft.
K	An equation coefficient which assumes a unique value for each pavement crown slope	none
K'	A dependent flow variable for curb inlets set on a continuous grade	
L	The length of curb opening required to capture 100% of the gutter flow on a continuous grade	Ft.
L'	The length of gutter grate required to capture 100% of the flow which is outside of the gutter section on a continuous grade	Ft.
L_o	The length of grate required to capture 100% of the central portion of the gutter flow on a continuous grade when the velocity of the flow is V_o	Ft.
L_i	Length of a curb opening inlet located in a sump	Ft.
L_2	The length of the downstream gutter transition for a depressed inlet located on a continuous grade	Ft.

SYMBOL	DEFINITION	DIMENSIONS
M	A symbol representing the expression $(LF'/a\tan\theta)$	
m	An equation coefficient which has a unique value for varying gutter grate bar orientations	
n	An equation exponent varying with the longitudinal gutter slope	none
n	The Manning roughness factor	none
Q	Total flow in the roadway gutter section	C.F.S.
Q_i, Q'	The total amount of flow entering the inlet	C.F.S.
q	The total carry-over flow past an inlet set on a continuous grade	C.F.S.
q_1	The carry-over flow past a gutter inlet on a continuous grade which passed directly overtop of that inlet	C.F.S.
q_2	The carry-over flow past a gutter inlet set on a continuous grade which passes by the outside edge of that inlet	C.F.S.
R	The Reynolds number of the gutter flow approaching an inlet	none
R	A symbol representing the expression (c/W)	none
R_o	The Reynolds number of the gutter flow approaching an inlet located in a test model	none
S	The longitudinal gutter slope of a roadway	none
S_x	The transverse slope of a roadway (also known as the crown slope)	none

SYMBOL	DEFINITION	DIMENSIONS
T	The width of flow spread of uniform gutter flow on a roadway	Ft.
t	Time	Sec.
U	The moment of momentum per second of the gutter flow about the centre of the inlet	
$\overline{U}$	The y-component of the gutter flow velocity	Ft./Sec.
V, V_o	The average velocity of the flow in the gutter section of the roadway	Ft./Sec.
$\overline{V}$	The x-component of the gutter flow velocity	Ft./Sec.
W	The width of the grate covering a gutter inlet	Ft.
	The width of the local gutter depression for any depressed inlet	Ft.
Wg	The width of the flow in the gutter section of a roadway	Ft.
y, y_o	The normal depth of the gutter flow measured at the curb	Ft.
y'	The depth of flow measured at the outside edge of a gutter grate inlet	Ft.
y_c	The elevation of the pavement crown above the intersection of the gutter and curb	Ft.
Z	The height of the roadway crown above the intersection of the gutter and curb	Ft.
ZP	The moment of hydrostatic pressure of the gutter flow about the centre of an inlet set on a continuous grade	

SYMBOL	DEFINITION	DIMENSIONS
	A characteristic used to describe the geometry of gutter grates	none
ϕ_o	The longitudinal gutter slope of a roadway	none
θ_2	The angle formed between the curb and the pavement cross-slope	none
θ'	The angle formed between the curb and the slope of a local gutter depression	none

CHAPTER I

INTRODUCTION

1.1 Background

Contrary to common belief, the rapid removal of storm water runoff from urban areas by the use of man-made storm drains, is not at all a recent innovation. All early Roman cities were equipped with elaborate storm drainage systems, some consisting simply of open channels along roadways, but many of subsurface conduits with attendant inlets. Some of these early urban storm water drainage facilities, dating from before the birth of Christ, are still in existence today. It is due to the fact that urban storm drainage was constructed centuries before any thought was given to the disposal of sewage from a city's concentrated populace, that we owe the existence of the combined sewer, a pestiferous device handling both raw sewage and storm runoff. When sewage disposal was finally undertaken in the nineteenth century, the objectionable material was simple dumped into the existing storm drains.

There have been two basic reasons which have moved people to construct storm runoff facilities in urban areas.

The first is one of concern for the safety of life and property, that is the prevention of major flooding in the cities. (This is less of a concern on the Canadian prairies, however, as the most serious flooding is caused by spring snowmelt.) The second is more a consideration of convenience, where storm drainage is installed so that the movement of people and vehicles will not be hampered by the presence of large amounts of water on the city's thoroughfares.

In North American cities, well into the third decade of the present century, the design of urban drainage facilities was rather a haphazard procedure[13)*], depending almost entirely on the personal experience of a particular municipal engineer, rather than on any rigorous scientific approach. The three major tools of today's urban hydrologist, statistics, fluid mechanics and economics, were seldom applied.

Early in the nineteen-thirtys, chiefly in the large cities of the American Eastern seaboard, a much more scientific and rational approach to the design of urban storm drainage systems began to emerge. The "rule of thumb methods" were being brought into serious question. The chief reasons for this were:

(1) In all phases of the engineering profession, new scientific knowledge was being made available for practical application. The emphasis had shifted from simply designing

* Numbers in parentheses refer to entries in the bibliography

projects using the engineer's past experience, to the awareness of what were the scientific principles behind the design. Reliable mathematical expressions were needed if the design of drainage systems was to become anything more than a "hit or miss" procedure.

(2) The rapidly expanding size of all cities meant that the extent and cost of storm drainage was becoming enormous, and that to expend large amounts of money on facilities which might either be grossly over or under-designed, without any reliable basis for deciding which, was not justified. This increase in size also meant that the numbers of people affected when an inadequate system resulted in property damage, was greatly increased.

(3) The intensified commercial nature of the city demanded that the movement of people and goods must be reliable. In consequence, storm drainage must also be made reliable, and at as low a cost as possible.

This process of formalizing the procedures of design of storm water drainage systems and refining and revising the methods as new information became available, has thus been active for almost forty years; since our knowledge is not yet complete, it is still going on today.

1.2 The Problem

An urban storm water drainage system is not a homogeneous entity, but rather it consists of a number of component parts, each with its own function and problems, and each of equal importance to the whole. This system usually consists of:

(1) A contributing drainage area analogous to a river drainage basin, onto which rain falls and over which the water travels to reach an opening in the ground called an inlet. This area will most often consist of both pervious and impervious surfaces. Most of the overland flow is channelled into the roadways located in the drainage area, and there it is concentrated in the gutter section formed at the curb by the geometry of the thoroughfare.

(2) The inlet through which the water from the contributing drainage area flows. There may be any number of these openings in any one drainage area. (That will depend on the amount of flow that an inlet will pass, and the intensity of the design storm.) They are almost always located on the roadways since that is where the overland flow is concentrated; the purpose of the inlets is to provide access for the storm runoff to subsurface conduits.

(3) A conveyence system leading from the inlets to the subsurface storm drains. Such a conveyence is required because the drains are several feet below the level of the street. It consists of three sections. The first is a box structure behind or below the inlet opening (depending on the type of inlet) which is required to form the connection between the opening and a length of pipe. The second is a

length of pipe which directs the water into a catch basin. Finally, there is a catch basin which itself connects to the main storm water conduit by means of a short length of pipe. The purpose of the basin is to remove sediment and debris from the storm runoff before it enters the main storm sewer.

(4) The main storm water runoff conduit. This is a very large conduit (really a network of varying sized pipes) located several feet below ground level, which carries the storm water which it receives from the inlets, to a place of disposal away from the city, usually to a nearby

To outline all of the steps involved in designing each of the above components so as to arrive at an overall design of a storm drainage system, is a lengthy undertaking and well beyond the scope of this study. One of the points readily apparent from this summary, however, is that one of the critical factors in any system design will be how much water flows through the storm water runoff inlets under design conditions. The design conditions at the inlet are in turn determined by the calculations performed to analyse the effect of a particular rainfall on the contributing drainage area.

The problem of the capacity of a particular type of storm water inlet under various conditions is of great concern to municipal engineers, as is evidenced by the multitude of literature written on the subject (see Bibliography). Without this knowledge a completely accurate design of subsurface drains is not possible.

The scope offered by the above stated problem is still extremely wide. The inlets may be any one of several types, all of which behave differently from a hydraulic point of view. They may be simple openings in the curb, with or without gratings, and with or without a local depression in the adjacent street gutter. They may be openings in the gutter itself, with any number of different types of cover grates. The curb and gutter inlets may be combined in countless different relative positions. The pavement may be made extremely rough in front of a curb opening in an attempt to deflect more flow into the opening. Also the terrain of an area will dictate whether the inlet will be set on a continuous gutter grade with the same slope above and below the inlet, or in a low point with the gutter grades approaching the inlet from each side.

Obviously, for one study to consider all of the permutations and combinations of these variables would be an impossible task. Fortunately, many of the above inlet configurations have been dealt with in previous investigations (see Chapter II, page 10), and enough information is available to intelligently design these components. Rather the present study proposes to concern itself with a particular facet of this problem which has not as yet received a great deal of study, that is the capacity of the most common types of Winnipeg inlets.

1.3 Justification for the Study

(1) The land on which the city of Winnipeg is built, being a part of the Western Canada plain, is quite flat. As a result, most of the inlets for the city's storm water drainage system are located at low points formed by the constructing of roadway grades so that they slope towards these inlets from both sides. It is the designing of such sump inlets which is of great concern in the Winnipeg area.

(2) The city of Winnipeg Engineering Department, rather than utilizing a very large number of inlet sizes and shapes, has standardized the gratings to be used on Winnipeg inlets. There is one standard grate for curb openings and another for gutter openings. These grates can be used to construct four standard inlets: (a) Undepressed curb inlet, (b) Depressed curb inlet using a standard local depression of the gutter surface at the face of the inlet, (c) Gutter inlet, and (d) a combination of the undepressed curb and gutter inlets.

(3) As this study began, little information was available as to how much flow would pass through the city's four standard inlet types under operating conditions.

(4) Past research on storm water inlet design was chiefly concerned with inlets set on a continuous gutter grade. Very little emphasis had been placed on sump inlets, and none of the existing design methods seemed suitable to

application for local design. At any rate, some improved knowledge of the capacities of the Winnipeg inlets was needed if the design formulae of previous investigators were to be checked for accuracy.

(5) The practical experience of local engineers had indicated that many of the city's subsurface storm drains were not operating near their design capacity even during the heaviest observed rainfalls. It was suspected that the inlets simply could not allow that much flow to reach the conduit. Serious doubt had arisen in the present practice of inlet design, and the enormous amounts of money being expended on the storm drainage in the city made it imperative that future designs eliminate waste by arriving at an accurate and reliable appraisal of the capabilities of each of the system's components.

The above progression of facts brought about the formulation of the primary goal of the present study, which is to undertake a series of tests utilizing a model of an actual roadway, for the purpose of determining how much flow passes through each of the City of Winnipeg standard sump inlets, under actual operating conditions. The testing was to be conducted with the gutter grades approaching the inlet and the roadway crown slope, set at a number of different values for each inlet type.

The data from the experimental program will be processed in order to construct rating curves for each inlet type, that can be used by designers in the City of Winnipeg. Also, a general mathematical expression of the flow will be formulated which will allow for the design of any inlet size which conforms to the geometry of the Winnipeg inlets. Finally, certain more general observations will be made on the behaviour of the various inlets during testing.

CHAPTER II

REVIEW OF PREVIOUS INVESTIGATIONS INTO THE BEHAVIOUR OF STORM WATER INLETS

2.1 Introduction

As has been outlined in the previous chapter*, urban storm water drainage systems have been an important part of Civil Engineering practice for over half a century; the importance of storm water inlets in this system has also been discussed. It is not at all surprising that attempts have been made to investigate the hydraulic performance of these inlets, both in qualitative and quantitative terms, dating back to the early part of this century[13]. The history of the research involves both field and laboratory work, becoming increasingly complex and sophisticated as attitudes changed and new research techniques became available.

The first attempts at research in this field were initiated by some of the more progressive American city engineering departments, who conducted rather crude field tests on the particular inlets used in their area[13,29]; the capacity of the inlet in each specific location was the

---

* Supra page 2.

only information sought, the causal relationships being of no particular interest at that time.

As research began shifting to a laboratory setting, the researchers' concern for more mathematically oriented explanations of the flow phenomena involved in the intake of water through the inlet increased. Early efforts were complicated as well as cumbersome and of dubious merit for modern design purposes, but they provided the impetus which led to further studies. Investigations increased in scope and sophistication, culminating in the Johns Hopkins University study of 1956 [16)] which is still the most ambitious and complete work on inlet design. As no one report can adequately cover all of the aspects of a complex fluid mechanics problem, gaps in the knowledge provided by the Johns Hopkins report have been noted; furthar investigations have been carried out in recent years but there remains many unanswered questions regarding the behaviour of storm water inlets.

It is interesting to note that virtually all of the research into the behaviour of various types of inlets has been carried out in the United States, and has for the most part been oriented towards much higher discharge conditions than we usually encounter in this region of North America. This is accounted for by the fact that the greatest impetus for research concerned with inlet design comes from urban centers located in high rainfall areas since obviously, higher runoff would mean an intensification of the problems arising from the failure of inlets to provide adequate capacity.

Research has been very heavily weighted towards the consideration of inlets located on a single continuous grade rather than in a sag; the reason for this is twofold. First, the topography of large American cities located in high runoff areas dictates that the continuous grade type of inlet will be by far the most widely used. Secondly, certain simplifications and assumptions have been made in the approach to inlets located in a sag, which although in most cases are quite valid, nonetheless suffer from being unable to fully describe the performance of the inlet under all conditions.

This chapter is certainly not an attempt to review all of the research and literature on the behaviour of storm water inlets; only the most comprehensive works which have relevance to the municipal engineer of today have been included. All others, however, have been listed elsewhere in this study*.

The following review has been included for three very important reasons:

(1) It will form a background for the theory and method of the present study, providing the reader with a genesis of the author's approach.

(2) Where previous studies deal with inlets located in

* Bibliography, page 184.

sags, it will provide a useful yardstick by which the data of the present study can be measured and compared.

(3) It will provide in essence a design manual, composed of the best available information, for those conditions of inlet location, flow and geometry not investigated in this report.

2.2 G. S. Tapley - Hydrodynamics of Model Storm Sewer Inlets Applied to Design (1943) [35]

The research on which this paper was based took place in 1937 and was confined entirely to laboratory work. All tests were conducted on a 3:32 scale model representing one-half of an actual roadway on a continuous grade, with a side opening and ten feet of approach channel to establish the flow. This model rested on a tilting framework so as to be fully adjustable. The studies conducted were limited by the fact that the inlet tested was a curb opening using a unique type of depression [2], and also that the prototype pavement section was of parabolic cross-section, no longer in use on modern streets.

Tapley conducted a rigorous theoretical analysis, first setting down the variables affecting flow into the inlet and then applying standard dimensional analysis techniques to obtain a series of dimensionless terms. For the inlet tested, keeping longitudinal and cross slopes constant and maintaining a constant ratio of approach flow depth over average depth at the inlet, the dimensionless relationship reduces to

$$K = f\ (Fr,\ R)\ , \qquad (2.1)$$

where dependent variable K = (zP)/U

ZP = moment of hydrostatic pressure about the center of inlet,

U = moment of momentum per second about the center of the inlet,

Fr = Froude number of the approaching flow, and R = Reynolds number of the approaching flow.

Due to the small scale of the model, in order to maintain similitude it would have been necessary to use a fluid less viscous than water for the testing. Tapley proceeded to compute this imaginary viscosity and in turn use it to compute R; this R utilizes the imaginary model viscosity (water was used as the testing fluid) and the actual model dimensions, and is related to the actual R by means of a correlation coefficient which was determined by running the model at several different longitudinal slopes.

An analysis of the data reveals that,

$$K = \frac{\text{constant}}{F}\ \phi\ (R), \qquad (2.2)$$

and

$$K = \frac{1}{2F}\ \left(A_o + \frac{y_c R_o}{R-R_o}\right), \qquad (2.3)$$

where A_o = ratio of the normal gutter flow depth over the depth of water at the mid-section of the inlet,

y_c = elevation of the pavement crown above the gutter,

R = Reynolds number of the prototype flow, and R_o = Reynolds number of the approach flow in the model.

The method which Tapley uses to solve equation 2.3 and the way in which he applies it to the design of actual inlets is too lengthy to be included here. Two points emerge, however, which are of some significance. First, this research may well prove useful to anyone investigating the behaviour of older inlet installations where parabolic pavement cross-sections are encountered. Although modern methods could easily be used to approximate this situation, Tapley's method would serve as a useful check. Secondly, the approach taken in this research is unique among investigations of inlets set on a continuous grade; Tapley's approach consists of relating the ratio of the moment of pressure of the flow taken about the center of the inlet (which is merely a measure of the tendency of the flow to drop into the inlet), over the moment of momentum of the flow (which is merely a measure of the tendency of the flow to pass by the inlet), to the Froude and Reynolds numbers of the flow. If this principal is understood, it provides a sound basis for understanding the methods of other investigators.

2.3 W. I. Hicks - Drainage Inlets for Parkways in Los Angeles (1944) [12)]

This paper, part of which deals with the computation of the amounts of run-off reaching the pavement gutters, was based on the experience of municipal engineering staffs in the Los Angeles area, both through general observation and actual field tests.

Since this author is most concerned with the design of inlets for catch basins to be used in the high speed roadway system of the city of Los Angeles, he devotes very little space to the consideration of side opening inlets, as the use of a depression would not be permitted on a high speed thoroughfare and an undepressed curb opening is quite inefficient.

Without stating the source, the author does give an equation for the length of curb opening required to capture all of the flow on a continuous grade without use of a local depression which is:

$$L = \frac{0.33Q}{(0.5(d_u + d_l))^{1.5}} , \qquad (2.4)$$

where L = the length of curb opening (without grate) required to capture all of the gutter flow, FT.,

Q = total flow in the gutter section, CFS.,

d_u = depth of gutter flow immediately upstream of the inlet, FT.,

and d_l = depth of flow immediately downstream of the inlet, FT.

A more rigorous treatment is afforded to the grate or gutter opening, which without depression is more amenable to use on high speed roadways. The type of grate to which the following development applies is shown in Figure 1, along with a definition sketch for the theoretical development.

The basis for the theory outlined in this paper is the equation for free falling bodies which is

$$F = \frac{1}{2} gt^2, \qquad (2.5)$$

where F = force exerted on the falling body, LBS.,

g = gravity acceleration, FT./SEC.^{2}, and t = time of free fall, SEC.

The free fall of water into the grate is hindered in three separate ways:

(1) Frictional resistance develops between the bars.

(2) The flow tends to skid along the tops of the bars until it is able to fall into the openings.

(3) If the velocity of the flow is high enough, the water will tend to overshoot the opening.

The author indicates that a length of opening equal to 1.5 feet is sufficient to account for the first two of these items. Also by using simple kinematics t = 1.5/V. Hence, the free fall equation now becomes

$$F = \frac{36.18}{V^2}, \qquad (2.6)$$

where V = the average velocity of the gutter flow, FPS.

It is now possible to equate the average depth of water above the grate to this force F of equation 2.6. When the

FIGURE 2 GUTTER GRATE DESIGN

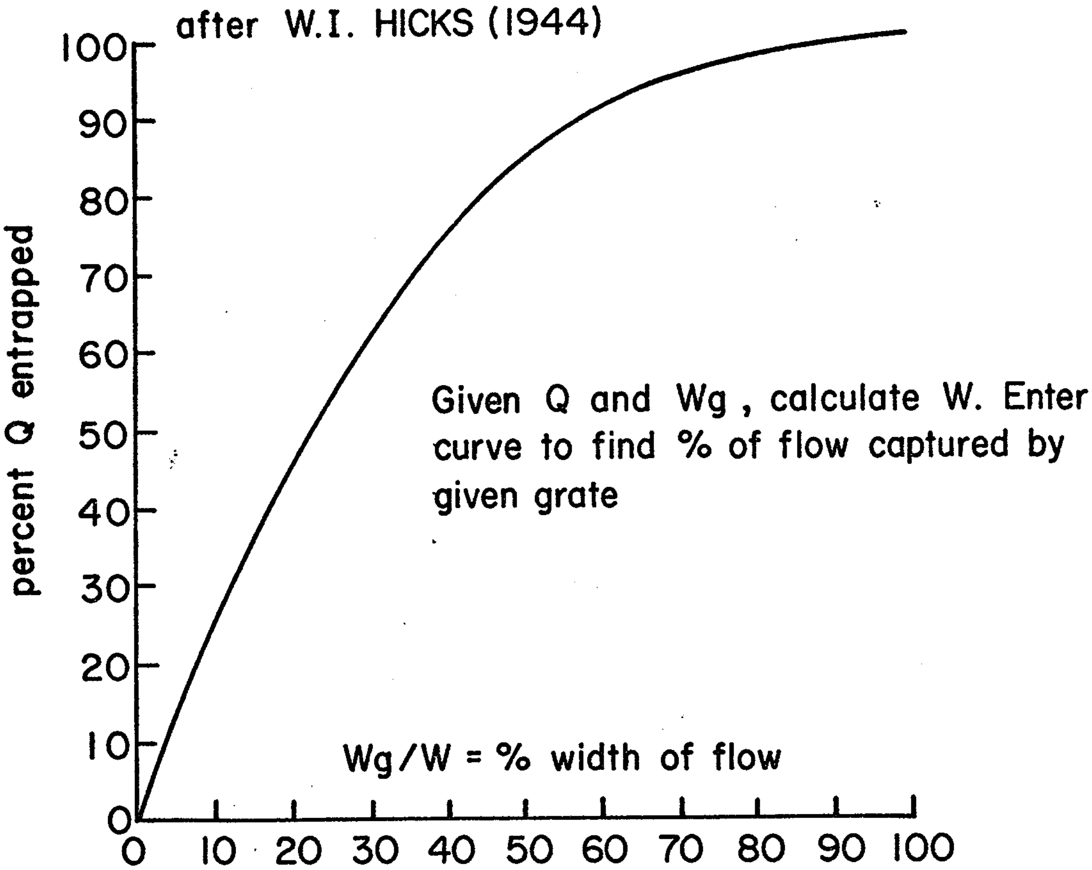
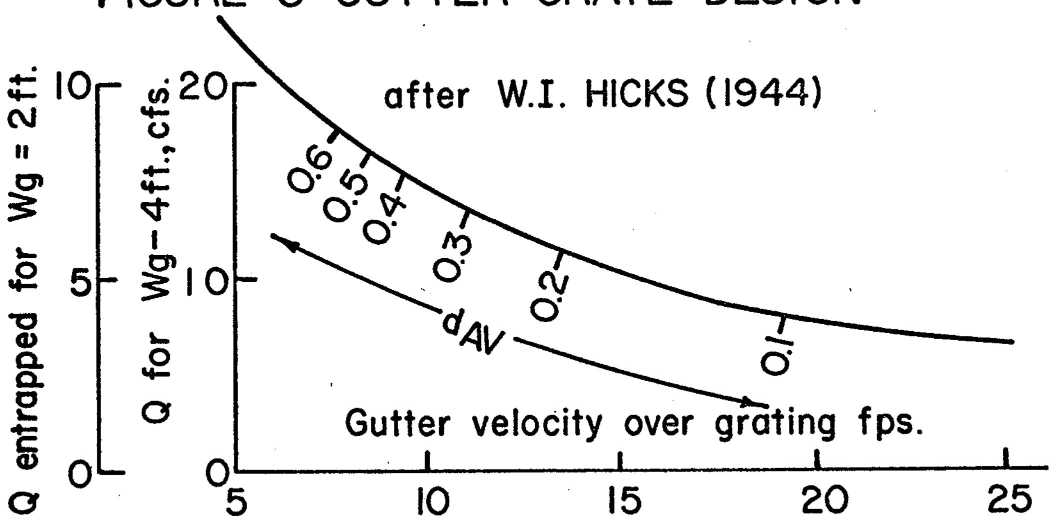


FIGURE 3 GUTTER GRATE DESIGN



Having data from figure 2 , compute velocity over grate using % flow captured. Compute d_{AV}. Enter figure 3. If calculated velocity is to right of computed d_{AV} on curve read Q from curve — if to the left use Q from Fig. 2

weight of water above the grate (computed using the average depth of water) is less than the calculated force F then all of the flow will be trapped by the grate, however, when that weight exceeds F, then a portion of the flow will escape the opening. The fraction of flow escaping the inlet is given by

$$1.00 - Q_i/Q = \frac{d_{AV} - F}{d_{AV}} , \qquad (2.7)$$

where Q_I = amount of flow entering the inlet, CFS., and d_{AV} = average depth of water over the grate, FT.

The velocity of the gutter flow above the grate has been computed using the simple application of the equation Q = vA which when expressed in terms of the gutter geometry is

$$V = \frac{Q}{W_g (d - \frac{W_g S_x}{2})} , \qquad (2.8)$$

where W_g = width of flow in the gutter section, FT., d = normal depth of flow in gutter section, FT., and S_x = crown slope of the roadway.

The above theory has been incorporated into the design curves shown in Figures 2 and 3, which are accompanied by an explanation of their use.

2.4 N. W. Conner - Design and Capacity of Gutter Inlets (1945) [8)]

These tests were carried out on a full scale model which, although not an actual street, was located out of doors; the apparatus was fully adjustable. The purpose of the tests was to determine the capacities of the existing inlets being used in Raleigh, North Carolina, and also to attempt a general appraisal of the hydraulic parameters governing inlet performance.

Three types of inlets were tested. Using standard nomenclature, these are:

(1) depressed curb inlet

(2) depressed combination inlet

(3) curb inlet with deflectors.

These are shown in Figure 4.

The testing consisted of running the model on a continuous grade with a set crown slope, measurements being taken of the gutter flow, gutter flow depth, and the width of flow on the roadway. The ultimate capacity of the inlet was considered to be the point at which the flow just began to lap past the inlet. No measurements were taken of the condition where there was untrapped flow continuing past the inlet.

For the depressed curb inlets which had no grating on the opening, the tests indicated that at some slope greater than ten percent, the capacity (using the definition of capacity given above) would approach zero. From a graphical analysis of the experimental data, the following relation was derived:

$$Q_i = CL^n \quad , \qquad (2.9)$$

leaf 22 ommitted in page numbering

FIGURE 4 TYPES OF INLETS
RALEIGH NORTH CAROLINA
after N.W. CONNER (1945)

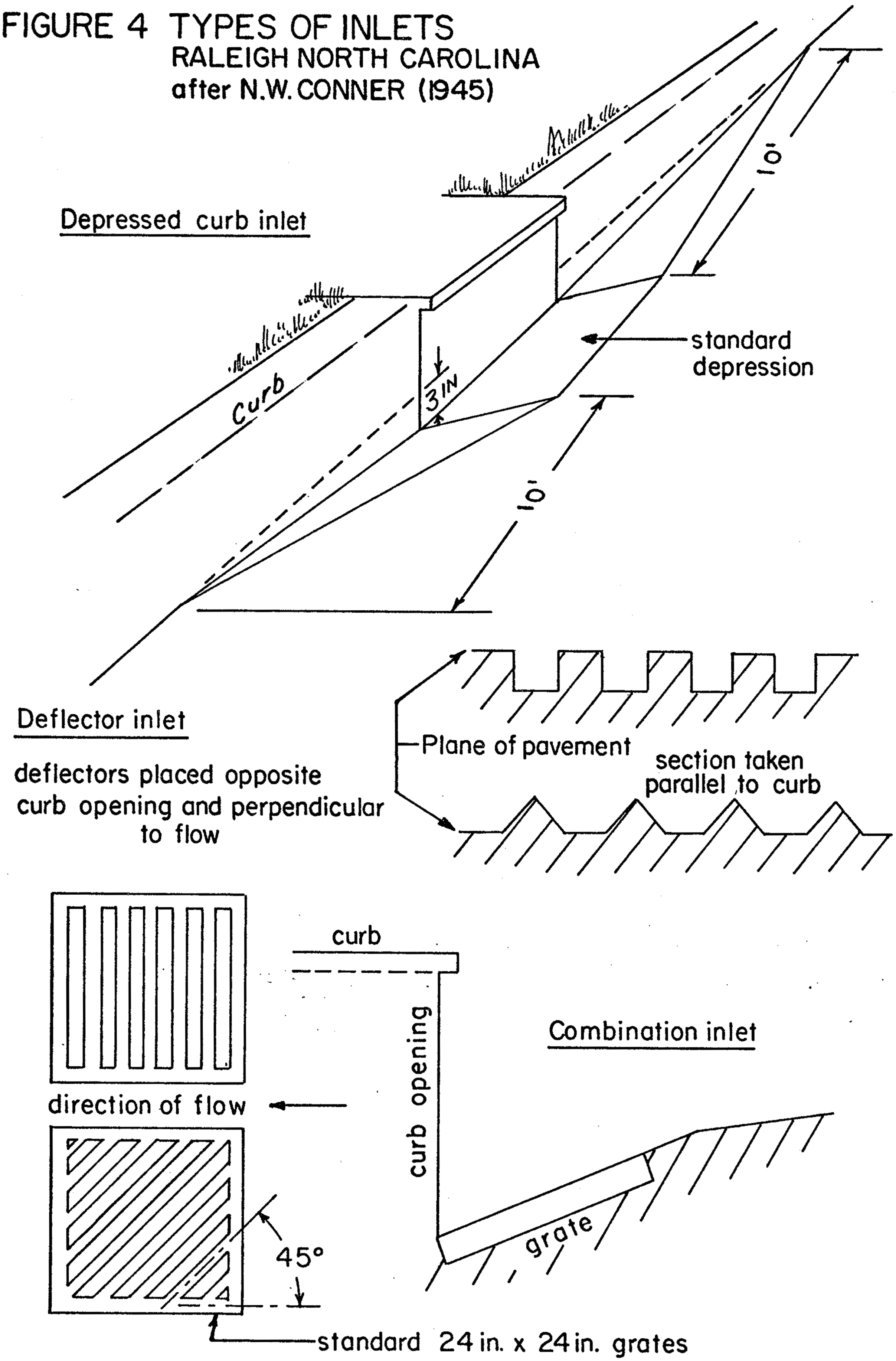
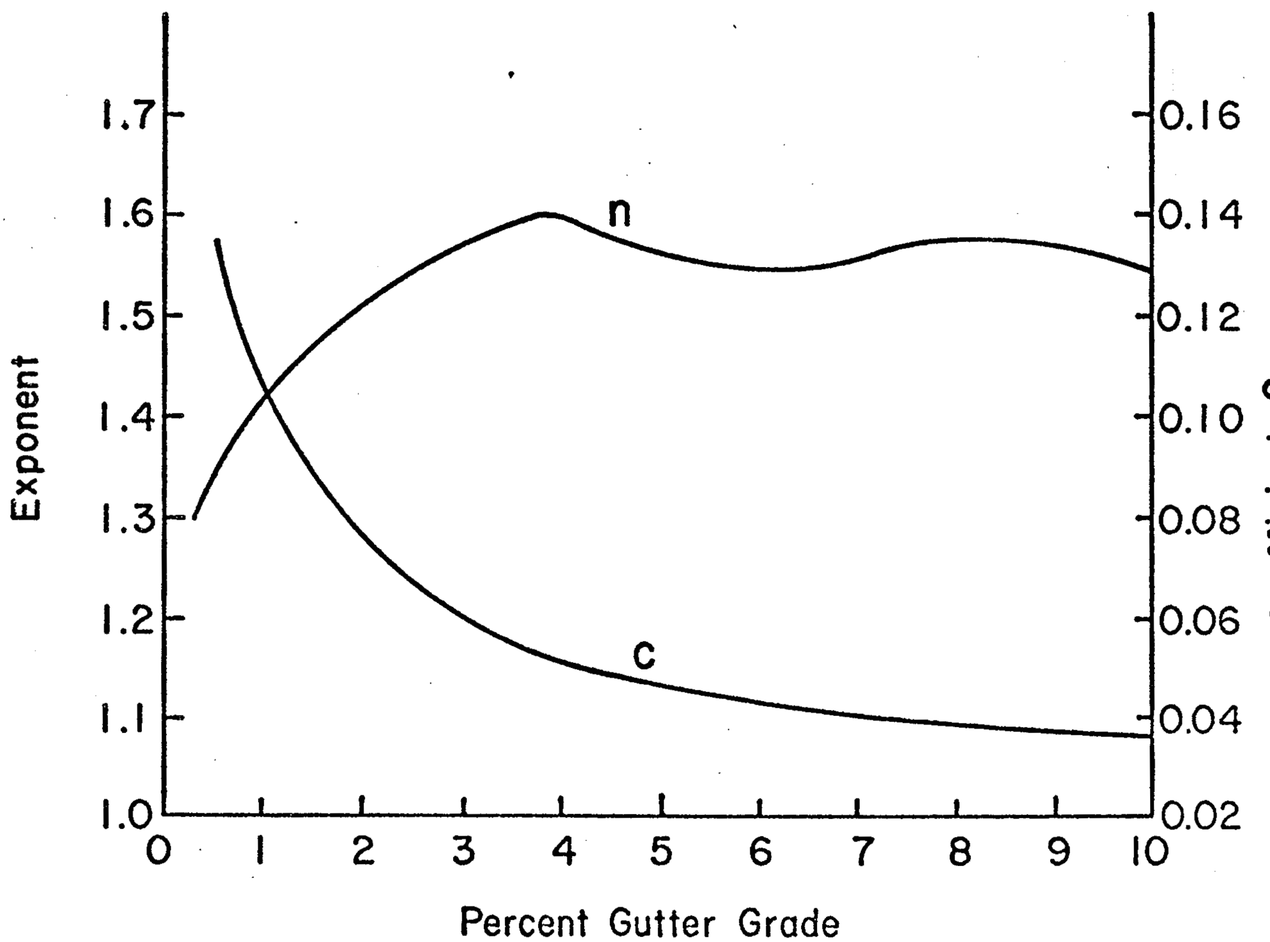


FIGURE 5 C AND n VS. GUTTER GRADE FOR $Q = CL^n$
AFTER N.W. CONNER (1945)



where C = coefficient varying with the longitudinal gutter slope as shown in Figure 5, and

n = exponent varying with the longitudinal gutter slope as shown in Figure 5.

For the combination inlet, no attempt was made to develope a rigerous mathematical approach to explain its behaviour. It was found that the combination inlet was more effective than the simple crub opening at low street grades and became increasingly less effective as the gutter grades became steeper. Also, the grate utilizing the forty-five degree bars (Figure 4) was more effective than that with the bars perpendicular to the curb in trapping the flow.

The use of deflecting vanes to direct the flow into the curb inlet greatly increased the capacity of the simple curb opening. Whether or not the vanes were curved or straight seemed to make very little difference in the capacities, but the use of vanes which were above the level of the pavement surface showed greater effectiveness than the depressed vanes.

2.5 The Johns Hopkins University - Design of Storm Water Inlets (1956) [16)]

The research contained in this report represents the co-operative efforts of several government agencies* and the Department of Sanitary Engineering and Water Resources

* Bureau of Sewers (city); Dept. of Public Works (county);

of the Johns Hopkins University, over a period of almost eight years; little wonder that this is considered the most comprehensive undertaking in the field of storm water inlet design.

All of the material contained in this study was based on tests which were run on models of 1:2, 1:3, and 1:4 scale. The results were in part verified by tests run on actual in-place inlets.

The inlets tested fall into six basic categories:

(1) undepressed curb inlets

(2) deflector inlets

(3) depressed curb inlets

(4) undepressed grate inlets

(5) depressed grate inlets

(6) combination inlets.

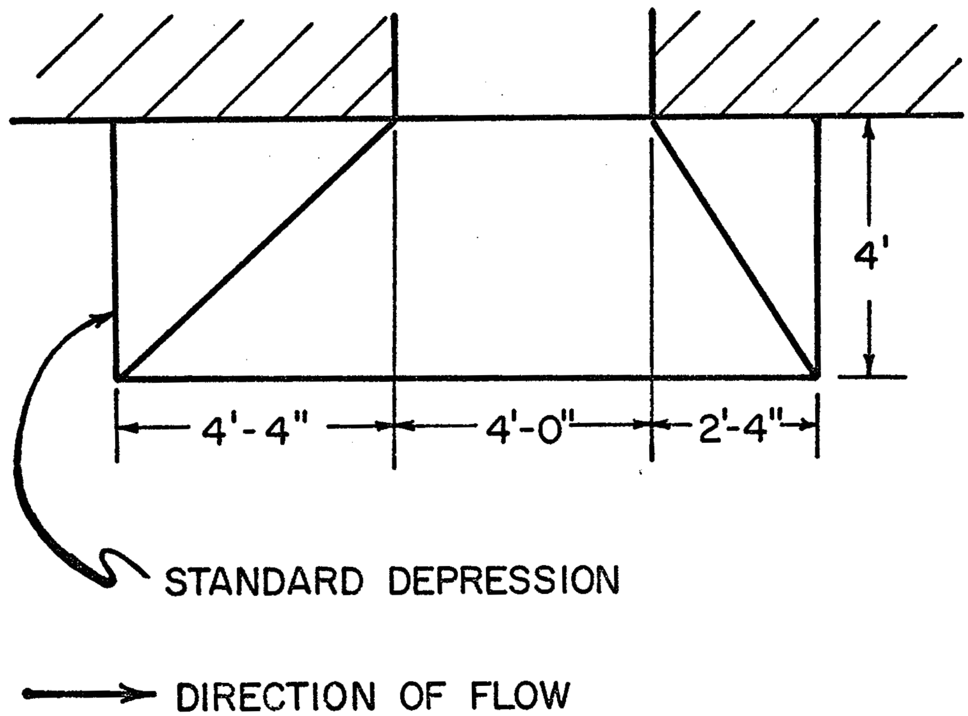
The inlet types are pictured in Figure 6 and the various grates used are shown in Figure 7. These inlets were tested under both the flow-by and sump conditions.**

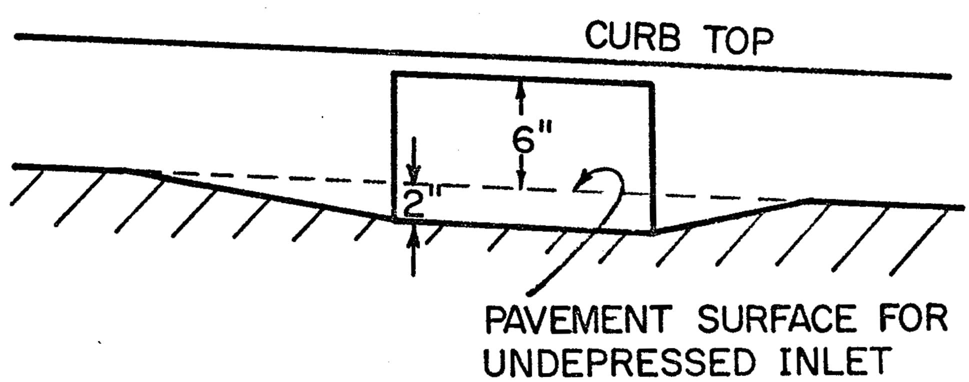
Theory for all of the inlets set on a continuous grade was developed in the same manner; a list was made of all the variables involved in the flow of water into the appurtinance and then conventional dimensional analysis techniques[32)] were applied to arrive at a series of dimensionless parameters. These parameters were then given a meaningful relationship by applying the experimental data to them. In the case of the sump condition, no actual theory

---

Maryland Board of Health (state); Wash. Sub. Sanitation Comm.
**Deflector inlets were not tested under sump conditions.

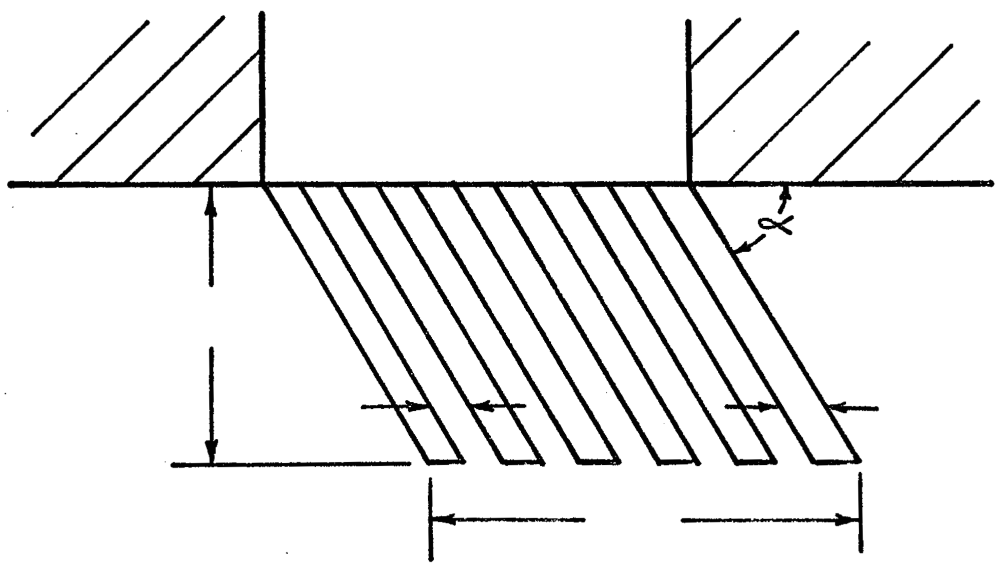
FIGURE 6A: STANDARD CURB INLET





AFTER JOHNS HOPKINS (1956)

FIGURE 6B: DEFLECTOR INLETS



CROSS-SECTION OF DEFLECTORS TESTED

FIGURE 6C: COMBINATION INLETS

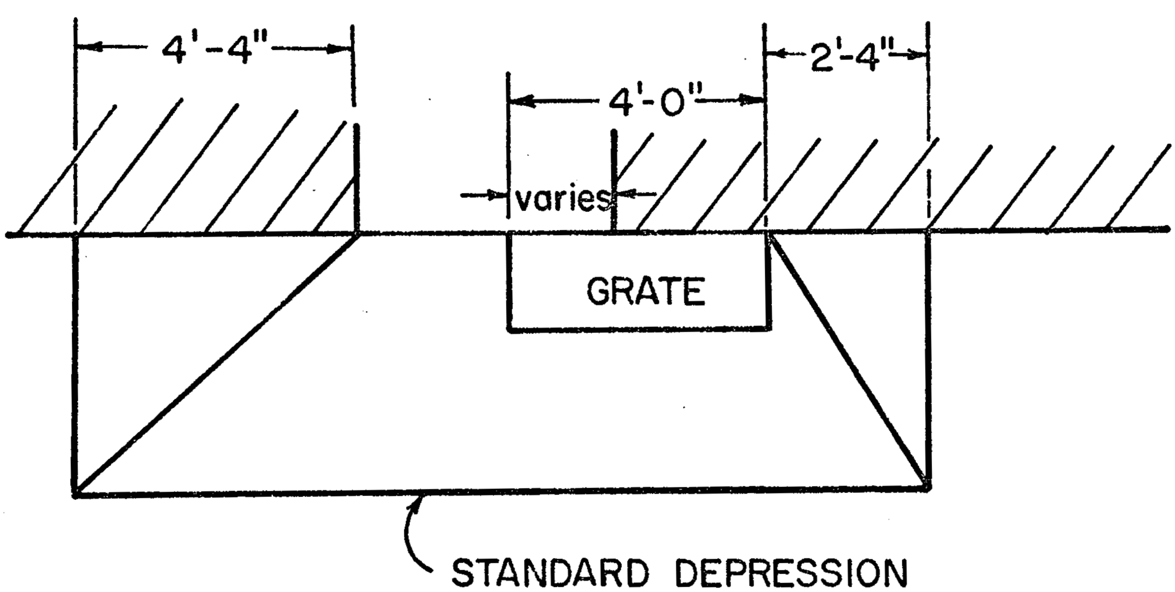
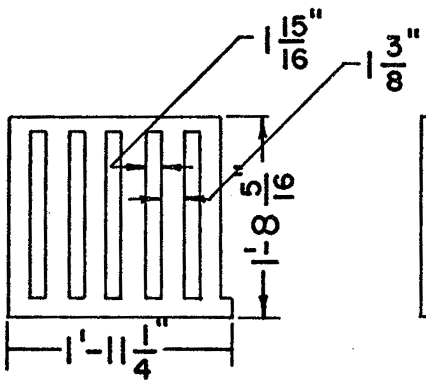


FIGURE 7 GUTTER GRATES, BALTIMORE Md. AFTER DESIGN OF STORM WATER INLETS. JOHNS HOPKINS UNIVERSITY (1956)

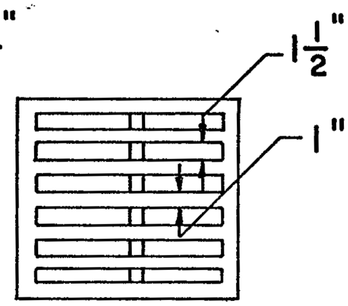
GUTTER INLETS

These are also known as grate inlets. The grates are placed immediately adjacent to the roadway curb and are either flush to the original pavement surface or set in the standard depression Fig. 6

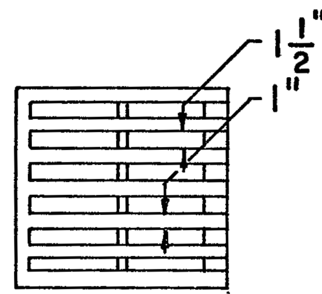
Types of grates tested .....



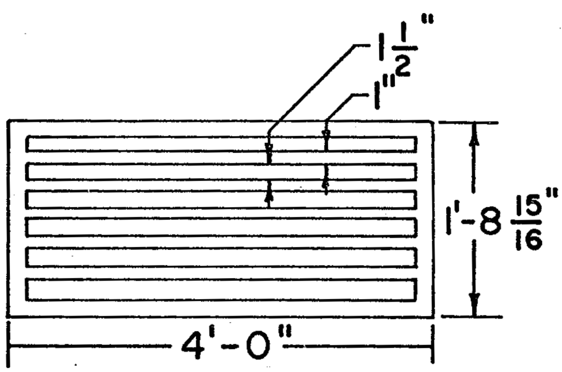
No. 1 - Grate



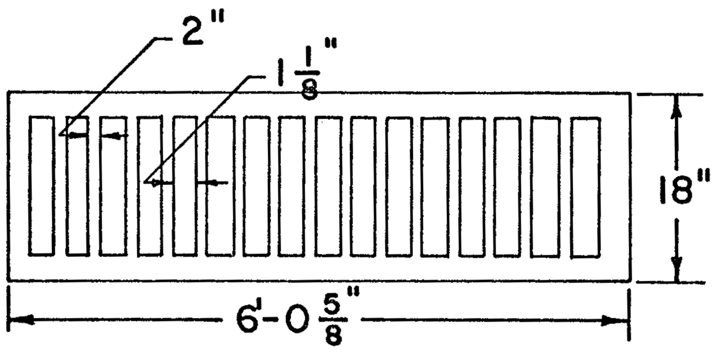
No. 2 - Grate



No. 4 - Grate



No. 6 - Grate



H - Grate

was developed save to utilize conventional fluid mechanics relations, slightly altered to fit the test data, for design purposes assuming that the inlet operates as an orifice or a weir.

2.5.1 Design of Curb Inlets [22,24)]

Undepressed curb inlets: For undepressed curb inlets on a continuous grade, the combination of experimentation with dimensional analysis yielded the following expression:

$$\frac{Q}{l y_o \sqrt{g y_o}} = K \ , \qquad (2.10)$$

where y_o = depth of gutter flow measured at the curb, FT., and K = constant for each particular side slope of pavement.

If $\tan\theta$ = pavement cross-slope, then for $\tan\theta$ = 12, K = 0.23 and for $\tan\theta$ = 24 and 48, K = 0.20.

For a particular known gutter flow Q, y_o is calculated by using the triangular form of the Manning equation [21,36,38,40)] , since the slope and the roughness of the gutter section is known.

The solution to equation 2.10 is found in Figure 8 which is the graphical form of the equation with y_o expressed in terms of gutter slope, pavement roughness and cross-slope, as per the Manning equation.

Depressed crub inlets: Formula 2.10 cannot be applied to depressed curb openings for two reasons. First, the depth of flow at the upstream edge of the inlet will not be the same as the depth of flow y_o in the undepressed gutter. Secondly, the testing revealed that a hydraulic jump forms in the depression increasing the flow into the opening. Analysis of the data revealed that for this type of inlet the following equation applies:

$$\frac{Q}{Ly_o\sqrt{gy_o}} = K + C' \quad , \qquad (2.11)$$

where C' varies according to the expression,

$$C' = 0.45/1.12^M \quad , \qquad (2.12)$$

where $M = LF''/a\tan\theta$, and $F'' = V^2/gy$.

The graphical solutions to equations 2.11 and 2.12 are presented in Figure 9, a and b; with the above information a curb opening set on a continuous grade can be designed to meet the local criteria such as permissable flow-by.

2.5.2 Design of Gutter Inlets [22,23)]

For a gutter opening placed on a continuous grade, there are three ways in which the flow tends to escape the inlet:

(1) Part of the flow moves along the tops of the bars before tumbling into the openings.

(2) Some of the flow may escape past the outside edge of the grate.

(3) High velocity flow tends to overshoot the grate.

Only the last of these need be considered for design purposes.

The following five items are important in the design of depressed and undepressed gutter inlets:

(a) The length of grate required to prevent an overshooting of the flow; dimensional analysis and experiment reveal that

$$(L_o/V_o)\sqrt{g/y_o} = m \quad , \qquad (2.13)$$

where L_o = length of grate (length measured parallel to the flow) required to capture all of the flow in the gutter section when the velocity of the flow over the grate is V, FT.,

V_o = average velocity of the flow in the gutter section, FPS., and m = constant for each bar orientation. For grates with bars parallel to the flow m = 4, and with bars perpendicular to the flow m = 8.

Equation 2.13 will be unaffected by the presence of a local depression adjacent to the inlet.

(b) The length of grate required to capture the flow outside of the gutter section (without depression); the following expression was derived using a combination of experiment and dimensional analysis:

$$(L'/V_o)\sqrt{g/y_o - W/\tan\theta)} = 1.2 \tan\theta_o \quad , \qquad (2.14)$$

where L' = length of grate required to capture all of the flow outside of the gutter section, FT.,

W = width of the grate (perpendicular to the curb), FT.,

θ_o = crossfall of the pavement measured in degrees from the horizontal.

(c) The length of grate required to capture the outside flow for a gutter inlet with local depression:

$$(L'/V_o)\sqrt{g/y'} = 1.2 \tan\theta' \quad , \qquad (2.15)$$

where y' = depth of flow at the outer edge of the grate, FT., and θ' = transverse slope of the local depression.

(d) It is sometimes convenient in design to make the length of the grate less than 1'; when this is the case a certain amount of the flow will escape past the outside of the inlet. The amount of flow thus passing by the inlet was found to be

$$q_2 = 0.25\ (1 - L')\sqrt{g}(y_o - W/\tan\theta_0) \quad , \qquad (2.16)$$

where q_2 = carry-over flow past the outside of the inlet, CFS., and L = actual length of grate. FT.

(e) For gutter inlets with local depression, when the length of grate is less than L', the flow-by past the outside of the grate can be found using

$$q_2 = (L - L')\ y'\sqrt{gy'/4} \quad . \qquad (2.17)$$

In all of the above equations, y_0 is found by applying the known gutter flow to the triangular form of the Manning equation. For the depressed inlet cases, having solved for this y_0, the total energy equation (conservation of energy) is applied between the upstream edge of the depression and the upstream end of the grate opening to obtain y'.

2.5.3 Design of Deflector Inlets [22,25)]

Deflectors placed immediately adjacent to an undepressed curb inlet, as shown in Figure 6, increase the flow into the simple opening by creating a standing wave of water in front of the opening; really any roughness in the pavement equivalent to that supplied by the notches would have the same effect. It was shown that by applying the data to dimensionless parameters the following equation could be derived:

$$\frac{Q}{Ly_o\sqrt{gy_o}} = 0.058(c/b)^{1/20}\ (\sqrt{S}/n)(\sqrt{W/L}) \quad , \qquad (2.18)$$

where c = clearance between the deflectors, FT.,

b = width of each deflector, FT.,

S = longitudinal slope of the gutter, FT./FT., and

n = Manning's roughness.

It can be seen that the above expression is not very responsive to the term c/b, which may be treated as a virtual constant, say 2. Equation 2.18 is presented graphically in Figure 10.

Actual vehicle tests were run on deflector inlet installations in the field and these revealed that for slots of up to four inches there was no noticeable vibration to the automobile but increases in width greatly increased the vibrations and intolerable levels were reached when the width of the slots was seven inches.

2.5.4 Design of Combination Inlets [22,26)]

(a) Undepressed Combination Inlets: These are designed in exactly the same way as undepressed grate inlets with one slight modification - in equation 2.13, let m = 3.3.

(b) Depressed Combination Inlets: The study of these inlets revealed three vital facts which must be considered in their design.

i) Grates with no transverse bars are the most efficient.

ii) The more transverse bars that a grate does contain, the less efficient it becomes.

iii) Efficiency is more readily obtained by an efficient grate than by placing the grate upstream or downstream of the curb opening.

Because it was revealed that the positioning of the grate to one side or the other of the opening did not greatly affect the efficiencies, the only design formula developed was for the case in which the grate is the same size as the curb opening and is placed immediately opposite that opening.

The same approach is used as was developed for simple grate inlets*; the chief concern was to eliminate overshooting of the flow and also to prevent water from

---

* See section 2.5.2.

escaping past the outside edge of the grate.

The length of inlet required to prevent overshooting of the flow was found to be

$$L_o = mV\sqrt{y/g} \quad , \qquad (2.19)$$

where m is a constant for each type of grate. For a grate with no transverse bars set flush to its surface m = 3.3, and for a grate with transverse bars set flush with its surface m = 6.6.

The length of inlet required to capture the outside portion of the flow is

$$L' = 1.2V\tan\theta\sqrt{(y - W/\tan\theta)/g} \qquad (2.20)$$

When the actual length of the inlet is less than 1', then there will be carry-over or flow past the inlet as given by the formula

$$q_2 = 0.25(L' - L)\sqrt{g}(y - W/\tan\theta)^{3/2} \qquad (2.21)$$

The total flow-by past the inlet will be somewhat less than the amount given by expression 2.21, however, since ponding in the depression will cause some additional water to flow into the opening. The amount of the flow into the curb can be approximated by treating the opening as a triangular weir and using the depth of ponding in the depression as the head. Hence, the total corry-over will be found using the following expression:

$$q=q_2-0.266R\sqrt{g}\tan\theta\left[(a-L_2S)+5/4(8q^2/g\tan^2\theta)^{1/5}\right]^{5/2} \quad , \qquad (2.22)$$

where q = total flow past the inlet, CFS.,

R = ratio of the clear width between the grate

FIGURE 8 UNDEPRESSED CURB INLET CAPACITIES

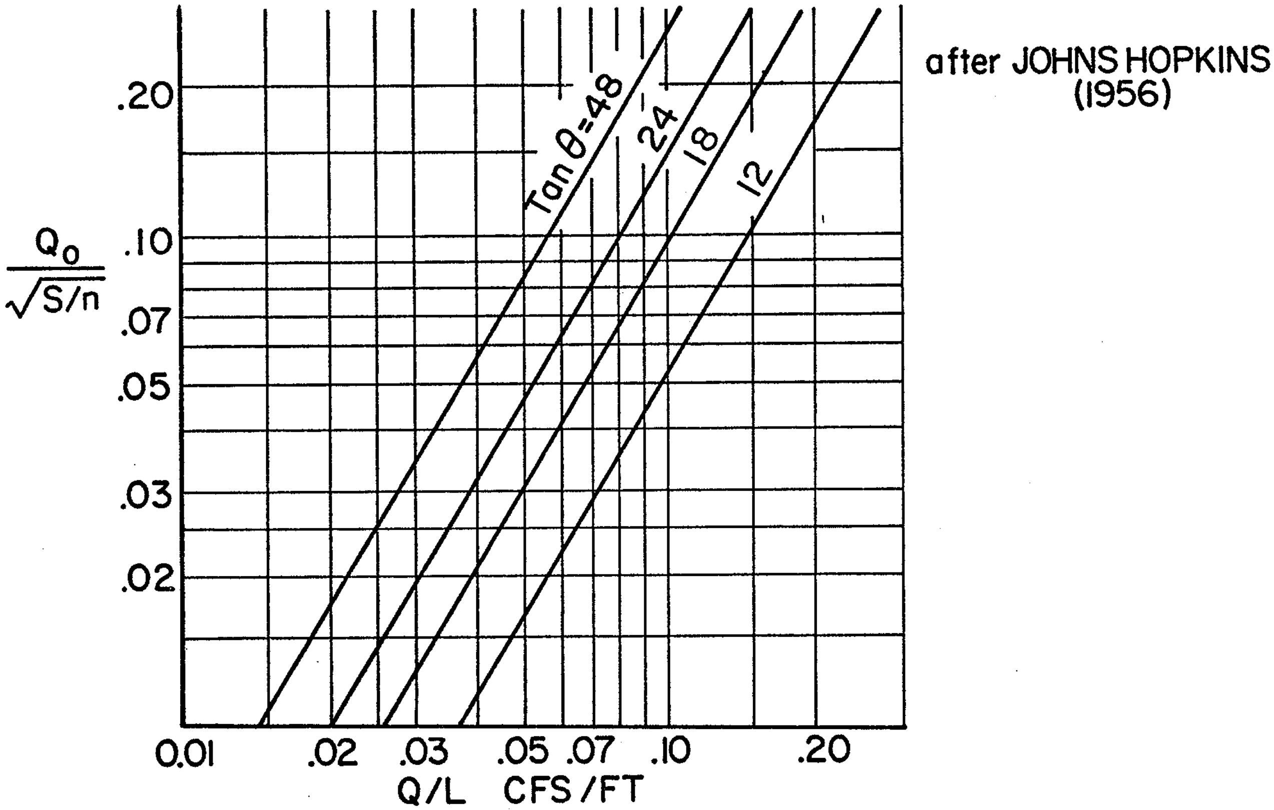


FIGURE 9 (A) CURVES FOR C VALUES IN EQUATION 2.11

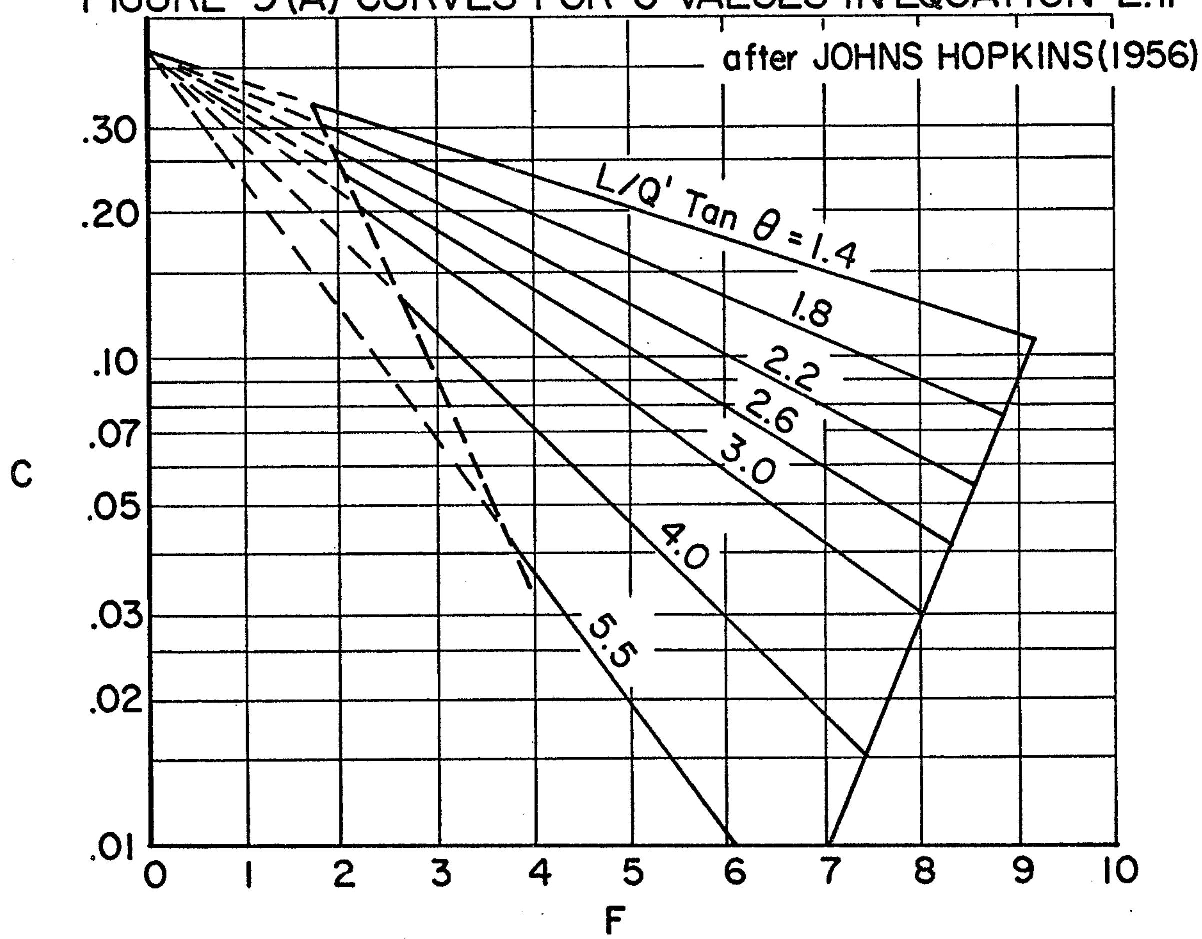


FIGURE 9(B) CAPACITY OF CURB OPENING INLETS WITH DEPRESSION

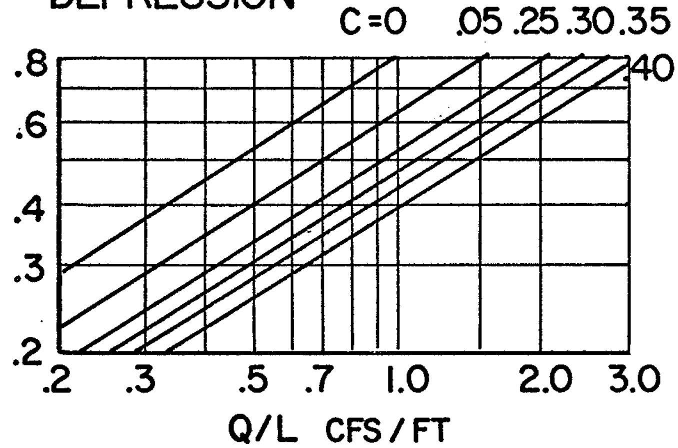


FIGURE 10 DEFLECTOR INLET CAPACITIES

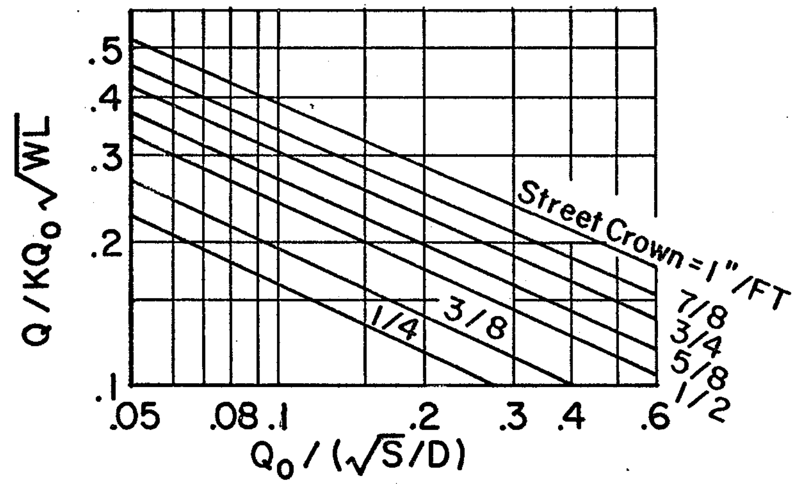
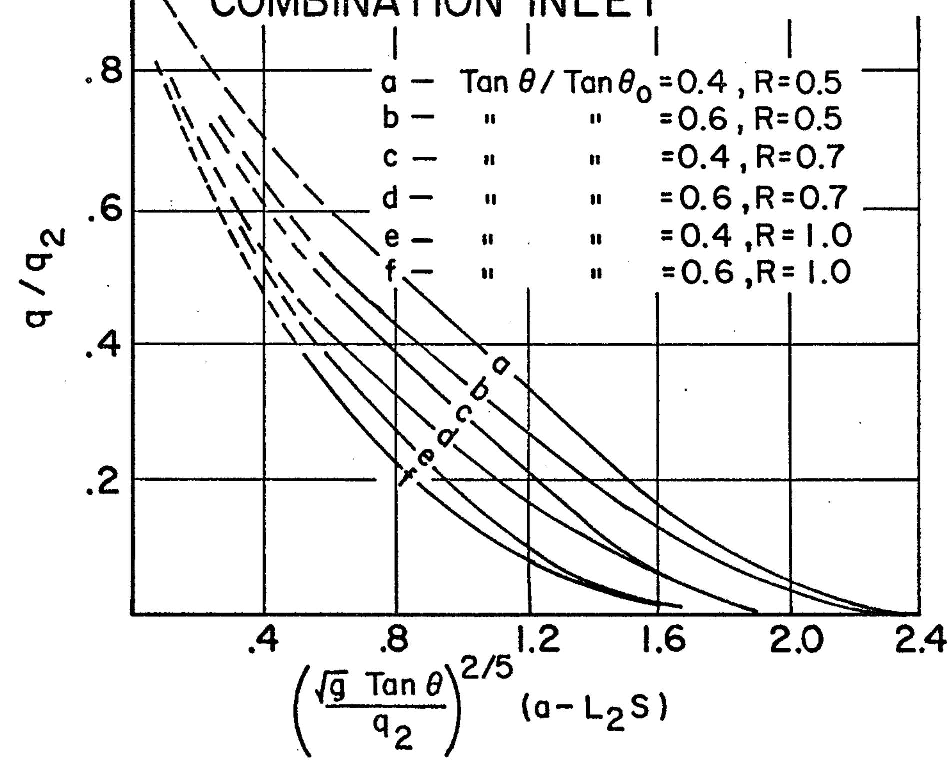


FIGURE 11 FLOW-BY FOR A DEPRESSED COMBINATION INLET



bars to the total width of the grate,

a = depth of gutter depression, FT., and L_2 = length of downstream gutter transition. FT.

Equation 2.22 is solved in Figure 11.

2.5.5 Inlets in Sumps[16)]

The theory for inlets in sumps was not developed in the same way as that for inlets on a continuous grade. Tests were run for this condition but they were not nearly as extensive as the continuous grade experiments. The theoretical analysis was conducted by merely applying what was thought to be the appropriate fluid mechanics relations, based on the experimental observations. The theory for the three types of inlets tested is given below.

a) Grate inlets: It was observed during the testing program that the inlet appeared to operate as an orifice through most of the flow conditions. The standard orifice equation was applied to the experimental data and the following evolved:

$$Q_i = 0.6A\sqrt{2gh} \quad , \qquad (2.23)$$

where Q_i = the total flow through the inlet made up of the gutter flows from each side of the inlet, CFS.,

A = area of the clear opening of the inlet, SQ.FT., and h = depth of water at the inlet. FT.

b) Curb Inlets: Observation on the operation of curb opening inlets seemed to indicate that they operated as a simple rectangular weir through most of the flow conditions encountered, hence the weir formula was applied to the data to yield:

$$Q_i = 3.0h^{3/2} L$$

where Q_i = the total flow into the opening made up of the flow from both sides of the inlet, CFS., and L = length of the opening. FT.

c) Combination Inlets: Although the report was not clear as to whether or not the reasoning was based on experimental data, it was concluded that the capacity of a combination inlet is simply the sum of the two separate inlets, gutter and curb.

Two other points of some importance should be mentioned here. The testing showed clearly that the capacity of any inlet located in a sump was greatly increased by placing that inlet in a local depression. Also it was demonstrated that the presence of transverse bars in a gutter grate, whether they be depressed or flush with its surface, have no effect on the capacity of the grate. Design curves for curb, grate and combination inlets in a sump, both with and without a depression are shown in Figure 12. These curves are based on equations 2.23 and 2.24.

The above summary of the Johns Hopkins report contains all of the important features of that study. It was not possible to include all of the design aids contained in the final publication. The two most important pieces

FIGURE 12A: CAPACITY OF UNDEPRESSED SUMP INLETS

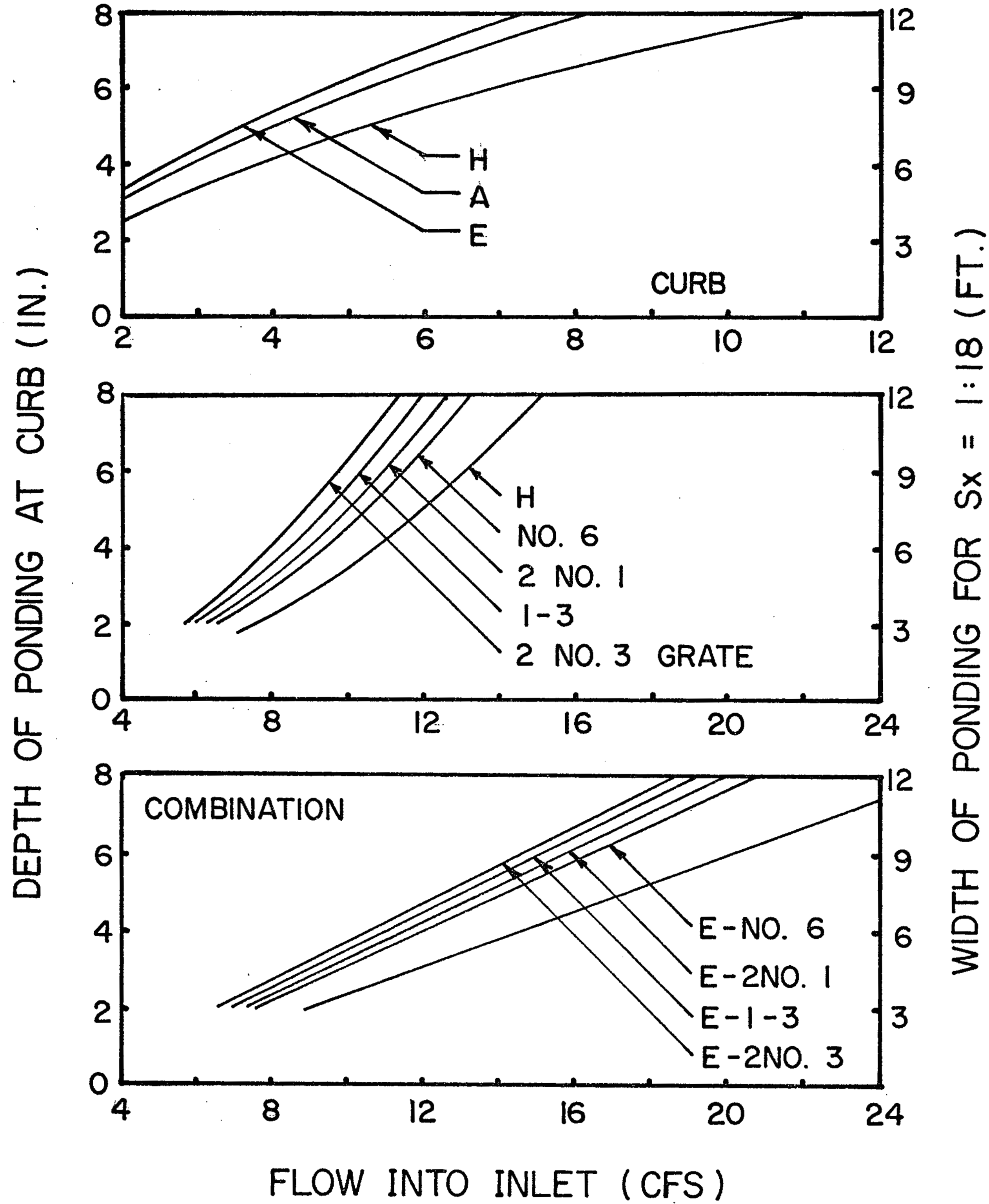
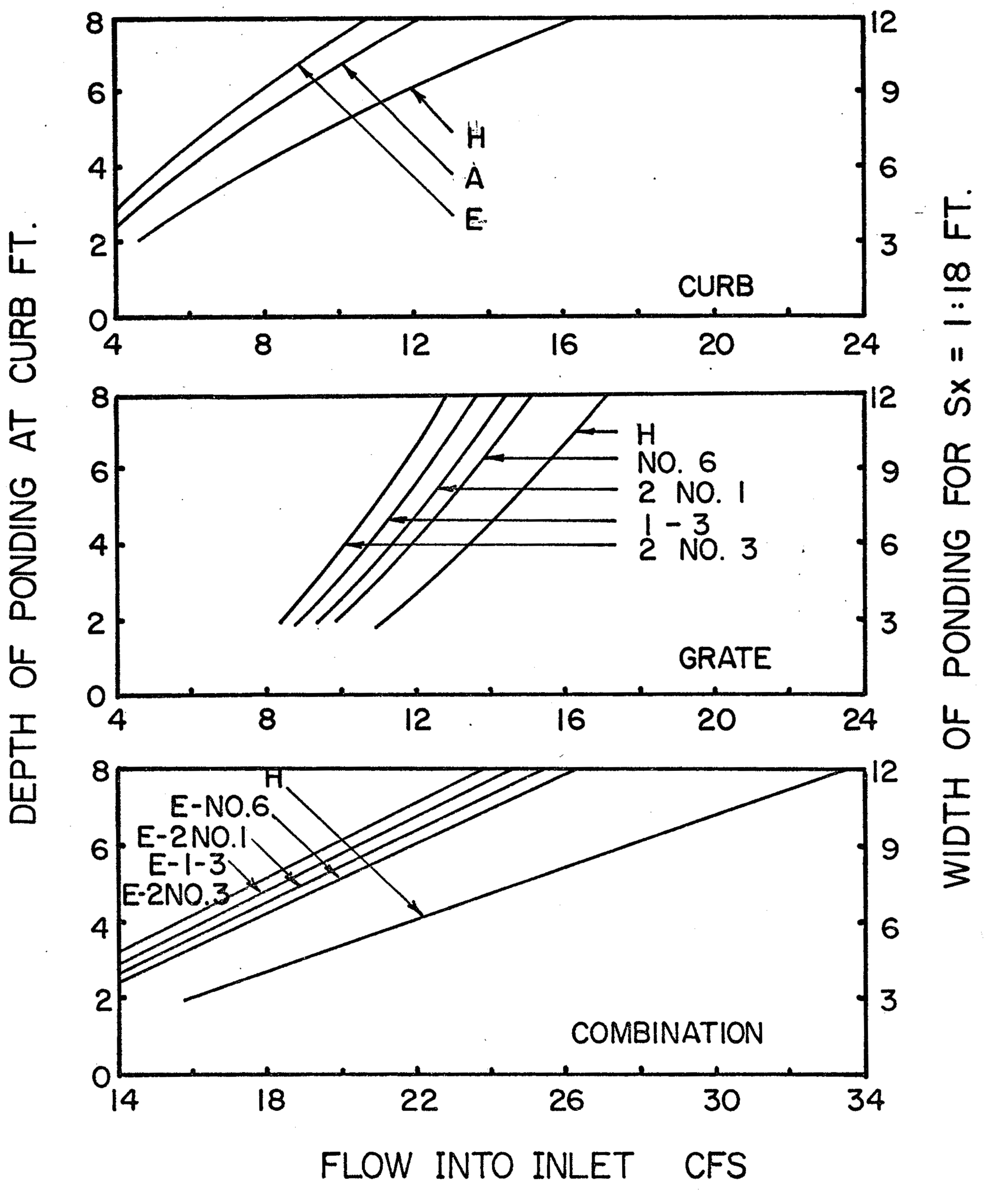


FIGURE 12B: CAPACITY OF DEPRESSED SUMP INLETS



omitted are the design charts for the solution of the triangular form of the Manning equation[38), and a simplified method of approximating the capacities of single and multiple inlets[5).

2.6 R. J. Wasley - Hydrodynamics of Flow into Curb Opening Inlets (1961)[39)

The research reported in this paper is confined to analyzing the case of a simple undepressed curb opening set on a continuous grade. A rigorous formulation for the flow was developed and then verified by experiment.

For the theoretical analysis, only gutter slopes which were greater than the critical slope were considered; this is because the complexities introduced by sub-critical flow make analysis almost impossible and also because sub-critical gutter slopes are almost never encountered in actual practice.

The approach taken by Wasley is to divide the flow through the inlet into two components, the flow parallel to the curb determined by the gutter slope, and the transverse flow determined by the crossfall of the pavement. These zones, as Wasley calls them, are shown in Figure 13 and are numbered I and II respectively.

Zone I is treated as simple open channel flow with a velocity distribution as derived from Darcy's equation given by

$$\overline{U} = (8g\phi_0/f)^{1/2} Z^{1/2} , \qquad (2.25)$$

where $\overline{U}$ = y component of the velocity (y axis parallel to curb), CFS.,

f = Darcy friction factor,

Z = height above the intersection of the pavement and curb, FT., and

ϕ_0 = gutter slope, %.

Zone II, the cross flow, is treated as being analagous to the instantaneous failure of a dam behind which is a triangular reservoir. This situation is pictured in Figure 14. The application of Newton's second law leads to the equation of motion for the flow and can be combined with the continuity equation to form a set of equations which, when solved*, will yield the following dimensionless parameters which describe the instantaneous failure of a dam;

$$\hat{x} = X/X_0 \text{ theo.}; \ \hat{y} = \phi_0 y/Z_0 ; \ \hat{z} = Z_0/Z; \ \hat{t} = \theta_0 g/Z_0 \, t;$$

$$\hat{\vec{u}} = \vec{u}/\bar{u}\text{theo.max.}; \ \hat{\overline{V}} = \overline{V}/ gZ_0 , \qquad (2.26)$$

where (^) indicates a dimensionless quantity,

x,y,z = distances measured parallel to the coordinate axis, (See Figures 13 and 14) FT,

x_0 , y_0 , z_0 = maximum distances, FT.,

* An extremely complex procedure; for an outline see "Unsteady

FIGURE 13: FLOW INTO A CURB OPENING AFTER WASLEY (1961)

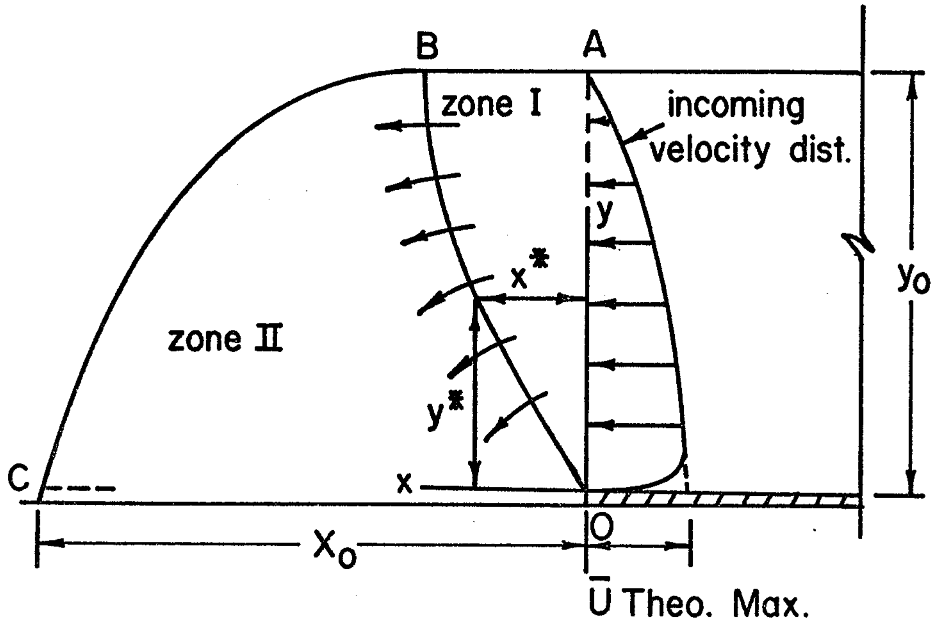
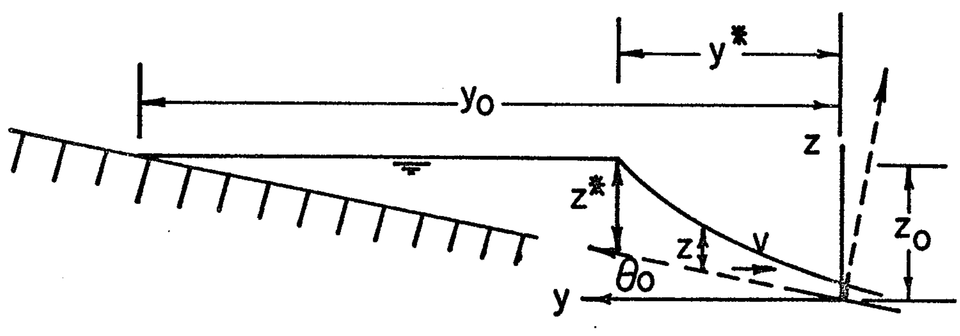


FIGURE 14: FAILURE OF A DAM WITH TRIANGULAR RESEVOIR .... AFTER WASLEY (1961)



t = time, SEC., and

$\overline{V}$ = x coordinate of the velocity, FPS.

Referring to Figure 13, the division between zones I and II is along the line OB and is the boundary in the y-direction of the negative surge crest as it passes downstream due to the x-component of the velocity; in other words, the information that the curb has terminated at 0 is transmitted in the y-direction at a certain finite rate. Combining the velocity of propagation of a small disturbance, C = gZ [32)], with equation 2.25, the boundary between zones I and II can be defined by

$$x_B = \frac{(8g\phi_0/f)^{1/2}\ y_o}{\sqrt{g}} \qquad (2.27)$$

The remaining step in the solution is to define the outside streamline BC (Figure 13); this is done by describing the trajectory of a given fluid element as it moves along that streamline. The equation of motion of a particle moving along BC is given by

$$y = -\ g\phi_0 \qquad (2.28)$$

Combining equations 2.27 and 2.28 (as well as translating the coordinate system, a step outlined in detail in Wasley's paper) yields an expression defining the outside streamline:

$$x = C_o\left(y_o + \frac{y_o - y}{\sqrt{2}}\right)^{2} \qquad (2.29)$$

where $C_o = \frac{\sqrt{g}}{(8g\phi_o/f)^{1/2}}$.

Hence, the length of curb opening required to

Non-linear Waves in Open Channels", R.F.Dressler, Proceedings Royal Society of London, Volume 229A.

capture all of the gutter flow is the value of x in equation 2.29 when y = 0. It would be possible to deal with the condition where only part of the flow is captured, by solving for the equations of the interior streamlines; this, however, is not nearly as simple as the solution derived for the exterior streamline. Once such equations are known, then the amount of flow-by may be calculated for any given length of inlet.

When the above method is applied to Wasley's experimental data, (obtained from a full scale adjustable model) the data tended to verify the theory, although the x-values were always lower than those predicted by the theory. Also, with gutter slopes less than 5 percent and/or cross slopes less than 0.5 percent, it cannot be said for certain whether or not the predicted results may be relied upon.

2.7 S. S. Karaki and R. M. Hamie - Depressed Curb opening Inlets (1961) [17)]

A major portion of this research dealt with curb openings located in a sag, a condition about which little was known until this paper was published.

Experiments were conducted on a 1:4 scale model, and the theoretical analysis consisted of observing the type of flow being encountered under the various conditions of model operation (i.e. orifice flow) and applying the appropriate fluid mechanics relations to the data. The data was used to determine equation constants.

uring the tests, the following observations were made;

i) The curb inlet operates as a weir until the water submerges the entrance.

ii) When the water depth exceeds about 1.4 times the height of the curb opening, the inlet operates as an orifice. iii) Between the weir and orifice type of operation the capacity of the inlet is indeterminant.

iv) For each particular inflow into the inlet (made up of the two incoming gutter flows), there is a minimum height of opening below which the inlet will not behave as a free overflow weir. This height has been termed h and its relationship to Q is shown in Figure 15.

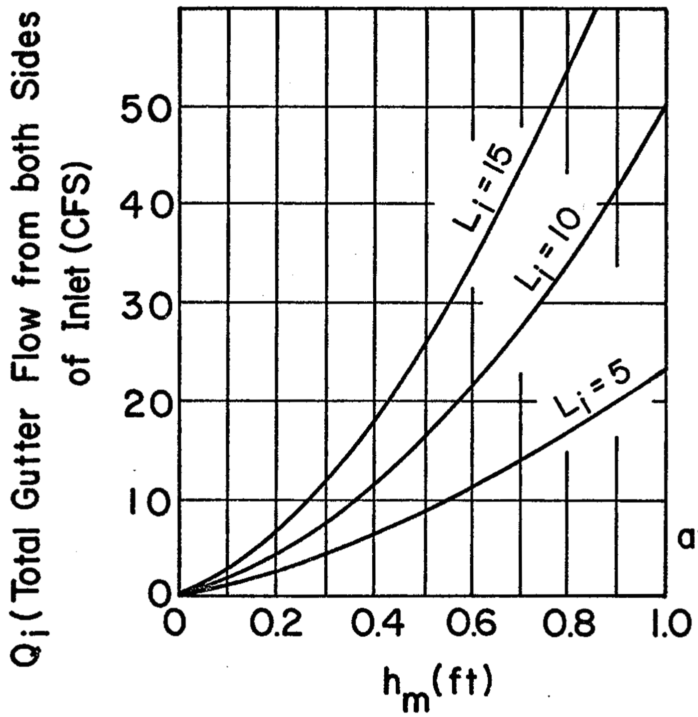
All of the tests run in this study were run with a pavement crossfall of zero; the range of gutter slopes was from 1.50 to 6.00 percent. Curb opening lengths of five, ten and fifteen feet were tested and three standard depressions of different sizes were used. The investigators were able to derive unique equations for each particular depression tested to describe the inflow into the inlet. These equations are as follows:

For a depression of one foot width and one inch depth,

$$Q_i = 2(L_i + 2.4W)\,(d_{MAX} + W/12)^{1.78} \qquad (2.30)$$

where Q_i = total flow into the inlet made up of

FIGURE 15: MINIMUM DEPTH OF FLOW FOR CURB INLET WEIR OPERATION



after Karaki & Hanie (1961)

FIGURE 16: CAPACITY OF DEPRESSED CURB INLETS IN A SUMP

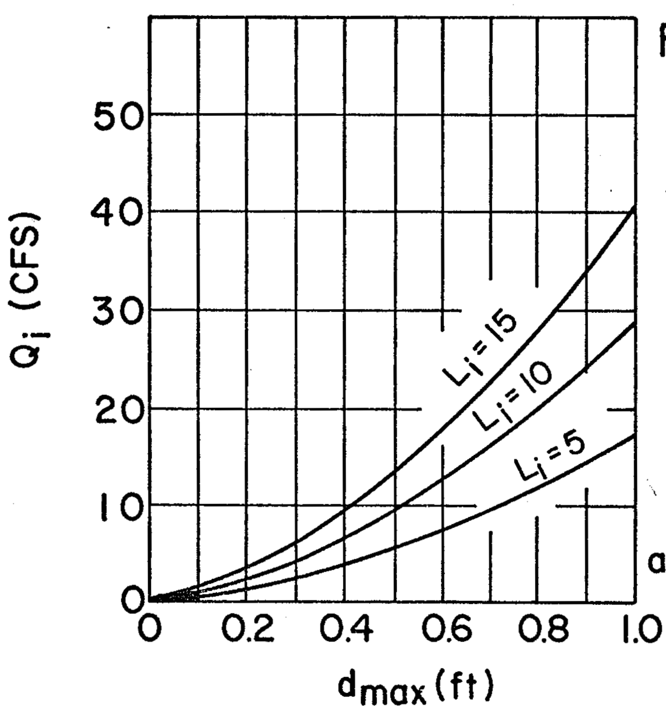


FIGURE 16 (A)

W = 1 ft   a = 1 in

S = 0.015 → 0.06

S_x = 0

after Karaki & Hanie (1961)

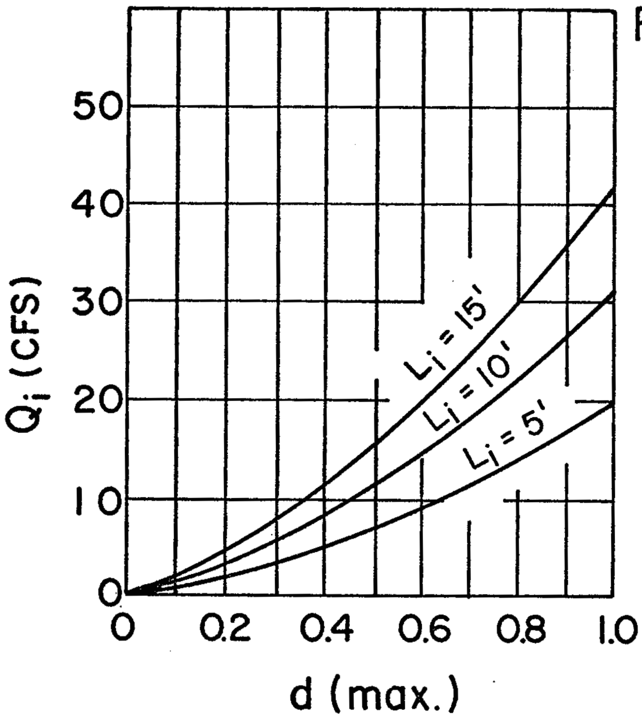


FIGURE 16 (B)

W = 2 ft a = 2 in
S = 0.015 → 0.06
S_x = 0

after Karaki & Hannie (1961)

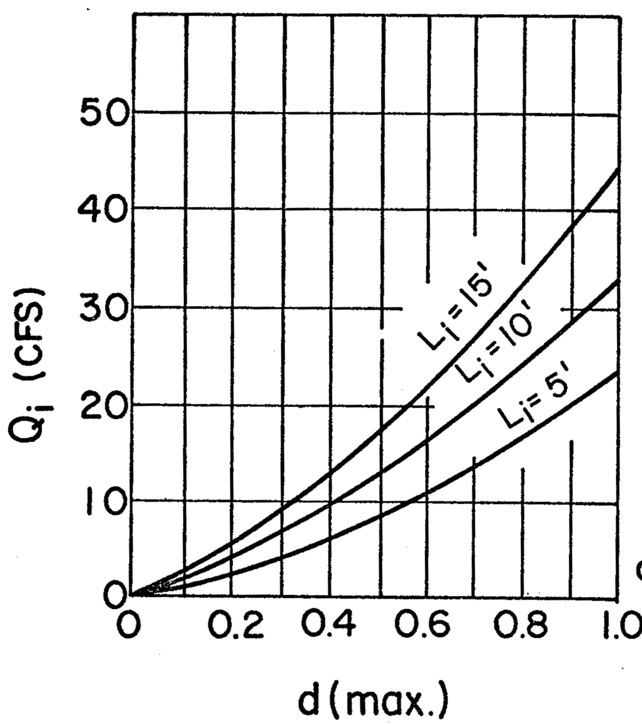


FIGURE 16 (C)

W = 3 ft a = 3 in
S = 0.015 → 0.06
S_x = 0

after Karaki & Hannie (1961)

the gutter flows from both sides of the inlet, CFS.,

L_i = length of clear opening of the inlet, FT.,

d_{max} = depth of water measured at the inlet opening, FT., and

W = width of the depression in front of the inlet, FT.

For a depression of two foot width and two inch depth,

$$Q_i = 1.7(L_i + 1.8W)\ (d_{MAX} + W/12)^{1.85} \qquad (2.31)$$

For a depression of three foot width and three inch depth,

$$Q_i = 1.475(L_i + 1.8W)\ (d_M + W/12)^{1.85} \qquad (2.32)$$

The above three equations have been solved in Figure 16. It can readily be seen that these equations are of the same basic form with different constants and exponents.

2.8 W. J. Bauer and D. C. Woo - Hydraulic Design of Depressed Curb Opening Inlets (1964)[4)]

The research reported in this paper consists of two parts: first a series of tests were run to select a standard depression geometry which would give the overall best performance. Secondly, curb opening inlets utilizing this standard depression were analyzed and then tests were conducted and the data applied to the theoretical analysis.

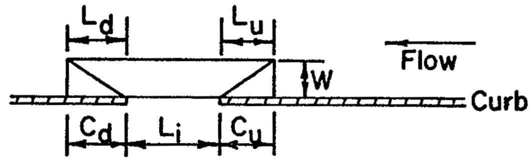
For inlets set on a continuous grade, the testing program was carried out on a full scale model, while for depressed curb openings located in a sump, a 1:4 scale model was used.

The selection of the depression geometry was the result of preliminary tests regarding the effect of changes of the depression geometry on the efficiency of the inlet. A summary of these tests is given in Figure 17.

During the continuous grade inlet experiments, it was observed that a disturbance line proceeds across the flow from the upstream end of the depression to the depressed zone, if one were present. Further it was discovered that downstream from the line of disturbance the flow outside of the depressed zone moved along trajectories that could be approximated by simple parabolas, calculated on the assumption that the velocity in the longitudinal direction remained constant, and that the acceleration perpendicular to the curb face corresponds to a piezometric surface parallel to the cross slope of the pavement. The flow across the depressed surface could also be considered to move in parabolic trajectories corresponding to a piezometric gradient proportional to the slope of the depressed surface in this direction. Using this mathematical approach, it was found that for each curve of W/T, the relation between Q_i/Q, and L_i/F_wT followed a straight line from its origin to a certain point. The location of that point can be described by the following equations;

FIGURE 17: SELECTION OF A STANDARD DEPRESSION

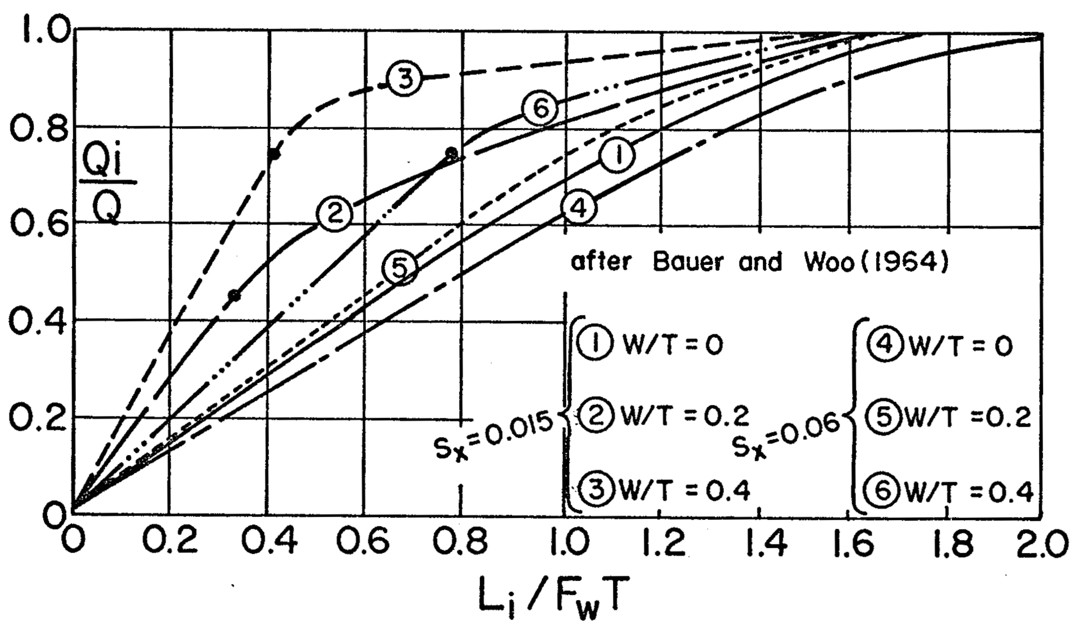
Definition of Transition Geometry



L_d (ft)	C_d (ft)	L_u (ft)	C_u (ft)	Sketch	Remarks
0	0	0	0	Vertical Faces	Poor Downstream Transition
2	0	0	0	Vertical Face	Worst Downstream Transition
2	2	0	0	Vertical Face	Good Downstream Transition
0	2	0	0	Vertical Faces	Best Downstream Transition
0	0	2	0	Vertical Face	Worst Upstream Transition
0	0	2	2	Vertical Face	Best Upstream Transition
2	2	2	2		Standard Adopted

after Bauer and Woo (1964)

FIGURE 18: DEPRESSED CURB INLET PERFORMANCE



$$Q_i/Q = (1 - W/T)^{1.85} - 1 \quad (2.33)$$

and $$L_i/F_w T = K(W/T)(d_w/a), \quad (2.34)$$

where T = width of spread of the uniform gutter flow, FT.,

F_w = Froude number based on the depth and velocity of uniform gutter flow at a distance w from the curb face,

K = empirical coefficient of transverse acceleration, and

d_w = water depth at a distance w from the curb face, FT.

The solution to the above equations is given in Figure 18.

In the sump condition, the inlet is treated as a simple weir with a slight modification based on the experimental data. Thus a modified weir equation is derived to give the following:

$$q = 1.7h^{1.85} \quad (2.35)$$

where q = the modified unit discharge given by $q = Q/(L_i/2 + 0.9W)$. This equation is shown in Figure 19.

The main design curves of the study consist of four-variable plots of gutter flow spread T, gutter slope S_o, cross-slope S_x, and the inlet interception rate Q_i/Q. They can be derived using equations 2.33 and 2.34.

2.9 J. J. Cassidy - Generalized Hydraulic Characteristics of Grate Inlets (1966)[6]

This study, conducted at the University of Missouri, was restricted to the consideration of undepressed grate inlets located on a continuous grade. Six different grates with varied bar configurations and orientation were tested and these are shown in Figure 20.

The first step in this study was to list the variables which effect flow into this type of inlet and then to perform a conventional dimensional analysis. This yielded the following expression:

$$Q_i/Q_o = \phi(V_o/\sqrt{gD}, L/D, D/W, \beta, S, S_x), \quad (2.36)$$

where D = y = normal depth of gutter flow, FT.,

W = width of grate (perpendicular to the flow), FT., and

β = a dimensionless characteristic which will be assumed to completely describe the geometric configuration of the grate.

The test apparatus used by Cassidy was somewhat different than that used by other investigators; in all other tests of storm water inlets conducted up to this time, the procedure was to establish a certain roughness on the surface of the model, then set the apparatus at a given longitudinal slope and cross slope, and then introduce flow at one or both ends of the flume. Cassidy, however, although setting his model at a given longitudinal and cross slope, maintained absolute control over the depth of flow by using a sluice gate at one end of the flume to control the

FIGURE 19 CAPACITY OF DEPRESSED CURB INLET IN A SUMP

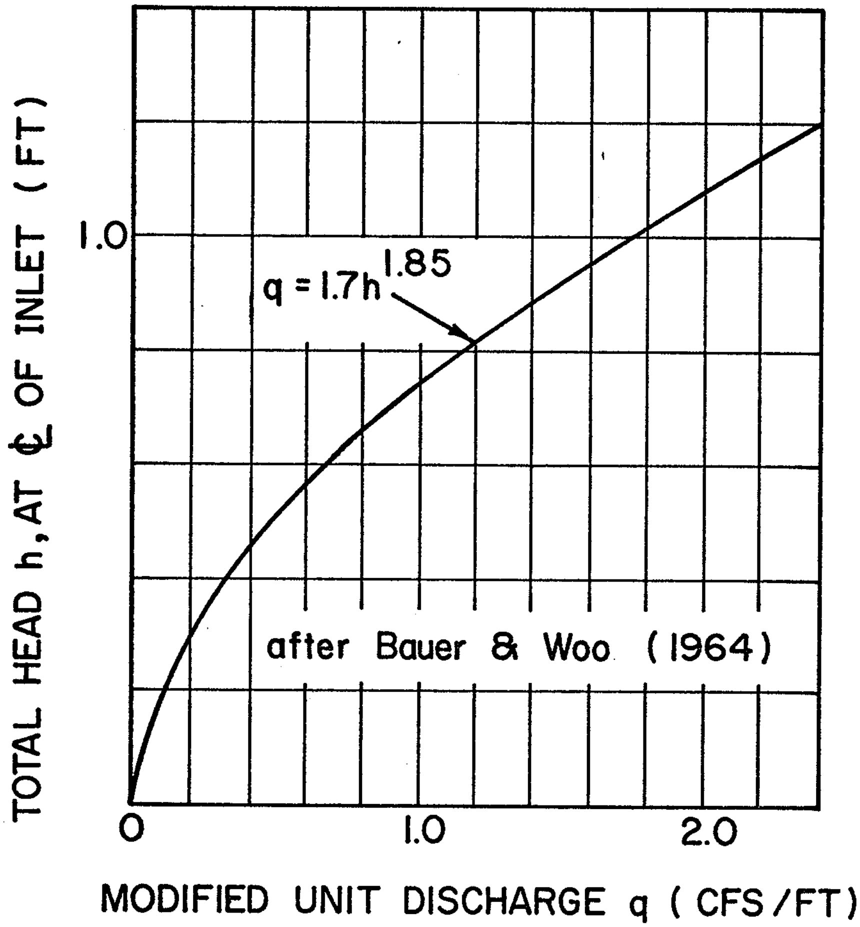
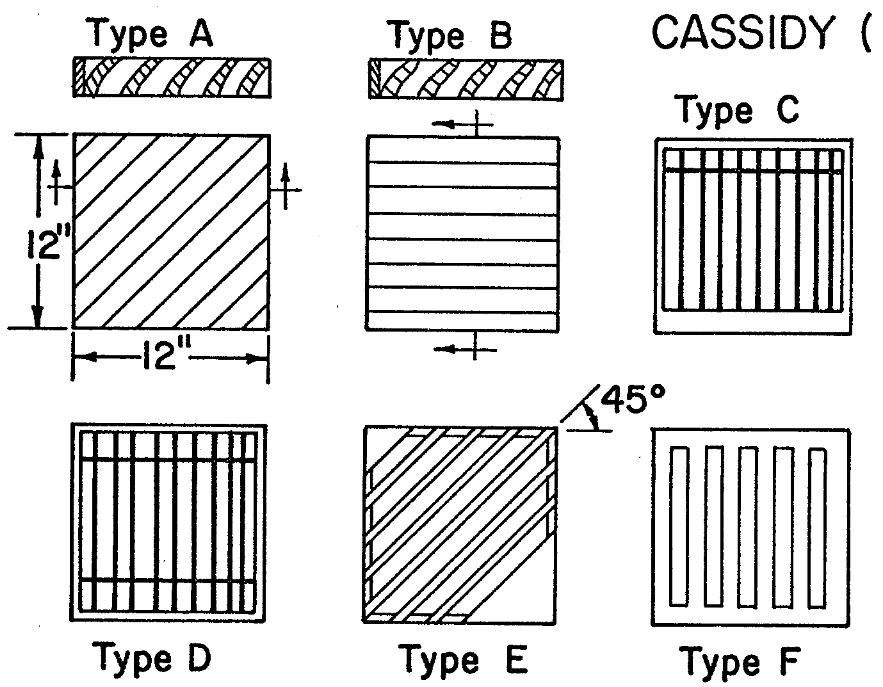


FIGURE 20 TYPES OF GRATES TESTED AFTER CASSIDY (1966)



depth. The model scale was 1:2; however, only the section of roadway adjacent to the curb was modeled, the maximum width of flow being only fourteen inches.

It was found early in the testing program that the longitudinal slope did not noticeably effect the efficiency of the grate inlet. The remainder of the tests were then conducted with a horizontal gutter slope.

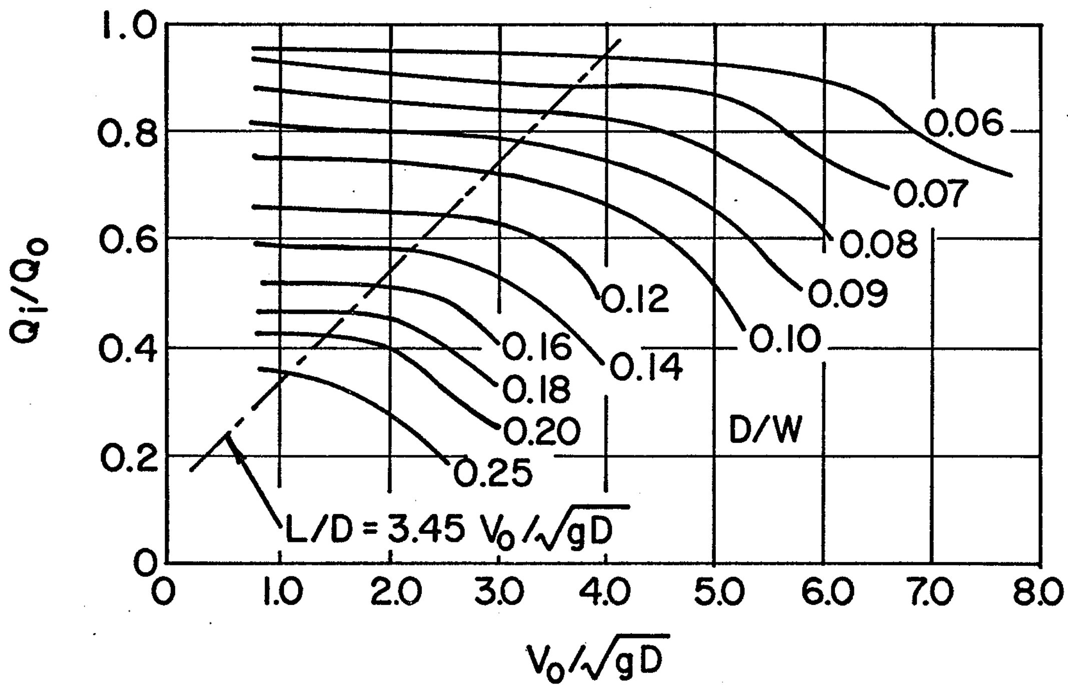
Two distinctly different flow patterns were observed during the experiments. At low values of D/W and/or V_o/gD, no flow overshot the grate and the flow pattern was very smooth; at relatively high values of these two numbers, however, flow was seen to strike the downstream side of the grate, creating a violent disturbance quite similar to an hydraulic jump. Flow then began to pass directly over the grate and the efficiency Q_i/Q was thereafter reduced.

Sample design curves for a type F grate (Figure 20) are given in Figure 21 (these may be used for any size of F grate); from these curves, it can clearly be seen that the point at which the disturbance begins to form is the point at which the efficiency curves begin to bend downwards. A straight line can be drawn through these points for a series of efficiency curves. It was found that the equation of this line could be expressed as

$$L/D = m(V_o/\sqrt{gD}) \qquad (2.37)$$

The magnitude of m is a measure of the grate's

FIGURE 21 : GRATE INLET PERFORMANCE GRAPH



Type F grate , 20.6 to 1.0 cross slope after Cassidy (1966)

Table I Values of m for equation $L/D = m\ V_o/\sqrt{gD}$

Type of grate	Cross slope	m valve
A	50 to 1.0	2.18
	20.6 to 1.0	2.32
B	50 to 1.0	2.50
	20.6 to 1.0	2.50
C	50 to 1.0	2.36
	20.6 to 1.0	2.38
D	50 to 1.0	2.86
	20.6 to 1.0	2.94
E	20.6 to 1.0	5.55
F	50 to 1.0	3.25
	20.6 to 1.0	3.45

after Cassidy(1966)

efficiency. The smaller the value of m, the greater is the efficiency of the grate. Knowing the value of m for the particular grate being used, equation 2.37 can then be utilized to determine the length of grate required to capture all of the gutter flow. Table 1 gives the values of m for each of the grates tested in this study.

The following conclusions were drawn regarding the various types of grates:

i) Grates A and B were the most efficient over the full range of flows.

ii) Grate C was efficient at lower flows only.

iii) Grate F was inefficient over the full range of flows.

iv) The diagonal bars used in grate E did not greatly increase the efficiency, although bars set on a forty-five degree angle were slightly more efficient than the configuration used in grate D.

2.10 J. A. Zwamborn - Storm Water Inlet Design Code, C.S.I.R. Report MEG433, Union of South Africa (1966)[44)]

The research contained in this design code was undertaken because none of the studies conducted elsewhere involved flow rates as large as those encountered in South Africa. A full scale street model and a 1:6 scale model were constructed; the only type of inlets tested were curb inlets, since the terrain and flow volumes of South Africa made the use of grate inlets undesireable.

The first step of the study was to run preliminary tests of both depressed and undepressed curb inlets on both the full size and 1:6 scale models, and then to compare the results to see if there were any scale effects which might render the data from the smaller model unusable. This preliminary work did, in fact, reveal that the 1:6 scale model could only be used to approximate the effects of the less important variables on the operation of the inlets*. All of the principal theory was consequently developed from the full scale model.

A mathematical expression to describe the performance of an undepressed curb inlet was formulated in three steps:

i) An analogy was drawn between the side opening and a free overflow weir. The discharge over a weir length dx may be expressed as:

$$dQ = 3my^{3/2}\,dx\,, \qquad (2.38)$$

where m = discharge coefficient which depends mainly on the velocity of the approaching flow.

ii) The test data for the undepressed inlet revealed that a relationship existed between the normal depth of flow in the gutter and the depth of flow at the upstream end of the inlet,

$$y = 0.53y_o^{0.83} \qquad (2.39)$$

where y = depth of flow at the upstream end of the

* These scale effects were responsible for higher values of length of opening required to capture all of the flow.

inlet, FT.

iii) It was found that the water depth decreases linearly along the length of the inlet opening; this defines the limits within which equation 2.38 may be integrated. By combining the integrated form of equation 2.38 with equation 2.39, an expression can be derived which may be used in the design of undepressed curb openings;

$$Q/L = 0.8y_o^{1.25} \qquad (2.40)$$

In the case of depressed inlets, no attempt was made to formulate precise theory of operation and only the design curves showing Q/L versus y_o for a given depth of depression have been plotted; these curves along with the graph of equation 2.40 are shown in Figure 22. An important observation made during the testing of the depressed inlet was that the capacity of the inlet was increased over that of the undepressed inlet, by the presence of the depression; this increase in capacity becomes constant when the depth of depression reaches 0.3 feet.

The design curves given in Figure 22 assume that the length of inlet is sufficient to trap the total gutter flow; when the length of inlet is less than that required to capture all of the flow, it is possible by integrating equation 2.38 to determine the amount of flow that will by-pass the inlet. This flow may be calculated using

$$Q'/Q = 1 - (1 - L'/L)^{3/2} \qquad (2.41)$$

where Q' = the actual amount of flow entering the

FIGURE 22: CURB INLET CAPACITIES

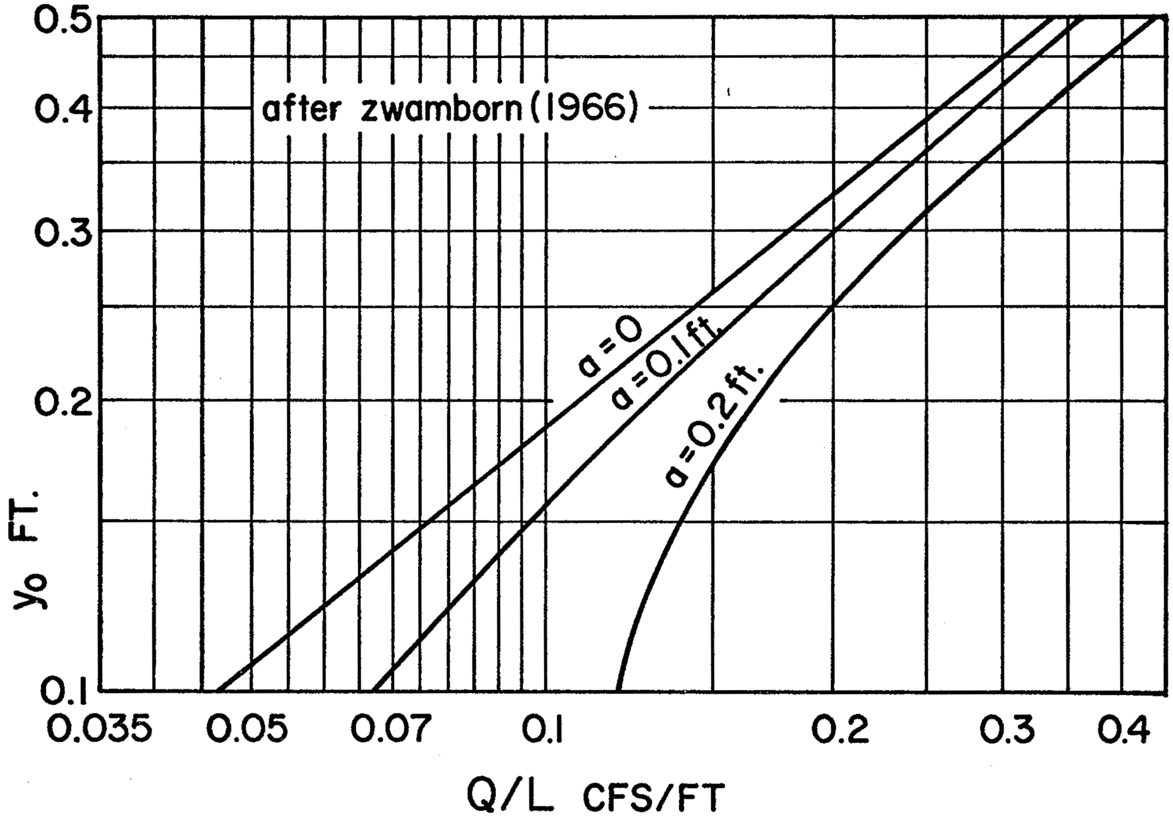
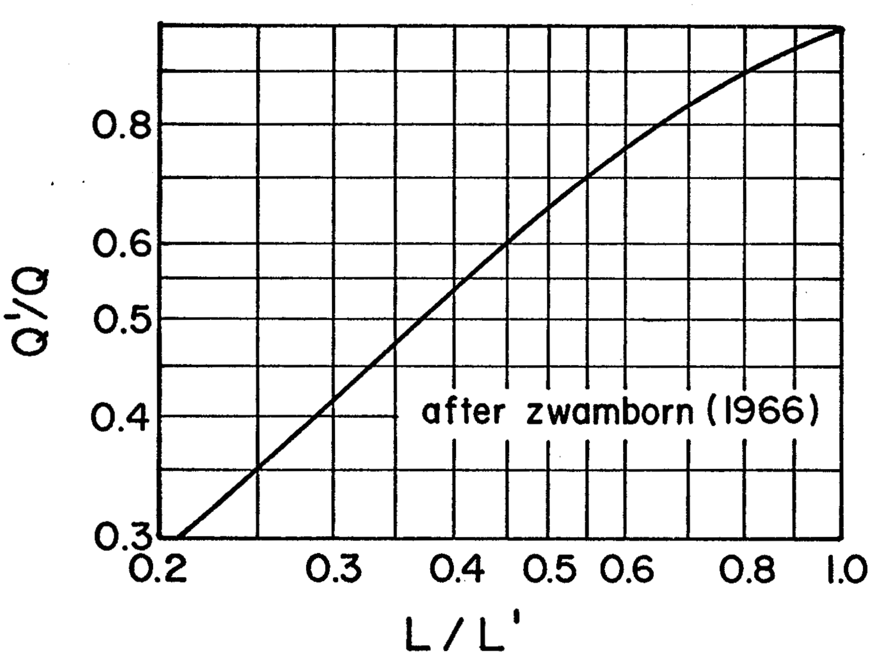


FIGURE 23: FLOW-BY PAST CURB INLET (undepressed)



inlet, CFS.,

L' = actual length of the inlet, FT., and

L = length of inlet required to capture all of the flow (calculated using equation 2.40), FT.

The above equation is shown in Figure 23.

In this study, no tests were conducted for inlets in the sump condition; however, it was concluded that since the approach velocities for inlets in sumps were so low, a simple weir formula could be applied for a curb opening to yield the following equation:

$$Q/L = 3.0y_o^{3/2} \qquad (2.42)$$

An interesting appendix to this study was an appraisal of the effects of parked automobiles on the allowable normal depth of flow in the gutter section.

2.11 Comparing the Reviewed Literature

Had each of the investigators conducting the studies reviewed in this chapter taken the same approach to their theoretical analysis, it would have been an easy task to compare their work for each type of inlet. For the most part, however, there is a diversity of approach which prevents the simple comparison of design formulae.

In view of the fact that almost all of the researchers conducted their tests on models of less than full size, the findings of Zwamborn in South Africa indicating considerable scale effects in small models casts some doubt, if even slight, on most of the design formulae. The South African findings, however, indicated at least for curb inlets on a continuous grade that the design procedures of previous investigations would yield conservative results.

Where an actual inlet design is being undertaken, the only meaningful comparison is to design the inlet using all of the methods reviewed in this chapter which apply to that particular inlet. For some types such as deflector inlets, only one method exists, while for others, there is at most four different approaches. It would be for the designer to choose which answer would be most acceptable, applying his own experience and also keeping in mind which of the methods was the most recently developed, the range of tests used to verify the method, and which approach provided the more conservative answer.

A summary of the reviewed literature appears in Table 2. This table gives the name of the researcher, what type of inlets were tested (inlets which may have been discussed in the paper, but which were not actually tested, do not appear in this table), and the conditions of flow into the inlet; that is, was it tested on a continuous grade or was the inlet located in a sump.

TABLE 2: SUMMARY OF THE LITERATURE REVIEWED

AUTHOR	YEAR	TYPES OF INLETS TESTED	TEST CONDITIONS
Tapley	'43	Depressed curb	Continuous grade
Hicks	'44	Undepressed gutter	Continuous grade
Conner	'45	Deflector, depressed curb, depressed combination	Continuous grade
Johns Hopkins	'56	Deflector	Continuous grade
		Undepressed curb, depressed curb, undepressed gutter, undepressed combination, depressed combination	Continuous grade and sump
Wasley	'61	Undepressed curb	Continuous grade
Karaki and Hanie	'61	Depressed curb	Sump
Bauer and Woo	'64	Depressed curb	Continuous grade and sump
Cassidy	'66	Undepressed gutter	Continuous grade
Zwamborn	'66	Undepressed curb, depressed curb	Continuous grade

CHAPTER III

THEORETICAL CONSIDERATIONS

3.1 INTRODUCTION

All of the investigations into the behaviour of storm water inlets may be classified in either of two ways: The grouping may be according to the objective of the studies or by the methods used to arrive at that objective. In the former case, there are two categories. The objective of the study may be particular; The only information sought is the capacities of the types of storm inlets used in the city or region where the study is being conducted. The objective of the research may be broader than this, however, and in that case the study would seek to uncover the principals of inlet operation which could generally applied to describe the performance of any inlet. The classification of research according to the methods used to arrive at the conclusions of the study can be divided into two categories. First is the purely empirical approach; Specific types of inlets are tested and the results of the tests are usually presented in graphical form. No attempt is made to analyze the data beyond the determination of the capacities of the inlets tested. An improvement of the emperical approach is the method which combines a theoretical analysis with the program of experimentation. There are two ways in which this may be done. A dimensional analysis may be conducted on the variables affecting the inlet flow, and then the dimensionless terms thus formulated are appraised using the experimental data from model tests of the type of inlet under consideration; From the data, constant and exponential terms are evaluated and the unimportant dimensionless terms deleted. Experiment and theory may be combined by making certain general observations of the flow during the testing program which allow the investigator to identify the type of flow with which he is dealing and hence to be able to apply classic fluid mechanics relations which may be numerically evaluated using the experimental data. The third category of the method classification is the purely theoretical approach. Here, the flow is analyzed starting from first principals of fluid mechanics, and the inlet performance is described mathematically. Often this analysis is followed by a program of inlet testing but only so the theory may be verified, not so that it may be altered in any way.

The most desirable approach to inlet research is to combine a rigerous mathematical analysis with thorough experimentation. For the testing to be comprehensive enough to apply to very general situations, however, an extremely wide range of inlet sizes and configurations must be utilized. In a limited program, this is not always possible. The other extreme is the testing of inlets from one specific area, with no regard for the theory underlying the inlet's performance. The present investigation undertook to find a middle ground between these two extremes.

Since the study was oriented towards the problems of inlet design in the Winnipeg area, it was decided to test only the standard appurtinances used on these inlets in the city. Also the inlets would only be tested in the sump condition as the local terrain dictates that most inlets will be located in a pavement sag. The flow conditions were varied during the testing so that it would be possible to extend the findings of these tests to other sump inlet sizes and configurations.

Thus, having defined the perifery of the study , it was necessary to decide on an approach to be taken in developing a theoretical basis for the flow into various types of inlets to be tested in the sump condition.

The literature review of CHAPTER II indicated that for inlets in sumps, previous investigators have employed the same approach; Tests were run and then the classic fluid mechanics relations were applied to the data to arrive at an inlet design formula. This is a reasonable procedure and perhaps the only workable one in view of the fact that the flow control for inlets in sumps is not constant over the full range of gutter flows. It was thus decided to use this approach for the theoretical development of the present study. In virtually any hydraulics problem, however, the thecnique of dimensional analysis has so much to offer that it was not thought wise to abandon it in connection with sump inlets without at least taking a cursory look at what results could be obtained by using this method.[41)]

in using the observation-oriented method of developing the theory outlined above, it becomes necessary to mention at least some of the general observations made during the course of the experimental program; Such observations will in a sense be out of place here, since all of the observations are set down in detail in CHAPTER V**, but remarks will be very general and brief in CHAPTER III and designed only to introduce the theory.

3.2 DIMENSIONAL ANALYSIS

In order to treat an extremely complex flow situation it is necessary to dimensionally organize the several variables into the smallest number of significant parametric groups. Since any mathematical equation of motion to be physically correct, must be dimensionally homogeneous, then the variables in any given flow situation must be so related such that the flow situation is dimensionally homogeneous.

The chief tool of dimensional analysis by which the variables are organized is the Buckinghan Pi the rem*, which

** Page 110.

states: "If the dependent variable A_1 depends on the independent variables A_2, A_3, ... A_n, the functional relationship may be written as

$$f(A_1, A_2, A_3, \ldots A_n) = 0. \qquad (3.1)$$

The Pi theorem states that if all of these n variables can be described by m dimensional units, then they may be grouped into n - m dimensionless terms."

$$(\pi_1, \pi_2, \pi_3, \ldots \pi_n) = 0. \qquad (3.2)$$

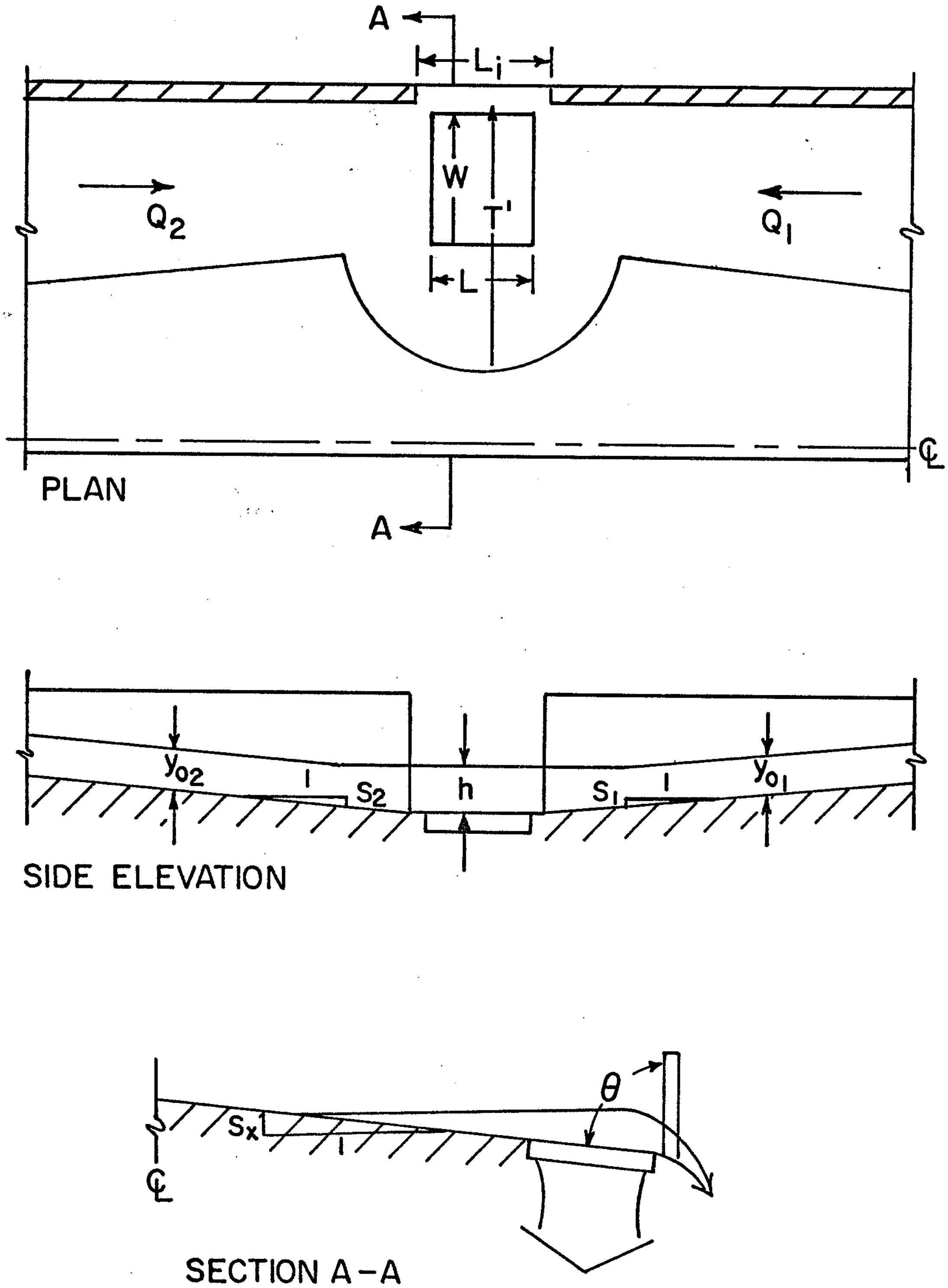
In each term there will be m + 1 variables, only one of which needs to be changed from term to term. If the m repeating variables are given unknown exponents in each pi term, the fact that there are m dimensions with which each term may be described provides a means by which these unknowns may be evaluated.

It should be noted that the dimensionless terms may be made to consist of different combinations of variables. It may be desirable in certain hydraulic situations to have a specific term (such as the Froude number) to appear in the analysis, while some other terms may be without significance. Thus dimensional analysis is an art requiring some experience in hydraulic studies and the judgement obtained therefrom.

For any inlet located in a sump there is a common set of variables which, along with the variables of the particular inlet type, will determine the flow into the inlet. Figure 24 shows one-half of a roadway with a

* Model Experiments and the Form of Empiricle Equations, Buckingham, E., A.S.C.E. Trans., Vol. 37, 1915.

FIGURE 24 FLOW VARIABLES



combination inlet in the gutter section; the variables affecting the inlet performance are shown. These common variables are:

Q_i , the dependent variable consisting of the two incoming gutter flows Q_1 and Q_2,

y_1 and y_2 , the normal gutter flow depths approaching the inlet,

V_1 and V_2 , the average gutter flow velocities approaching the inlet,

θ_0, the cross slope of the pavement, and

g, the gravity acceleration.

Now for each type of inlet there will be the following additional variables:

I) Undepressed curb inlet; L_i, the length of the curb opening.

II) Depressed curb inlet; L_i, the length of the curb opening, and θ, the slope of the local depression.

III) Gutter inlet; L , the length of the gutter grate, and W , the width of the gutter grate.

IV) Combination inlet; L_i , L, and W.

The above variables were then utillized in a standard dimensional analysis to obtain a set of dimensionless parameters for each inlet type. Since the variables were all in terms of either length or time, or both, it was only possible to obtain two fewer dimensionless terms than there were variables for any given flow situation. The dimensionless parameters for each inlet type expressed in a functional relationship are:

I) Undepressed curb inlet;

$$Q_i = \phi(y_1^3/V_1^2 g,\ y_1^2/V_1 V_2,\ y_1/L_i,\ y_1/y_2, \theta_o) \quad (3.3)$$

II) Depressed curb inlets;

$$Q_i = \phi(y_1^3/V_1^2 g,\ y_1^2/V_1 V_2,\ y_1/L_i,\ y_1/y_2, \theta_o) \quad (3.4)$$

III) Gutter inlet;

$$Q_i = \phi(y_1^3/V_1^2 g,\ y_1^2/V_1 V_2, y_1/L,\ y_1/\overline{W},\ y_1/y_2, \theta_o) \quad (3.5)$$

IV) Combination inlet;

$$Q_i = \phi(y_1^3/V_1^2 g,\ y_1^2/V_1 V_2,\ y_1/L,\ y_1/L_i,\ y_1/W,\ y_1/y_2, \theta_o) \quad (3.6)$$

3.3 GENERAL OBSERVATIONS AS TO THE NATURE OF THE FLOW INTO EACH OF THE INLETS AS NOTED DURING THE EXPERIMENTAL PROGRAM

As was noted earlier in this chapter, it is necessary to present a very general outline of the observations made during the testing program, in order to justify the theoretical presentation of certain classical fluid mechanics relations. This will be done in turn for each of the four types of inlets tested.

I) Undepressed Curb Inlet: From the smallest recorded flows up to the point at which the water entering the inlet was just below the top of the grate opening, (that is the point at which part of the opening was always visible), the inlet simply resembled a free overflow weir. A free water surface was visible, unimpeded by the top of the inlet appurtenance opening. As the flow was increased beyond this point however, the top of the inlet grate opening came into play and for a small range of flows , the operation fluctuated between that of a weir and an orifice; in the latter instance the opening became completely filled with water.A furthar increase in the flow saw the opening completely submerged and hence it acted as a rectangular orifice. It should be noted , however, that true orifice operation could only continue up to the point at which the actual grating (as opposed to the grating opening), was submerged; then the water continued to flow through the opening as an orifice but also over a broad crested weir.

II) Depressed Curb Inlet: The same observations were made for the depressed inlet as for the undepressed case, the only difference being that the flow values at which these various conditions occurred were different.

III) Gutter Inlet: At low flow values the gutter grate was not submerged and the water fell freely between the bars. In this situation the outer periphery of the grate merely acted as the crest of a circular weir. At some point, the flow becomes great enough to submerge the opening , and from then on the inlet operates as an orifice with the unique shape formed by the openings between the bars.

IV) Combination Inlet: Since in this configuration, the curb and gutter inlets are both operating simultaneously, the situation is more difficult to categorize than the other inlet types. At this stage, it will be sufficient to note that the same weir and orifice type of flow was noted as for the gutter and curb inlets, but that the points defining the operating ranges of these phenomina were rather more complex than in the other three cases. A more detailed appraisal is given in later Chapters.

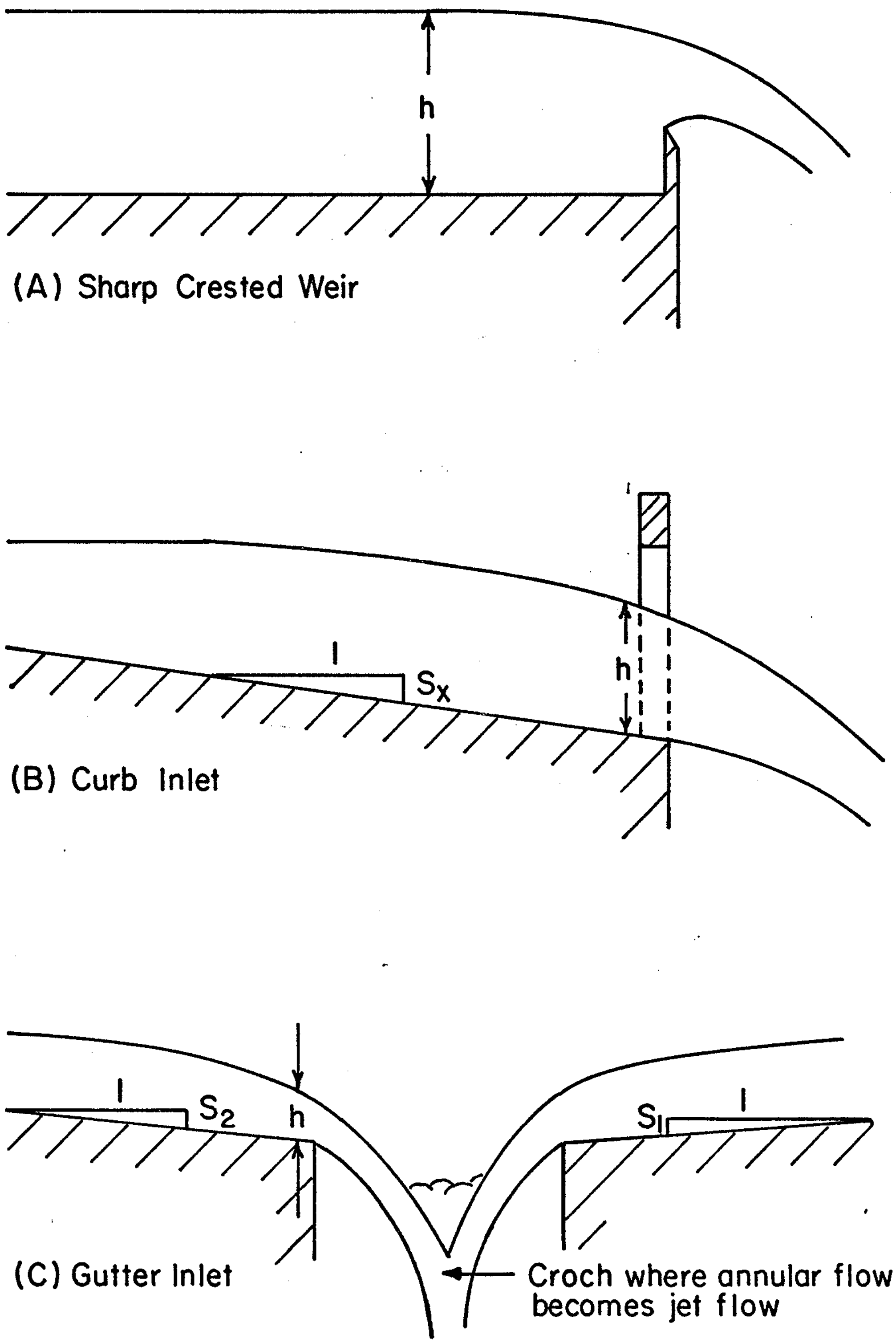
3.4 WEIR FLOW THEORY

Scrutiny of the observations of the previous section reveals that two types of weir should be considered. The free overflow through the side opening of the curb inlet can best be approximated by a simple sharp crested weir, although it should be noted that, strictly speaking, the free fall of water on all sides of the gutter grate can best be approximated by a circular sharp crested overflow of the type used as a spillway entrance on some small dams*.

I) Sharp Crested Weir: The flow profile over a sharp crested weir is shown in Figure 25(A); this is contrasted with a cross-section of the flow through a curb opening inlet (B), and a gutter inlet at low flows (C). It can readily be seen that the three situations are not identical. The most significant difference is that the slope of the , which means that the hydraulic grade-line (the water surface) is depressed or drawn down over a greater distance from the overfall for the side opening and gutter inlets than for the weir. Many years of experimentation** have

* Design of Small Dams, U.S.Dept. of the Interiour.
** Handbook of Hydraulics (5th ed.), H.W.King, McGraw-Hill.

FIGURE 25. THE SHARP CRESTED WEIR COMPARED TO INLET OPERATION



indicated, however, that a general weir equation may be derived for sharp crested weirs varying in height from zero upwards. The equation is of the form,

$$Q_i = CLH^{1.5} \quad , \qquad (3.7)$$

Where Q_i = the discharge over the weir, CFS.,

C = the discharge coefficient,

L = the effective length of the weir crest, FT.,and

H = the height of water over the weir crest, FT.

The discharge coefficient C is really a measure of the effect of the incoming velocities as determined by the height of the weir; hence the differences between the three flow situations as shown in Figure 25 are taken care of by this constant term, and equation 3.4 may be applied to either the practical curb opening situation, or to the low flow gutter inlet condition.

Since the curb opening is not continuous it is necessary to apply an empirical formula for effective weir length*;

$$L = L' - 0.1NH \quad , \qquad (3.8)$$

Where L' = the measured length of the weir crest, FT., and N = the number of contractions in the weir crest.

II) <u>Circular Sharp Crested Weir</u>: Although this situation is obviously different from the weir considered above , equation 3.7 still describes the behaviour of a circular or odd shaped weir; the crest length is simply measured along whatever is the irregular shape of the crest.

*Discussion of Precise Weir Measurements, Rehback,T., A.S.C.E. Trans., Vol. 23, 1929.

Of course, each particular shape will have its own discharge coefficient.

It should also be noted that the discharge coefficient reflects the defenitions one has chosen for H and L. Thus, the fact that for the curb opening the H will be measured at the face of the inlet, and that L is measured around the square periphery of the gutter grate inlet, will be accounted for in the C value appearing in the respective equations.

3.5 Orifice Flow Theory

There are two types of orifice situations which apply to the present study. The first is an orifice set in a vertical plane and the second is an orifice in the horizontal plane. These correspond to the submerged curb and gutter inlets respectively, as shown in Figure 26.

For any orifice which discharges into the atmosphere the discharge can be determined by the following empirical expression;

$$Q_i = CA\sqrt{2gh} \quad , \qquad (3.9)$$

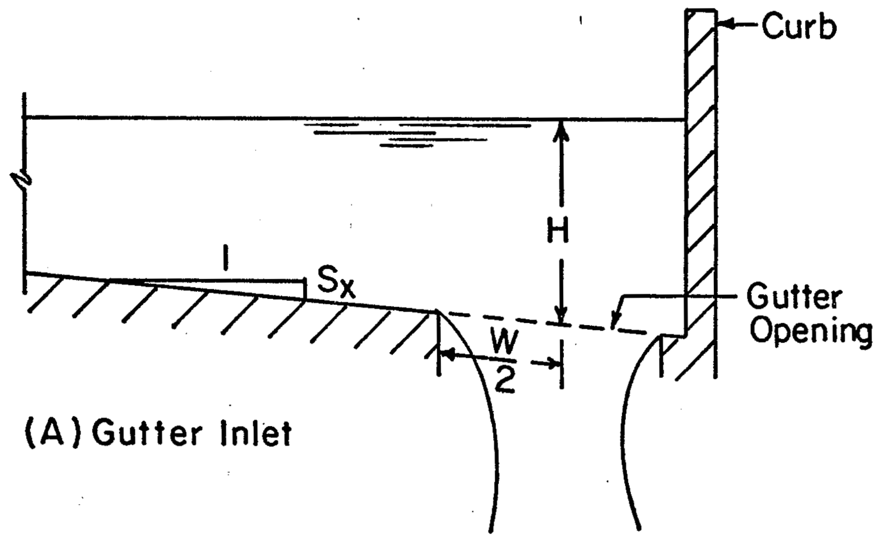
where Q_i = the flow through the orifice, CFS.,

C = the discharge coefficient,

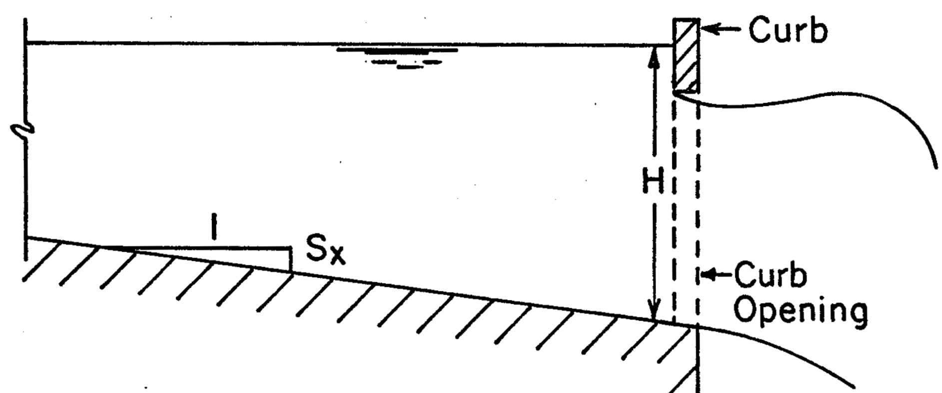
A = area of the clear opening of the orifice, $FT.^2$, and

h = the height of water over the orifice (see Figure 26). FT.

FIGURE 26. INLETS OPERATING AS AN ORIFICE



(A) Gutter Inlet



(B) Curb Inlet

The discharge coefficient accounts for the shape of the inlet (which in this case is irregular due to the grating over the opening), and the variance in the flow velocities in the vicinity of the inlet. The value of C will be determined from the test data for each particular situation in which orifice flow occurs.

3.6 The General Flow Equation

A close inspection of equations 3.7 and 3.9 reveals that they are really of the same form. For weir flow, the length of the weir crest L may be kept constant and as a result may be made a part of the equation coefficient C. Also the exponent, which was given as 1.50 for a straight weir crest perpendicular to the flow, may assume different values for varied crest configurations; hence, it could be expressed as a variable n.

In the case of orifice flow, the area of the opening A when it is kept constant, and the value of $\sqrt{2g}$, may both be included as a part of the equation coefficient C. Where the shape of the orifice is not circular and sharp edged, the flow through the opening may not vary as $h^{1/2}$. Instead, the flow could be expressed as a function of h^{n}, where n is some as yet indeterminate exponent.

For inlets of constant dimensions, it is thus possible to formulate a general flow expression which will be valid whenever the flow through the inlet is either weir or orifice controlled. This equation is:

$$Q_i = Ch^n . \qquad (3.10)$$

The above formula is an exponential function and as such, when Q_i is plotted on logarithmic graph paper as a function of h, the result will be a straight line for constant C and n values. When the values of C and n change, the slope of the straight line will be altered.

The values of C and n for any section of the logarithmic plot with constant slope may be determined in the following manner:

Exponential function 3.10, when plotted on logarithmic paper can be rewritten as

$$\log Q_i = n \log h + \log C . \qquad (3.11)$$

For any section of the plot with a constant slope, the value of the coefficient may be evaluated by first determining the value of Q_i at the point where $h = 1.00$, since the logarithim of 1.00 is 0.00, where $h = 1.00$, $Q_i = C$. Similarly, if the value of h is found where $Q_i = 1.00$, then the exponent n may be evaluated from the expression $n = -\log C/\log h$.

It should be noted that, although a particular curve may not include the region in which $Q_i = 1.00$, or $h = 1.00$, the curve may be extended to include these numbers without detracting from the accuracy of the values obtained for the coefficient and exponent.

CHAPTER IV

EXPERIMENTAL APPARATUS AND PROCEDURE

4.1 INTRODUCTION

Since the central purpose of this study was, as has been discussed in the opening chapter , to test the storm water inlets of the City of Winnipeg, an experimental program had to be formulated to meet this end. This really consisted of a series of steps, with each step involving two decisions. First, it had to be decided what information was required from the tests to fulfill the goals of the study, and secondly, what was the best method of obtaining that information taking into account expediency, accuracy, and physical limitations. A brief outline of the factors involved in this decision-making process will be given here, in Table 3, with the actual choices and the reasoning behind them following in the remainder of this chapter.

4.2 MODEL ROADWAY

For reasons that have been dealt with earlier in this paper*, the types of inlets to be tested and the approach

* Chapter I, pps. 6 - 8; Chapter II, pg. 11.

TABLE 3: FORMULATING THE EXPERIMENTAL PROGRAM

STEP	DECISION	FACTORS
Choosing the type of model	Model scale	Size of the laboratory
		Effects of scale on the results
		Size of the inlet appurtinences to be tested
	Model size	Boundary effects caused by making the model too small
		Length of gutter required to fully develope the flow
	Model layout	The layout of a modern, standard Winnipeg roadway
	Model adjustment	What quantities would it be desirable to vary, keeping in mind that a general expression is sought
		What range of values are used for the geometry of the road and inlet in actual practice
	Model construction	Loading of the model while its operating
		Ease of operation
		Simplicity of erecting
Choosing the conditions of flow	Where to introduce the flow into the model	The actual conditions of storm water flow

TABLE 3 ..... Continued

STEP	DECISION	FACTORS
Choosing the conditions of flow	Where to introduce the flow into the model	Physical layout of the lab
	How to control the flow	Maximum and minimum required flows
		Size of the flow increments required in the testing
		Ease of operation
		Permissable turbulence ie. are baffles required?
Taking of measurements	What measurements to take	The physical quantities as indicated by the theory of Ch. 3 to: (a) Determine the capacities of the inlets (b) Formulate a general expression of inlet behaviour
	Location of measurements	Fluctuations which may render the reading inaccurate
		Ease of taking measurements
		What quantities have been decided upon as necessary
	Accuracy of the measurements	Order of accuracy desirable
		Accuracy with which instruments may be read

flow conditions to be simulated, were to be limited to the reproduction of the storm water inlet conditions encountered in the Winnipeg area. This factor eliminated the need to duplicate many of the conditions which have been modelled elsewhere and have been summarized in Chapter II of this work.

Actual full-scale castings of the storm water inlet appurtenances used by the City of Winnipeg Engineering Department were made available for these tests; hence, rather than scale them down to smaller dimensions, it was decided to test the full scale inlet. This in turn meant that a full-scale model of the roadway which would determine the approach flow conditions into the inlet would have to be constructed.

The impracticability of constructing the model with a width equal to a full curb to curb street width was apparent. The impoundment of water on the pavement to a depth greater than the road crown is seldom tolerated in actual practice and also the flow conditions as far away from the inlet as the centreline of the roadway are of little or no importance in the operation of the inlet. Therefore, the model width was restricted to eight feet with a vertical wall forming the boundary on the side corresponding to the street centreline. Figure 27 details the model.

With regards to the length of the channel, the main

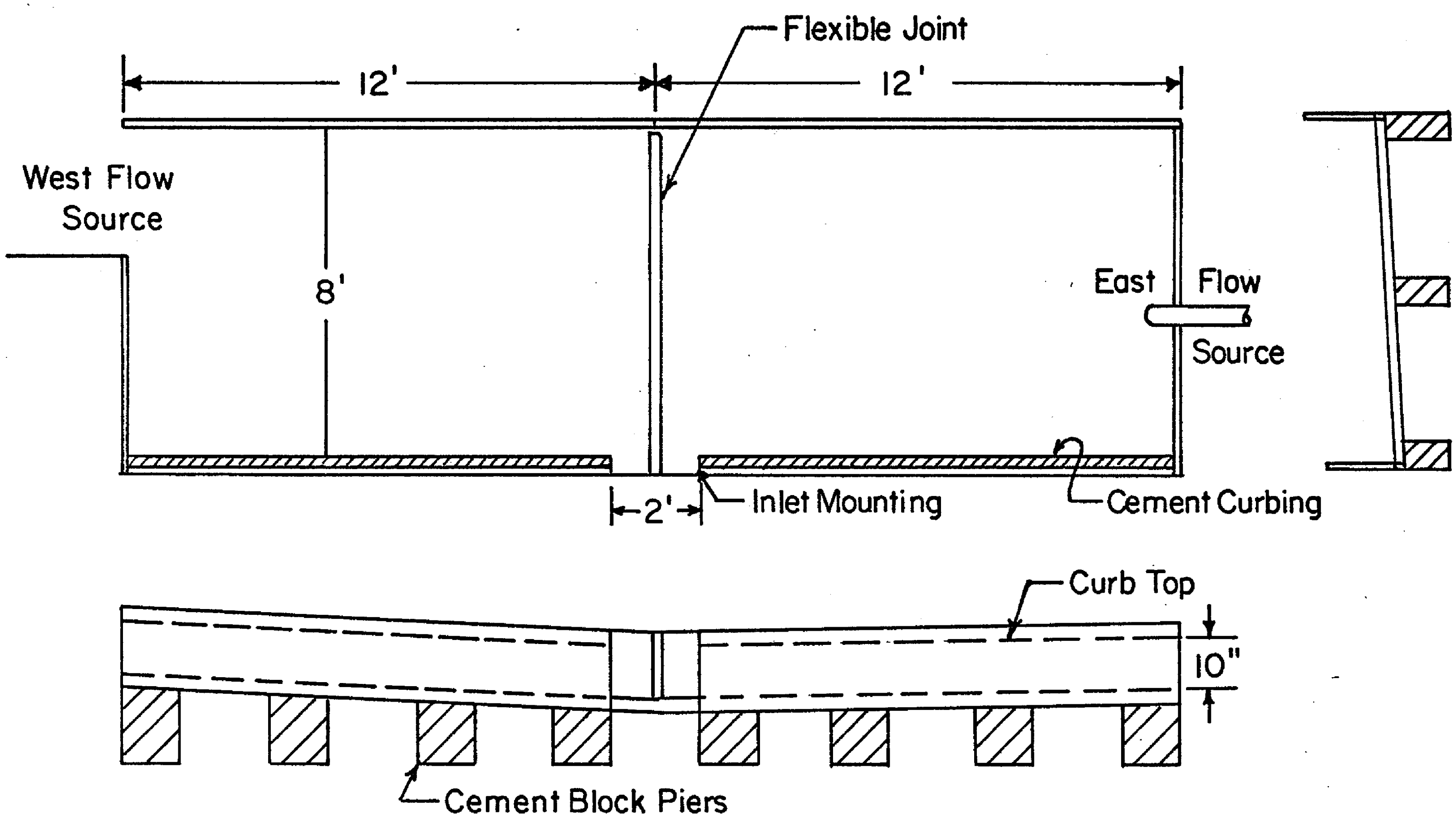


FIGURE 27. MODEL DIMENSIONS

consideration was that the model be long enough to allow full development of the flow as it approached the tested inlet. Twelve feet was chosen as an adequate distance for this purpose and therefore each section (Figure 27) was set at this length.

Since in the Winnipeg area almost no flowby type inlets are in use, it was thought necessary to reproduce only the so-called sump condition in these tests. Hence, each section of the channel must slope towards the inlet and these slopes must be fully adjustable. Also, the model must have a constant slope towards the gutter section corresponding to a road crown slope, which could be altered to simulate the various crown slope values encountered in actual practice. These requirements were met by the use of cement block piers of varying heights as shown in Photograph 1, upon which the channel is rested.

It was decided that only one surface material would be used for the channel throughout the tests. Since most thoroughfares in the City of Winnipeg are surfaced with concrete, a thin layer of this material was placed on the model surface. Light guage reinforcing was used to bond the concrete to the roadway and the surface over which the water would flow was trowel finished. The roughness value of this surface was not determined by tests, but rather the value of "n" was selected from a handbook. The edge of the flume corresponding to the curb of an actual street was also faced with concrete.

Although the structural features of the model, strength, framing, and support have no direct bearing on the final results of these tests, it was nonetheless though prudent to include a structural plan which may prove of some use to future investigators. This plan is found in Appendix A.

The roadway was constructed entirely of wood following a design performed by the author to meet the expected loading conditions and to minimize deflections*. As is shown in Figure 27, the model was built in two half sections, each section being a duplicate of an actual roadway from curb to crown. These halves were connected with a waterproof, flexable joint at the center so that each could be sloped towards the center and produce the sump condition sought, and also so that these slopes could easily be adjusted. Both sections were identical.

The first step in the construction was to build a rectangular framework consisting of three, four inch by four inch, longitudinal beams, and two inch by four inch joists at two foot spacings, both of white spruce. Overlayed on this framework were four foot by eight foot sheets of half-inch plywood which was the basis for the roadway. Eighteen inch wide lengths of plywood were then fastened to the outside longitudinal beams, perpendicular to the flooring; this was the flume siding. The same procedure was

* Timber Construction Manual, Can. Inst. of Timber Const.

used to apply walls to the end of each section. Then the two sections were mounted on cement block piers (Photograph 1), the open ends butted together and was sealed with a waterproof joint. A fine guage chicken wire mesh was then tacked to the flooring and one sidewall (which would represent the roadway curb). On the floor a one-half inch layer of concrete was placed using screeds, and then trowel finished, while for the siding, forms were constructed and utilized to place a one inch thick curb, wet trowel finished after the removal of the forms. The entire structure was sealed water-tight except for an opening on one side to accomodate the inlets.

4.3 INLET APPURTENANCES

As has been previously stated, the inlet appurtenances used in these tests were actual castings of inlets being installed in the Winnipeg area at the present time. They have been in use for some while here and there is no indication of a change to other types in the near future. All of the devices tested were of cast iron.

4.3.1 Curb Opening Inlet Grate

Since this work was to be practically oriented to situations encountered locally, that is in metropolitan Winnipeg, it seemed unnecessary to conduct tests on ungrated curb openings as few have been used in the city. Following the above reasoning, since there is only one standard curb opening grate in use here, only that grate was tested. The casting is detailed in Figure 28(A). The measured length of the grate opening is equal to fourteen inches, and the area of this opening is 0.855 square feet.

The curb grating was used in three different situations:

i) Curb grate with no local depression below the normal crossfall of the roadway.

ii) Curb grate with local depression (section 4.5) below the normal crossfall of the pavement.

iii) Curb grate in combination with a gutter grate of the type described in section 4.3.2.

4.3.2 Gutter Grate

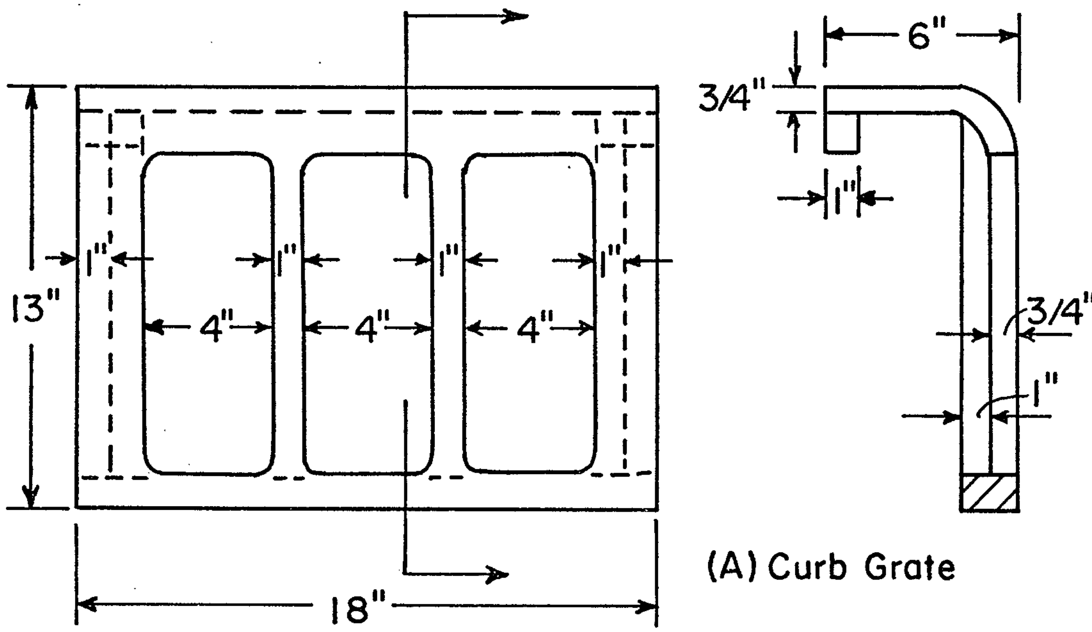
The standard gutter grate used in the City of Winnipeg is shown in Figure 28(B). Using the dimensions of this drawing, it is quite a simple matter to calculate the basic grate properties. The equivalent length L of the grate is 0.875 feet, while its width is 0.843 feet, and the total area of opening between the bars is 0.82 square feet.

This grating was used in two different situations:

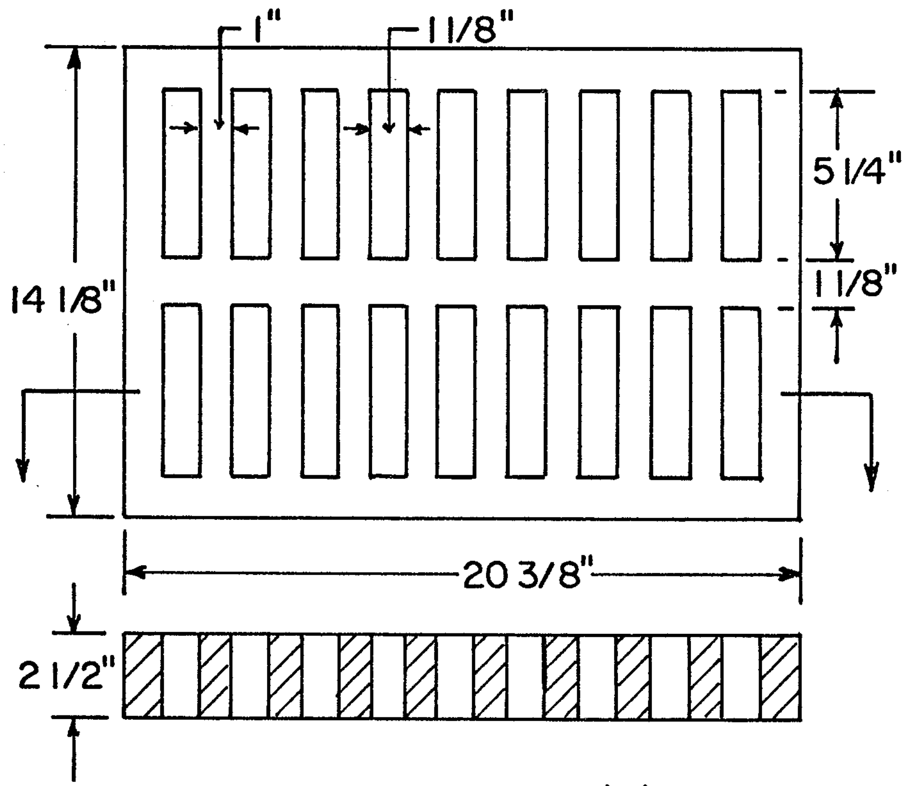
i) Gutter grate set flush to the pavement surface in the gutter section immediately adjacent to the street curbing.

ii) Gutter grate set flush to the pavement surface in

FIGURE 28. CITY OF WPG. STANDARD INLET GRATES



(A) Curb Grate



(B) Gutter Grate

the gutter section and adjacent to a curb inlet set in the curb.

The practice of setting grate inlets in a local depression in the gutter section is not generally followed in the City of Winnipeg.

4.4 INLETS

The actual inlet configurations tested are four in number. They are illustrated in Figure 29*.

i) Undepressed Curb Inlet: The fact that the curb height is only six inches above the gutter surface means that the full opening (eleven inches high) will not be utilized. Thus, the total area open to the flow is reduced to 0.354 square feet.

ii) Depressed Curb Inlet: The gutter is depressed two inches below the normal pavement surface in the vicinity of the inlet (section 4.5). This increases the available area of opening to 0.520 square feet.

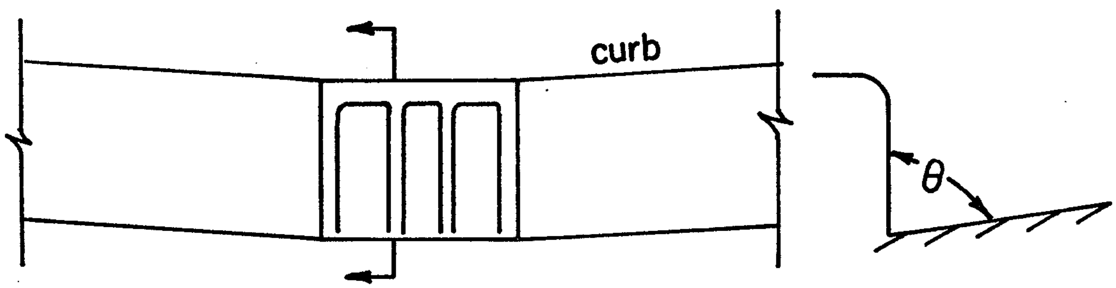
iii) Gutter Inlet: This inlet employs the standard gutter grate as described in section 4.3.2.

iv) Combination Inlet: This configuration consists simply of an undepressed curb inlet, and a gutter inlet, located adjacent to one another, the length of both grates being about equal.

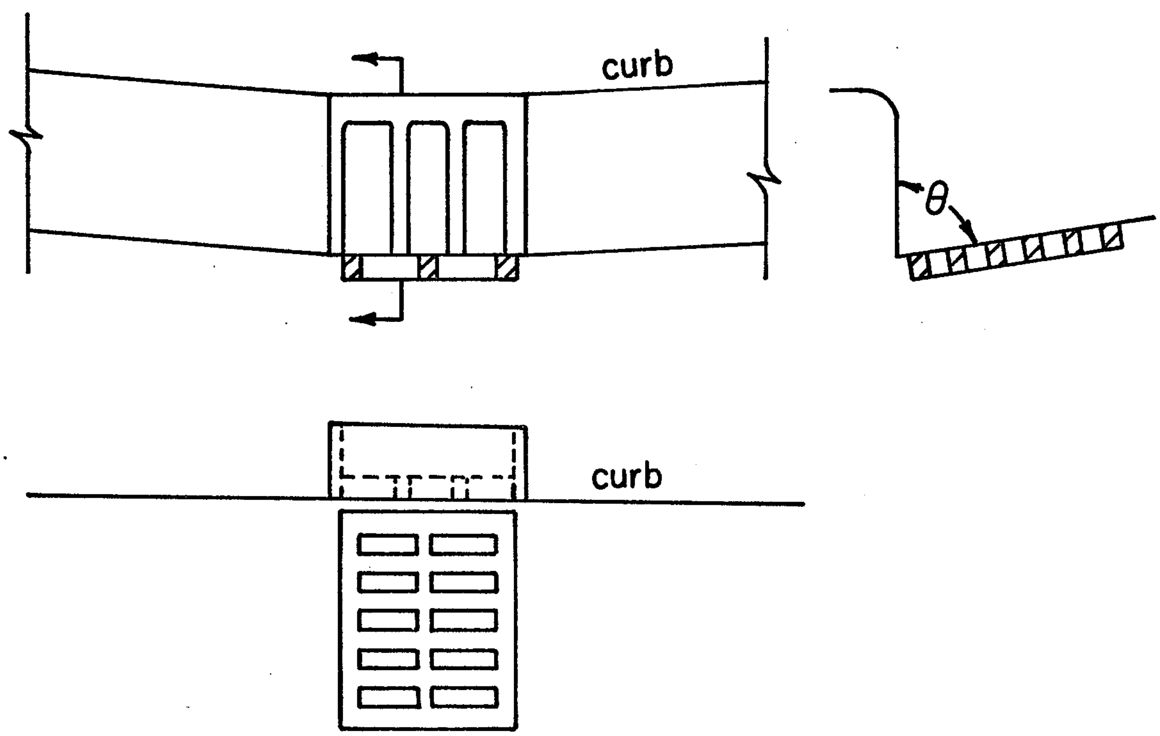
4.5 STANDARD DEPRESSION

* The gutter grate inlet is not shown by itself, but in combination

FIGURE 29. STANDARD INLET CONFIGURATIONS



(A) Undepressed Curb Inlet



(B) Combination Inlet

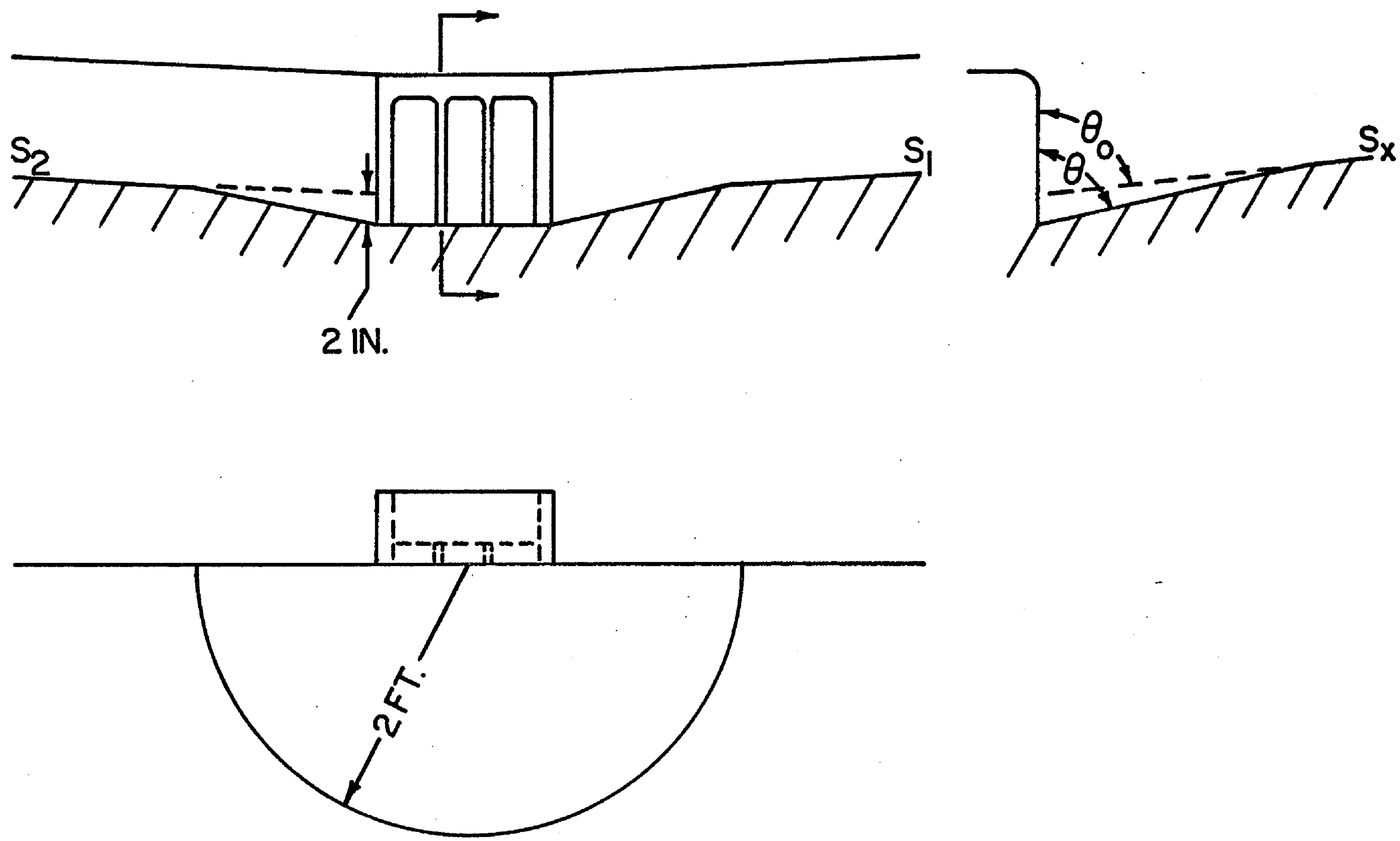


FIGURE 29(c). DEPRESSED CURB INLET

Previous research* has indicated that by depressing the gutter section below the normal pavement crossfall in the vicinity of a curb inlet, the capacity of the inlet is increased over the simple undepressed case. For this reason, the City of Winnipeg has adopted a standard depression to be used on many of their installations. This depression was used in the present study. It consists of an area semi-circular in plan, with a radius of two feet centered at the center of the curb inlet. From the circumference of this circle inwards, the pavement slope is such that the surface of the gutter is depressed two inches below the normal surface established by the pavement crossfall. Figure 29(B) shows this depression.

In building the model, a semi-circular area in the flume flooring was constructed two inches lower than the remainder of the floor (see Appendix A). This was filled with concrete for tests of the undepressed inlet, but was sloped towards the inlet at one inch per foot using concrete for the depressed inlet tests.

4.6 ESTABLISHMENT OF CROWN SLOPE

The theoretical analysis of Chapter III indicated that one of the variables influencing the inlet performance tests, which had to be simulated in the model roadway, was the pavement crown slope or the slope of the road surface from the centerline of the roadway to the point at which the

with a curb inlet.

* Chapter II, pps. 40 - 44.

pavement meets the curb. It was decided that this slope would be continuous; that is, that there be no local increase in the slope immediately adjacent to the curb. This was, in fact, consistant with paving practice in the Winnipeg area.

As is shown in Photograph 1, each of the two flume sections was placed on a series of concrete piers, the elevation at the centerline edge being greater than that at the gutter edge, imparting the desired slope to each section. Crown slope adjustment could be affected by raising the centerline edge off the piers using hydraulic jacks, placing pre-measured plates on these piers and then easing the flume section back on its supports, hence increasing the crown slope. All such slopes were checked using a Theodolite leveling instrument and surveyor's rod.

4.7 ESTABLISHMENT OF GUTTER GRADES

The dimensional analysis of section 3.2 indicated that the approach slope of the gutters was an important factor. In order to relate the slope of the channel bottom parallel to the curb and towards the inlet, to the inlet behaviour, it was necessary to establish these values with some degree of accuracy. After the crown slope had been set at the initial value, the rear corners of each section of the model were raised an equal amount by means of hydraulic jacks. Shims were used between the piers and the footings in order to equally distribute the load. In this way, a gutter slope was imparted to each channel section by means of these shims without disturbing the crown slope. These grades were also checked using a Theodolite level and surveyor's rod. In all tests, both gutter slopes were kept equal.

4.8 FLOW MEASUREMENT

The use of a model roadway with two adjustable approach grades sloping towards the location of the tested inlet, necessitated the construction of two accurately calibrated sources of flow. These sources were to meet the following requirements:

i) accuracy of measurement to within five percent.

ii) design accuracy to be maintained to a lower limit of 0.10 c.f.s. and an upper limit of 3.00 c.f.s.

iii) The flow sources must be readily adjustable.

iv) instrumentation that could be read quickly and easily and which would allow the two flow sources to be equalized with a minimum of effort.

Figure 30 shows the location of the sources and labels them East Flow and West Flow respectively. The physical constraints of the laboratory mitigated against the use of identical flow measurement techniques.

A triangular or V-notch weir with the central angle equal to ninety degrees was used to gauge the West Flow. An adjustable point gauge with electronic level finder provided

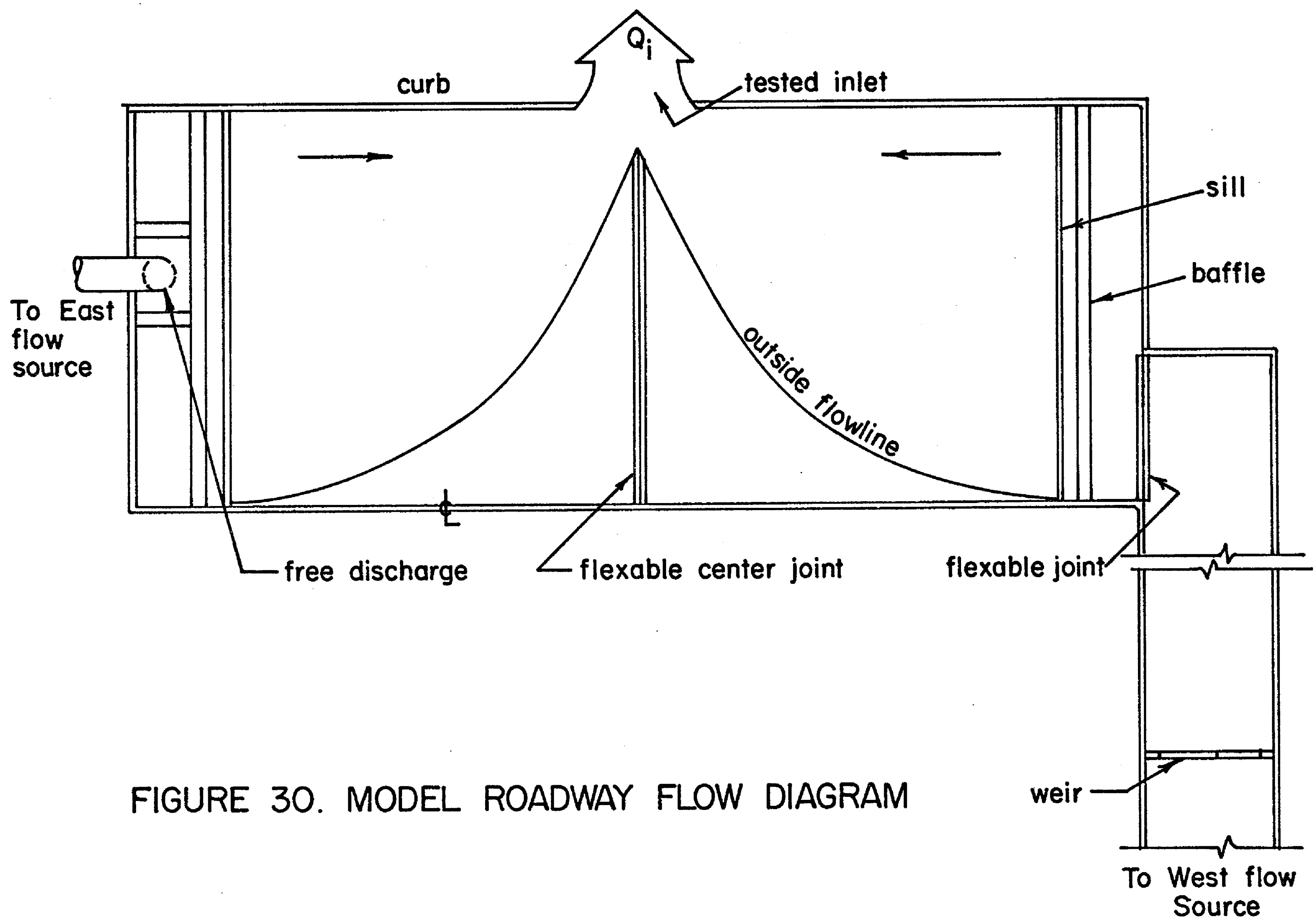


FIGURE 30. MODEL ROADWAY FLOW DIAGRAM

measurements of the head over the weir to an accuracy of 0.005 feet. This arrangement is illustrated in Photograph 2. The entire device was calibrated using the laboratory's float gauged volumetric tanks and a stop watch.

For the East Flow source dimensional constraints dictated the use of an orifice meter freely discharging into the atmosphere. Pressures upstream of the orifice could be read by means of a gauge threaded into a piezometer opening in the approach pipe. The gauge used was a Bourdon type with a scale range of zero to thirty p.s.i.g. The Bourdon mechanism itself had an accuracy of 2.00 percent. A calibrated V-notch weir box using an electronic point gauge to measure the head over the weir was the apparatus used to calibrate the orifice meter.

4.9 APPROACH FLOW CONDITIONS

The only way that the field conditions which occur during an actual rainstorm could be simulated in a laboratory would be to construct a scale model of the entire drainage area contributing to an inlet and then somehow to reproduce a rainfall over this entire region. In order to represent what is actually happening at the inlet, however, it is not necessary (if indeed it were possible) to know what is happening over the entire catchment area, but only how much total flow that area contributes. This is because once the flow reaches the inlet, it has (except for the

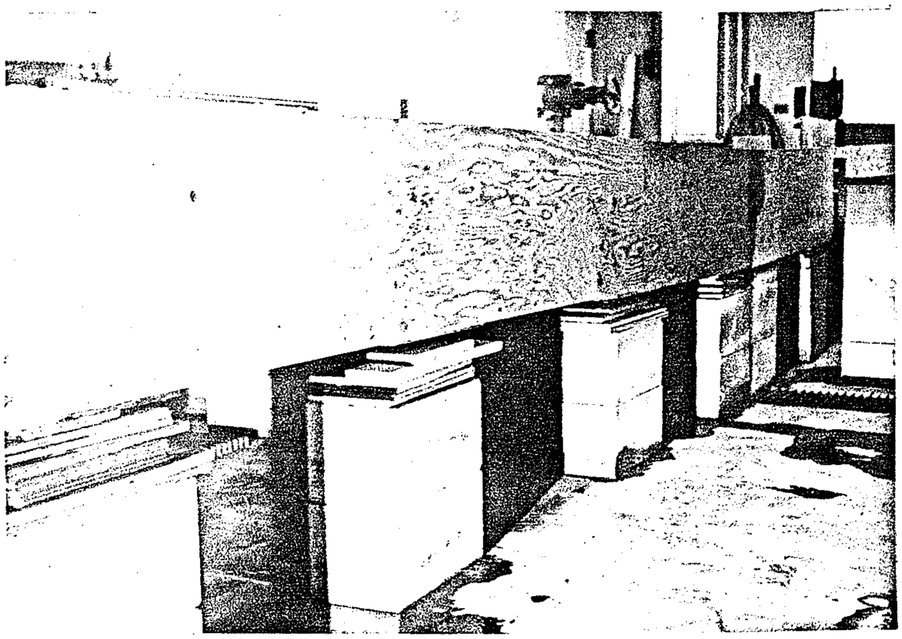


PHOTO 1: FLUME SUPPORT SYSTEM

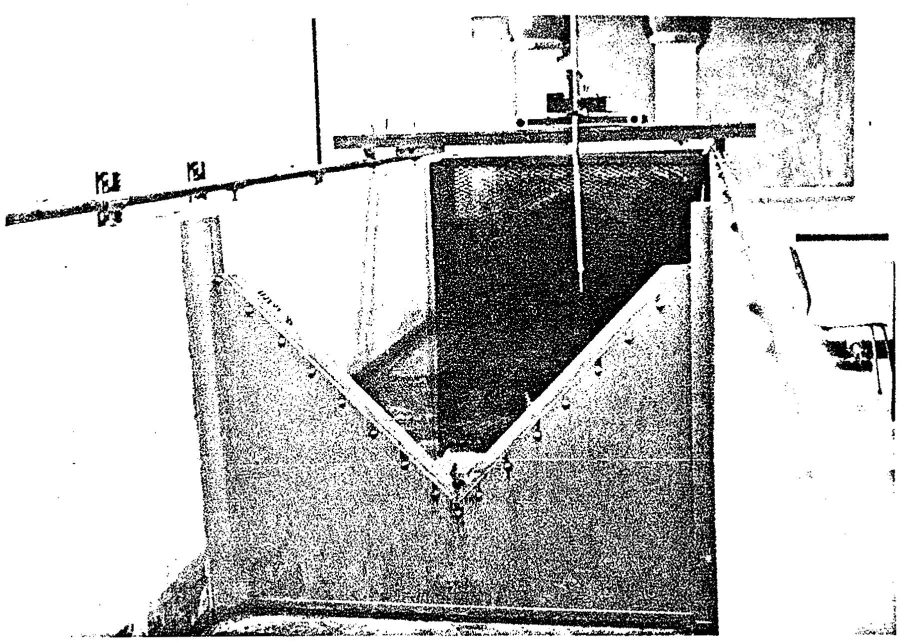


PHOTO 2: WEST SOURCE MEASURING DEVICE

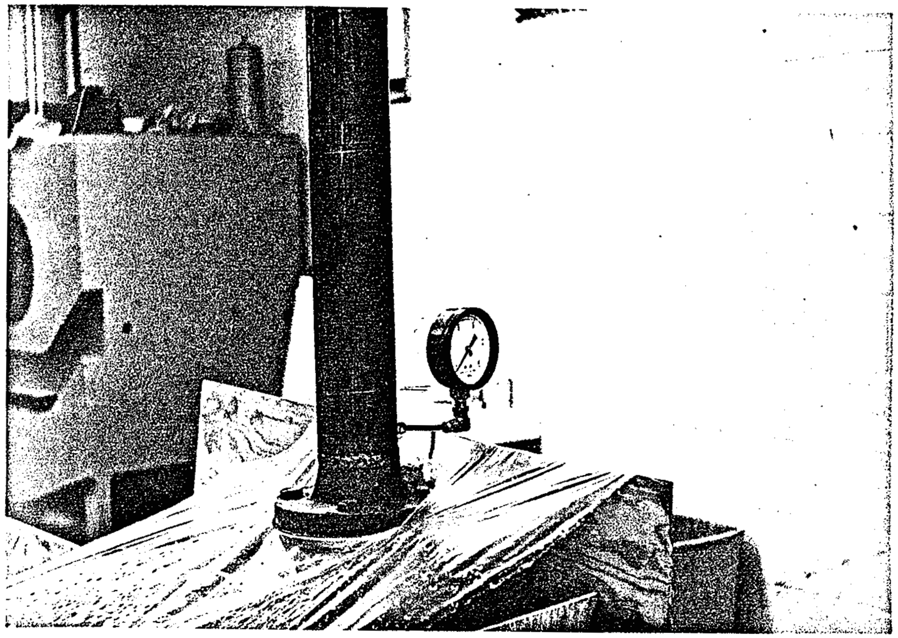


PHOTO 3: EAST SOURCE MEASURING DEVICE

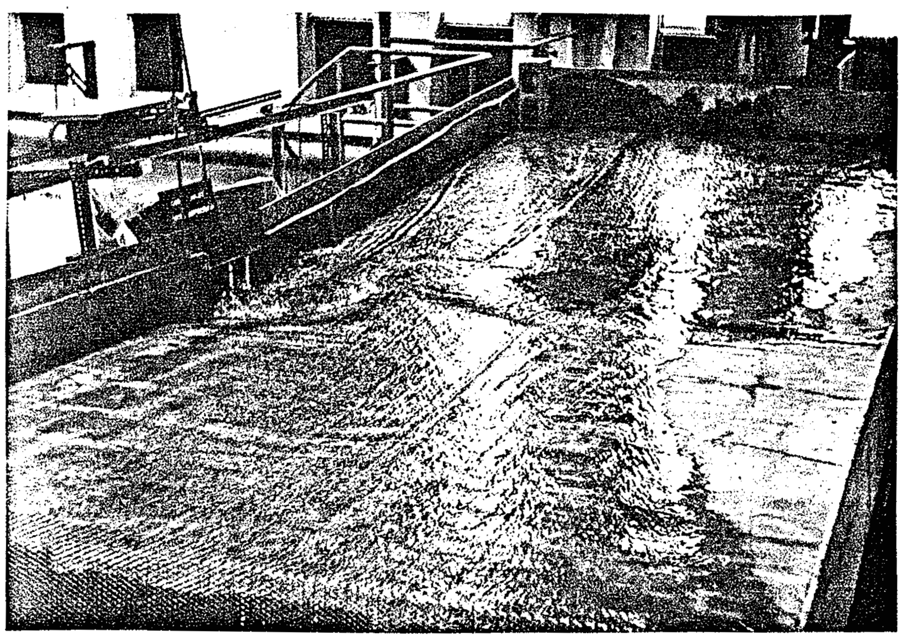


PHOTO 4: OVER-ALL VIEW OF APPROACH FLOW CONDITIONS

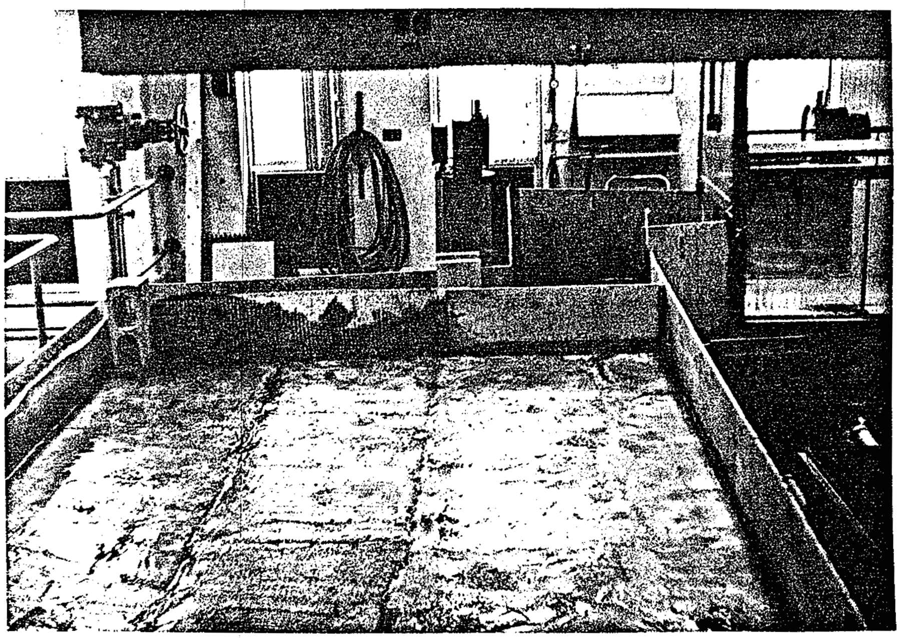


PHOTO 5: WEST END OF TEST FLUME

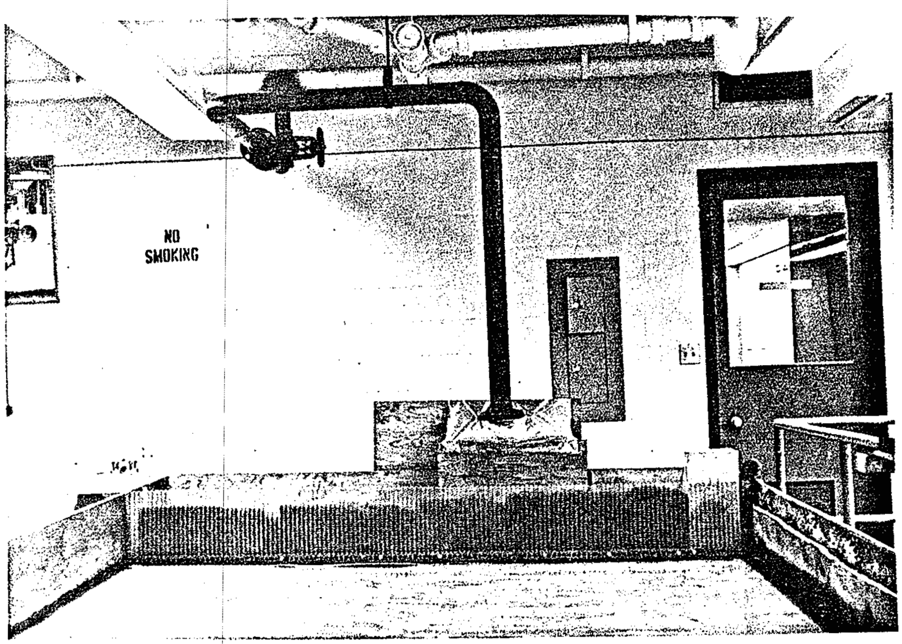


PHOTO 6: EAST END OF TEST FLUME

negligible amount of rainfall on the immediate few square feet around the inlet) been entirely concentrated in the gutter section.

For the present study, it was decided that the flow entering at either end of the model would be spread over the entire width of the roadway by means of an overflow sill placed across the width of the flume where the flow enters. In this way, the bulk of the flow would still be concentrated in the gutter section due to the cross slope of the model but the small amount of sheet flow in the area of the tested inlet would still be simulated. It was thought necessary also to install a baffle across the entire width of the flume at either end, to damp out any turbulence which may have arisen from the passage of flow from the sources into the model. This baffle consisted of a number of blocks of a very course fibrous material placed end-to-end across the roadway. Figure 30 illustrates the sill and baffle while Photograph 4 shows the approach flow conditions of the model in operation.

4.10 MEASUREMENT OF DEPTH OF FLOW ADJACENT TO THE CURB

Since one of the chief criteria for inlet capacities is the depth of flow of the storm water immediately adjacent to the roadway curb, the accurate measurement of this depth was critical to these series of tests. The recording of this depth was complicated by the fact that there were two distinct flows approaching the inlet, and although these flows were to be equal in magnitude, it would be unreasonable to expect that they would be exactly so, considering that two different sources were in use. Also, it had to be resolved how close to the curb and how close to the inlet these measurements should be taken. The location of the measurements decided upon is shown in Figure 31 which points out that four depth measurements were taken of the approaching flows. A natural check was present on the equality of the two flows; if the upstream depths on either side were equal, then presumably the flows would be equal. The location of the observation of depth on either side of the inlet was at a point just upstream of where the streamlines were affected by the presence of the inlet a distance of 32.5 inches from the center of the inlet, and then two more at 5.5 inch spacings closer to the inlet. Another reading was taken six inches from the inlet center. The depth at each location was observed as close to the curb as possible without actually touching it. The vertical datum was the road surface immediately adjacent to the curb.

The readings were taken using two point gauges solidly fixed to a trolly, which rolled along an immobile metal framework, as seen in Figure 31. These gauges were equipped with electronic level finders and provided an accuracy of 0.005 feet.

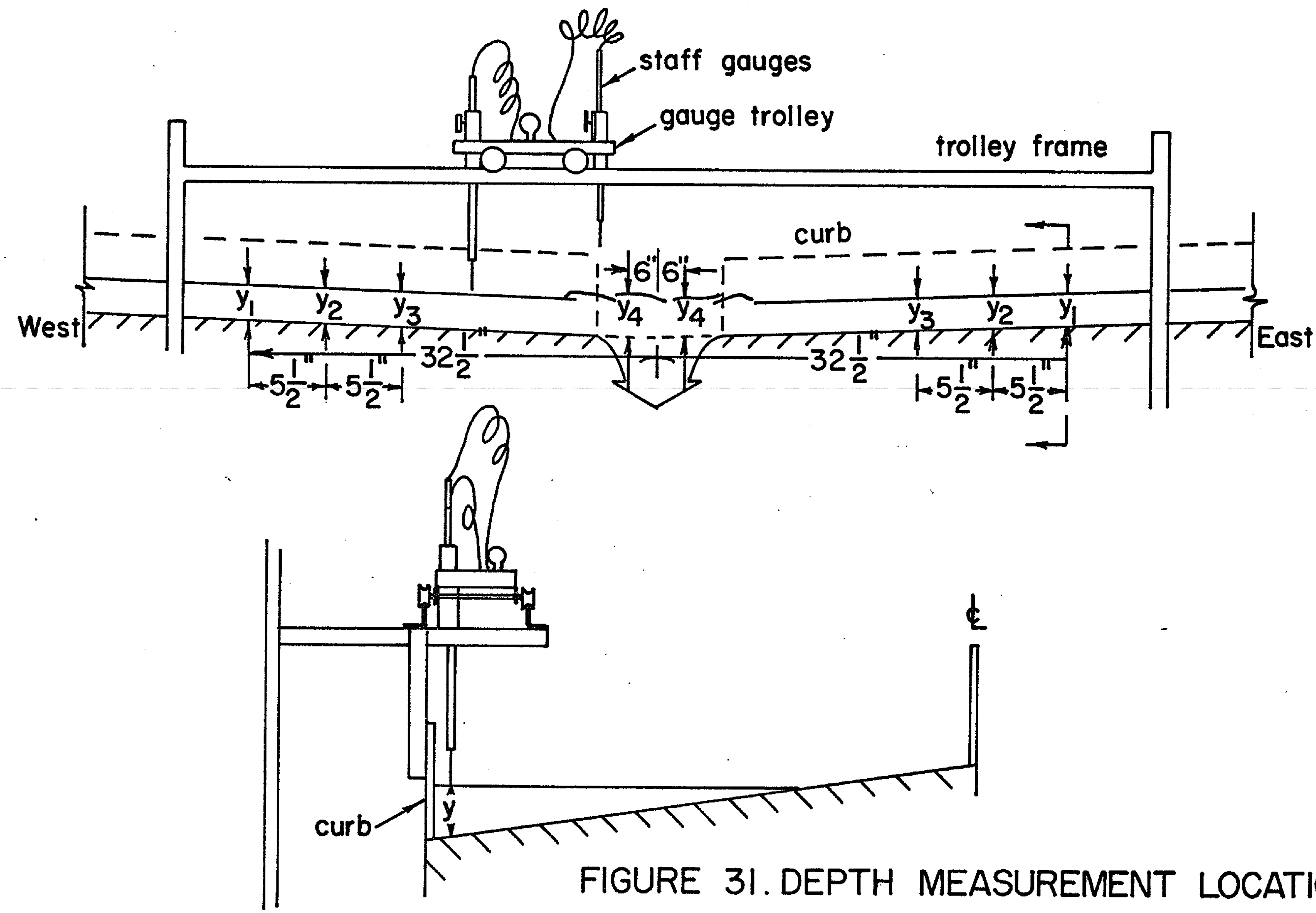


FIGURE 31. DEPTH MEASUREMENT LOCATIONS

4.11 TESTING PROCEDURE

The testing procedure really involved two distinct phases; the first phase was the adjustment of the apparatus to the desired setting before each test run, while the second was the testing itself.

Prior to each test, the following steps were followed:

(1) Using a surveyor's level, the crown slope and gutter grades of the flume were determined.

(2) Using hydraulic jacks to lift the structure off the support piers, wooden plates of the appropriate thickness were placed on these supports and the flume lowered onto them. The plates were of a pre-determined size which would impart the appropriate slopes to the model.

(3) The slopes were checked again with the level and shims were used to make any adjustments necessary.

For each inlet tested, the crown slope was first fixed at 1/4 inch per foot and the gutter slopes at 0.50 percent. Then the inlet was tested for a range of flows at this setting. With the crown slope still fixed at 1/4 inch per foot, the gutter slopes (both gutter slopes were always kept equal) were set at one percent through six percent, and tests run at one percent intervals. Then the crown slope was raised to 1/2 inch per foot where it remained as tests were run for the same gutter slopes as before.

Throughout the program, the testing procedures followed were logical, orderly, and underwent no changes as the experiments progressed. For each test run, the following steps were followed:

(1) The source valves were open part way and the pumps supplying these sources were then started causing flow through the model.

(2) The flow from both sources was equalized at some very low value, using the control valves and consulting the source rating curves, and then these flows, once stabilized, were recorded.

(3) The point gauges measuring the flow depth in the vicinity of the inlet were zeroed by recording readings of the gutter surface at the depth-measuring points. These readings would later be subtracted from the readings taken on the flowing water surface to give the actual depths of flow in feet.

(4) Readings on the flowing water surface were taken at the appropriate sections (Figure 31), enough time having been allowed for the flow to stabilize.

(5) A photograph was taken of the flow in the immediate vicinity of the inlet.

(6) A dye stream was introduced into the flow and the flow pattern thus detected was sketched.

(7) The flow from the sources was increased by some arbitrary increment (taking care to keep both flows equal), and then steps (4) through (7) were repeated until the inlet was flooded out. At that point, the pre-testing procedure

was once again followed to impart new slopes to the model; having done that, the above testing method was again employed.

A standard data sheet upon which all of the above readings were recorded in presented in Chapter V.

CHAPTER V

OBSERVED DATA

5.1 INTRODUCTION

Having carried out the testing program which has been outlined in Chapter IV, the observations of these tests must be set down in a logical and lucid form.

The test observations really fall into two separate categories. The first consists of quantities such as depths of flow which were measured and which could be represented with a numerical value. The second category contains those observations which were made during the course of the experimentation but which were qualitative rather than quantitative in nature; this would include, for example, the flow patterns sketched after the introduction of a dye stream into the water.

As four inlet configurations were each tested at seven gutter grade settings for each of two crown slopes (a total of fourteen tests per inlet), the numerical data is of too great a volume to present in tabular form in this chapter; rather the pertinant data will be presented in a graphical form which will give sufficient information for the reader to intelligently follow the calculated results of Chapter VI. The complete experimental data is given in Appendix B.

The qualitative observations showed less of a variation and were of a much more general nature than the measured quantities and, hence, it was possible to summarize them without omitting any of the pertinant details that would necessitate presentation in an appendix. These general observations could be separated into three groups:

i) observations on the type of flow governing the inlet discharge.

ii) dye tests on the patterns of flow in the vicinity of the inlet.

iii) observations of any unusual features of the flow.

Photographs have been used wherever possible to illustrate the pertinant qualitative observations*.

5.2 PRESENTATION OF THE NUMERICAL DATA

All of the readings that were taken during the course of any of the test runs were recorded on a standard data sheet which is given in Table 4. When the experimental procedure of Chapter IV is referred to, all of the quantities in this table are easily identifiable. Since over sixty test runs were made, the presentation of this bulk of data in tabular form within the main body of the work was not though to be either practical or enlightening. It was decided, instead, to reserve the tabular presentation

* It was not feasible to photograph the dye tests.

INLET: DEPRESSED CURB

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 5.83 %

DATE TESTED : FEB. 25/71

WEST GUTTER SLOPE : 5.84 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4

TABLE 4. SAMPLE DATA SHEET

of data to Appendix B, and to summarize the pertinant quantities here by means of graphs.

The graphs plotted the total flow through the inlet $Q_i = Q_1 + Q_2$, versus the depth of water ponded in front of, or over, the inlet, y_4, on a log-log scale. Since y4 was read on both sides of the inlet centerline, the two values were averaged to obtain the number which appears on the graphs.

The reasons for choosing this type of plot were four in number:

i) Previous investigations indicated that for inlets located in sumps the main factor governing the inlet capacities was the depth of water ponded in front of, or over, the inlet.

ii) A log-log plot would be of great use in dealing with phenomena described by exponential functions.

:iii) At very high flows, it was not possible to keep the two flow sources equal and, hence, the normal gutter flow depths in this range were not equal. Therefore, a plot including normal gutter flow depths would be useful only for lower flows.

iv) The damping effect of the ponded water in the sump would, without question, alter the velocities of the incoming flow so that the velocity distribution and magnitude associated with normal gutter flow depth would not apply at the inlet.

For each inlet tested, a single graph was drawn which

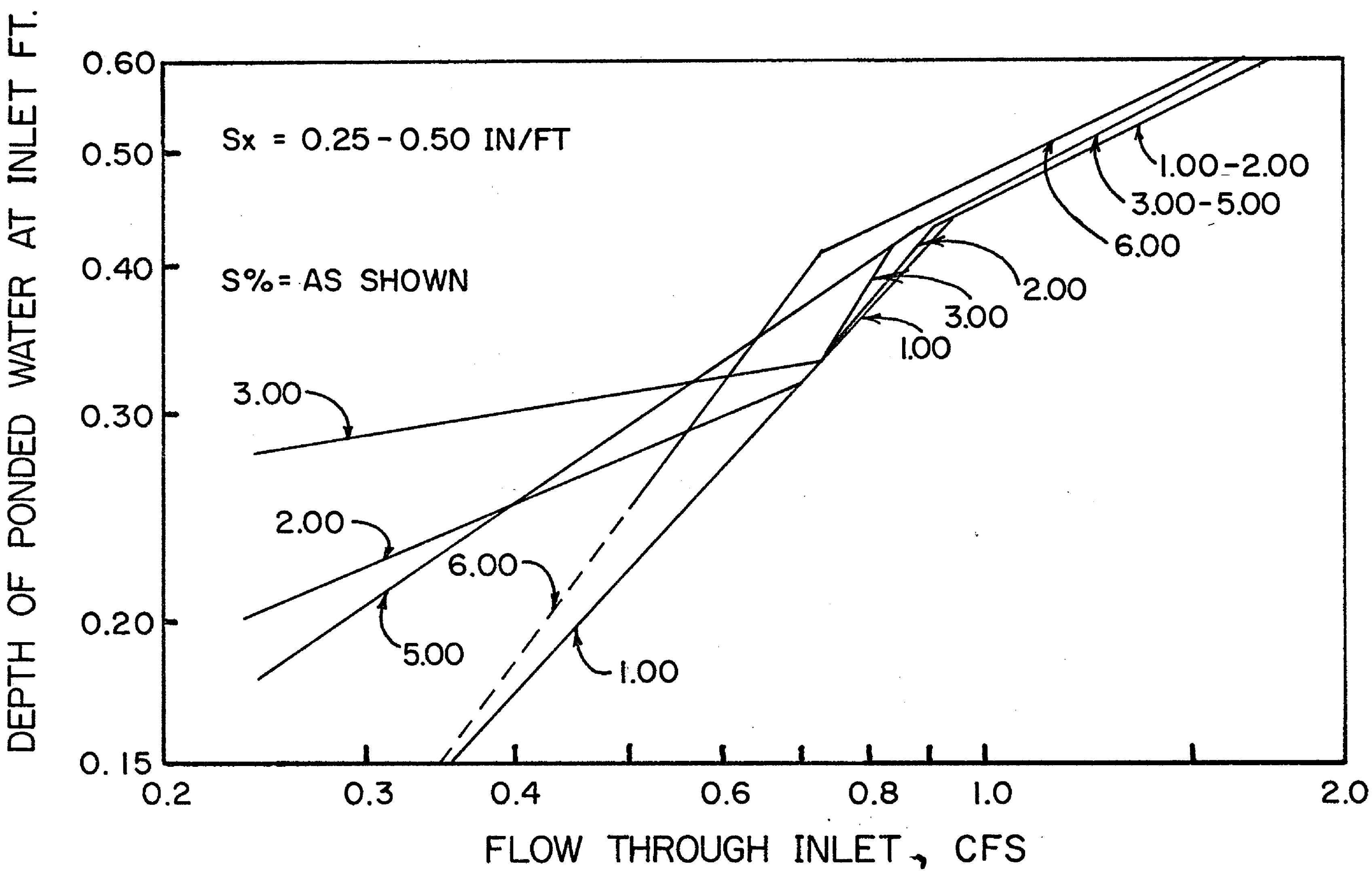


FIGURE 32: UNDEPRESSED CURB INLET RATING CURVE

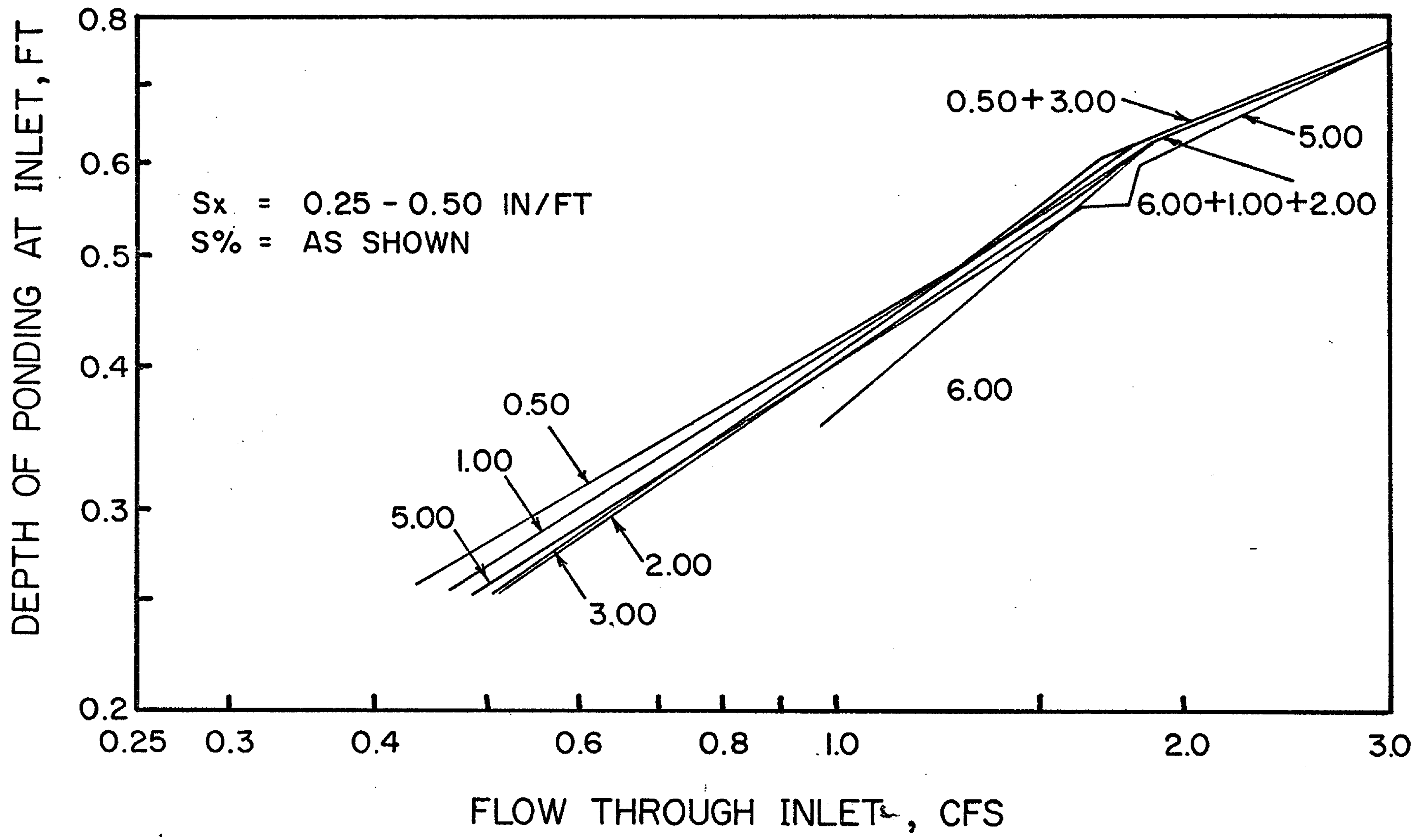


FIGURE 33: DEPRESSED CURB INLET RATING CURVES

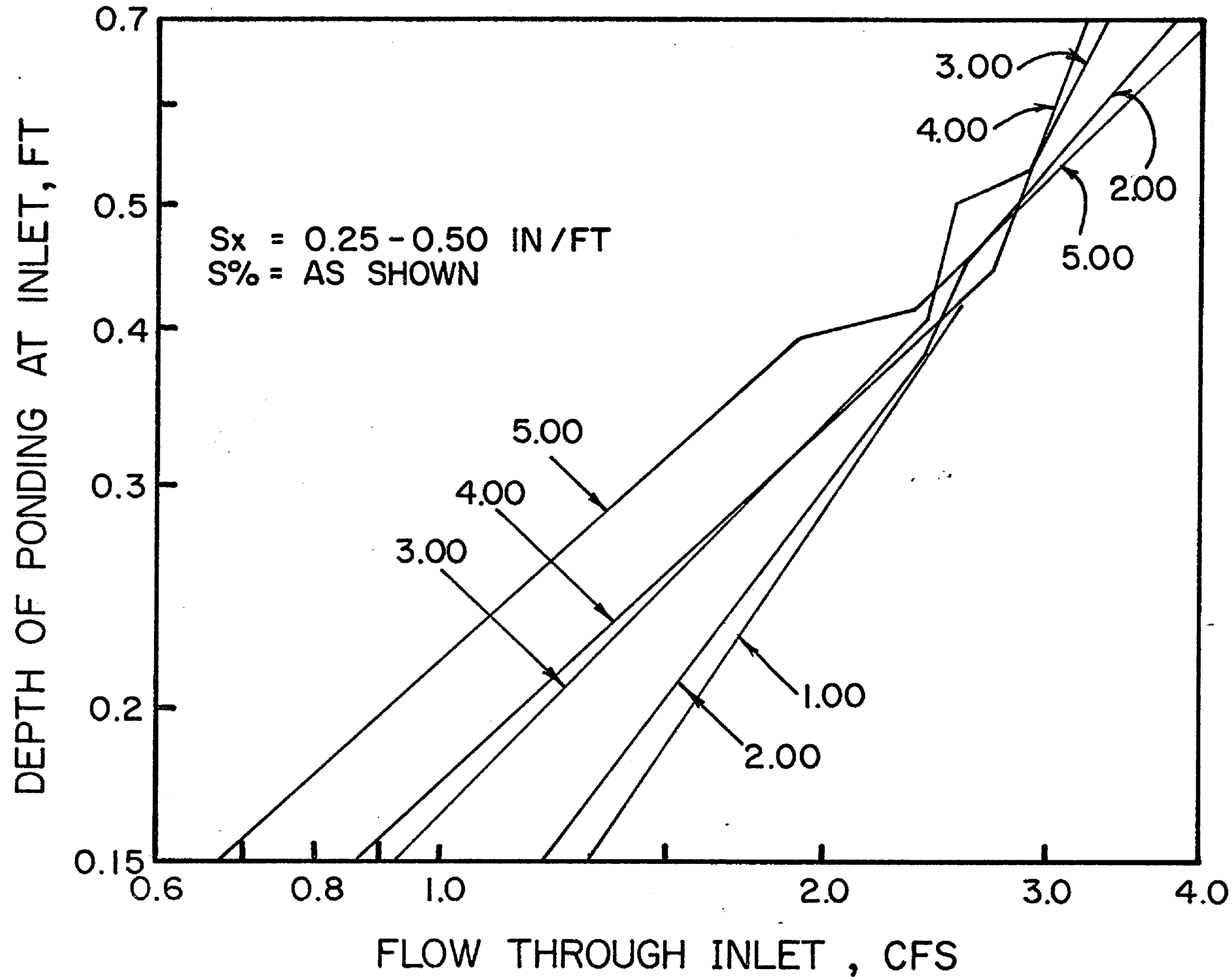


FIGURE 34: GUTTER INLET RATING CURVE

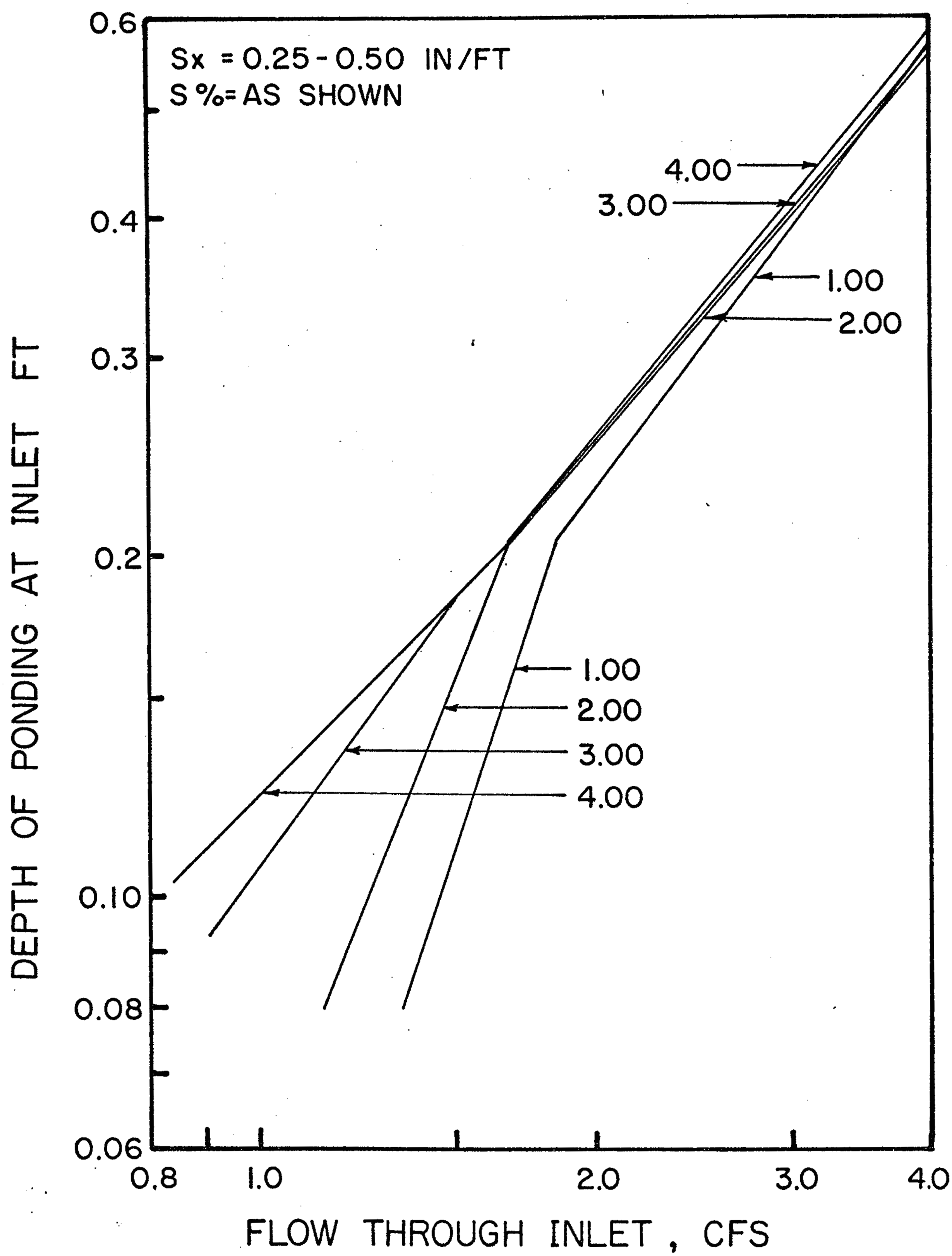


FIGURE 35: COMBINATION INLET RATING CURVES

included the data for all of the test runs. Figures 32 and 33 are for the curb inlet, undepressed and depressed respectively. Figure 34 plots the data obtained from the gutter inlet while Figure 35 is for the combination inlet.

5.3 QUALITATIVE OBSERVATIONS

Qualitative observations of inlet behaviour obviously cannot be described by assigning numbers to the flow phenomena involved. What can be done, however, is to combine these observations with numerical observations recorded at the same time, to allow the assignment of numbers to describe the limits within which these flow phenomena operate. Hence, the following observations on the control of flow into inlets may at first sight appear to be so general as to be useless; however, when they are combined with the plots of section 5.2, it may well be possible to assign a numerical meaning to these observations. This, in fact, has been done in Chapter VI.

5.3.1 Flow Control at the Inlet

Control of the flow into an inlet located in a sump may fall into one of three categories. There may be weir control, orifice control, or some fluctuation between these which is best called indeterminate. The criteria for classifying the flow as one of the above are the following:

i) Weir Control: In order that weir control determine a sump, very low flows could not properly be termed weir controlled as the flow from either side had entirely dropped into the inlet before joining in the center to form a continuous stream over the crest length*; there was no ponding of water in front of the inlet. Since this condition is not amenable to simple mathematical analysis, and since the flow range in which it occurs is of little importance in the design of inlets, it was not analysed in this paper although it is shown in Photograph 7.

Once flow had begun to pond in front of the inlet, true weir control was observed. The lower limit of this phenomena is not of particular importance, since it occurs at comparatively low flows. The upper limit of weir control was noted to occur at about the same depth of for all of the tests, about six inches. This can be noted as a change in curve slope in Figure 33. From Figure 29(C), it can be seen that the point is located just below the top of the inlet opening. Photographs 8, 12, 16 and 17 are of the inlet operating under this condition.

From a depth of ponded water of six inches to seven inches, the flow was neither weir nor orifice controlled but fluctuated between the two conditions. Consequently, the curves of Q_i versus y were quite irregular. This intermediate condition is shown in Photographs 9, 13 and 18.

Once the depth exceeded seven inches, the flow was quite regular. Between seven and eight inches depth, orifice

* See Figure 15, page 49.

control prevailed exclusively. When y exceeded eight inches, orifice flow continued through the inlet, but weir controlled flow passed over the top of the inlet appurtenance as over a broad crested weir. It would be expected that this point would show up on the inlet rating curve (Figure 33), but such was not the case. Exclusive orifice flow appears in Photographs 10, 14 and 19, while the orifice-weir combination can be seen in Photographs 11, 15 and 20.

(2) Undepressed Curb Inlet: Since the depressed inlet differs from the undepressed only in that there is a steeper gutter grade and crown slope at the inlet and a larger area to accomodate the flow, it is not unreasonable to expect that the same phenomena were observed for the undepressed inlet operations, but that the depths of flow defining the limits of these occurences were different. This was in fact the case. The upper limit of weir controlled flow occurred at a y value of approximately four inches. Weir control is shown in Photographs 21 and 25.

Depths of ponding of between four and five inches produced erratic flow as seen in Photographs 22 and 26.

Between five and six inches of depth produced exclusive orifice control as in Photographs 23 and 27, while the weir-orifice phenomena produced by water passing over the top of the inlet occurred with y exceeding six inches. Photographs 24 and 28 depict this.

(3) Gutter Inlet: At very low flows, the width of water in the gutter was quite narrow. The water fell into the opening over the edge of the grating which forms an irregular and changing weir crest, not amenable to mathematical analysis and of little concern in the design of inlets. This condition applies in Photograph 29.

As the water began to pond in the sag, a point was reached where the width of the ponding exceeded the width of the gutter grate, and the flow fell into the opening over the crest formed by the outer periphery of the grate. The flow was weir controlled over the crest being formed by the edges of the openings in the grate, which formed the square grate periphery. This crest was certainly irregular in shape but constant for this flow condition. Weir control was observed up to the point at which the depth of ponding at the inlet was about four and three-quarters inches. Operation in this range is shown in Photographs 30, 31 and 36.

For ponding between four and three-quarters inches and the upper limit of the testing, a rather violent vortex action was noted which introduced large amounts of air into the grate opening and prevented true orifice operation. It should be kept in mind, however, that it was very difficult to determine if a point had been reached where vortices were infrequent enough to allow virtual true orifice flow. Photographs 32, 33, 37, 39 and 40 show intermediate operation both at long range and close-up, while Photographs 34, 35, 38 and 41 illustrate apparent orifice flow.

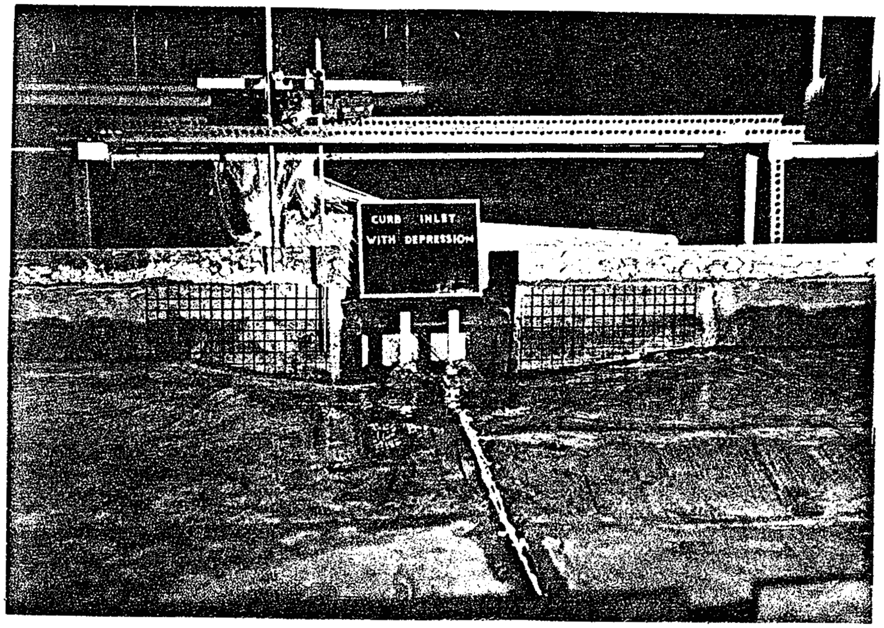
(4) Combination Inlet: At very low flows, before ponding occurs in the sag, it is impossible to visually estimate the proportion of flow entering either the curb or gutter openings.

After ponding has developed, however, the gutter inlet handles most of the flow, behaving as a weir with an enclosed rectangular crest. Photographs 42, 46 and 49 show this. At this stage, the curb inlet cannot yet be said to be operating as a weir.

When the depth of ponding reaches about two and one-half inches, the curb inlet begins to operate under weir control and the gutter grate under partial orifice control. This condition can be seen in Photographs 43, 44 and 47.

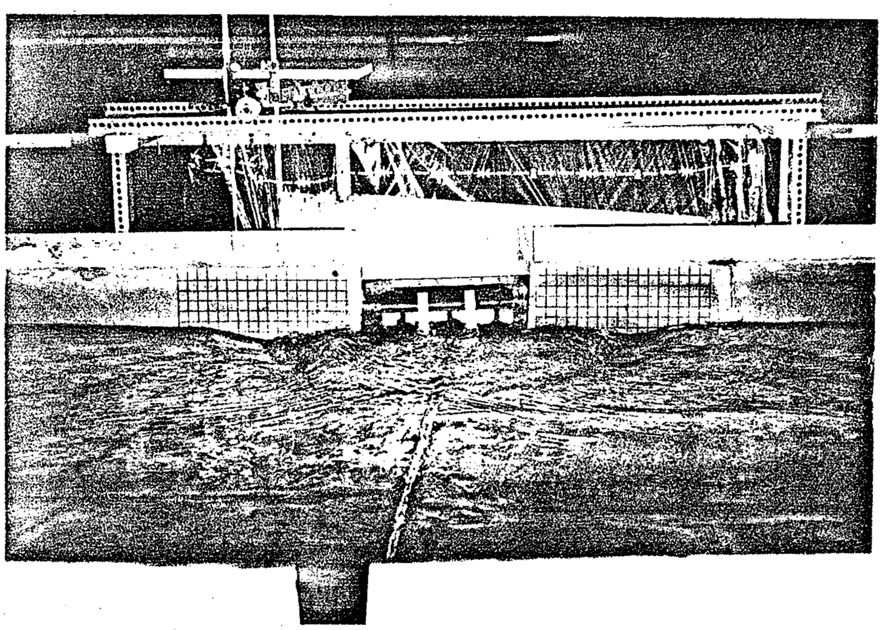
The gutter grate developes full orifice control while the curb opening is still acting as a weir, and continues that operation when the curb inlet becomes indeterminate at a depth of ponding of four inches; reference is made to Photographs 45, 48 and 50.

When ponding is between about four and one-half and six inches, both the gutter and curb inlets are orifice controlled as can be seen in Photograph 51. The capacity of the apparatus was not such that tests could be run beyond this point.



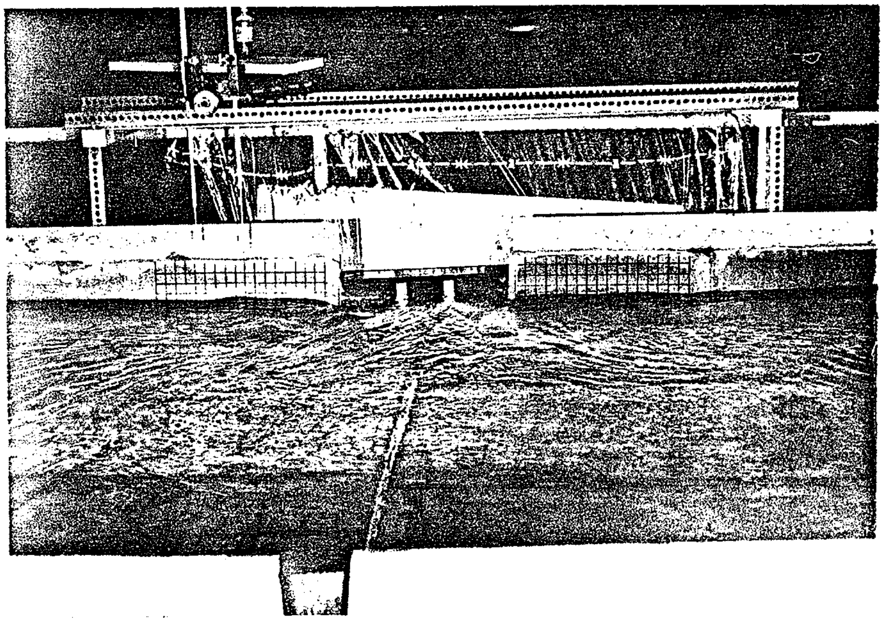
7. $S_E = 0.52\%$ $S_W = 0.50\%$

$S_X = 0.25$ in./ft. $Q_1 = 0.20$ c.f.s.

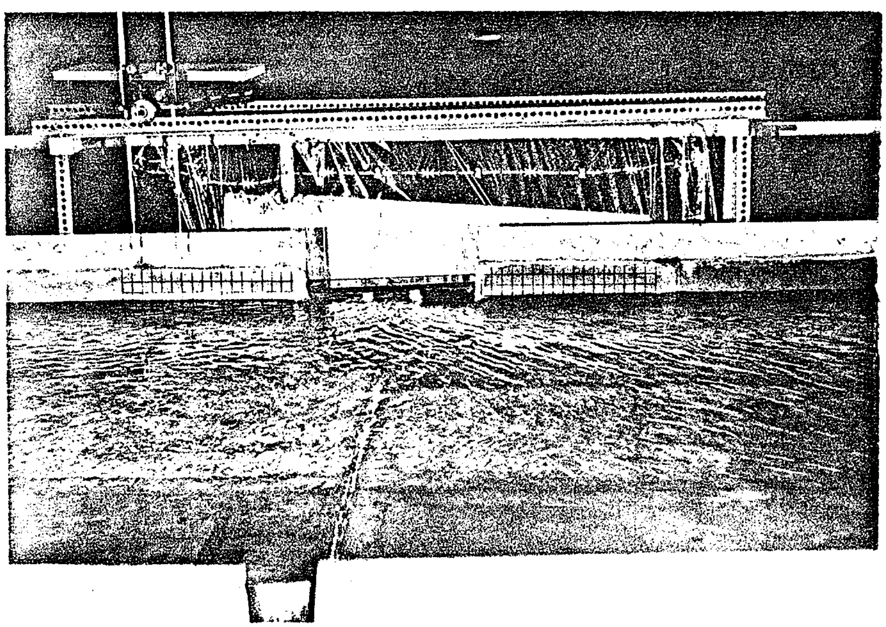


8. $S_E = 0.49\%$ $S_W = 0.52\%$

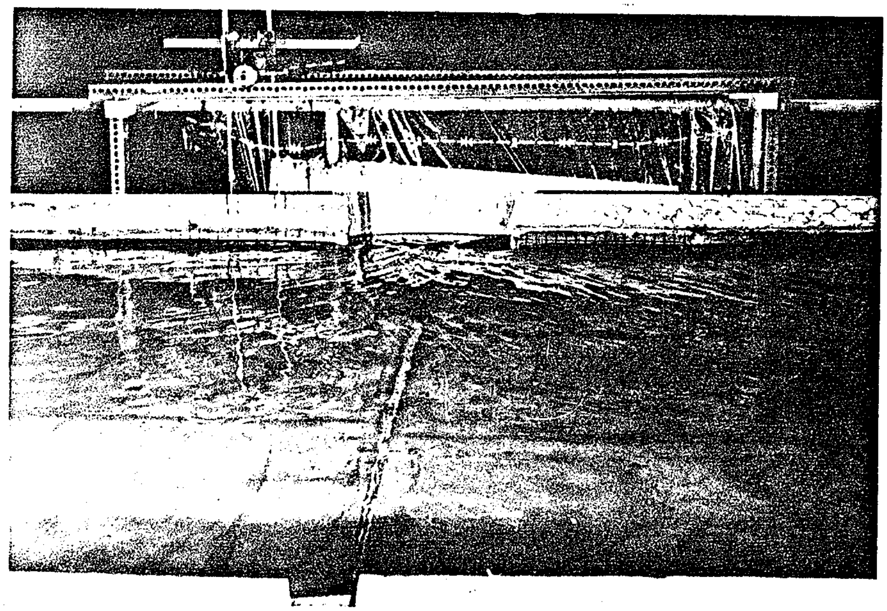
$S_X = 0.50$ in./ft. $Q_1 = 0.75$ c.f.s.



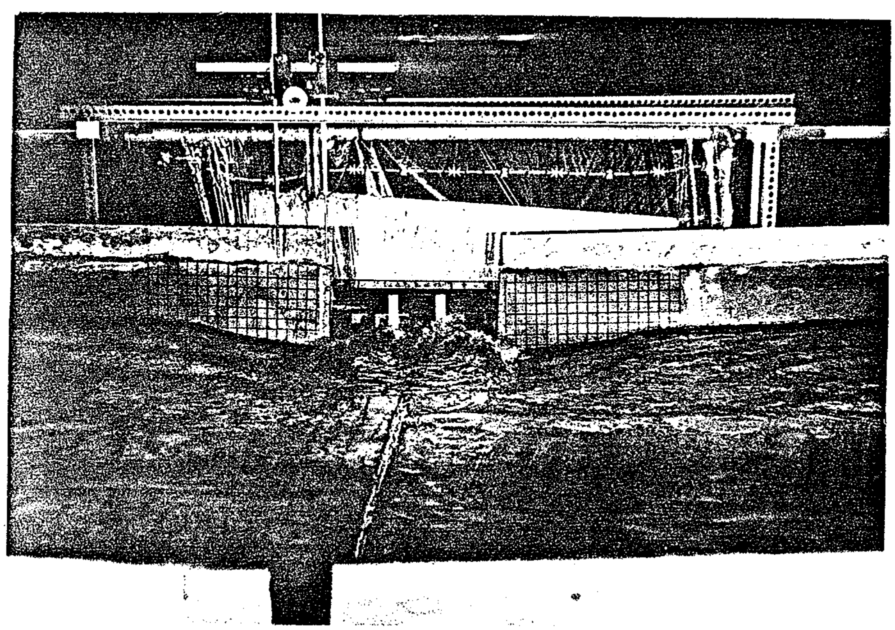
9. $S_E = 0.49\%$ $S_W = 0.52\%$
$S_X = 0.50$ in./ft. $Q_1 = 1.44$ c.f.s.



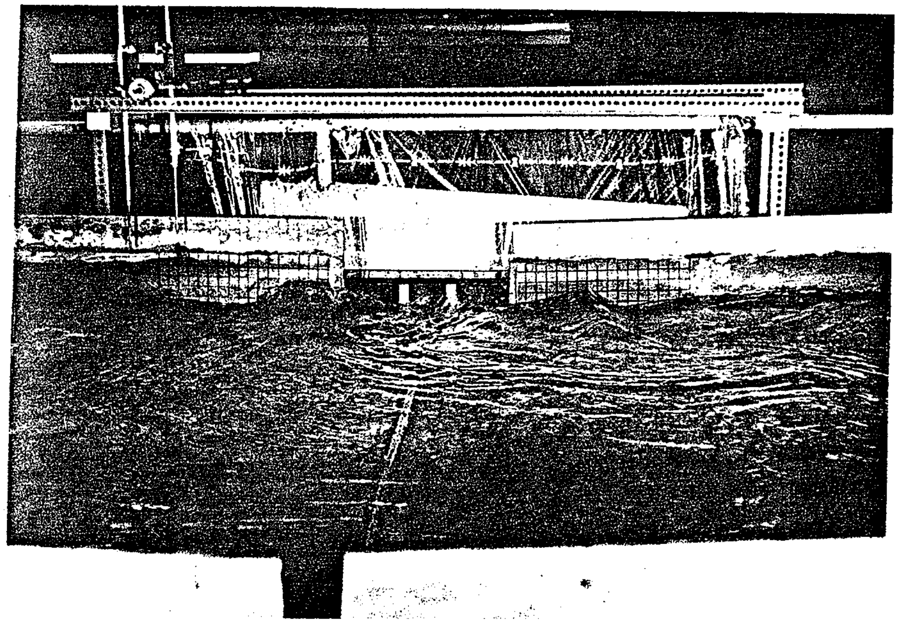
10. $S_E = 0.49\%$ $S_W = 0.52\%$
$S_X = 0.50$ in./ft. $Q_1 = 1.61$ c.f.s.



11. $S_E = 0.49\%$ $S_W = 0.52\%$
$S_X = 0.25$ in./ft. $Q_1 = 1.84$ c.f.s.

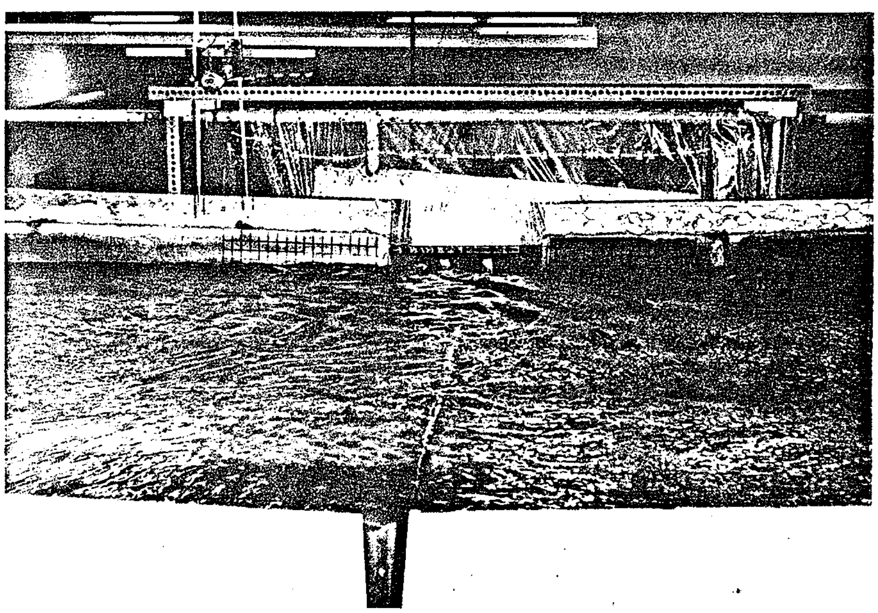


12. $S_E = 2.95\%$ $S_W = 3.08\%$
$S_X = 0.50$ in./ft. $Q_1 = 0.80$ c.f.s.



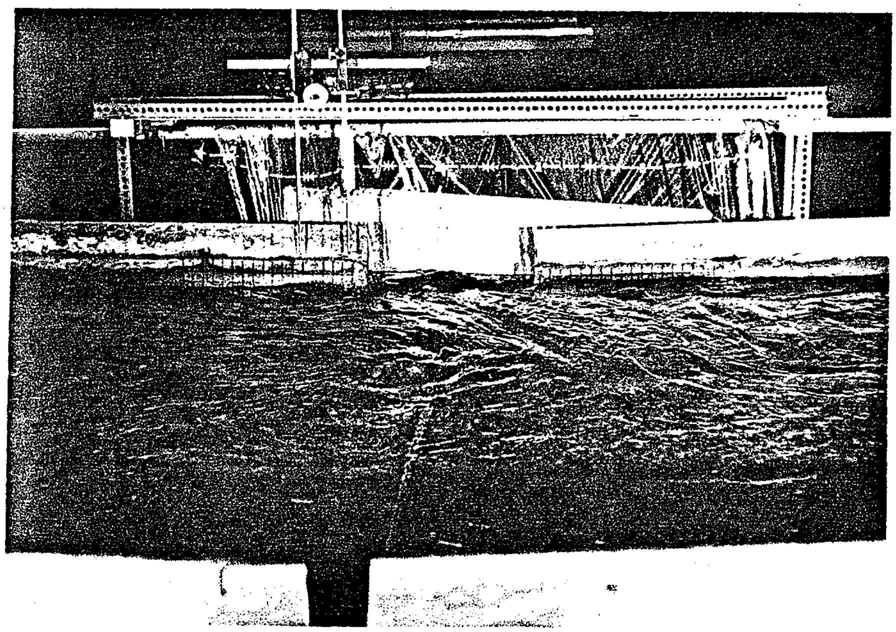
13. $S_E = 2.95\%$ $S_W = 3.08\%$

$S_X = 0.50$ in./ft. $Q_1 = 1.56$ c.f.s.

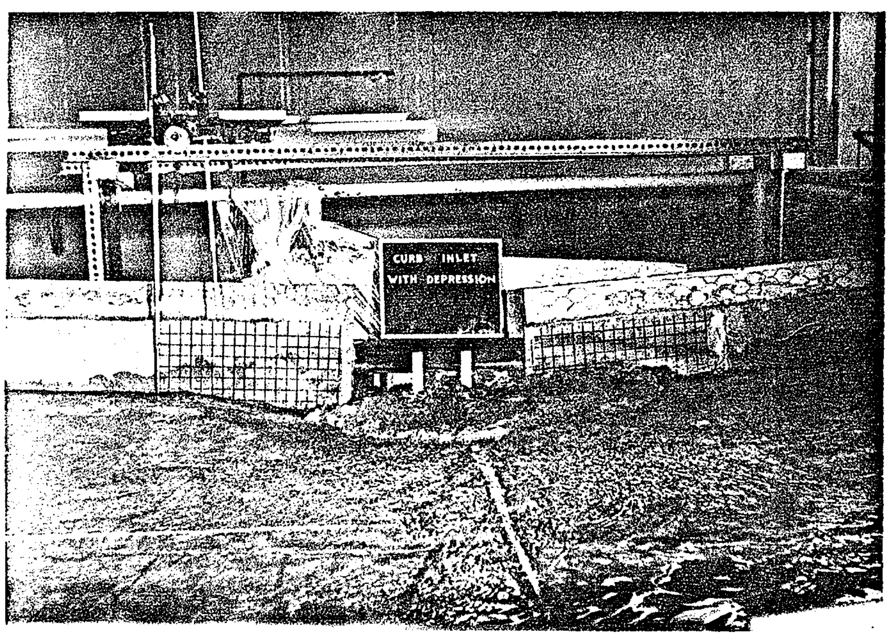


14. $S_E = 3.09\%$ $S_W = 2.96\%$

$S_X = 0.25$ in/ft. $Q_1 = 1.69$ c.f.s.

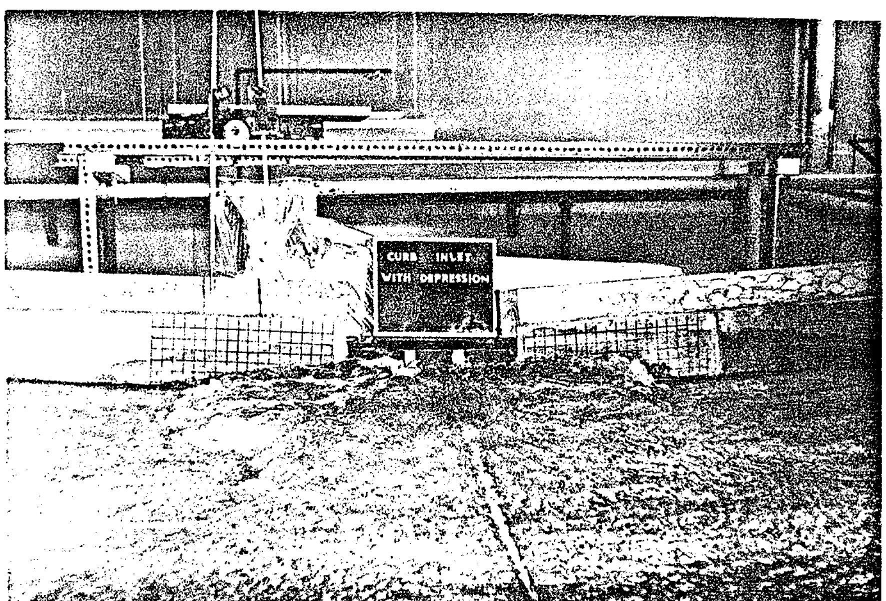


15. $S_E = 2.95\%$ $S_W = 3.08\%$
$S_X = 0.50$ in./ft. $Q_1 = 2.25$ c.f.s.

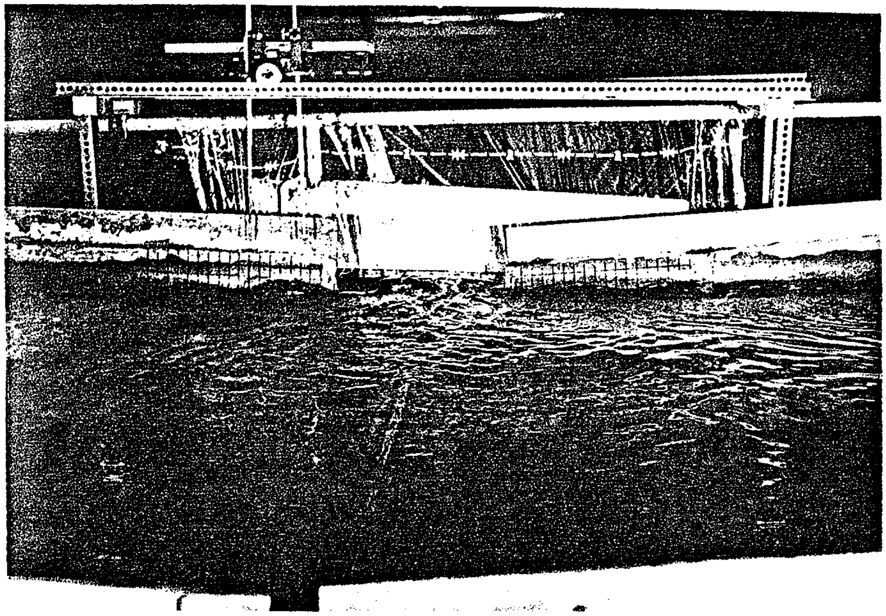


16. $S_E = 6.00\%$ $S_W = 6.00\%$
$S_X = 0.25$ in./ft. $Q_1 = 0.87$ c.f.s.

17. $S_E = 6.00\%$ $S_W = 6.00\%$
$S_X = 0.25$ in./ft. $Q_1 = 1.00$ c.f.s.

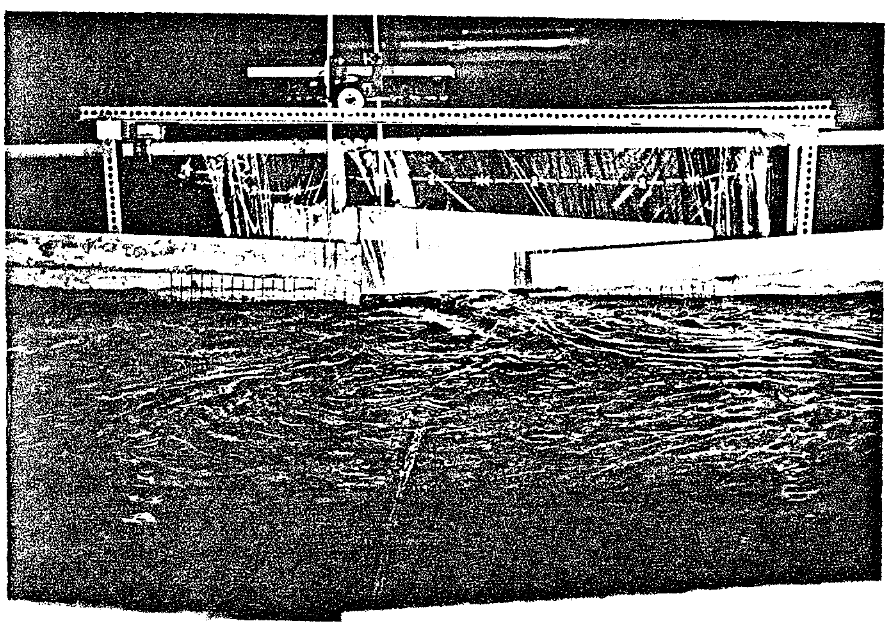


18. $S_E = 6.00\%$ $S_W = 6.00\%$
$S_X = 0.25$ in./ft. $Q_1 = 1.69$ c.f.s.



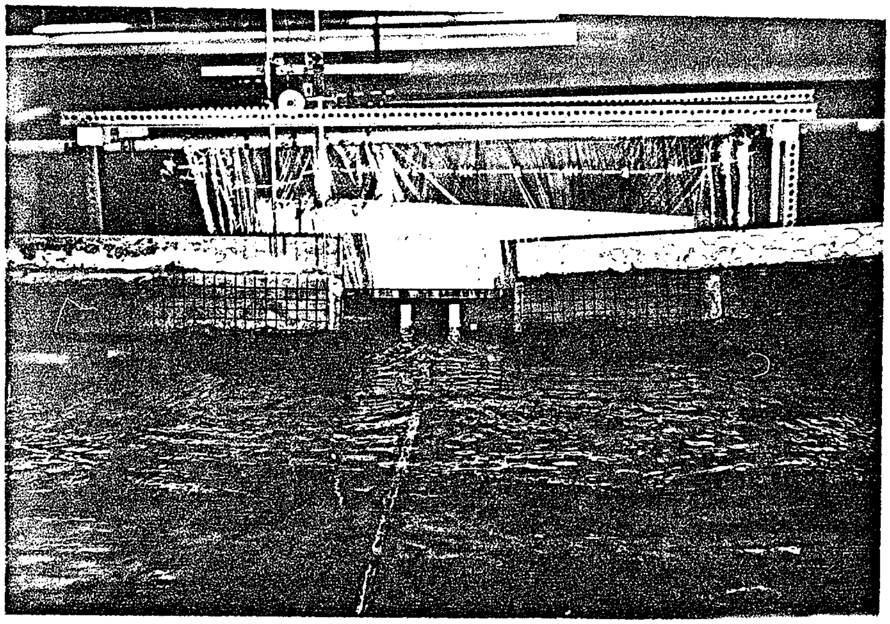
19. $S_E = 5.83\%$ $S_W = 5.84\%$

$S_X = 0.50$ in./ft. $Q_1 = 1.95$ c.f.s.

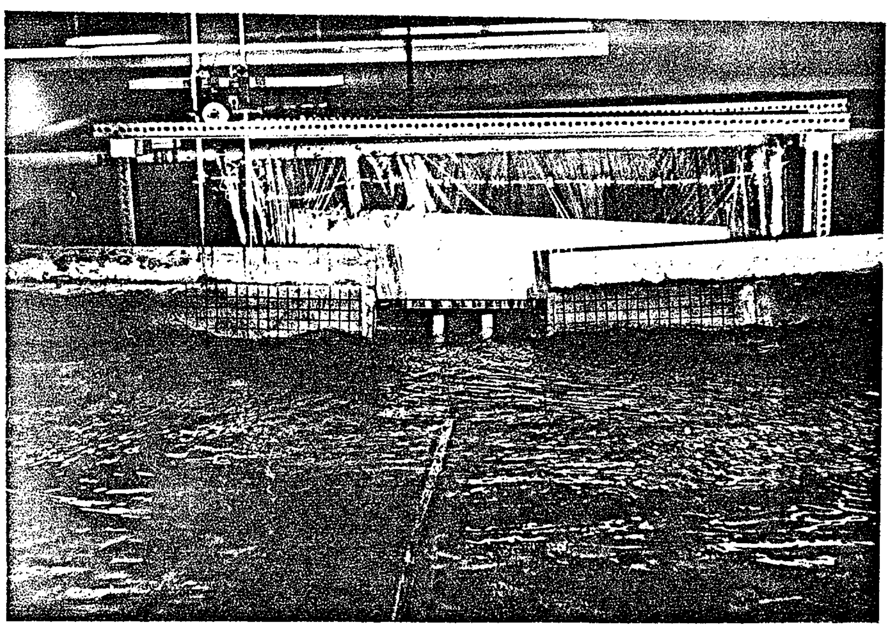


20. $S_E = 5.83\%$ $S_W = 5.84\%$

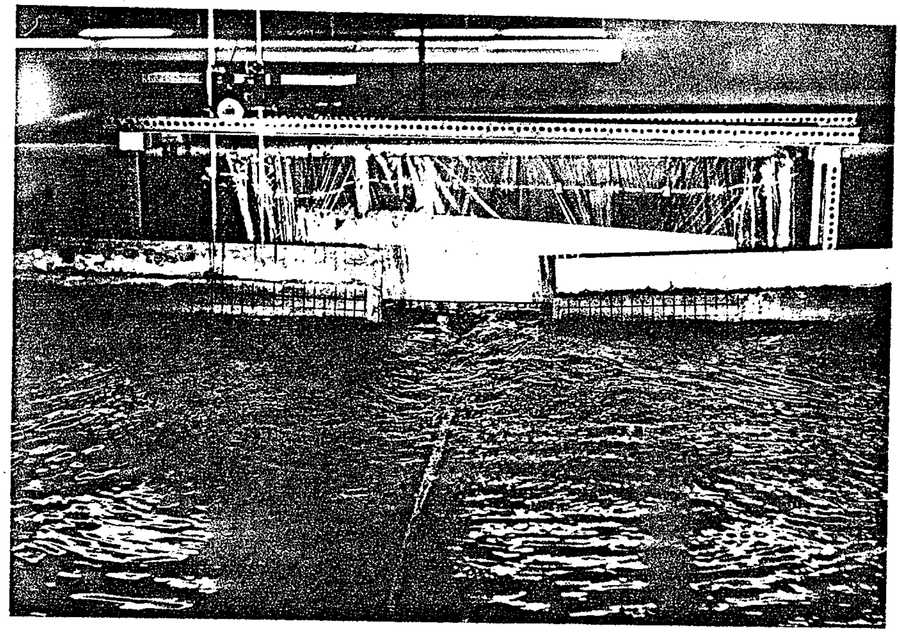
$S_X = 0.50$ in./ft. $Q_1 = 2.32$ c.f.s.



21. $S_E = 5.83\%$ $S_W = 5.84\%$
$S_X = 0.50$ in./ft. $Q_i = 0.64$ c.f.s.

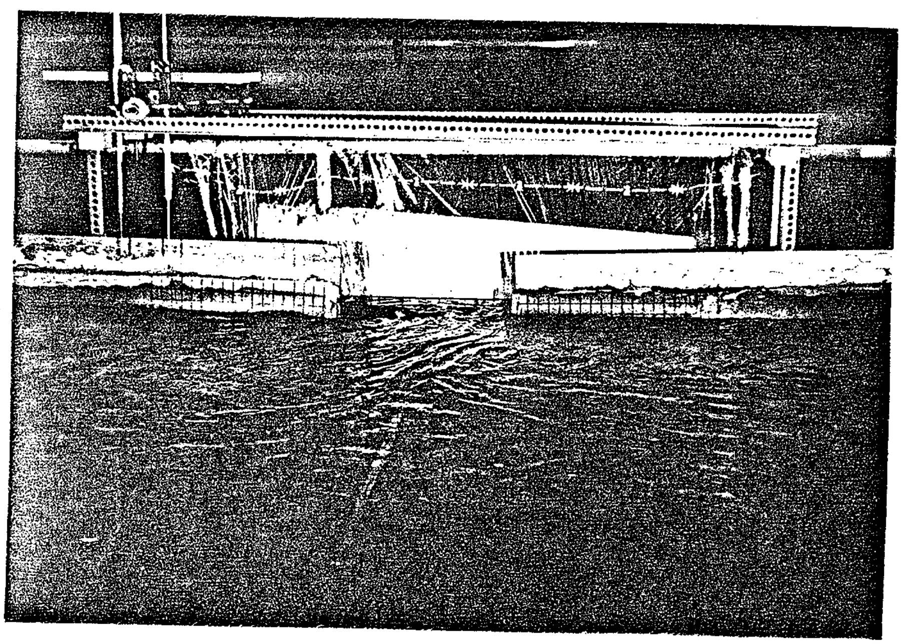


22. $S_E = 5.04\%$ $S_W = 4.93\%$
$S_X = 0.50$ in./ft. $Q_i = 0.79$ c.f.s.



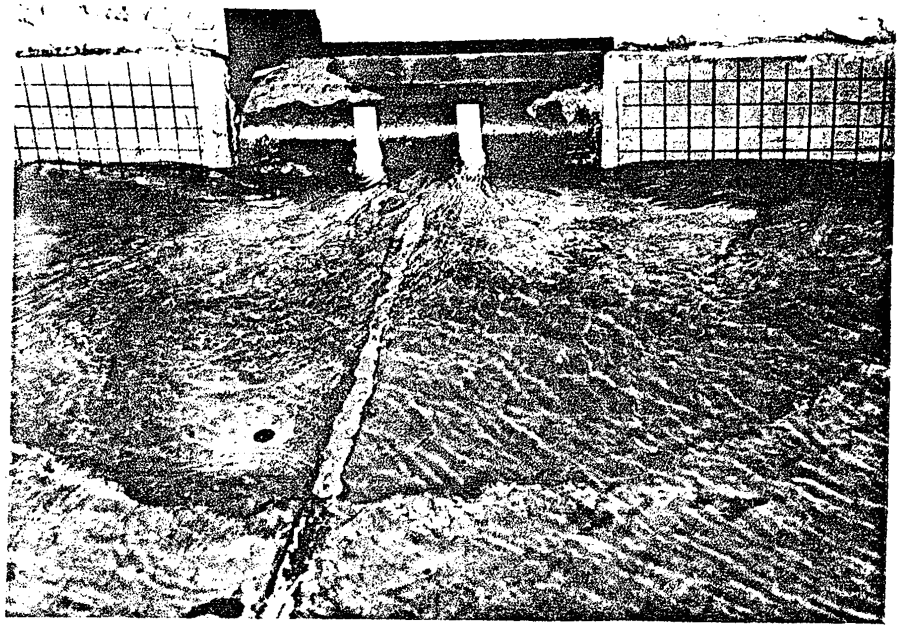
23. $S_E = 5.83\%$ $S_W = 5.84\%$

$S_X = 0.50$ in./ft. $Q_i = 0.80$ c.f.s.

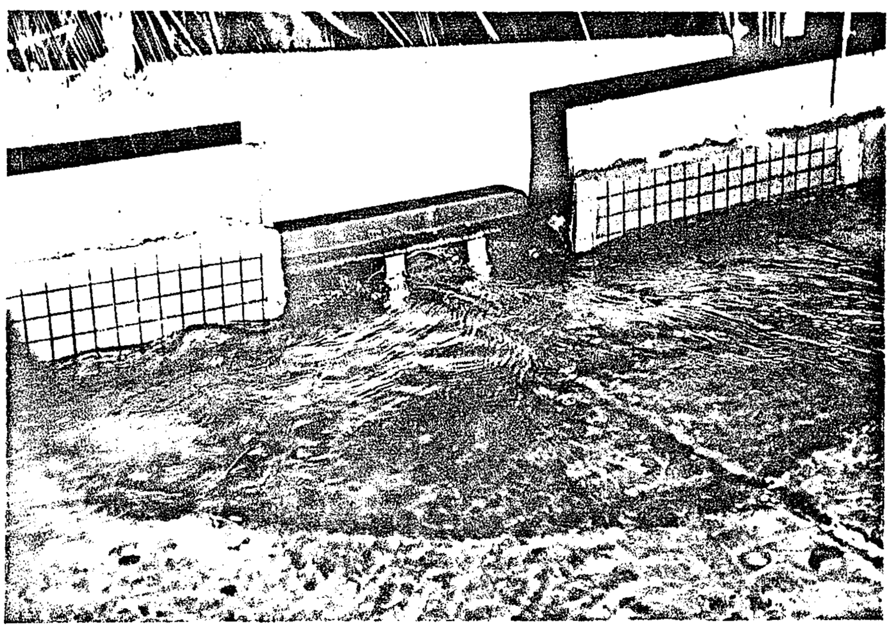


24. $S_E = 5.83\%$ $S_W = 5.84\%$

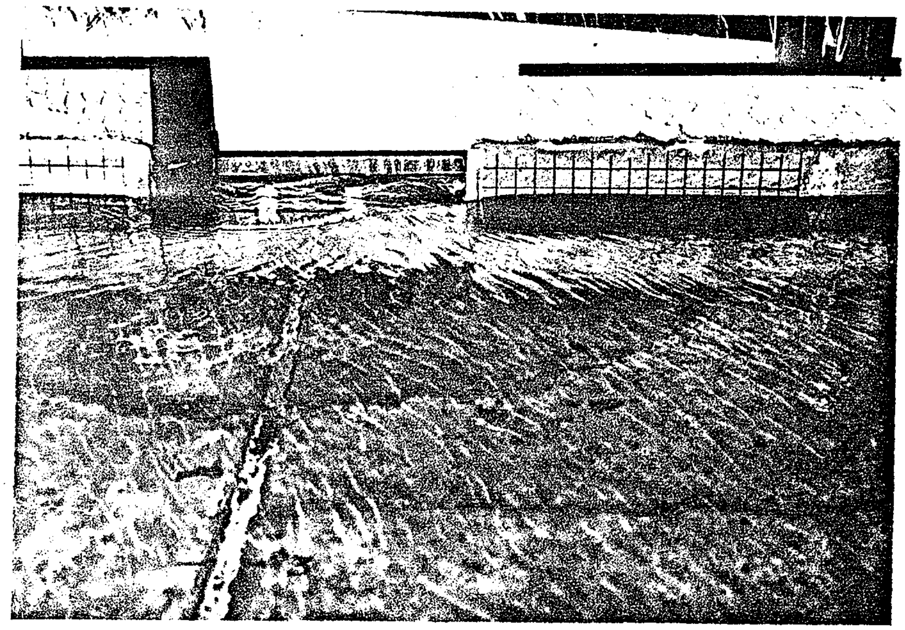
$S_X = 0.50$ in./ft. $Q_i = 1.05$ c.f.s.



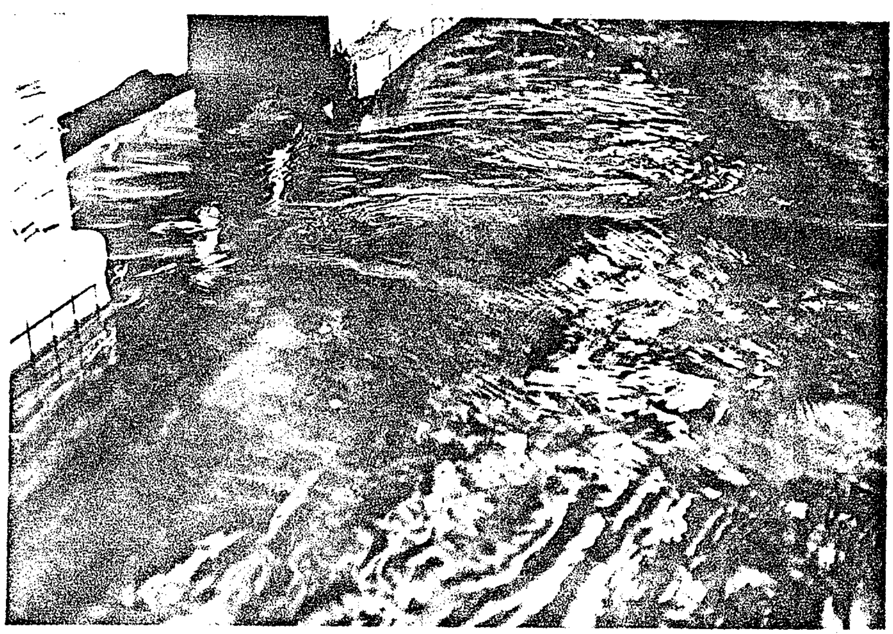
25. WEIR CONTROL



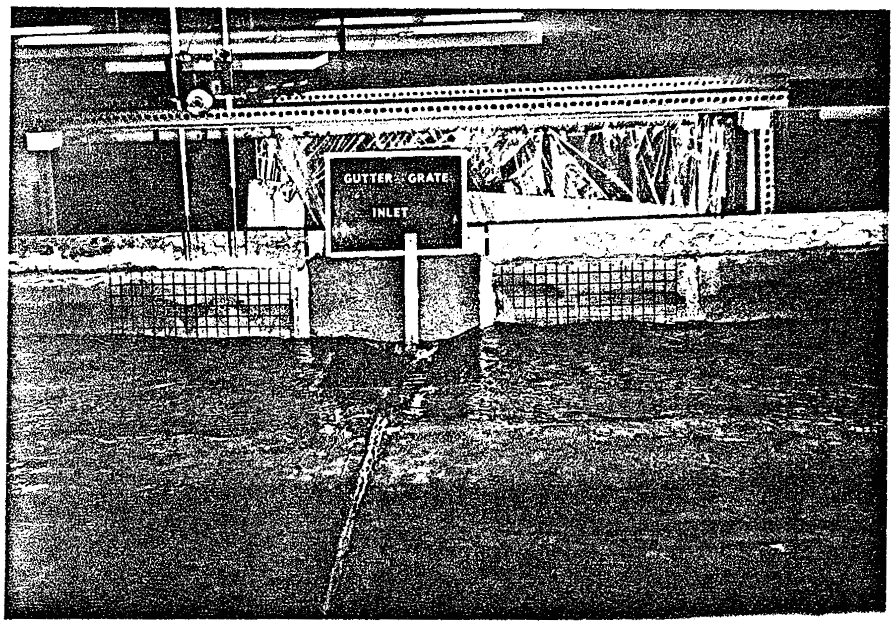
26. INDETERMINATE CONTROL



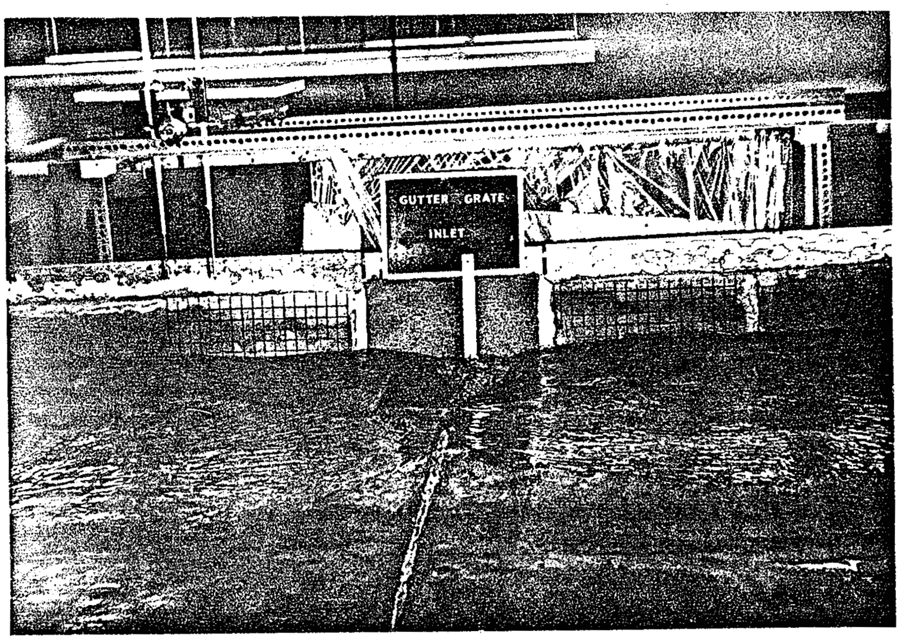
27. ORIFICE CONTROL



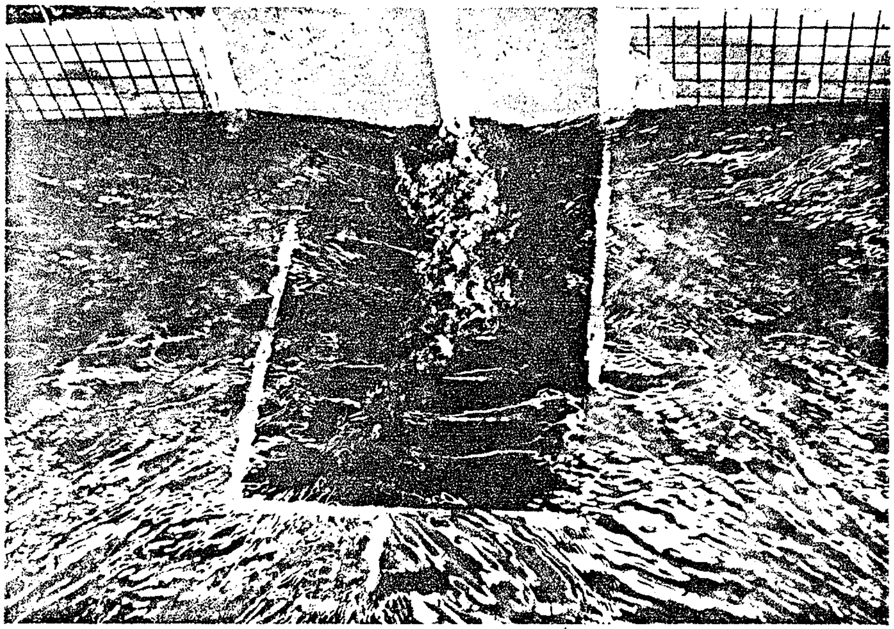
28. WEIR AND ORIFICE CONTROL



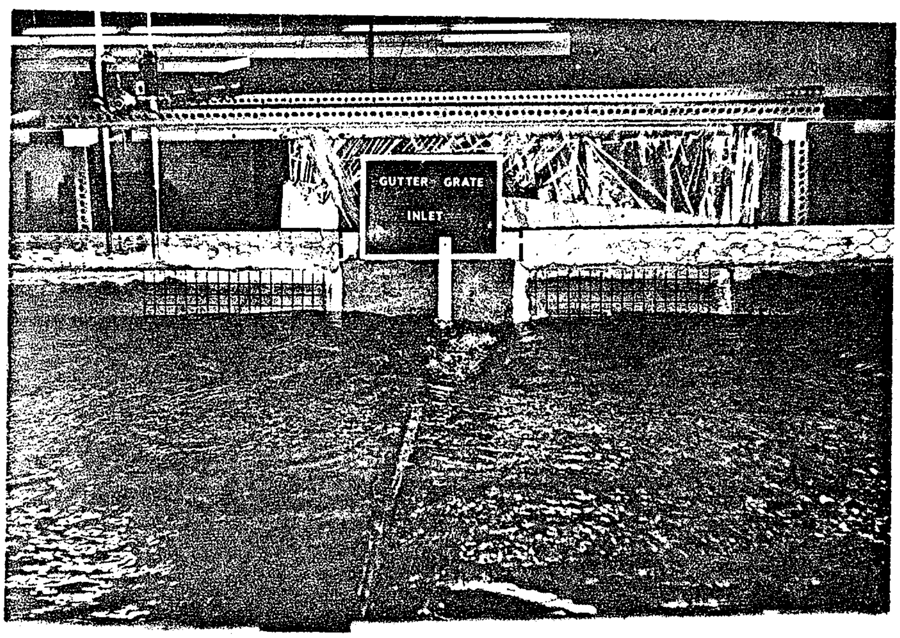
29. $S_E = 1.02\%$ $S_W = 1.05\%$
$S_X = 0.50$ in./ft. $Q_1 = 0.65$ c.f.s.



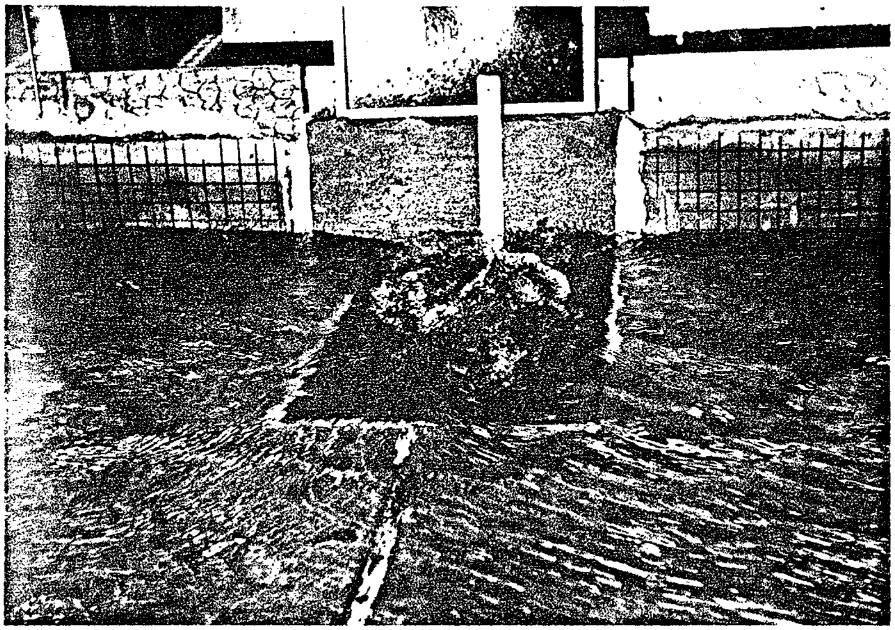
30. $S_E = 1.02\%$ $S_W = 1.05\%$
$S_X = 0.50$ in./ft. $Q_1 = 1.05$ c.f.s.



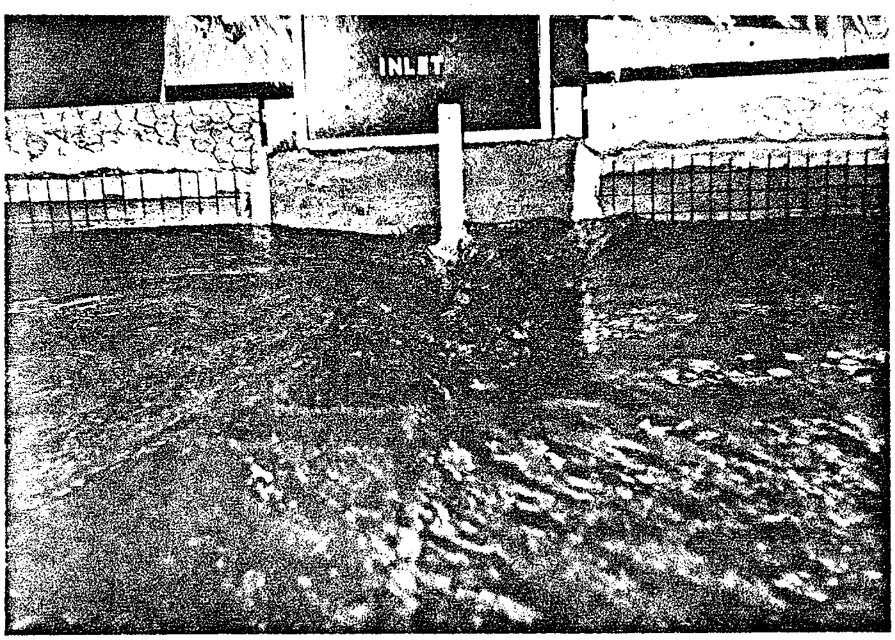
31. $S_E = 1.02\%$ $S_W = 1.05\%$
$S_X = 0.50$ in./ft. $Q_1 = 1.05$ c.f.s.



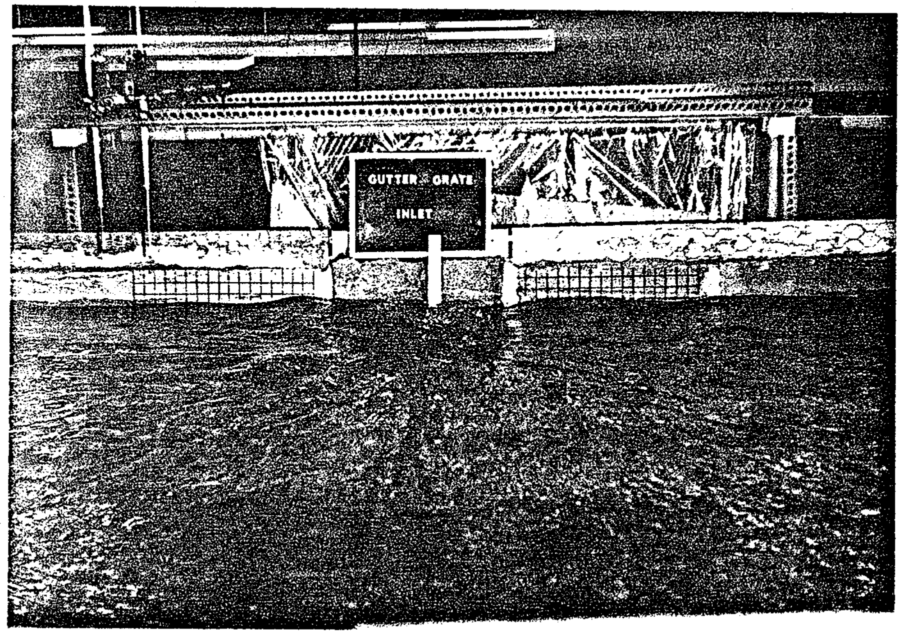
32. $S_E = 1.02\%$ $S_W = 1.05\%$
$S_X = 0.50$ in./ft. $Q_1 = 1.60$ c.f.s.



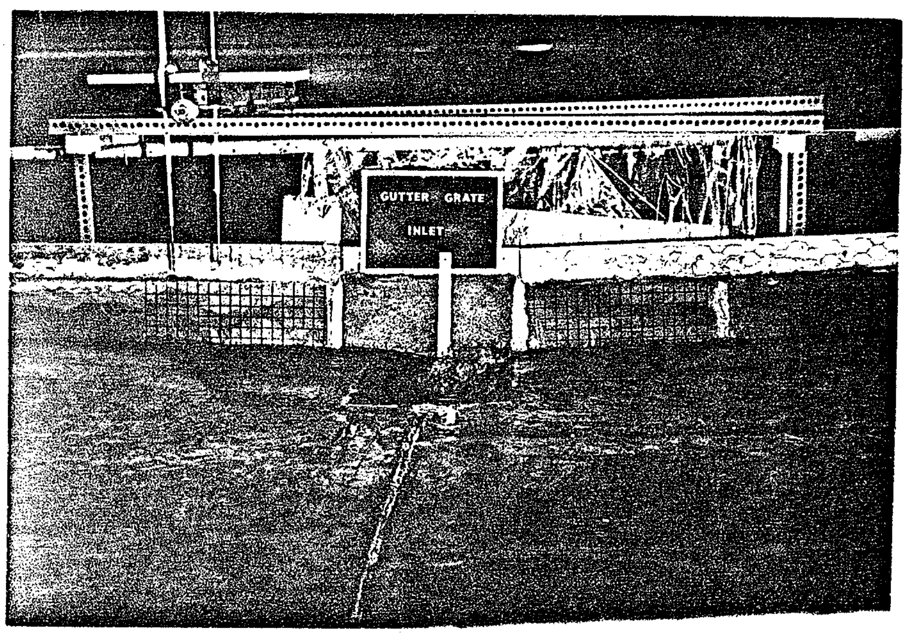
33. $S_E = 1.02\%$ $S_W = 1.05\%$
$S_X = 0.50$ in./ft. $Q_i = 1.93$ c.f.s.



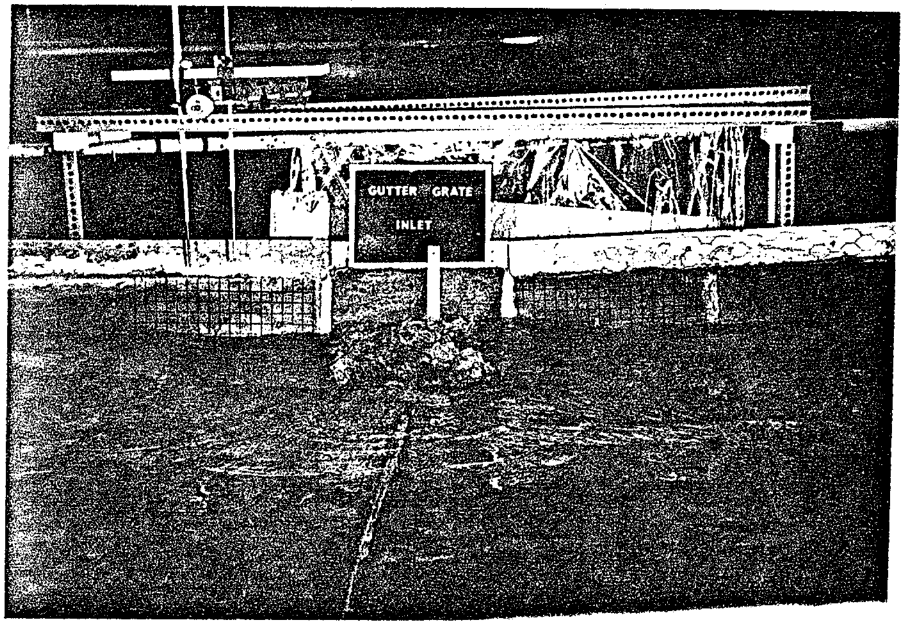
34. $S_E = 1.02\%$ $S_W = 1.05\%$
$S_X = 0.50$ in./ft. $Q_i = 2.37$ c.f.s.



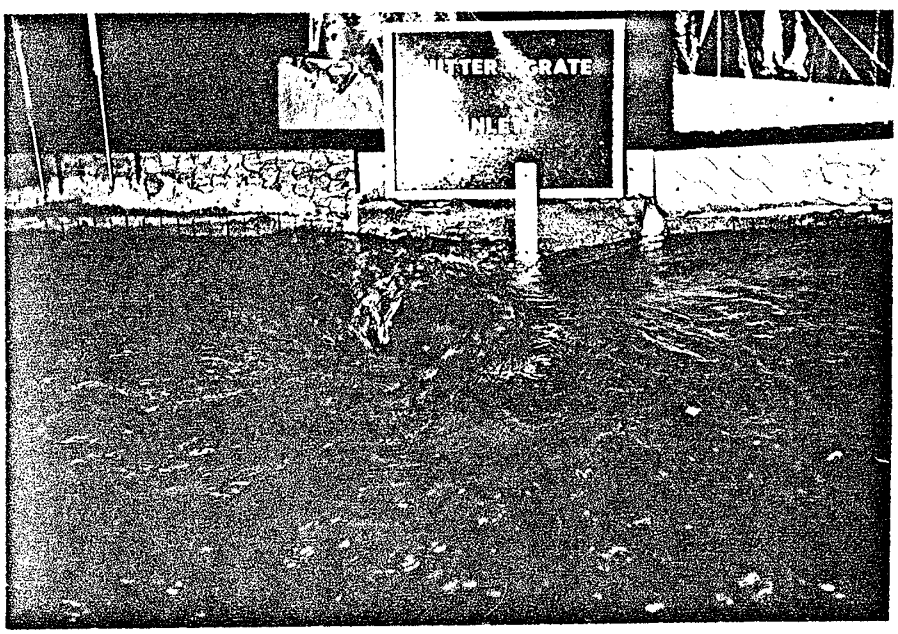
35. $S_E = 1.02\%$ $S_W = 1.05\%$
$S_X = 0.50$ in./ft. $Q_1 = 2.87$ c.f.s.



36. $S_E = 3.03\%$ $S_W = 2.97\%$
$S_X = 0.50$ in./ft. $Q_1 = 0.89$ c.f.s.

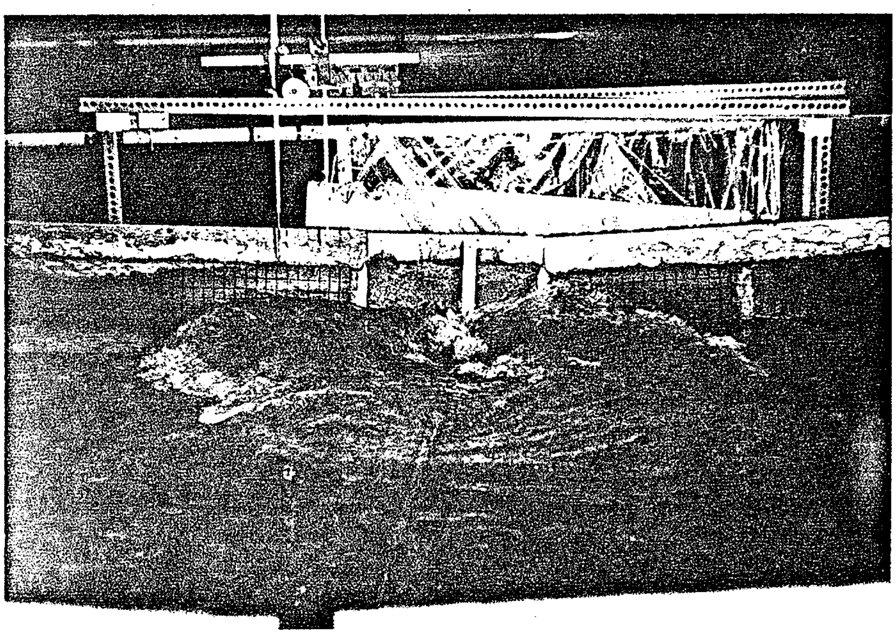


37. $S_E = 3.03\%$ $S_W = 2.97\%$
$S_X = 0.50$ in./ft. $Q_i = 2.00$ c.f.s.

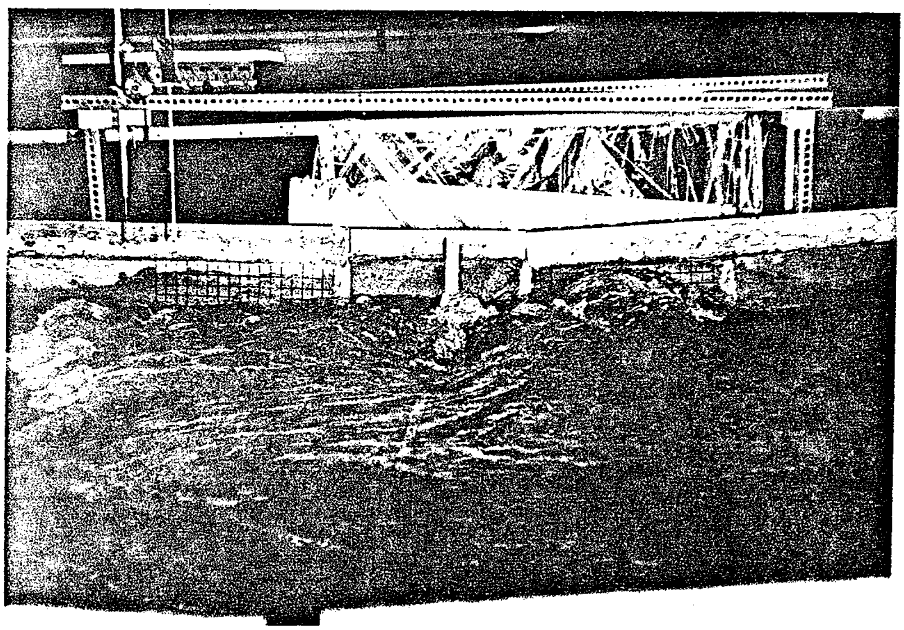


38. $S_E = 3.03\%$ $S_W = 2.97\%$
$S_X = 0.50$ in./ft. $Q_i = 3.00$ c.f.s.

39. $S_E = 3.03\%$ $S_W = 2.97\%$
$S_X = 0.50$ in./ft. $Q_i = 3.00$ c.f.s.

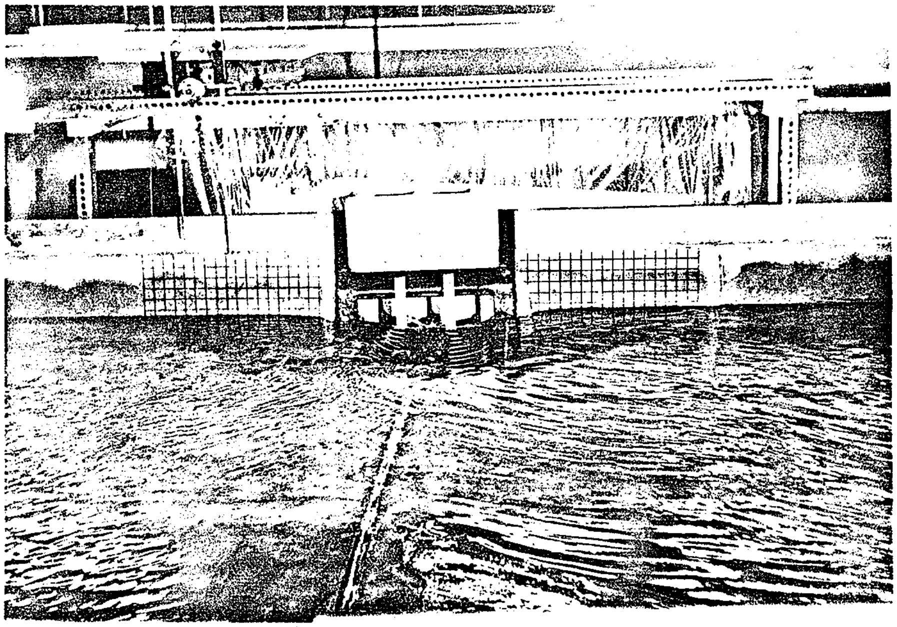


40. $S_E = 5.07\%$ $S_W = 5.04\%$
$S_X = 0.50$ in./ft. $Q_i = 2.61$ c.f.s.

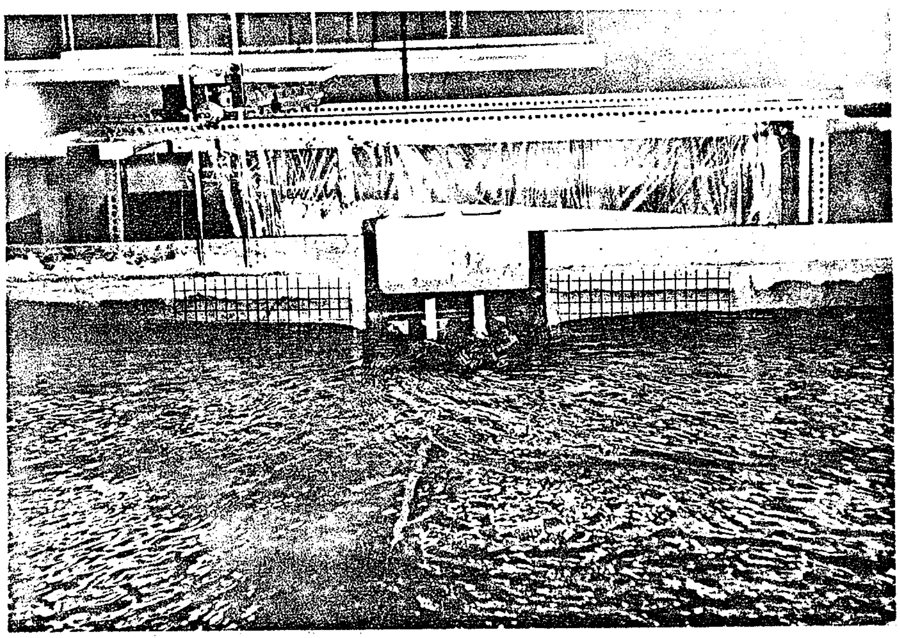


41. $S_E = 5.07\%$ $S_W = 5.04\%$

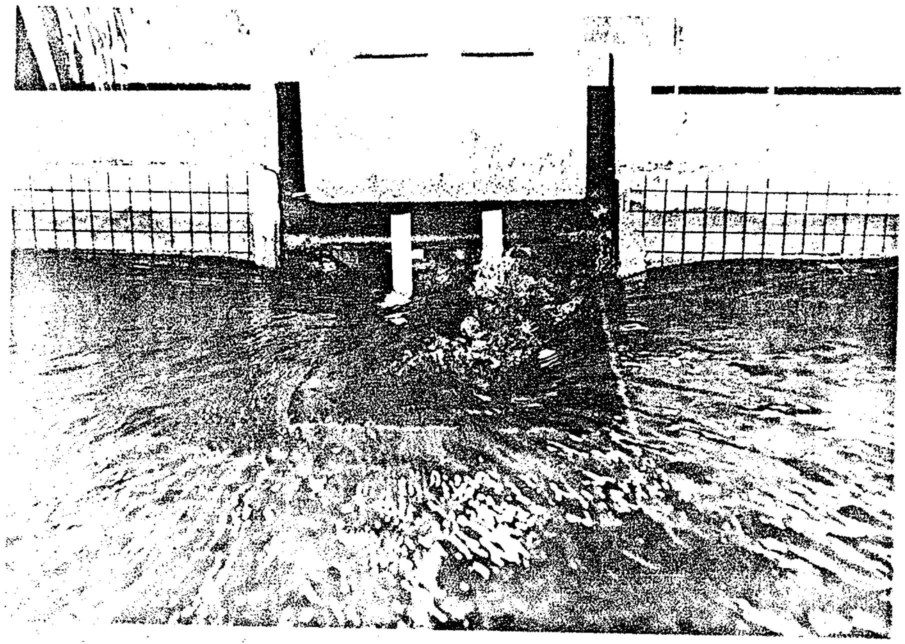
$S_X = 0.50$ in./ft. $Q_1 = 2.86$ c.f.s.



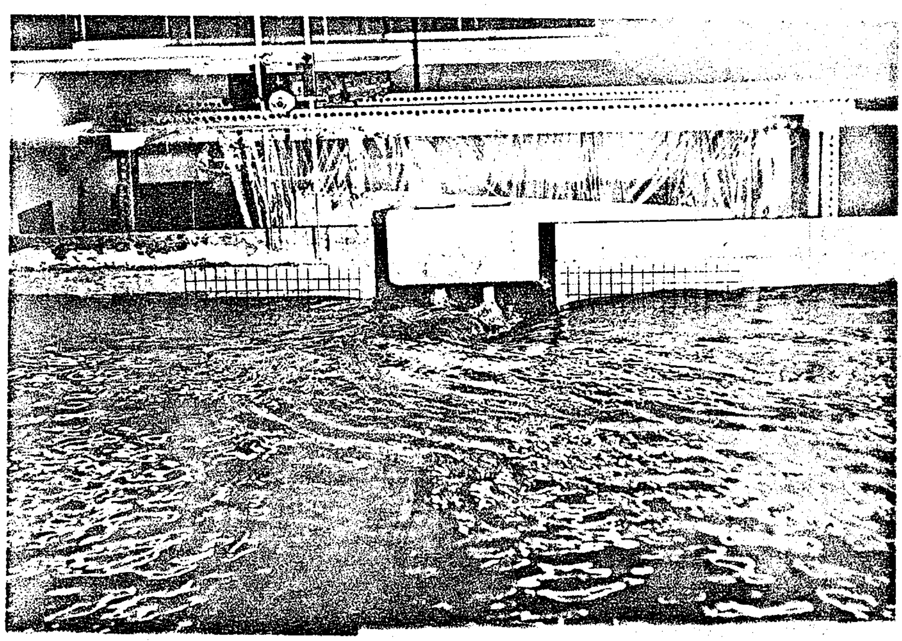
42. $S_E = 0.51\%$ $S_W = 0.54\%$
$S_X = 0.25$ in./ft. $Q_i = 0.66$ c.f.s.



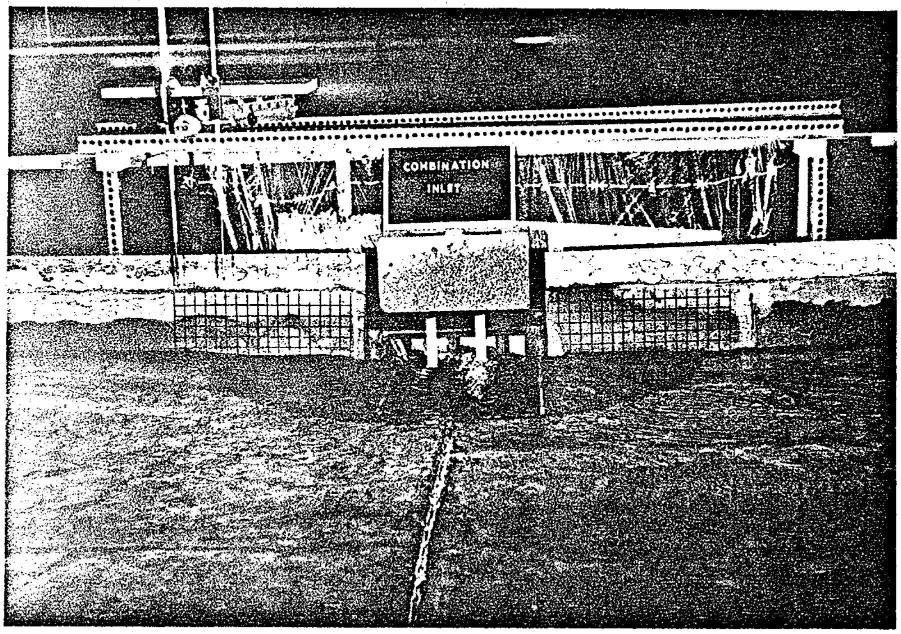
43. $S_E = 0.51\%$ $S_W = 0.54\%$
$S_X = 0.25$ in./ft. $Q_i = 1.98$ c.f.s.



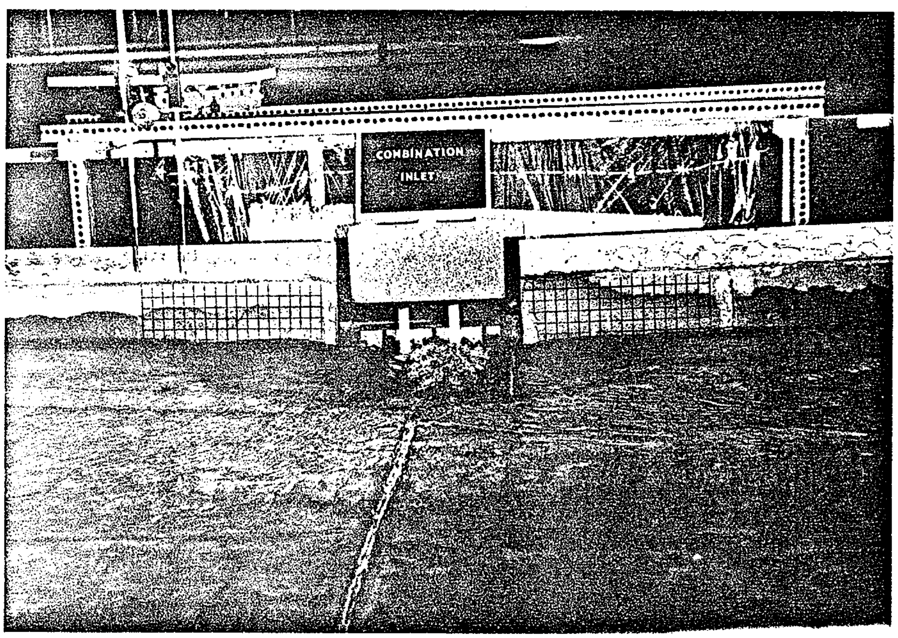
44. $S_E = 0.51\%$ $S_W = 0.54\%$
$S_X = 0.25$ in./ft. $Q_i = 1.98$ c.f.s.



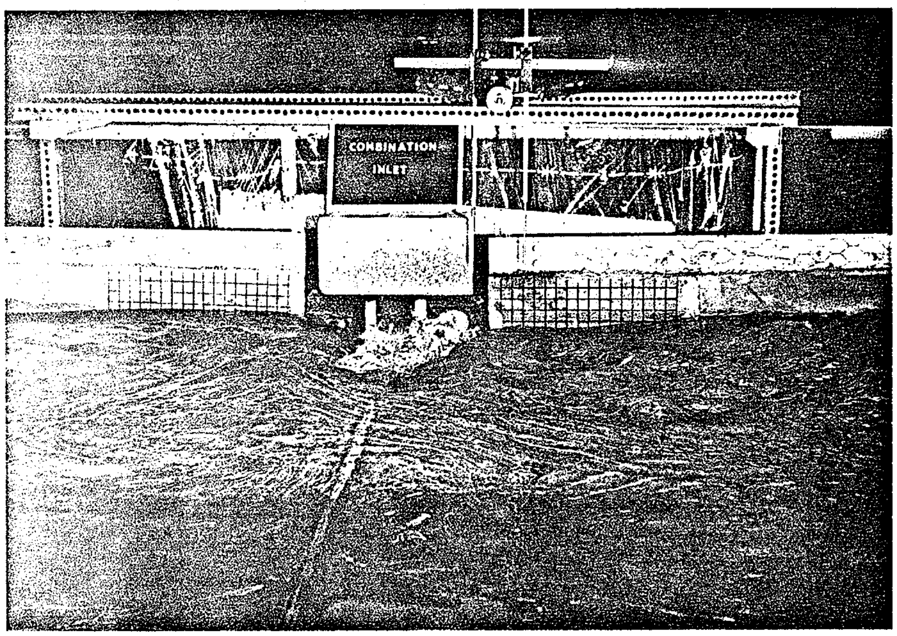
45. $S_E = 0.51\%$ $S_W = 0.54\%$
$S_X = 0.50$ in./ft. $Q_i = 3.15$ c.f.s.



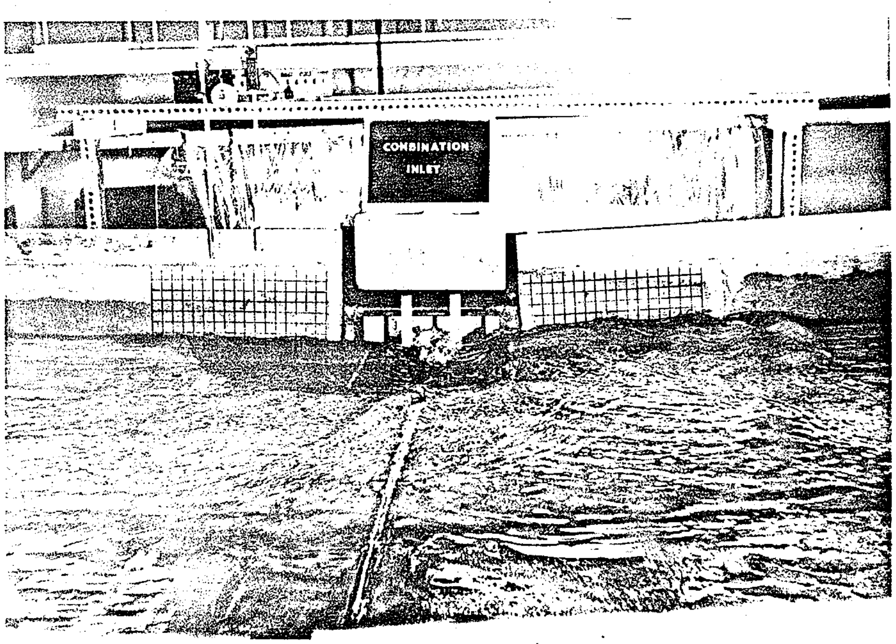
46. $S_E = 2.02\%$ $S_W = 1.96\%$
$S_X = 0.50$ in./ft. $Q_i = 0.79$ c.f.s.



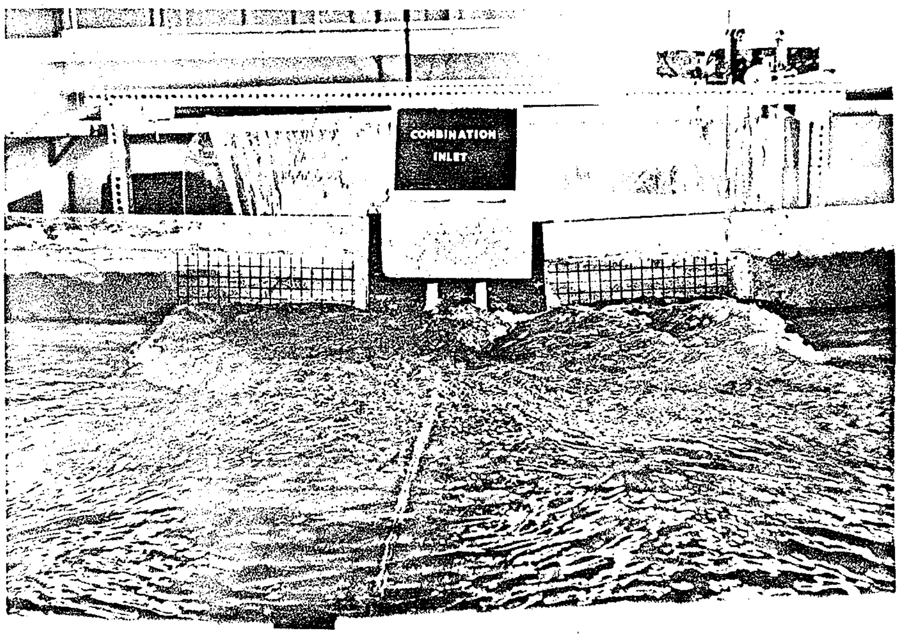
47. $S_E = 2.02\%$ $S_W = 1.96\%$
$S_X = 0.50$ in./ft. $Q_i = 1.60$ c.f.s.



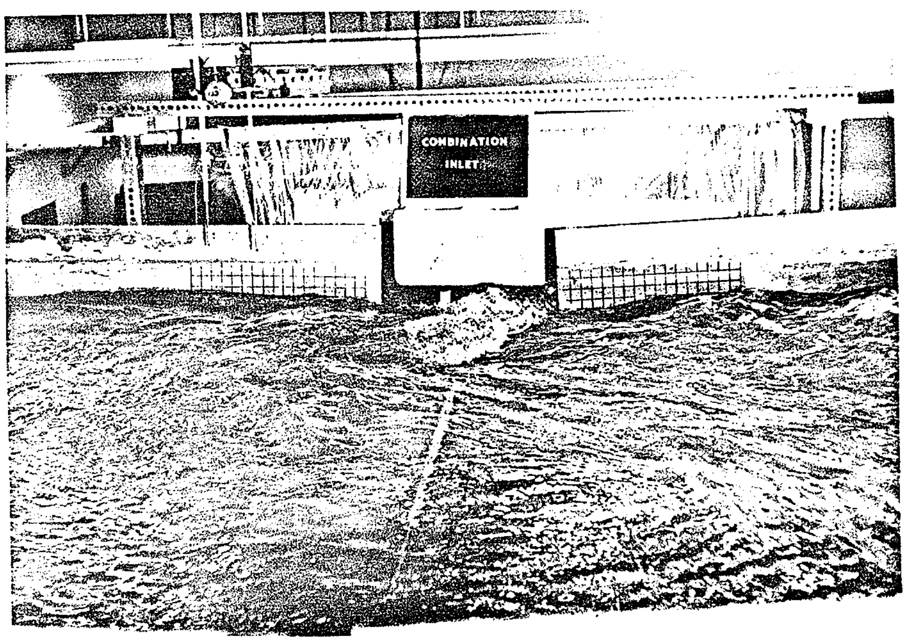
48. $S_E = 2.02\%$ $S_W = 1.96\%$
$S_X = 0.50$ in./ft. $Q_1 = 2.87$ c.f.s.



49. $S_E = 4.01\%$ $S_W = 4.03\%$
$S_X = 0.25$ in./ft. $Q_1 = 0.75$ c.f.s.



50. $S_E = 4.01\%$ $S_W = 4.03\%$
$S_X = 0.25$ in./ft. $Q_i = 2.46$ c.f.s.



51. $S_E = 4.01\%$ $S_W = 4.03\%$
$S_X = 0.25$ in./ft. $Q_i = 3.19$ c.f.s.

5.3.2 Dye Test Results

Since the dye was introduced into the flow on the surface using a hand operated syringe-type apparatus, the results obtained were of a very general nature and purely qualitative.

Two indications of importance were given by the dye stream. First, the horizontal velocity distribution (on the surface) of the gutter flow approaching the inlet was similar in all of the tests to that which is shown in Figure 36. For a curb inlet (depressed or undepressed) and combination inlet, V_{MAX} is located closer to the curb than for a gutter inlet.

The second observation made during the dye tests concerned the circulation of water ponded in the sump, as shown in Figure 37. The same circular pattern on either side of the inlet centerline was observed in all cases, with the only difference being that as the gutter slopes were increased, so the rate of circulation of the water increased.

5.3.3 General Observations

Two general observations of some interest were noted during the inlet tests; these were independent of the type of inlet being tested.

First, at gutter slopes of four percent or greater, the area of ponded water formed a noticeable 'bulge' in the sag,

FIGURE 36. GUTTER FLOW VELOCITY DISTRIBUTION

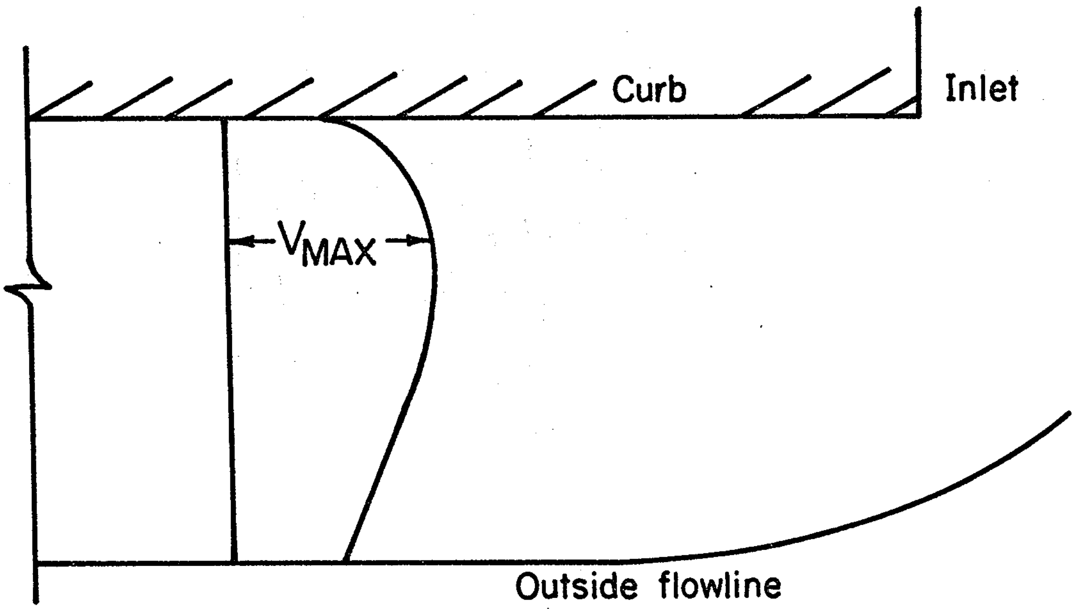
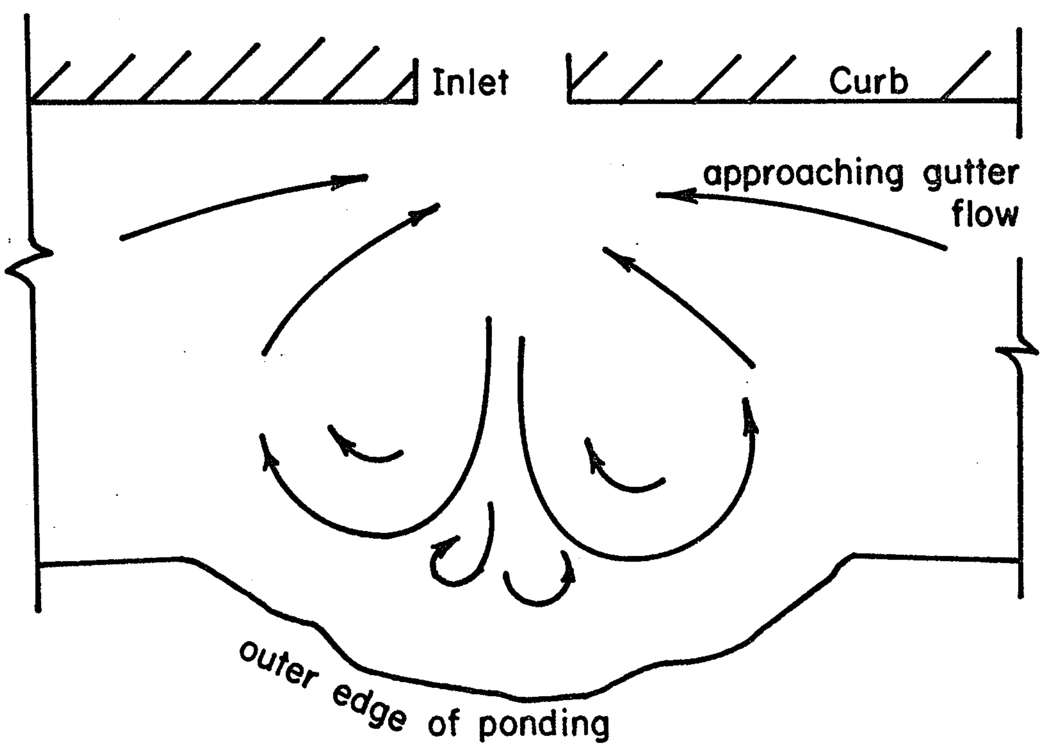


FIGURE 37. FLOW PATTERN IN PONDED AREA



as is pictured in Photographs 18, 40 and 50. At high flows (exceeding about two c.f.s.) this 'bulge' tended to roll, first up one of the approaching gutter slopes and then back towards the nadir of the sag, back up the other approaching gutter slope. Beyond four percent, this action increased in violence with increasing gutter slope, so that measurements of depth and observations of flow control became very difficult.

The second general observation is with regard to the surface turbulence of the flow in the vicinity of the inlet, for total flows exceeding one and one-half c.f.s. For all types of inlets, the flow was completely placid with gutter slopes up to two percent. Beyond this, the flow became increasingly turbulent until the 'rolling bulge' described above was produced.

As in any testing program, innumerable observations were made during the course of this study. Those of major importance are given above, while points of lesser significance can be observed from the data presented in Appendix B.

CHAPTER VI

EXPERIMENTAL RESULTS AND DISCUSSION

6.1 INTRODUCTION

Having presented the experimental data in the previous chapter, it is now possible to interpret that data in order to achieve the two central aims of this study:

(1) To determine the exact capacities of the City of Winnipeg sump inlets.

(2) To formulate a general mathematical statement for predicting the behaviour of these inlets under all operating conditions.

The first goal seems rather easy to obtain; however, it must be well understood what is meant by "ultimate capacity" before actual numbers can be quoted. The term may be defined in either of the following ways:

(1) The inlet flow at which the depth of ponded water in the sag will not exceed a pre-determined value. (This value is usually chosen so that one traffic lane will be left free of water at inlet capacity and will vary depending on the size of the roadway.)

(2) The inlet flow at which the depth of water at the

inlet does not exceed the height of the curb top.

The formulation of a general expression to describe the inlet flow has several facets which must be considered. First, an appraisal of the expressions derived by previous investigators of sump inlets must be checked against the data of the present study to determine to what extent these are valid when applied to the City of Winnipeg inlets. Next, the dimensionless terms derived in Chapter III must be combined with the data to find out whether or not this approach may be successfully applied to the design of inlets located in a sump. Finally, it must be determined if the constant and co-efficient of the appropriate flow control formula (weir or orifice) can be found from the data, and whether or not this approach will produce useful design equations.

The presentation of the results may then be concluded with a comment upon the general observations which were given in sections 5.3.2 and 5.3.3 of the present study.

6.2 CAPACITIES OF CITY OF WINNIPEG STANDARD INLETS

One certain result of the testing program was to reveal the amount of water passing through the inlets under various conditions of depth of ponding and width of flow spread on the pavement; in other words, the inlet capacities. This information was arranged in a series of rating curves for each inlet, plotting inlet flow capacity Q_i versus depth of ponding y, each curve representing a unique gutter and crown slope. The abscissa of the plot was y; however, two charts have been included in Appendix C which give flow spread as a function of depth and crown slope thus, the ultimate design capacity for any of the tested inlets may be read from the graphs regardless of the criteria used to define capacity.

The rating curves were analysed for each inlet, revealing the following results, which are discussed according to type of inlet.

6.2.1 Undepressed Curb Inlet

Having kept all other factors constant during the tests, it could be concluded from Figure 38 that the approaching gutter slope has no effect on the inlet performance up to a slope of four percent. Beyond four percent, the inlet capacity is reduced slightly with increasing steepness of the gutter. This decrease is less than five percent, for each percent of gutter slope increase, at least up to and including a gutter slope of six percent. It also could be observed from the graphs that the pavement cross-slope was not a factor in the behaviour of this inlet.

6.2.2 Depressed Curb Inlet

The effect of gutter slope in this case was somewhat more difficult to assess, as the curves were closely grouped and in no clear order. The influence of slope for values of S between one and six, although operative, did not significantly alter the capacities. The fact that the lowest slope (0.50%) produced the lowest capacity, and the highest (6.00%) the greatest flow through the inlet, indicates that the slope effect was to slightly increase the capacity of the inlet with an increase in the gutter slope. Crown slope did not effect the inlet operation.

6.2.3 Gutter Inlet

In the lower flow range (from 0.0 to about 2.50 c.f.s.), the effect of gutter slope is clear. An increase in the gutter slope causes a decrease in the inlet capacity. Beyond a flow of 2.50 c.f.s., however, only the curves for gutter slopes of one percent or less remain regular. For slopes exceeding one percent, the flow turbulence causes a violent vortex action which so disrupts the flow as to render it indeterminate; this action was described in section 5.3.1. The effect of crown slope appears to be minimal.

6.2.4 Combination Inlet

The curves seem to follow no logical pattern with regard to gutter slope, so that no comment could be made on its effect. It seems odd that this should be the case as the curves are quite smooth and consistant, which tends to

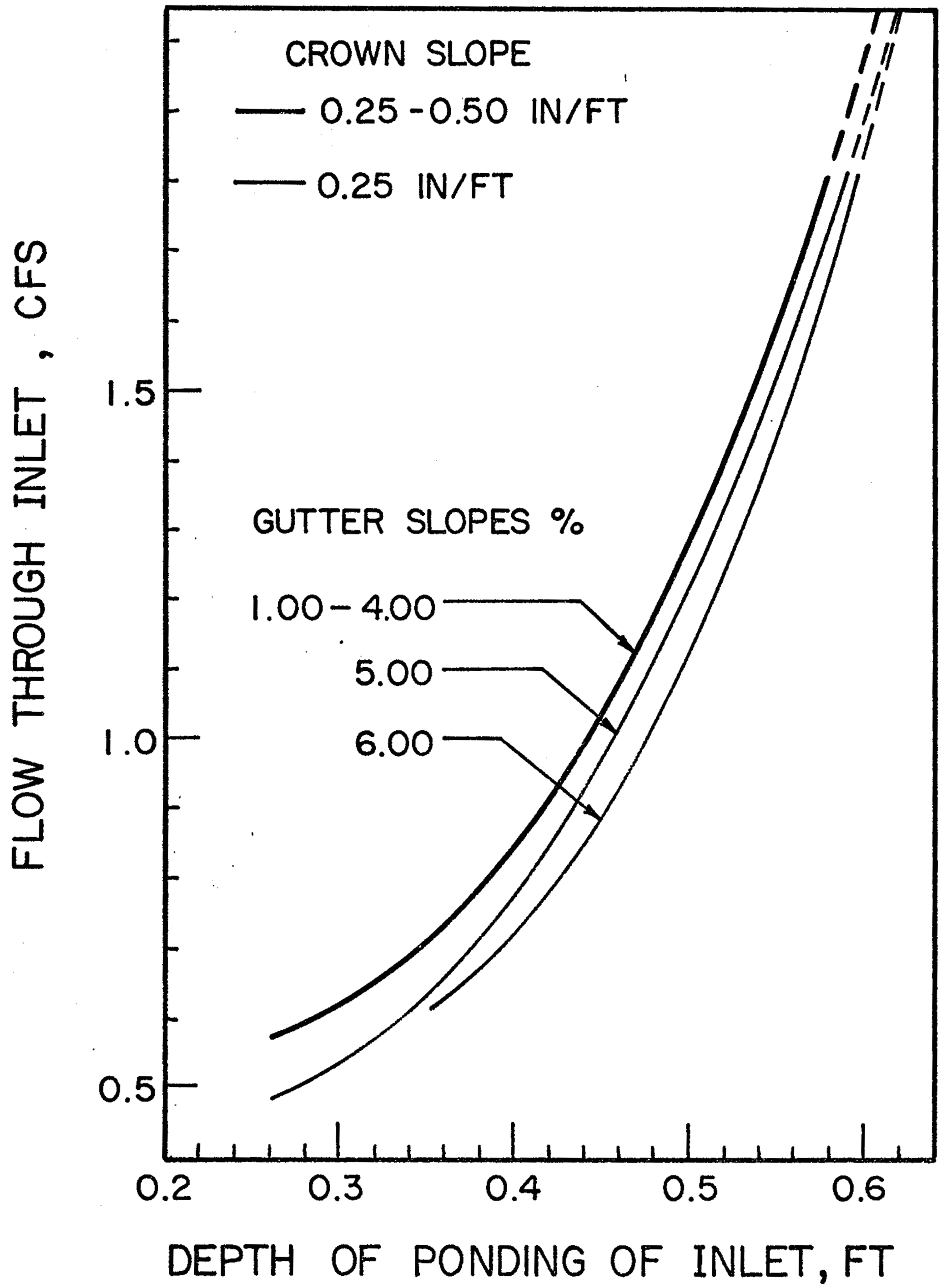


FIGURE 38: UNDEPRESSED CURB INLET RATING CURVES

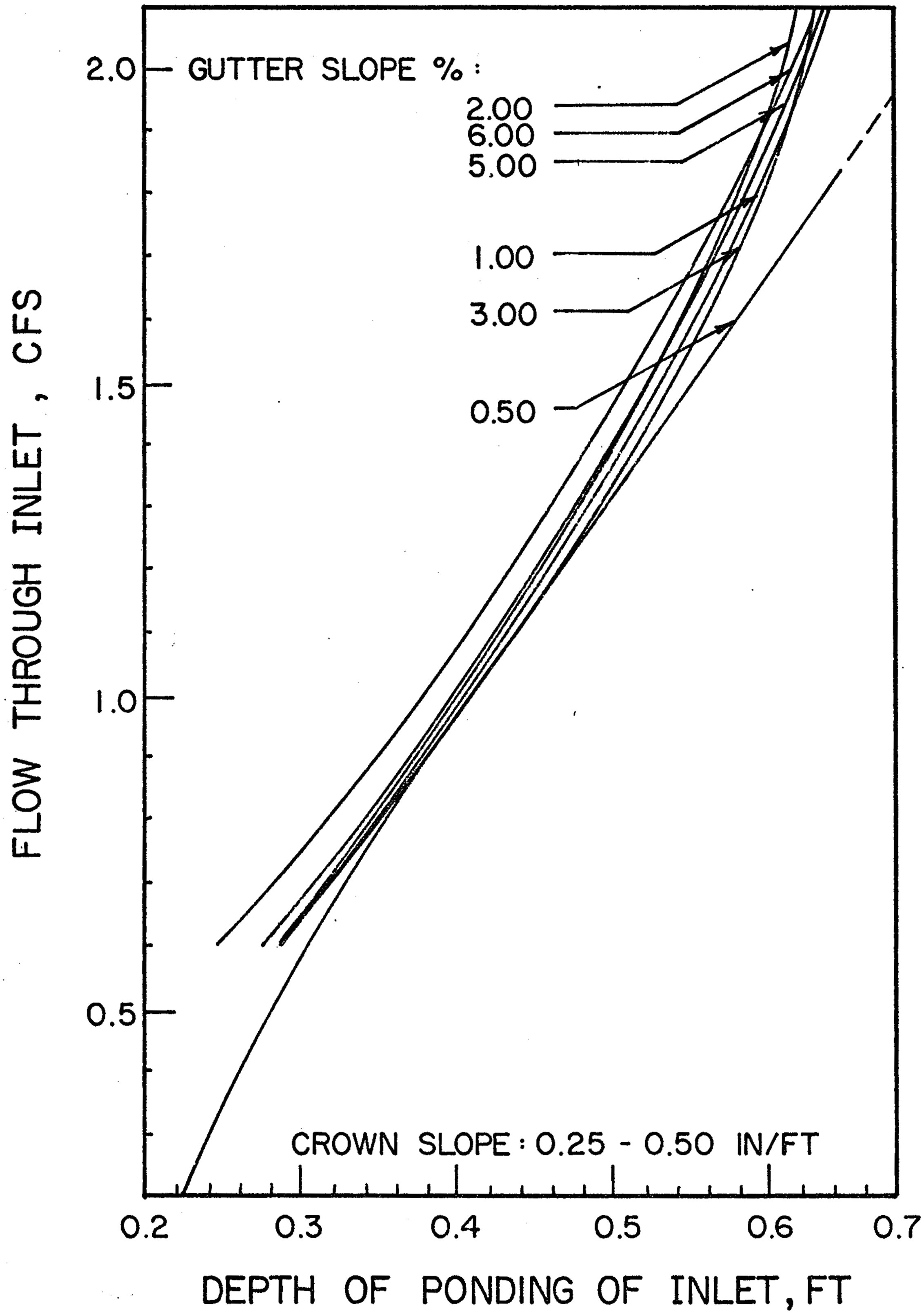


FIGURE 39: DEPRESSED CURB INLET RATING CURVES

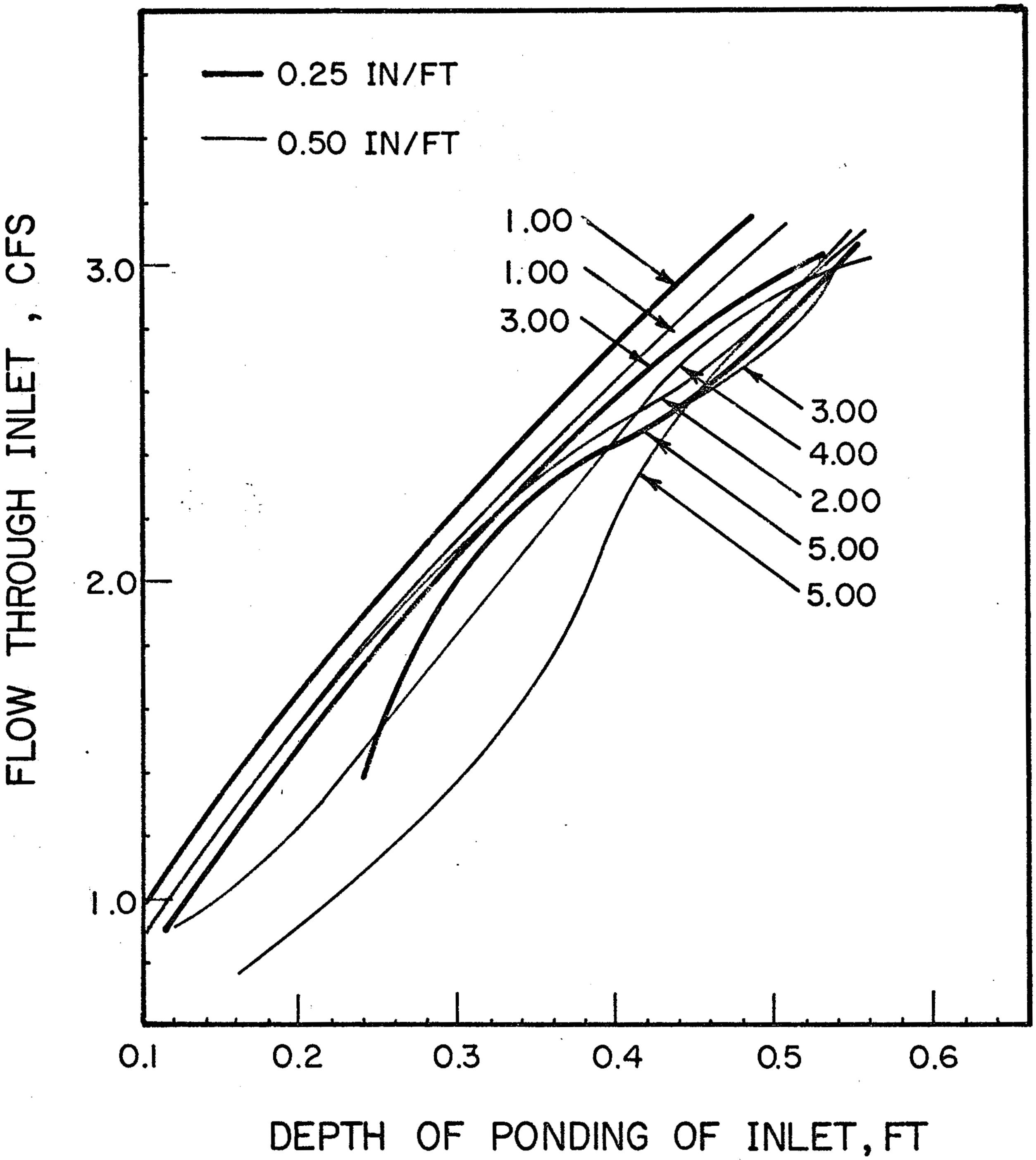


FIGURE 40: GUTTER INLET RATING CURVES

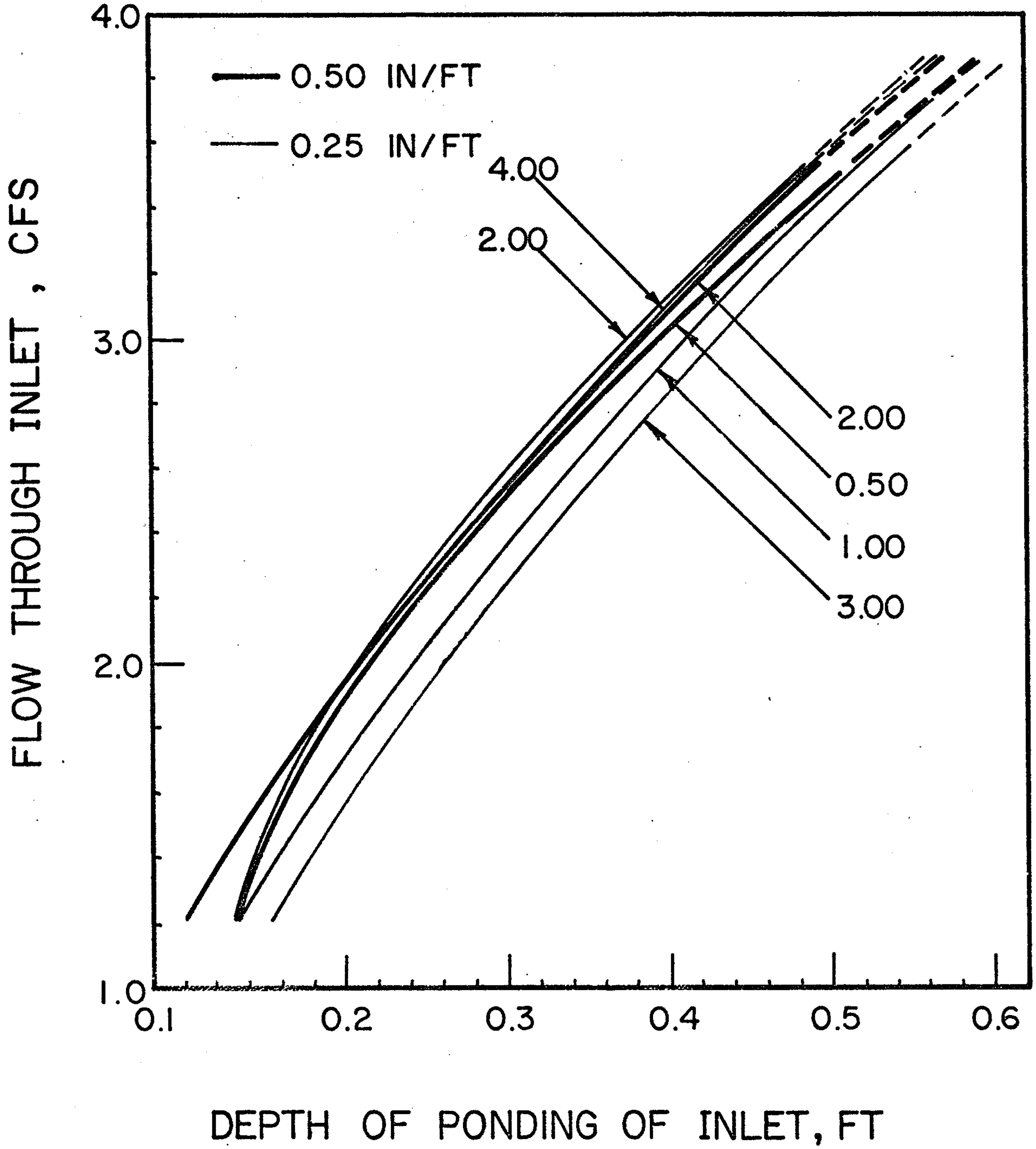


FIGURE 41: COMBINATION INLET RATING CURVES

dispell thoughts of error in the data. As was the case for the other inlets tested, the crown slope had no effect on the performance of the inlet.

6.3 RESULTS PREDICTED BY PREVIOUS SUMP INLET DESIGN FORMULAE

In the literature review of Chapter II, the design formulae proposed by other investigators for various types of inlets located in sumps has been outlined. These have been summarized in Table 5.

From Table 5, the following conclusions can be drawn:

(1) All of the formulae are independent of the crown slope of the roadway.

(2) All of the formulae are independent of the approaching gutter slopes.

(3) All of the curb-opening formulae are of the same basic form; i.e. $Q_i = Cy^n L_i$.

(4) Since the depression tested in the present study was of dimensions w = 2', and a = 2", the two formulae proposed by Karaki and Hanie which are not for depressions of this size are not applicable to the present data.

When dealing with only one inlet size and a standard depression, all of the formulae can be expressed in the form $Q_i = f(y)$, where y is the depth of ponded water at the inlet. In order to compare the design expressions of Table 5 with the data from this study, a graph of Q versus y

TABLE 5: SUMP INLET DESIGN FORMULAE

AUTHOR	INLET TYPE	FORMULA
Johns Hopkins	Depressed and undepressed curb	$Q_i = 3.0L_iy^{1.5}$
	Gutter	$Q_i = 0.6A\sqrt{2gy}$
	Combination	$Q_i = (3.0L_iy^{1.5}) + (0.6A\ 2gy)$
Karaki and Hanie	Depressed curb	
	W = 1 a = 1	$Q_i = 2(L_i + 2.4W)(d_M + W/12)^{1.78}$
	W = 2 a = 2	$Q_i = 1.7(L_i + 1.8W)(d_M + W/12)^{1.85}$
	W = 3 a = 3	$Q_i = 1.5(L_i + 1.8W)(d_M + W/12)^{1.85}$
Bauer and Woo	Depressed curb	
	W = 2 a = 2	$Q_i = 1.7y^{1.85}(L_i/2 + 0.9W)$
Zwamborn	Depressed and undepressed curb	$Q_i = 3.0L_iy^{1.5}$

based on the data and on the formulae were used for comparison. If the data curves coincided with the theoretical plots, then it could be concluded that the theoretical expression accurately described the operation of the City of Winnipeg standard inlets.

As the design formulae were all independent of gutter slope and pavement crossfall, all of the graphs based on the experimental data were plotted for a gutter slope of 0.50 percent, and a crossfall of one-quarter inch per foot. These settings were most likely to favour an expression which did not consider channel slope, as the gutter velocities would be at their lowest.

Figure 42 compares the actual and theoretical rating curves for all of the tested inlets. From this diagram, the following conclusions may be drawn on the basis of inlet type.

6.3.1 Curb Inlets

The experimental data yielded a single curve for both the depressed and undepressed inlet, the only difference being that the flow does not begin to spread across the pavement for the depressed inlets until the depth of flow at the inlet reaches two inches which is the depth of the depression. The Johns Hopkins formula[16)] also yields a single curve for both of these inlets; the capacity predicted by the formula is less than that which was recorded during the testing of the inlets. Using this formula would therefore have the effect of overdesigning the inlet by a factor of approximately eight percent; that is, the Johns Hopkins formula is conservative.

Bauer and Woo have developed a formula for depressed inlets only [4)]; using the form of this expression which applies to a depression of the dimensions of the standard Winnipeg depression which was used in the present study, produces the curve shown in Figure 42. At flows below 0.86 c.f.s., the formula diverges from the actual data slightly more than does the Johns Hopkins expressions discussed above, but as the flows increase, the predicted performance converges towards the actual such that at higher flows, the two are in almost exact agreement. For design purposes, this formula would be quite accurate, as the high flow ranges are critical in determining the final design.

The formula for depressed curb inlets developed by Karaki and Hanie [17)] ,which applies to a depression of the dimensions of the one tested, can be seen from Figure 42 to give results which are totally incompatable with the test data. Three factors were likely to be responsible for this:

(1) The flows of most interest to these investigators were much higher than the ultimate capacity of any of the City of Winnipeg inlets.

(2) The inlets tested were far larger than the Winnipeg inlets, the smallest having a length of five feet.

(3) Karaki and Hanie only tested inlets with no grating.

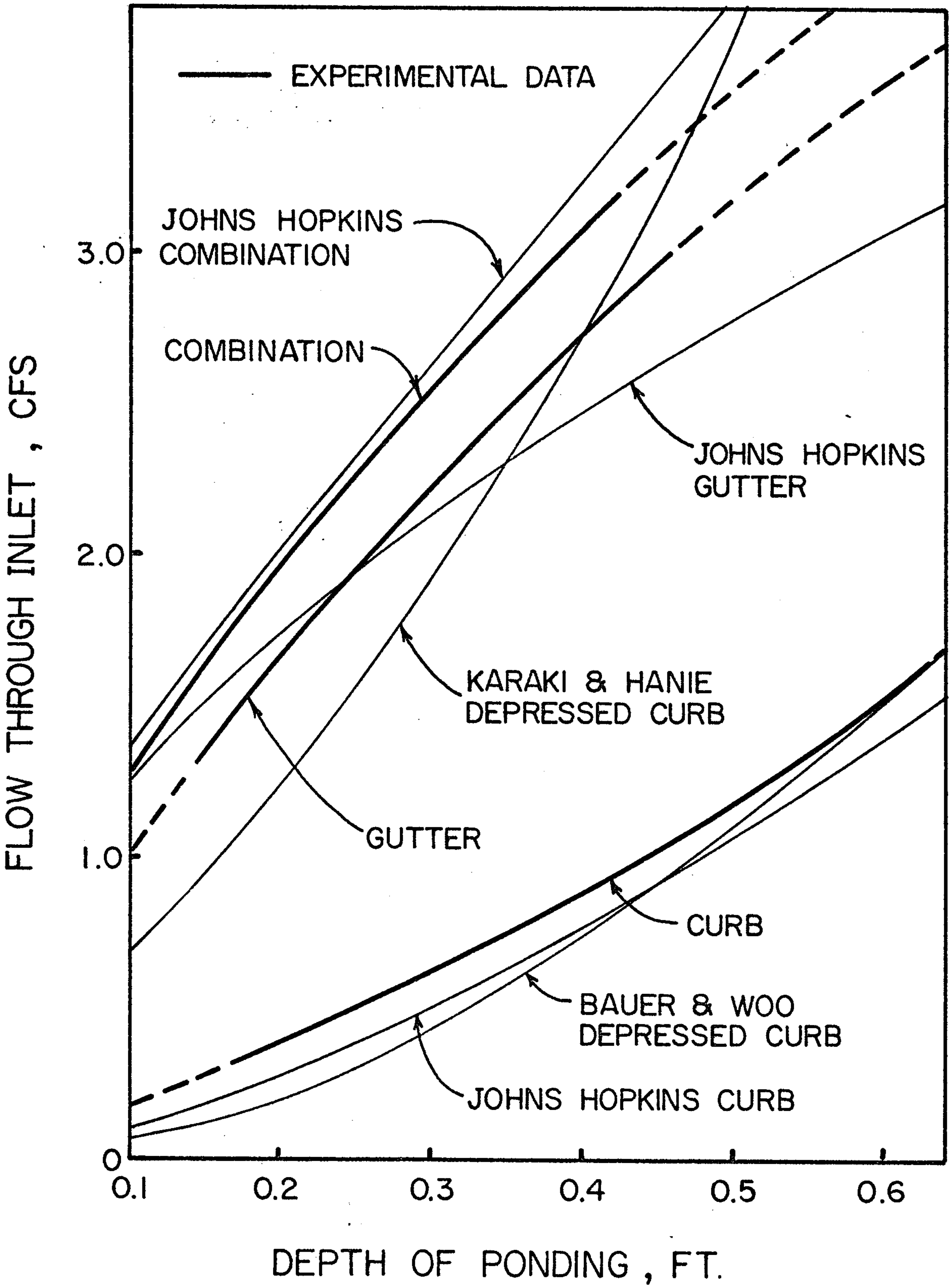
6.3.2 Gutter Inlets

The only design equation available for gutter inlets was developed by the Johns Hopkins University [16]. It has been plotted in Figure 42. Only at one point (Q_i = 2.0 c.f.s.) does the formula conform to the actual test data. Up to flows of 2.0 c.f.s., there is a convergence towards the actual performance, but beyond that flow the theoretical curve diverges rapidly from the empirical relation, so that in the region of the inlets ultimate capacity, the difference between the two is greater than thirteen percent, the Hopkins formula being conservative.

6.3.3 Combination Inlets

The report entitled "Design of Storm Water Inlets" from the Johns Hopkins University indicated that the capacity of a combination inlet could be obtained by adding the capacities of the components, the gutter and curb inlets, those capacities being found using the appropriate Johns Hopkins formula. (See Table 5) Figure 42 shows that this approach resulted in a close agreement with the test data up to a flow of 2.50 c.f.s., while beyond that the theoretical flows were increasingly greater than those determined experimentally. Although the theory closely approximated

FIGURE 42: EVALUATION OF PREVIOUS INVESTIGATIONS



the data, it was nonetheless based on an incorrect premise. Simple addition of the empirical gutter and curb inlet curves did not produce a third curve which coincided with the combination inlet test data; the curve produced indicated much higher flows than were actually observed during the testing program.

6.4 DIMENSIONAL ANALYSIS INTERPRETATION

Of the twelve independent variables which were used in the analysis conducted in Chapter III, eight of these were recorded on the standard data sheet shown in Table 4, while the other four could readily be calculated from the experimental data. Those calculated variables were the normal gutter flow depths (the ponded water sometimes drowned out the furthest downstream reading), y_1 east and y_1 west, and the average velocities of the gutter flows at these depths, V_E and V_W. The calculations were performed using the triangular form of the Manning equation for open channel flow [21,36,38,40]. The channel geometry was defined by the known crown slopes, and the gutter slopes which were also known for each test. The 'n' value for the roughness of the channel was chosen as 0.016*, which is compatible with the trowel finished surface used on the model. The calculation then merely consisted of choosing a value for the flow and plugging the known quantities into the Manning equation to arrive at an answer for the normal gutter flow

* Drainage of Highway Pavements, Hydraulic Circular #12, United States Dept. of Transportation.

depth. The velocity was then obtained by dividing the chosen flow by the area of flow determined by the normal depth.

It should be mentioned that actual velocity readings were not taken during the tests, as the fluctuations in the readings were so rapid as to make accuracy impossible. Also the exact direction of the velocity was difficult to determine under the very turbulent flow conditions.

Having made the above calculations, the data was then applied to the dimensionless terms and various combinations were tried in graphical dimensionless plots, in an attempt to assess the various terms. No coherent results were obtained. The probable reasons for this are:

(1) The normal gutter flow depths approaching the inlet and their associated related velocities may have little effect on what happens at the inlet, since in the flow range which is critical to the inlet design, the gutter flow enters a reservoir formed by the water ponding in the sag and the incoming velocities are greatly altered by the reservoir's damping effect and by the rotational turbulence noted in Figure 37.

(2) The control of flow into the inlet varies over the operating range, the inlet behaving alternately as a weir, an orifice, or neither of these. This phenomenon was described in section 5.3.1.

6.5 DEVELOPMENT OF DESIGN FORMULAE FOR THE TESTED INLETS

Sections 6.3 and 6.4 have indicated that, first, the design formulae developed by other investigators do not adequately describe the behaviour of the Winnipeg inlets, and, secondly, dimensional analysis does not yield useful design formulae for sump inlets. Hence, an attempt was made to develop expressions which would be relied upon in the design of the City of Winnipeg standard sump inlets.

In doing this, three points must be kept clearly in mind:

(1) The observations of section 5.3.1 make it quite clear that any design formula developed will apply only for a certain range of operation, due to the changes in the flow control over the full range of inlet operation.

(2) Only two regions of the rating curve are of importance to designers. The point at which the ultimate capacity is reached (and it will vary depending on the criteria used to determine the capacity) is obviously of primary importance. The designer is also concerned with what happens at even higher flows than this, to gauge the effect of storms in excess of the design rainfall for the system, and hence to decide whether or not overdesigning is desirable.

(3) Any formula developed will apply specifically to the City of Winnipeg standard inlets and may only be extended with a certain amount of judgement and caution (see

section 6.6).

The theory of weir and orifice flow was developed fully in Chapter III. Equations 3.4 and 3.6 may, for the present testing program, be reduced to the form $Q_i = Cy^n$ (equation 3.7), since the inlet sizes were kept constant throughout the experiments. An equation of this form would result in a straight line when plotted on a logarithmic scale. This was expected to happen when a log-log plot was made of the test data, since orifice and weir flow control were observed during the course of the testing. Figures 32, 33, 34 and 35 were presented in section 5.2 of this study; these are logarithmic graphs of Q versus y (depth of ponding) for each type of inlet. They, in fact, did plot as a series of straight lines, confirming the form of the inlet equation given above.

The observations of section 5.3.1 allow the identification of the flow control in sections of the curves in Figures 32 to 35. Wherever the flow control was observed to be indeterminate, the behaviour of the inlet was very erratic; hence, no design equations could be developed for these regions. Wherever the flow was clearly weir or orifice controlled, however, the equation $Q_i = Cy^n$ could be applied to the data curves and the coefficient C and the exponent n could be evaluated* for that section of the curve with a constant slope. A constant slope on the logarithmic graphs represented a particular flow control, and a change

* A First Year of College Mathematics, Brink, Chapter 37.

in the slope meant that there was a change in the flow control. Therefore, as mentioned earlier, design equations had to be developed for particular ranges of operation for each type of inlet, the limits of these ranges being defined by the depth of ponded water at which a particular flow control began and ended.

The logarithmic rating curves for the various inlets were affected by only three variables, the inlet flow Q_i, the depth of ponded water y, and the gutter slope S. This is because the inlet size was kept constant for each type, and the crown slope S_x was proven not to be a factor in the performance of the inlet (see section 6.2). Wherever possible, an attempt was made to relate the values of C and n of the design equation for a particular range of operation to the independent variable, the gutter slope S. This was not possible wherever

(a) no logical relationship existed between C, n and S.

(b) where the number of design equations for a particular range was insufficient to determine whether or not a relationship existed.

The following represents a summary of the development of the design equations for each of the inlets tested:

6.5.1 Undepressed Curb Inlet

When Figure 32 was combined with the test observations, it was noted that for the section of the logarithmic rating curves lying between the ponded depths of 0.32 feet and 0.42 feet, the flow into the inlet was indeterminate, being neither weir nor orifice controlled. A very roughly approximate expression could have been derived for use in the design of inlets; however, its use would be questionable, considering that slope effects could not be evaluated by this method. Beyond a depth of 0.42 feet, the flow was observed to be either orifice, or orifice and weir controlled. The logarithmic curves were of constant slope in this range, allowing an application of the general flow equation 3.7. The method of determining the value of the coefficient C and the exponent n was used as outlined in section 3.6. C and n values were tabulated for each curve, every curve representing a particular gutter slope, and then a graph was constructed plotting C and n versus the gutter slope S, as appears in Figure 43. The discharge through the inlet was seen to vary as the square of the depth of ponding, with the coefficient varying as in Figure 43.

In summation, the general flow equation may be used to design an undepressed inlet utilizing the standard City of Winnipeg curb inlet grate (Figure 28-A), for any approach gutter slopes, providing that the depth of ponding designed for is not less than 0.42 feet. If the designer wishes to know how the inlet performs at some lower range, the rating curves of Figures 32 and 38 may be consulted. For depths of ponding below 0.32 feet, the general flow equation may be applied since weir control determines the flow. Values of the coefficient and exponent could be found from Figure 32. This range of flows is of little concern to designers, however.

6.5.2 Depressed Curb Inlet

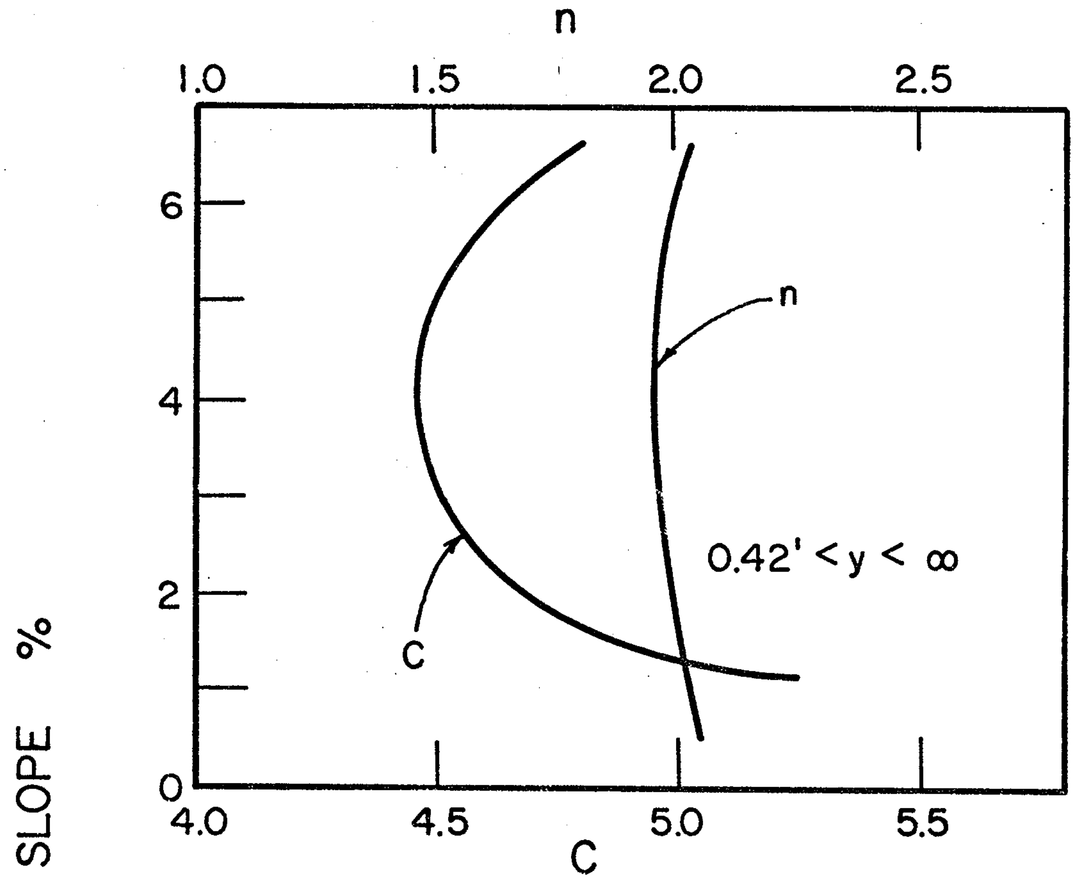
As can be seen from Figure 33, the zone of indeterminate flow for the depressed curb inlet encompasses a rather narrow range; for depths of ponding greater than 0.54 feet and less than 0.60 feet, the flow is neither weir nor orifice controlled. The logarithmic rating curves are not all irregular in this region, however, and in fact they seem to behave merely as an extension of the weir controlled flow which occurs throughout the region below a depth of ponding of 0.54 feet. Below that value, the flow was considered to be weir controlled, and above, both weir and orifice controlled. As was the case for the undepressed inlet, there was no indication by way of a change of slope of the rating curve, where the location was of the point at which the grate was overtopped and weir flow began over the grate.

The general flow equation was applied to both the upper and lower ranges as defined above, and the coefficients and exponents were evaluated. For the lower range (y less than 0.60 feet), C and n were plotted against the approach gutter slope S. This graph is shown in Figure 44. For the upper range, however, the curves for each particular slope were not readily distinguishable. Only one equation was derived for this range. This design equation is: $Q_i = 5.60y^{2.22}$, for y greater than 0.60 feet. The above equation is the one which would be of greatest use to the designer as it includes the region in which the ultimate capacity of the inlet would likely be found. Hence, unlike the undepressed curb inlet, the design of the depressed inlet would be independent of the gutter slope. It must be noted, however, that this does not mean that the slope has no effect on the inlet flow in this range, but only that the effect is not great enough to be incorporated into as gross an expression as the general flow equation based on the logarithmic rating curves.

The design equations for the upper flow range for the depressed and undepressed curb inlets are reasonably close to equality, with the depressed inlet coefficient being larger by about eight percent. The exponent is approximately ten percent larger than those values for the undepressed case. Thus, the increased capacity of the depressed inlets is due in large measure to the greater depth of ponding allowed by a local depression in the gutter surface.

6.5.3 Gutter Inlets

FIGURE 43: UNDEPRESSED CURB INLET DESIGN CURVES



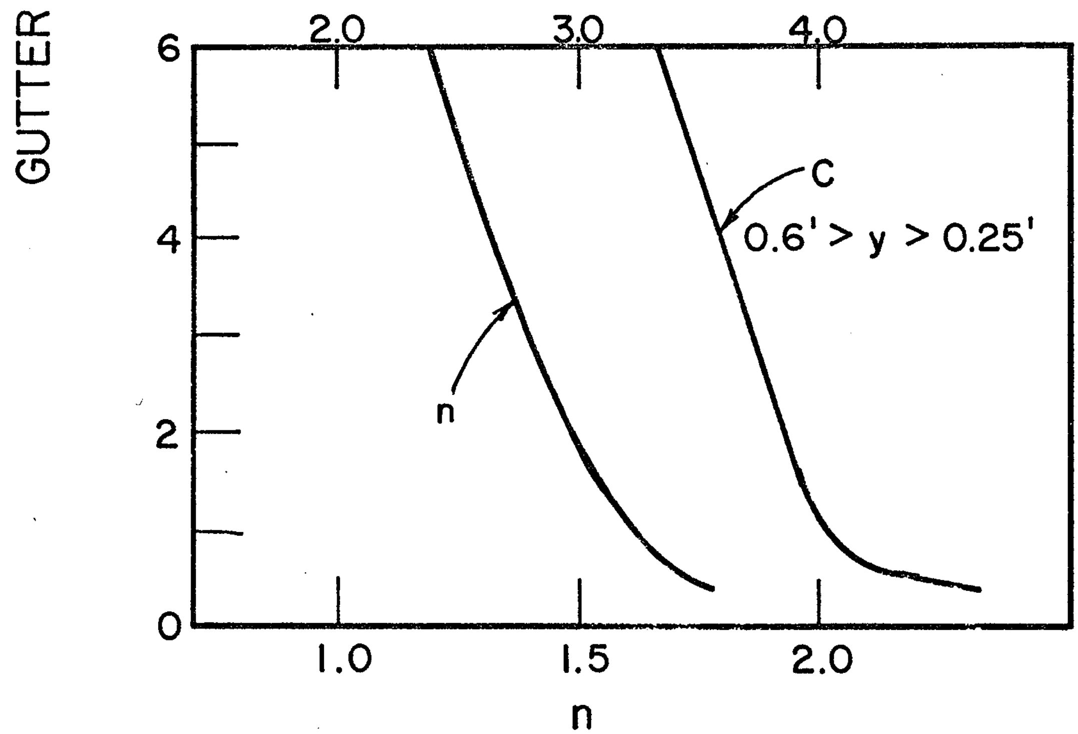


FIGURE 44: DEPRESSED CURB INLET DESIGN CURVES

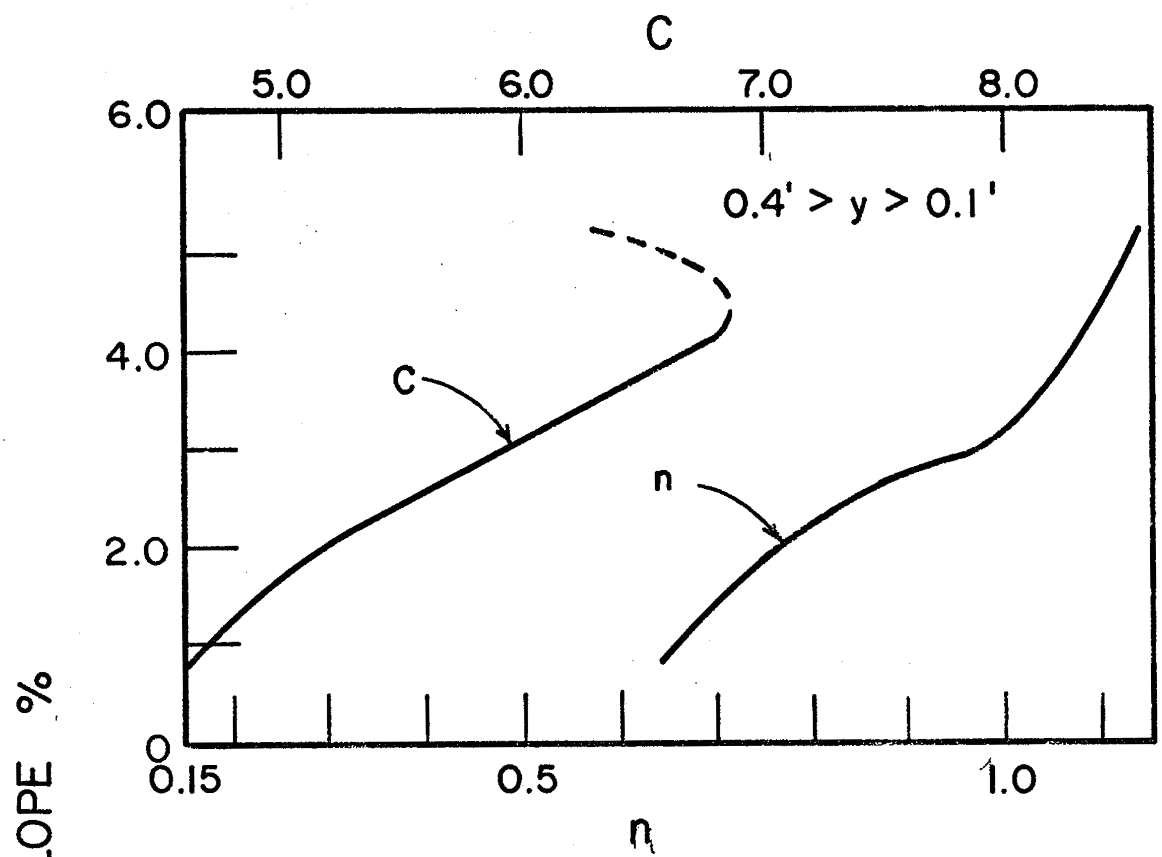
Figure 34 revealed that beyond a depth of ponded water of 0.40 feet, the flow was extremely erratic. This was described in section 5.3.1, and as was stated there, the vortices and general turbulence of the flow was so great in this region that it was obvious that full orifice flow was not being developed. The apparatus did not have a large enough capacity to produce sufficient flow to completely submerge the gutter grate, consequently producing orifice flow. Because of this, it was not possible, using the general flow equation, to derive a design equation for the depth range which would include the ultimate capacity of the inlet. It would be possible to use Figure 40, the gutter inlet rating curve, to arrive at a number for the approximate capacity of most practical installations.

For ponded depths below 0.40 feet, the flow was weir controlled and the general flow equation was applied to the logarithmic curves of Figure 34. Once the values of C and n were determined, a graph was constructed plotting these numbers against the approach gutter slope of the roadway. This is shown in Figure 45.

6.5.4 Combination Inlet

It was noted from Figure 35 that the logarithmic rating curves were each composed of two sections of constant slope. The lower section extended to a depth of ponding of 0.205 feet. From section 5.3.1, this was recognized as the region

FIGURE 45: GUTTER INLET DESIGN CURVES



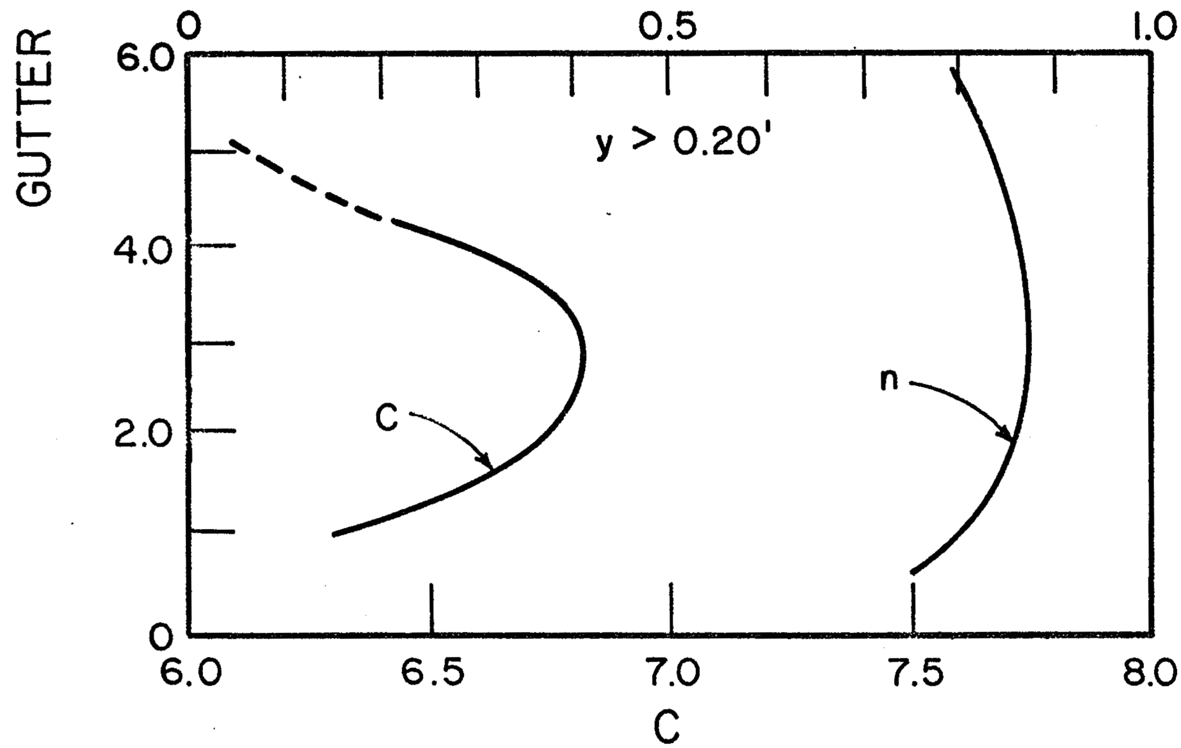


FIGURE 46: COMBINATION INLET DESIGN CURVES

in which flow was weir controlled into the gutter grate with almost no flow entering the curb inlet. Beyond a depth of 0.205 feet, the curves assumed a steeper slope, with the test observations indicating orifice flow into the gutter grate and increasing weir controlled flow into the curb opening. Since the region falling below y = 0.205 feet is of little concern in the final inlet design, the general flow equation was applied only to the upper region of the rating curves. As was done with the results obtained from the other inlets, C and n were evaluated and plotted against the gutter slope S, approaching the inlet. This design curve appears in Figure 46.

No discernable relationship could be found between the combination inlet capacities and the capacities of the component inlets (gutter and undepressed curb).

6.6 EXTENSION OF THE DESIGN FORMULAE

The formulae derived in sections 6.5.1 to 6.5.4 applied only to the Winnipeg standard inlets, and their appropriate grates, since the test data from which the equation coefficients and exponents were evaluated were only for these inlets.

In order to extend the design expressions to other inlet sizes, it would be necessary to re-evaluate the coefficient C in the equation $Q_i = Cy^n$, because of the fact that this is a generalized form of the weir and orifice equations, 3.4 and 3.6. Thus, C in the generalized equation really contains the value of L_i (length of clear opening of the inlet), when the inlet is operating as a weir, and the value of A (the area of the clear opening of the inlet), when it is operating as an orifice. Consider both of these possibilities:

(1) <u>Inlet Operating as a Weir</u>: Where the design equation for the inlet is $Q_i = Cy^n$, the value C may be divided by the value L_i, the inlet opening length for the tested grate, to yield a new coeffecent C' which is independent of the size of the inlet. When an inlet is being designed which is either larger or smaller than the tested appurtenance, the design equation becomes $Q_i = C'L_i y^n$.

(2) <u>Inlet Operating as an Orifice</u>: Again the design equation is $Q_i = Cy^n$. The coefficient C is divided by the area of the inlet opening A, to yield C' which is independent of the size of the inlet. For designing an inlet of different size from the City of Winnipeg standard inlets, the design equation then becomes $Q_i = C'Ay^n$.

Three notes of caution must be sounded with regards to the extension of the empirically derived design formulae. First, since no tests were conducted in which the inlet size was treated as a variable, the above extension is a purely theoretical analysis based on weir and orifice flow theory as outlined in Chapter III of this work. This extension should not be applied where any better means of determining capacities is available. Furthermore, if it is applied, a clear understanding of its approximate nature must be well understood. Secondly, the extension is likely to lose even its approximate value if it is applied to inlets with a geometry differing from that of the test grates. Thirdly, a complication arises in connection with combination and curb inlets which cannot be accounted for by the extension of the design formulae derived above. In the case of the combination inlet, the flow is handled by two separate openings, and at no time during the test program was it determined how much flow passed through each. Hence, the single coefficient C of the inlet design equation includes both the length of inlet openings L_i, and the area of inlet openings A. However, the effect of each will not simply be a linear one as with exclusive wier or orifice control; at least such a supposition is totally unwarranted without extensive testing. The general design equation cannot then be extended to other sizes of combination inlets without further information being available. A similar problem arises when a curb inlet grate is overtopped. In this case, the flow is orifice controlled through the grate, and weir controlled over the grate, the exact proportioning of the flow being unknown. Exactly the same difficulty is encountered as for the combination inlet; C contains both L_i and A, and this fact prevents the extension of the curb inlet design equation to inlets of varied size, for flow depths exceeding curb-top depth.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The conclusions drawn from this experimental study follow logically from the results which were given in Chapter VI. They are presented below in the same order in which the results appeared in the previous chapter.

(1) The inlet rating curves presented in Figures 38 to 41 may be used to determine the capacity of any standard City of Winnipeg sump inlet, providing that the approach gutter grade does not exceed six percent.

(2) The pavement crown slope was not a factor in determining the flow through any of the inlets tested, except at very low flows.

(3) The gutter slope did have an effect on all of the inlets tested. For an undepressed curb inlet, an increase in the gutter slope caused a decrease in the inlet capacity, for the range of slopes tested. This decrease was less than one percent for every one percent increase in the gutter slope.

For a depressed curb inlet, the slope of the gutter seemed to have an influence, but there was no discernable pattern to that effect. Also, it was so slight (less than that observed for the undepressed inlet) that it could safely be ignored.

For gutter grate inlets, an increase in the gutter slope caused a decrease in the inlet capacity. This decrease was much less than one percent for every one percent of slope increase; thus, it was significant for design purposes.

In the case of the combination inlet, there was a slight variance in the rating curves representing the different gutter slopes. Its magnitude was very slight and there was no rational pattern to the effect.

In summation, it can be stated that the gutter slopes approaching a sump inlet of the types tested in this study do have an effect on the amount of flow passing through that inlet. Although this effect may be accounted for, by ignoring it the designer would not be significantly altering the final system design.

(4) The depressed curb inlet passes approximately fifty percent more flow than does the same undepressed inlet, for the same depth of ponding in the sump.

(5) The increase in the capacity gained by depressed inlets is simple due to the greater depth of ponding allowable at the face of the inlet opening, rather than the local increase in the gutter slope afforded by the

depression.

(6) The design formula presented by Bauer and Woo [4] quite accurately predicts the behaviour of the City of Winnipeg standard depressed curb inlet. This expression could be used in design with very good results.

(7) The Johns Hopkins University formula [16] for designing depressed and undepressed curb inlets gives results which are conservative by about ten percent when compared to the study test data. This expression could be applied to the design of Winnipeg inlets of this type to give reasonably accurate results.

(8) The combination inlets tests showed that the flow through that inlet could not be determined by adding the gutter inlet and the undepressed curb inlet flows, for a given depth of ponding.

(9) The dimensional analysis technique does not offer useable solutions to problems dealing with sump inlets. Perhaps it would prove useful if an accurate determination of the flow velocities could be made in the immediate vicinity of the inlet, in future test programs.

(10) The general flow equation $Q_i = Cy^n$ may be successfully applied to the design of City of Winnipeg sump inlets, after evaluating the coefficient and exponent from the test data. Figures 43 to 46 may be used to find the values of C and n for the various inlets, and these numbers in turn can be applied to the general flow equation to

arrive at an accurate design of an inlet system.

(11) The general flow equation method of design may be extended to gutter inlets of any size (provided that the grate geometry is the same as the standard Winnipeg grate) for any depth of ponding below 0.41 feet. Also, any size of curb inlet (depressed or undepressed) may be designed using this method, for any depth of ponding below curb-top height, provided that the grate geometry is the same as for the inlets tested in this study.

7.2 RECOMMENDATIONS FOR FURTHER STUDY

During the course of this work, it became obvious that, although the inlets were being isolated from the over-all storm water runoff system for purposes of study, the results obtained would have little meaning unless more information became available concerning the parts of the system adjacent to the inlet. The inlet is merely a part of the "inlet system" leading into the storm drains, which consists of the following:

(a) the inlet.

(b) an inlet box immediately behind or below the inlet opening.

(c) a catch basin into which the flow moved befor entering the storm drain.

(d) the piping connecting the inlet box with the catch basin.

It is suggested that a laboratory test program be established to determine the performance and effects of the standard inlet boxes and catch basins which are in use in the City of Winnipeg.

It also became apparent during the tests that one investigator with limited time and funds could not hope to cover all of the various aspects of the design of storm water inlets. With this in mind, it is suggested that future investigations be conducted to deal with the following matters:

(1) Further tests are required utilizing the standard City of Winnipeg inlet geometry, but varying the size of the tested opening.

(2) Sump inlet tests which are thoroughly instrumented to record the velocity of the flow in the region of ponding are required so that a more rigorous mathematical analysis than that which was conducted in the present study could be attempted.

(3) More details are required on the standard gutter inlet. Experimentation using apparatus which is capable of producing flows resulting in orifice control of the inlet would supply this information.

(4) A study of combination inlets located in sumps is required which could determine the relative apportioning of the flow between the two components of this inlet.

In closing, one further point is worth mentioning for future consideration. The tests conducted in this study have utilized standard grates installed using a standard procedure. Future tests will quite likely follow this approach as well. It would thus be extremely useful for the designers of inlet systems to know how closely the field installations of the City of Winnipeg standard inlets conform with the practice of the laboratory investigators. A survey of some of the existing inlets on city streets would supply this information; the data would consist of the area of the inlet opening, the length of the clear opening, and the height of the curb at the inlet.

BIBLIOGRAPHY

American Society of Civil Engineers, The Design and Construction of Sanitary Storm Sewers: Manuals of Engineering Practice, #27, New York, 1960.

Armstrong L. W., and Tapley, G. S., Engineering News Record, p. 54, July 9, 1931.

Babbitt, H. E. and Baumann, E. R., Sewerage and Sewage Treatment, Chapter 6, Wiley and Sons, 1958.

Bauer, W. J., and Woo, D. C., Hydraulic Design of Depressed Curb Opening Inlets, Highway Research Board Record, #58, 1964.

Bock, P., Li, W. H., and Geyer, J. C., A Simplified Method of Determining Capacities of Single and Multiple Inlets, Sewage and Industrial Wastes, Volume 26, 1956.

Cassidy, J. J., Generalized Hydraulic Characteristics of Grate Inlets, Highway Research Board Record, #123, 1966.

Clark, J. W., and Viesmann, W., Water Supply and Pollution Control, Chapter 6, International Textbook Company, 1966.

Conner, N. W., Design and Capacity of Gutter Inlets, Highway Research Board Proceedings, Volume 25, 1945.

Conner, N. W., North Carolina State College Bulletin, #30, July, 1945.

Guillou, J. C., The Use and Efficiency of Some Gutter Grate Inlets, University of Illinois Experimental Station Bulletin, #450, 1959.

Hamlin, J. G., and Bautista, J., On the Spot Tests to Check Gutter Capacities, The American City, April, 1965.

Hicks, W. I., Runoff Computations and Drainage Inlets for Parkways in Los Angeles, Highway Research Board Proceedings, Volume 24, 1944.

Horner, W. W., Municipal and County Engineering, October, 1919.

Izzard, C. F., Hydraulics of Runoff from Developed Surfaces, Highway Research Board Proceedings, Volume 26, 1946.

Izzard, C. F., Tentative Results on Drop Opening Inlets, Highway Research Board Report, #11-B, 1948.

Johns Hopkins University, Design of Storm Water Inlets, Baltimore, Maryland, 1956.

Karaki, S. S. and Hanie, R. M., Depressed Curb Opening Inlets - Supercritical Flow Data, Colorado State University Research Foundation, Civil Engineering Section, June, 1961.

Knapp, J. W., Schakke, J. C. and Viesmann, W., Measuring Rainfall and Runoff at Storm Water Inlets, A.S.C.E. Hydraulics Journal, Volume 89, 1963.

Larson, C. L., Experiments on Flow Through Inlets and Gratings for Street Gutters, Highway Research Board Report, #6-B, 1948.

Larson, C. L., Grate Inlets for Surface Drainage of Streets and Highways, St. Anthony Falls Hydraulics Laboratory Bulletin, #2, University of Minnesota, 1949.

Larson, C. L., Transverse Distribution of Velocity and Discharge in a Shallow Triangular Channel, M.Sc. Thesis, University of Minnesota, 1949.

Li, W. H., Hydraulic Theory for the Design of Storm Water Inlets, Highway Research Board Proceedings, Volume 33, 1954.

Li, W. H., Geyer, J. C., and Benton, G. S., Gutter Inlets With no Depression, Sewage and Industrial Wastes, Volume 23, 1951.

Li, W. H., Geyer, J. C. and Sorteberg, K. K., Flow Into Curb Opening Inlets, Sewage and Industrial Wastes, Volume 23, 1951.

Li, W. H., Geyer, J. C. and Goodell, B. C., Flow Into Deflector Inlets, Sewage and Industrial Wastes, Volume 26, 1954.

Li, W. H., Geyer, J. C. and Goodell, B. C., Flow Into Depressed Curb Inlets, Sewage and Industrial Wastes, Volume 26, 1954.

Linsley, R. K. and Franzini, J. B., Elements of Hydraulic Engineering, McGraw-Hill, 1955.

Los Angeles, City of, Design Charts for Catch Basin Openings Determined by Experimental Hydraulic Model Studies, Office Standard 108, Storm Drain Design Division.

Metcalf, L. and Eddy, H. P., American Sewerage Practice, Volume 2, Chapter 15, McGraw-Hill, 1928.

Nester, N. W. and Guillou, J. C., Public Works, July, 1955.

Nester, N. W. and Guillou, J. C., Public Works, May, 1954.

Rouse, H., Fluid Mechanics for Hydraulic Engineers, McGraw-Hill, 1938.

Rouse, H., Boota and Hsu, High Velocity Flow in Open Channels: Design of a Channel Expansion, A.S.C.E. Transactions, Volume 116, 1951.

Steel, E. W., Water Supply and Sewerage, Chapter 16, McGraw-Hill, 1960.

Tapley, G. S., Hydrodynamics of Model Storm Sewer Inlets Applied to Design, A.S.C.E. Transactions, Volume 116, 1951.

Tapley, G. S., Velocity Distribution in a Street or Similar Channel, Highway Research Board Proceedings, Volume 34, 1955.

U. S. Army Corps of Engineers, Airfield Drainage Structure Investigations, Hydraulic Laboratory Report, #54, Iowa City, April, 1949.

U. S. Bureau of Public Roads, Design Charts for Open Channel Flow, Hydraulic Design Series, #3, 1961.

Wasley, R. J., Hydrodynamics of Flow into Curb Opening Inlets, A.S.C.E. Engineering Mechanics Journal, Volume 87, 1961.

Wasley, R. J., Uniform Flow in a Shallow Triangular Open Channel, A.S.C.E. Hydraulics Journal, September, 1961.

Whittington, R. B., A Simple Dimensional Method for Hydraulics Problems, A.S.C.E. Hydraulics Journal, Volume 89, 1963.

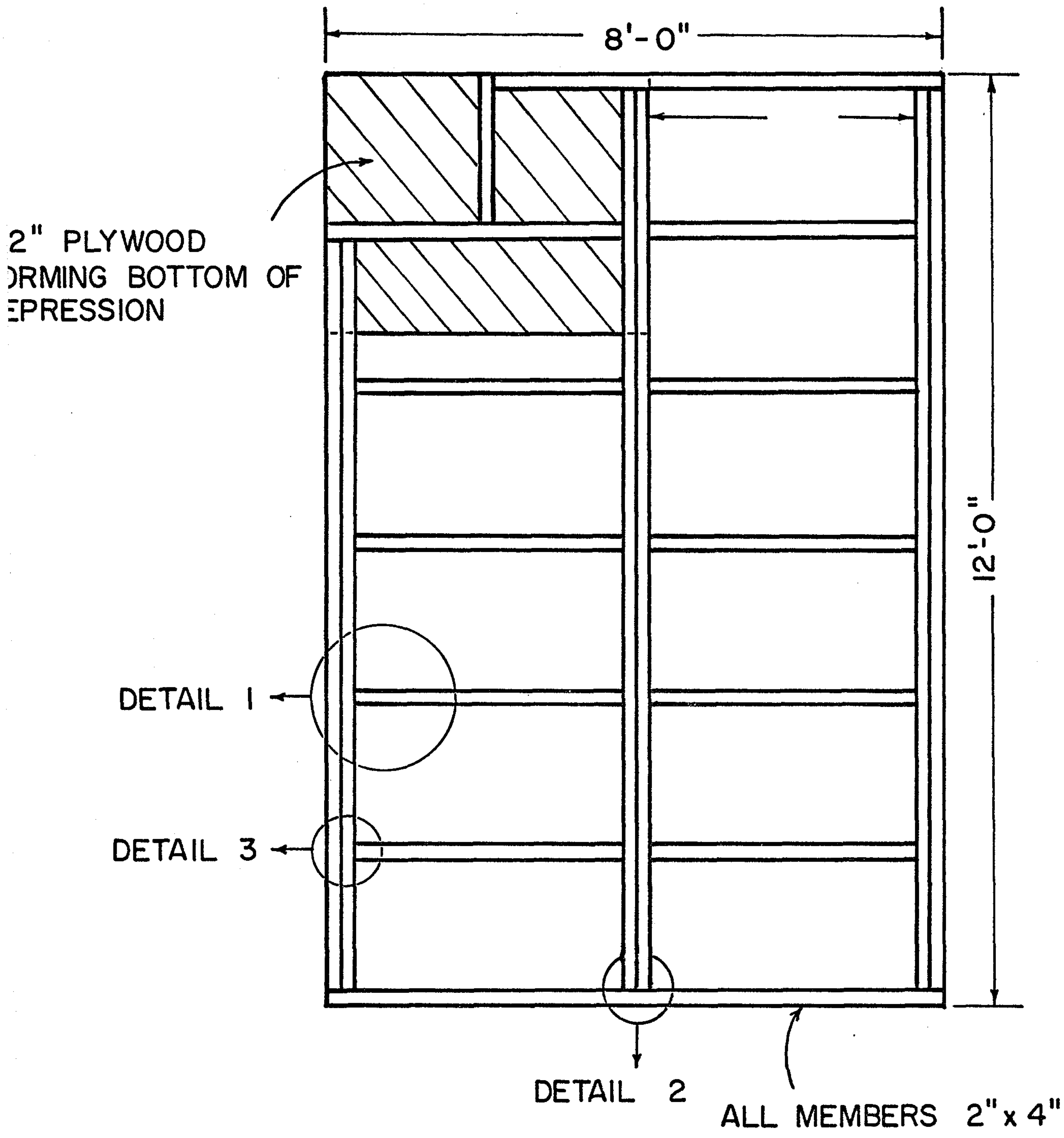
Wintz, W. A. and Kus, Y. H., A Study of Storm Water Inlet Capacities, Louisiana State University and Agricultural and Mechanical College, Baton Rouge, Louisiana, 1970.

Yong, K. C., Hydraulic Model Investigation of Curb Inlets, Water Research Laboratory Report, #79, Manley Vale N.S.W., Australia, April, 1965.

Zwamborn, J. A., Storm Water Inlet Design Code, MEG 433, Hydromechanics Research Department, National Mechanical Engineering Research Institute, Council for Scientific and Industrial Research, Union of South Africa, 1966. **u52,60,2

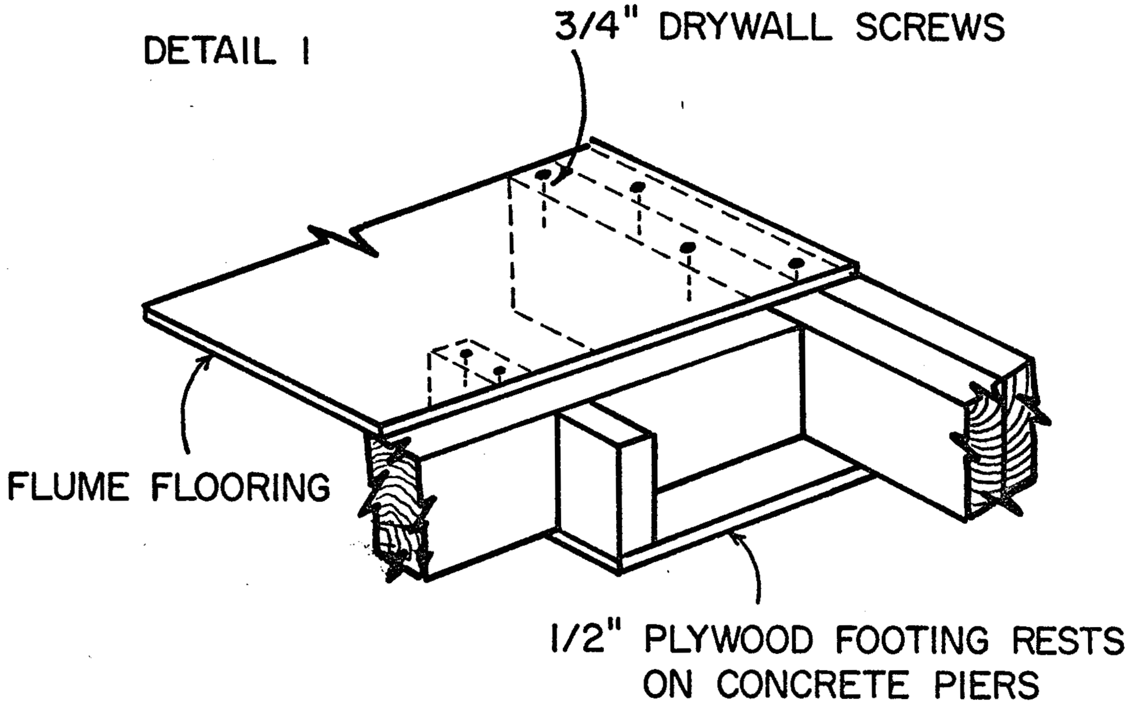
APPENDIX A

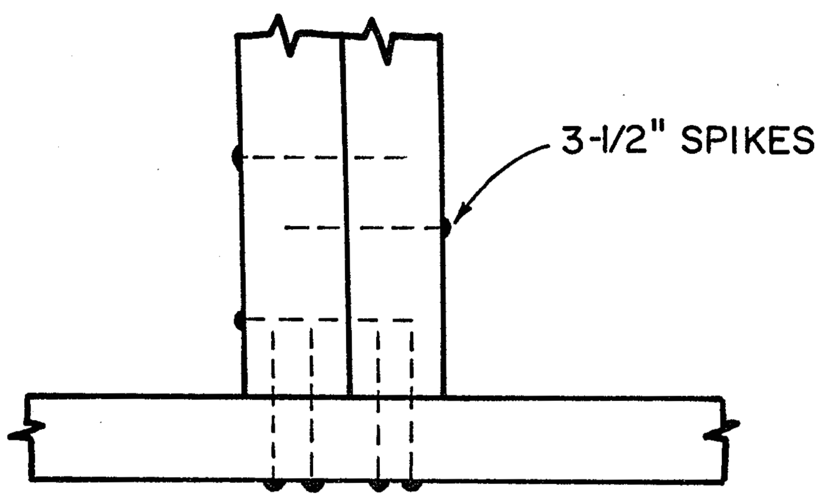
FLUME CONSTRUCTION DETAILS WITH DRAWINGS



A-1 FLUME FRAMING PLAN

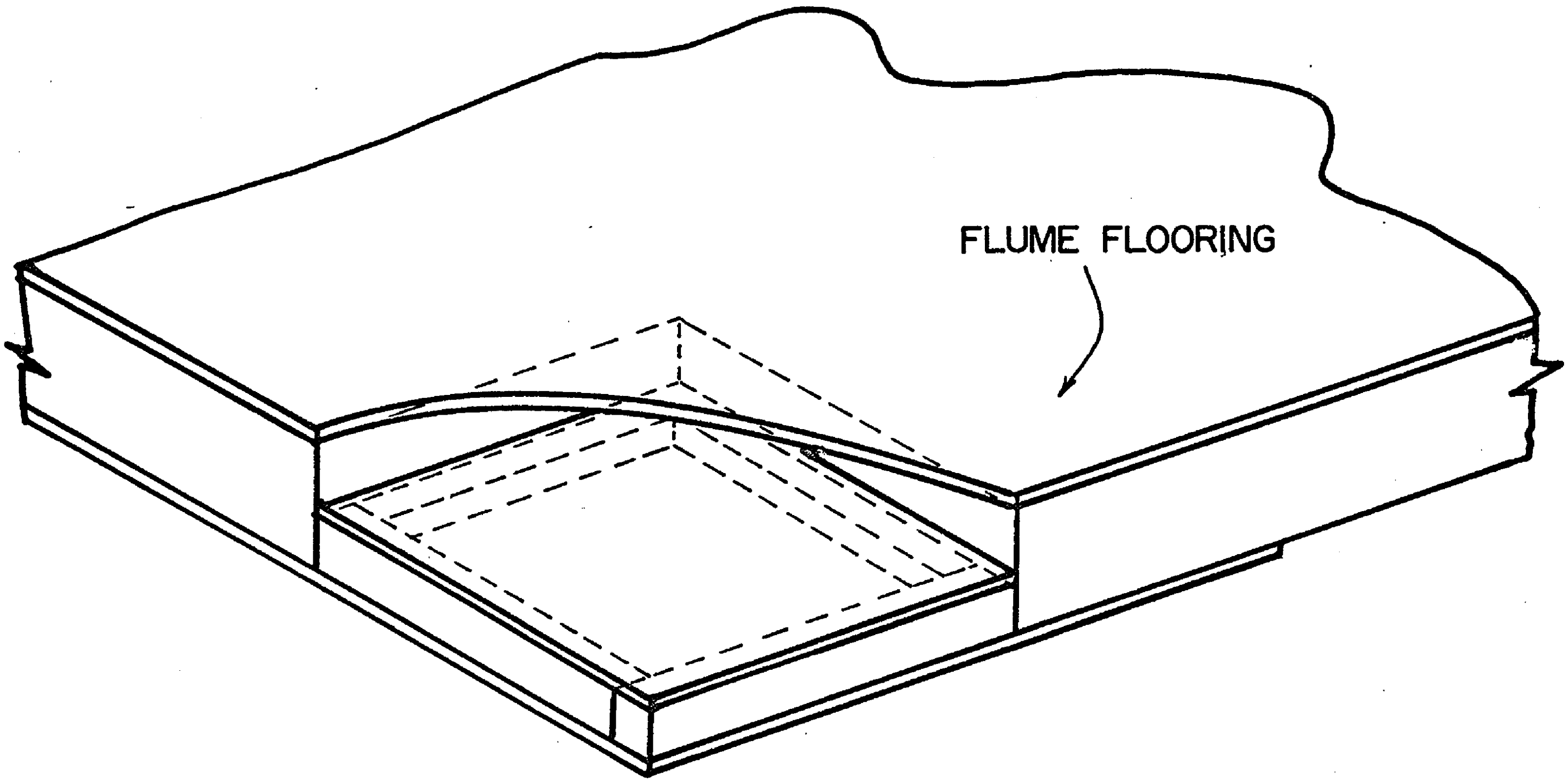
DETAIL 1



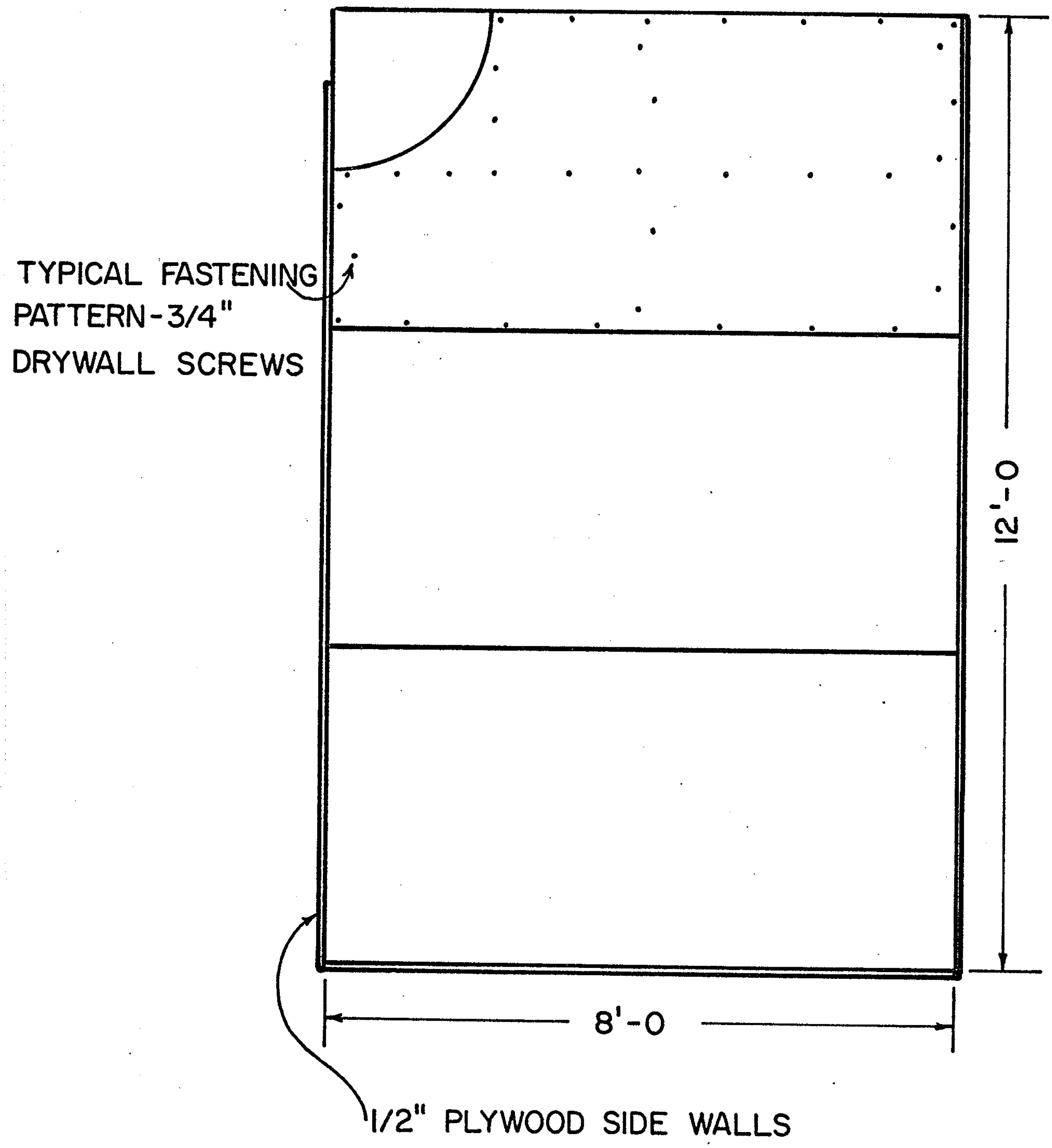


DETAIL 2

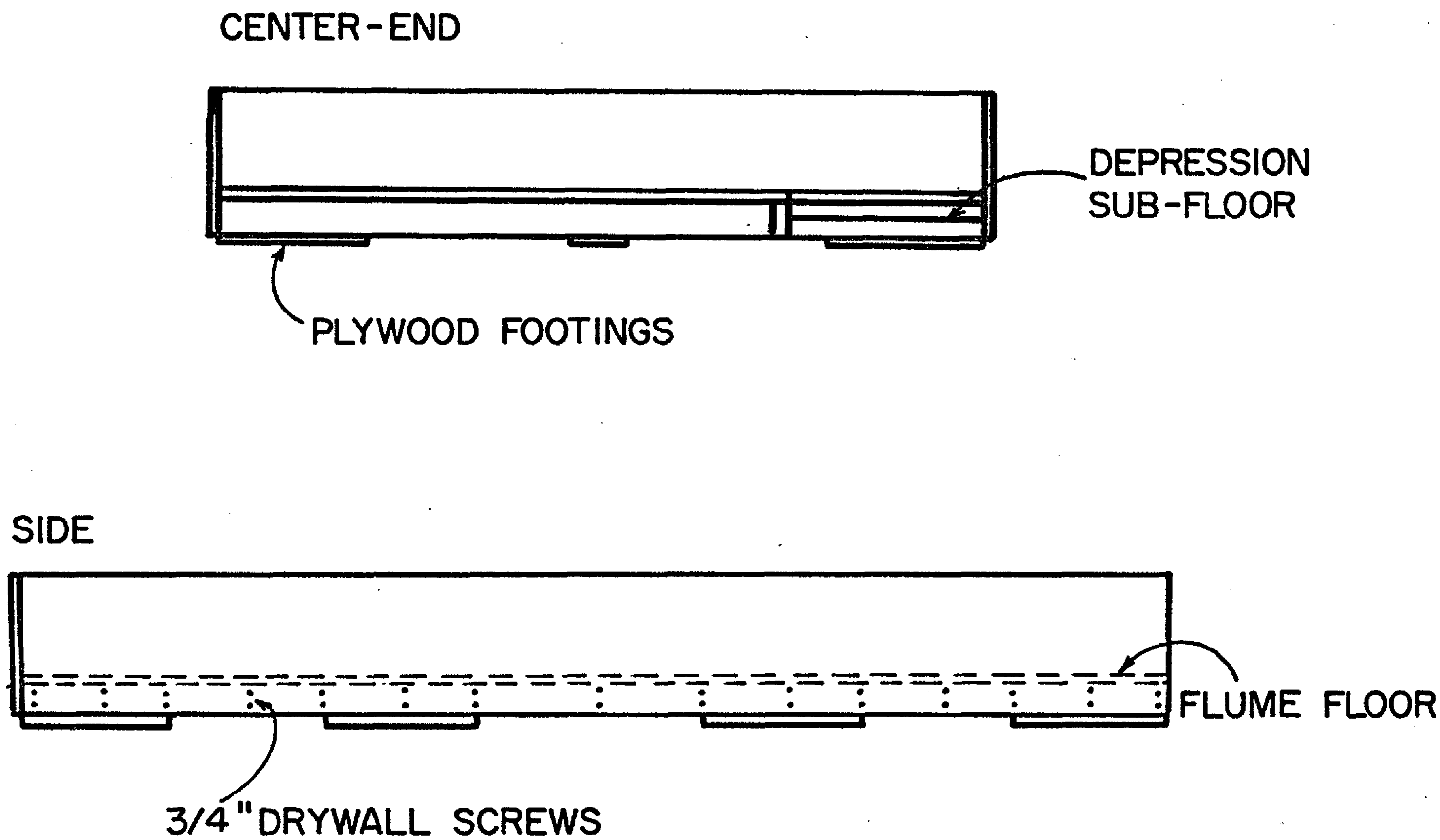
A - 2 FRAMING DETAILS



A-3 DEPRESSION DETAILS



A-4 COMPLETED FLUME PLAN VIEW



A - 5 COMPLETED FLUME ELEVATION VIEWS

APPENDIX B

EXPERIMENTAL DATA

LIST OF SYMBOLS FOR THE STANDARD DATA SHEET

SYMBOL	MEANING	DIMENSIONS
H	Measured height of water over the weir controlling the West flow source.	$Ft.x10^{-3}$
Q_1	Amount of flow entering the West end of the model.	c.f.s.
P	Measured pressure upstream of the orifice plate controlling the East flow source.	p.s.i.
Q_2	The amount of flow entering the East end of the model.	c.f.s.
Z_n	Zero reading of the mobile test gauge before each test run.	$Ft.x10^{-3}$
R_n	Reading taken from the staff gauge under a particular flow condition	$Ft.x10^{-3}$
Y_n	The depth of flow found by subtracting Z_n from R_n. The standard locations of these readings may be found in Figure 31.	$Ft.x10^{-3}$
EY_n	Indicates that the particular depth measurement is on the East side of the inlet.	None
WY_n	Indicates that the particular depth measurement is located on the West side of the inlet.	None

THE UNDEPRESSED CURB INLET

INLET: UNDEPRESSED CURB

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 1.00 %

DATE TESTED : /71

WEST GUTTER SLOPE : 1.00 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
535	0.68	8.00	0.76	457	957	500	455	963	508				533	154	672	518	147	670	523				533
510	0.59	6.00	0.60		920	463		921	466				483		628	474		630	483				483
470	0.48	4.20	0.49		860	403		861	406				450		563	409		560	413				450
457	0.44	3.40	0.44		799	342		798	343				400		503	349		500	353				400
418	0.35	1.90	0.34		706	249		700	245				320		430	276		433	286				320
395	0.30	1.40	0.30	↓	680	223	↓	682	217				260	↓	402	248	↓	400	253				260

INLET: UNDEPRESSED CURB

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 2.08 %

DATE TESTED : /71

WEST GUTTER SLOPE : 2.00 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
570	0.80	10.50	0.80	445	970	525	440	970	530				566	147	705	578	138	698					566
539	0.68	7.60	0.68	|	908	463	|	911	471				533	|	640	493	|	645					533
505	0.58	5.65	0.58	|	858	413	|	863	423				490	|	605	498	|	593					490
459	0.45	3.50	0.45	|	745	300	|	747	307				420	|	500	353	|	497					420
412	0.34	1.90	0.34	|	668	223	|	670	230				310	|	392	245	|	389					310
369	0.27	1.10	0.27	↓	603	158	↓	610	170				280	↓	350	203	↓	347					280

INLET: UNDEPRESSED CURB

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 3.06 %

DATE TESTED : /71

WEST GUTTER SLOPE : 3.06 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
555	0.75	9.00	0.74	436	881	445	428	889	461				533	138	648	510	120	640	520				533
535	0.68	7.60	0.68		860	424		872	444				520		610	472		618	498				520
505	0.58	5.65	0.58		820	384		820	392				480		567	429		561	441				480
485	0.52	4.60	0.52		771	335		778	350				450		529	391		524	404				450
445	0.42	3.10	0.42		702	266		699	271				420		435	297		430	310				420
425	0.37	2.35	0.37		646	210		640	212				330		390	252		385	265				330
395	0.30	1.40	0.30	↓	580	144	↓	585	157				320	↓	341	203	↓	340	220				320

INLET: UNDEPRESSED CURB

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 4.00 %

DATE TESTED : /71

WEST GUTTER SLOPE : 4.06 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
565	0.78	10.50	0.80	427	880	453	423	875	452				—	136	645	509	109	638	529				—
545	0.70	8.25	0.71		873	446		866	443				—		613	477		605	496				—
525	0.64	6.80	0.64		828	401		828	405				—		585	449		880	771				—
505	0.58	5.60	0.58		800	373		795	372				—		550	414		565	456				—
485	0.52	4.60	0.52		749	322		750	327				—		508	382		502	393				—
465	0.47	3.80	0.47		708	281		710	287				—		463	327		464	355				—
445	0.41	3.00	0.41		666	239		660	237				—		408	272		404	295				—
420	0.35	2.00	0.35		610	183		610	187				350		356	220		350	241				350
370	0.25	0.88	0.25	↓	537	090	↓	537	114				320	↓	296	160	↓	290	181				320

INLET: UNDEPRESSED CURB

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 5.04 %

DATE TESTED : /71

WEST GUTTER SLOPE : 4.93 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
580	0.83	11.00	0.82	418	840	422	411	838	427				575	130	643	513	096	640	544				575
565	0.77	8.50	0.72		812	394		817	406				533		606	476		595	499				533
538	0.68	7.00	0.65		786	368		788	377				500		561	431		556	460				500
503	0.67	5.50	0.57		734	316		736	325				483		513	383		500	404				483
473	0.49	4.00	0.48		695	277		688	277				450		423	293		432	336				450
438	0.40	2.80	0.40		542	124		650	239				390		390	260		382	286				390
408	0.33	2.00	0.35		540	122		543	132				360		294	164		365	259				360
365	0.24	0.84	0.24		524	106		513	102				290		229	099		217	121				290

INLET: UNDEPRESSED CURB

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 5.83 %

DATE TESTED : /71

WEST GUTTER SLOPE : 5.84 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
551	0.74	10.50	0.80	410	828	418	390	830	440				575	117	592	475	080	580	500				575
533	0.67	6.75	0.64		754	344		757	367				533		524	407		510	430				533
498	0.54	5.20	0.56		709	299		716	297				490		457	340		479	399				490
466	0.47	3.85	0.47		564	154		687	184				450		418	301		410	330				450
448	0.42	3.00	0.41		528	118		574	138				420		352	235		396	316				420
431	0.38	2.35	0.37		521	111		528	129				410		345	228		332	252				410
410	0.33	1.75	0.33		516	106		519	283				340		320	203		326	246				340
480	0.50	4.25	0.50		684	274		673	388				450		418	301		430	350				450
540	0.70	8.00	0.70		776	366		778					533		543	426		545	465				533
510	0.60	6.00	0.60	↓	737	327	↓	733	343				471	↓	482	365	↓	480	400				471

INLET: UNDEPRESSED CURB

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 1.00 %

WEST GUTTER SLOPE : 1.00 %

DATE TESTED : /71

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
535	0.68	7.75	0.68	457	951	494	455	953	498				520	154	668	514	147	663	516				520
515	0.61	6.25	0.61		927	470		929	474				490		637	483		637	490				490
495	0.55	5.20	0.55		897	440		899	434				470		609	455		604	457				470
470	0.48	4.00	0.48		848	391		850	395				450		558	404		556	409				450
440	0.40	2.85	0.40		757	300		758	303				380		467	313		462	315				380
420	0.35	2.07	0.35		720	263		724	269				340		435	281		434	287				340
380	0.27	1.07	0.27	↓	657	200	↓	656	201				270	↓	377	223	↓	370	223				270

INLET: UNDEPRESSED CURB

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 3.08 %

DATE TESTED : /71

WEST GUTTER SLOPE : 2.99 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
555	0.74	10.00	0.79	442	919	477	436	924	488				550	146	693	547	121	690	569				550
531	0.67	7.50	0.67	↓	873	431	↓	881	445				520	↓	645	499	↓	643	522				520
495	0.55	5.25	0.56	↓	816	374	↓	824	388				470	↓	585	439	↓	584	463				470
469	0.47	4.00	0.48	↓	759	317	↓	760	324				450	↓	537	391	↓	523	402				450
436	0.39	2.75	0.39	↓	660	218	↓	667	231				340	↓	433	287	↓	430	309				340
403	0.32	1.50	0.31	↓	587	145	↓	600	164				300	↓	385	239	↓	376	255				300
384	0.28	1.15	0.28	↓	573	131	↓	580	144				260	↓	357	211	↓	352	231				260

THE DEPRESSED CURB INLET

INLET: DEPRESSED CURB

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 0.52 %

DATE TESTED : /71

WEST GUTTER SLOPE : 0.50 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
558	0.75	10.00	0.78	453	759	306	456	768	312	376	773	397	550	145	475	330	139	469	330	109	472	363	550
528	0.65	7.00	0.65		706	253		707	251		707	331	490		408	263		402	263		406	297	490
446	0.41	2.95	0.41		574	121		549	093		569	193	400		280	135		261	122		273	164	400
492	0.54	5.00	0.54		643	190	↓	637	181	↓	649	273	440	↓	359	214	↓	342	203	↓	350	241	430
635	1.05	10.25	0.79		946	493	457	932	475	366	927	561	650	130	557	427	132	560	428	113	560	447	650
605	0.93	10.25	0.79		878	425		869	412		864	498	630		508	378		510	378		514	401	630
575	0.82	10.25	0.79		829	376		821	364		815	449	610		465	335		465	332		470	357	610
554	0.74	8.75	0.73		783	330		774	317		772	406	560		424	294		423	289		432	319	590
509	0.59	5.90	0.59		710	257		709	252		707	351	480		356	226		351	219		360	247	480
480	0.50	4.30	0.50	↓	669	216	↓	665	208	↓	660	294	450	↓	313	183	↓	310	178	↓	309	196	450

INLET: DEPRESSED CURB

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 0.99 %

DATE TESTED : /71

WEST GUTTER SLOPE : 1.02 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
510	0.59	7.00	0.65	452	655	203	459	660	201	373	664	291	480	147	391	244	135	397	262	100	400	300	480
429	0.37	2.75	0.39		557	105		543	084		432	059	350		272	125		295	124		174	074	360
463	0.46	3.50	0.45		577	125		550	091		532	159	380		296	149		274	139		235	135	390
482	0.51	4.60	0.52		597	145		587	128		600	227	430		320	173		310	175		316	216	430
399	0.31	1.65	0.32		542	090		539	080		428	055	300		228	081		225	090		173	073	300
339	0.20	0.65	0.22	↓	545	073	↓	526	067	↓	417	044	250	↓	209	062	↓	219	084	↓	155	055	250
681	1.26	11.00	0.82	450	937	487	444	937	493	360	933	573	630	125	580	455	126	590	464	107	595	488	630
625	1.01	11.00	0.82		916	466		902	458		900	540	600		531	406		525	399		530	428	600
583	0.85	10.50	0.81		848	398		837	393		829	469	550		467	342		471	345		480	373	550
557	0.72	8.50	0.72	↓	768	319	↓	765	321	↓	753	393	520	↓	400	275	↓	400	274	↓	410	303	520

INLET: DEPRESSED CURB

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 2.04 %

DATE TESTED : /71

WEST GUTTER SLOPE : 2.00 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
555	0.74	10.00	0.78	444	651	207	450	664	214	360	672	312	530	145	423	278	126	411	285	086	424	338	530
507	0.58	5.90	0.59		580	136		588	138		602	242	450		357	212		337	211		337	251	450
476	0.49	4.20	0.49		555	111		546	096		439	179	400		318	173		297	171		240	154	400
450	0.43	3.25	0.43		549	105		537	087		440	180	360		290	135		285	159		217	131	360
425	0.37	2.35	0.37		546	102		537	087		435	175	330		240	095		236	110		156	070	330
401	0.32	1.40	0.30	↓	535	091	↓	533	083	↓	423	163	280	↓	230	085	↓	220	094	↓	151	065	280
665	1.18	10.25	0.79	440	898	458	430	898	458	344	894	550	—	120	547	427	110	550	440	096	550	454	—
625	1.01	10.25	0.79		855	415		854	424		848	504	—		513	393		510	400		510	414	—
580	0.83	10.25	0.79		790	350		781	351		773	439	—		440	320		439	329		440	354	—
551	0.73	8.25	0.71	↓	718	278	↓	702	272	↓	700	356	500	↓	388	268	↓	384	274	↓	382	286	500

INLET: DEPRESSED CURB

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 3.09 %

DATE TESTED : /71

WEST GUTTER SLOPE : 2.96 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
680	1.26	10.50	0.81	426	866	440	420	860	440	440	864	563	650	112	542	430	098	529	431	065	547	482	650
615	0.97	10.50	0.81	↓	795	369	↓	788	368	↓	785	464	—	↓	474	362	↓	462	364	↓	474	409	—
591	0.88	10.50	0.81	↓	725	299	↓	750	330	↓	738	417	610	↓	436	324	↓	444	346	↓	440	375	610
551	0.73	8.50	0.72	↓	680	254	↓	695	275	↓	688	367	520	↓	350	238	↓	336	238	↓	342	277	520
523	0.64	6.75	0.64	↓	628	202	↓	615	195	↓	633	312	500	↓	321	209	↓	316	218	↓	316	251	500
474	0.49	4.25	0.495	↓	513	087	↓	496	076	↓	481	160	400	↓	182	070	↓	181	083	↓	221	156	400
436	0.39	2.50	0.38	↓	509	083	↓	499	079	↓	391	070	350	↓	176	064	↓	175	077	↓	115	050	350
500	0.56	5.30	0.56	↓	517	081	↓	545	1.25	↓	560	239	—	↓	249	137	↓	258	160	↓	273	208	—
510	0.60	6.00	0.60	↓	521	095	↓	560	140	↓	565	244	—	↓	262	150	↓	270	172	↓	269	206	—

INLET: DEPRESSED CURB

CROWN SLOPE: 0.25 IN/FT

DATE TESTED: /71

EAST GUTTER SLOPE : 4.00 %

WEST GUTTER SLOPE : 3.90 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
730	1.38	11.00	0.82	417	859	442	400	861	461	311	851	540	—	200	560	360	086	563	477	054	566	512	—
693	1.16	11.00	0.82		806	389		817	417		804	493	—		511	311		500	414		520	466	—
653	0.97	11.00	0.82		762	335		763	363		757	446	—		455	255		456	370		452	398	—
608	0.78	11.00	0.82		716	299		684	284		700	389	—		390	190		382	296		391	337	—
560	0.69	10.00	0.79		624	207		616	216		642	331	—		343	143		338	252		350	296	—
535	0.47	8.00	0.70		483	066		542	142		556	245	—		305	105		295	209		290	136	—
500	0.41	6.00	0.60		477	060		481	081		435	124	—		287	087		234	148		246	092	—
448	0.27	2.75	0.39		474	057		475	075		373	062	—		276	076		161	075		097	043	—
402	0.20	1.80	0.33	↓	469	052	↓	470	070	↓	371	060	—	↓	265	065	↓	154	068	↓	095	041	—

INLET: DEPRESSED CURB

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 5.10 %

DATE TESTED : /71

WEST GUTTER SLOPE : 5.02 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
464	0.46	3.75	0.47	405	453	049	390	456	066	287	345	058	380	097	170	073	071	165	094	018	137	119	380
488	0.53	4.25	0.50		457	052		454	064		345	058	400		171	074		169	098		145	127	400
505	0.58	5.75	0.58		459	054		454	064		419	132	—		170	073		174	103		211	183	—
542	0.70	7.50	0.67		461	056		458	068		462	175	490		171	074		235	164		290	272	490
672	1.23	10.50	0.80		715	310		725	335		740	453	630		464	367		457	386		438	420	630
637	1.05	10.50	0.80		684	279		692	302		693	406	600		426	329		421	350		420	402	600
604	0.93	10.50	0.80		649	245		630	240		650	363	580		388	291		374	303		377	359	580
580	0.84	10.50	0.80		589	183		606	216		646	359	550		372	275		373	302		378	360	550
703	1.30	11.00	0.81		780	375		777	387		772	485	642		512	415		510	439		512	494	642
749	1.61	11.00	0.81	↓	809	404	↓	803	413	↓	822	535	663	↓	561	464	↓	546	475	↓	546	528	663

INLET: DEPRESSED CURB

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 6.00 %

DATE TESTED : /71

WEST GUTTER SLOPE : 6.00 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
590	0.87	11.00	0.82	403	459	056	383	454	071	285	563	278	560	098	183	085	062	343	281	000	380	380	560
399	0.31	0.70	0.23	|	440	037	|	439	056	|	324	039	250	|	179	074	|	145	083	|	070	070	300
425	0.36	1.55	0.31	|	446	043	|	445	062	|	331	046	350	|	173	075	|	154	092	|	072	072	300
458	0.44	3.25	0.43	|	453	050	|	447	064	|	342	057	350	|	172	074	|	160	098	|	123	123	350
479	0.50	4.25	0.50	|	455	052	|	447	064	|	342	057	350	|	173	075	|	165	103	|	198	198	350
490	0.54	5.10	0.55	|	457	054	|	448	065	|	343	058	400	|	174	076	|	165	103	|	230	230	400
517	0.61	6.25	0.61	|	458	055	|	452	069	|	349	064	420	|	177	079	|	194	132	|	257	257	420
530	0.66	7.60	0.68	|	460	057	|	452	069	|	387	102	460	|	178	080	|	253	191	|	288	288	460
555	0.74	8.80	0.73	↓	460	057	↓	454	071	↓	473	188	—	↓	181	083	↓	311	249	↓	336	236	—

INLET: DEPRESSED CURB — CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE: 0.492 %

DATE TESTED: /71 — WEST GUTTER SLOPE: 0.525 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
652	1.13	10.75	0.80	457	950	493	455	940	485	376	935	559	—	149	590	441	144	589	445	120	596	476	—
607	0.93	10.75	0.80		910	453		902	447		890	514	—		542	393		540	396		538	418	—
573	0.81	10.50	0.80		835	378		834	379		828	452	630		499	350		509	365		494	374	630
547	0.71	8.25	0.73		766	309		767	312		754	478	490		433	284		432	288		442	322	490
506	0.58	5.90	0.59		720	263		726	271		724	348	480		384	235		380	236		370	250	480
483	0.52	4.30	0.50		665	208		660	205		643	267	430		328	179		330	186		307	187	430
454	0.44	3.40	0.43		639	182		637	182		590	214	380		301	152		300	156		283	163	380
428	0.37	2.50	0.38		590	133		573	118		463	087	360		250	101		263	119		208	088	360
410	0.33	1.75	0.33		585	128		564	109		450	074	330		247	098		255	111		205	085	330
345	0.21	0.50	0.20	↓	542	085	↓	541	086	↓	437	061	300	↓	240	091	↓	247	103	↓	178	158	300

INLET: DEPRESSED CURB

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 2.95 %

DATE TESTED : /71

WEST GUTTER SLOPE : 3.08 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
717	1.45	11.00	0.81	437	875	438	429	883	454	345	868	523	660	140	608	468	119	613	494	080	590	510	660
660	1.16	11.00	0.81		819	382		821	392		825	480	640		544	404		512	393		519	439	640
609	0.94	10.75	0.80		746	309		742	313		748	403	630		470	330		470	351		458	378	630
562	0.77	10.00	0.79		710	273		712	283		700	355	600		423	283		429	310		430	350	600
538	0.70	8.00	0.70		664	227		670	241		656	311	550		400	260		385	266		368	288	550
510	0.60	6.00	0.60		616	179		600	171		490	145	490		288	148		290	171		262	182	490
480	0.50	4.30	0.50		605	168		588	159		475	130	450		269	129		271	152		193	113	450
440	0.40	2.85	0.40		598	161		570	141		464	119	400		260	120		260	141		189	109	400
390	0.30	1.40	0.30	↓	556	119	↓	550	121	↓	444	100	330	↓	232	092	↓	221	102	↓	154	074	330

INLET: DEPRESSED CURB

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 5.83 %

DATE TESTED : /71

WEST GUTTER SLOPE : 5.84 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
741	1.60	11.00	0.82	410	779	369	390	787	397	303	800	497	690	117	566	449	080	560	480	017	488	471	690
675	1.23	11.00	0.82		754	344		754	364		736	433	640		524	407		512	432		447	430	640
615	0.96	11.00	0.82		538	128		554	164		560	257	620		358	241		395	315		380	363	620
570	0.80	11.00	0.82		533	123		540	150		450	147	580		283	166		342	262		367	350	580
545	0.71	8.00	0.70		528	118		532	142		435	132	520		276	159		255	175		260	243	520
650	1.14	11.00	0.82		543	133		572	182		653	350	—		454	337		483	403		401	384	—
680	1.28	11.00	0.82		638	228		720	330		730	427	—		506	389		500	420		450	433	—
710	1.44	11.00	0.82	↓	718	308	↓	708	318	↓	720	417	—	↓	548	431	↓	520	440	↓	500	483	—

THE GUTTER INLET

INLET: GUTTER

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 1.02 %

DATE TESTED : /71

WEST GUTTER SLOPE : 1.05 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
815	2.05	11.00	0.82	458	910	452	454	920	466	439	922	483	440	170	625	445	160	620	460	160	603	443	440
731	1.55	11.00	0.82		815	357		810	356		810	371	360		501	331		512	352		497	337	260
650	1.11	11.00	0.82		727	269		710	256		713	274	280		408	238		413	253		410	250	380
565	0.78	11.00	0.82		686	228		683	229		680	241	200		347	177		346	186		345	185	200
485	0.52	4.75	0.53		625	167		616	162		583	144	110		309	139		306	146		315	155	110
402	0.32	1.75	0.33		581	123		571	117		535	096	060		255	085		272	112		288	128	060
780	1.80	11.00	0.82		880	430		893	439		900	461	420		566	396		571	411		583	423	420
540	0.68	7.60	0.68	↓	660	202	↓	658	204	↓	659	230	150	↓	333	163	↓	330	170	↓	332	172	150

INLET: GUTTER

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 2.04 %

DATE TESTED : /71

WEST GUTTER SLOPE : 2.01 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
908	2.70	11.50	0.83	450	1.041	591	445	—	—	426	—	—	630	166	810	644	155	—	—	146	—	—	630
775	1.78	11.50	0.83	↓	845	395	↓	855	410	↓	860	434	440	↓	567	401	↓	561	406	↓	544	398	440
669	1.14	11.50	0.83	↓	680	230	↓	679	234	↓	660	234	280	↓	390	224	↓	394	239	↓	359	213	280
565	0.78	11.50	0.83	↓	645	195	↓	636	191	↓	607	181	220	↓	312	146	↓	323	168	↓	311	165	220
730	1.51	11.50	0.83	↓	724	274	↓	722	267	↓	726	300	350	↓	460	294	↓	461	306	↓	458	312	350
752	1.67	11.50	0.83	↓	808	358	↓	820	375	↓	803	377	390	↓	520	354	↓	500	345	↓	487	341	390
527	0.65	7.00	0.65	↓	628	178	↓	618	173	↓	587	161	160	↓	303	137	↓	306	151	↓	281	135	160
455	0.44	3.50	0.45	↓	598	148	↓	591	146	↓	558	132	100	↓	274	108	↓	287	132	↓	262	116	100

INLET: GUTTER

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 3.03 %

DATE TESTED : /71

WEST GUTTER SLOPE : 2.97 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
835	2.18	11.25	0.82	452	958	506	432	—	—	417	—	—	560	166	703	537	143	—	—	130	—	—	560
745	1.61	11.25	0.82		723	271		720	288		746	329	400		470	304		482	339		426	296	400
661	1.18	11.25	0.82		637	185		634	202		610	193	330		344	178		353	210		328	198	330
577	0.82	11.25	0.82		633	181		636	204		605	188	270		319	153		330	187		289	159	270
455	0.44	3.50	0.45		596	147		593	161		554	137	100		287	121		286	143		270	140	100
770	1.78	11.25	0.82		813	361		820	388		831	414	500		584	418		593	450		582	452	500
820	2.08	11.25	0.82	↓	910	458	↓	—	—	↓	—	—	530	↓	663	497	↓	—	—	↓	—	—	530

INLET: GUTTER

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 3.97 %

DATE TESTED : /71

WEST GUTTER SLOPE : 4.00 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
837	2.19	11.50	0.83	438	946	508	427	—	—	408	—	—	590	160	728	568	134	—	—	112	—	—	590
750	1.62	11.50	0.83		650	212		628	201		686	278	400		453	293		500	366		456	344	400
657	1.15	11.50	0.83		620	182		613	186		612	204	320		331	171		330	196		289	177	320
573	0.81	11.50	0.83		619	181		611	184		602	194	280		325	165		310	176		272	160	280
518	0.61	6.00	0.63		602	164		598	171		575	167	200		299	139		302	168		253	141	200
770	1.77	11.50	0.83		728	290		743	316		766	358	420		510	350		505	371		423	311	420
795	1.92	11.50	0.83		750	312		770	343		800	392	440		606	446		597	463		550	438	440
822	2.12	11.50	0.83		871	433		—	—		—	—	550		650	490		—	—		—	—	550

INLET: GUTTER

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 5.07 %

DATE TESTED : /71

WEST GUTTER SLOPE : 5.04 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
817	2.05	10.75	0.81	428	796	368	413	811	398	389	840	451	500	153	587	434	120	603	483	091	560	469	500
779	1.80	10.75	0.81		605	177		633	220		640	251	450		357	204		464	344		450	359	450
733	1.55	10.75	0.81		566	138		570	157		592	203	410		314	161		340	220		273	182	410
650	1.12	10.75	0.81		562	134		573	160		545	156	380		326	173		322	202		252	161	380
565	0.78	10.75	0.81		560	132		567	154		546	157	340		314	161		305	185		246	155	340
425	0.37	2.50	0.38		546	118		545	132		525	136	160		268	115		260	140		203	112	160
800	1.94	10.75	0.81	↓	675	247	↓	—	—	↓	—	—	470	↓	475	322	↓	—	—	↓	—	—	470

INLET: GUTTER

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 1.02 %

DATE TESTED : /71

WEST GUTTER SLOPE : 1.03 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
835	2.17	11.25	0.83	463	880	417	460	889	429	450	900	450	450	166	604	438	160	602	442	157	593	436	450
800	1.97	↓	↓	↓	850	387	↓	848	388	↓	841	391	410	↓	545	379	↓	542	382	↓	527	370	410
770	1.77	↓	↓	↓	810	347	↓	808	348	↓	802	352	380	↓	512	346	↓	504	344	↓	488	331	380
720	1.47	↓	↓	↓	755	292	↓	748	288	↓	740	290	310	↓	455	289	↓	466	306	↓	431	274	310
660	1.17	↓	↓	↓	710	247	↓	693	233	↓	700	250	260	↓	426	240	↓	430	270	↓	410	253	260
615	0.97	↓	↓	↓	687	224	↓	682	222	↓	680	230	230	↓	378	212	↓	380	220	↓	376	219	230
562	0.77	↓	↓	↓	679	216	↓	670	210	↓	660	210	190	↓	374	208	↓	354	194	↓	352	195	190

INLET: GUTTER

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 3.00 %

DATE TESTED : /71

WEST GUTTER SLOPE : 2.97 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
915	2.75	11.25	0.83	446	950	505	437	959	522	420	953	533	570	158	681	523	139	686	547	122	650	528	570
860	2.35	11.25	0.83	|	908	463	|	—	—	|	—	—	540	|	654	496	|	—	—	|	—	—	540
772	1.78	11.25	0.83	|	823	378	|	832	395	|	842	422	430	|	560	402	|	586	427	|	546	424	430
706	1.39	11.25	0.83	|	608	263	|	632	195	|	642	222	300	|	408	250	|	420	281	|	390	268	300
628	1.02	11.25	0.83	|	518	073	|	543	106	|	532	112	270	|	344	186	|	333	194	|	350	228	270
535	0.77	10.00	0.78	|	518	073	|	533	096	|	529	109	180	|	314	156	|	302	163	|	310	188	180
825	2.17	11.25	0.83	↓	881	436	↓	892	464	↓	890	470	510	↓	633	475	↓	636	497	↓	618	496	510

INLET: GUTTER

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 5.07 %

DATE TESTED : /71

WEST GUTTER SLOPE : 5.04 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
888	2.55	11.25	0.83	426	900	474	411	—	—	386	—	—	600	144	719	575	113	—	—	083	—	—	600
805	1.99	11.25	0.83		775	349		798	387		803	417	510		605	461		594	481		570	487	510
733	1.55	11.25	0.83		644	218		645	234		670	284	380		435	291		416	303		370	287	380
623	1.00	11.25	0.83		496	070		502	091		486	100	270		326	082		272	159		320	237	270
770	1.77	11.25	0.83		710	284		719	308		738	352	450		527	383		500	387		472	389	450
830	2.17	11.25	0.83		840	414		857	446		860	474	550		640	496		—	—		—	—	550
561	0.76	9.50	0.76	↓	490	064	↓	497	086	↓	470	084	—	↓	207	062	↓	300	187	↓	303	120	—

THE COMBINATION INLET

INLET: COMBINATION

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 0.51 %

DATE TESTED : /71

WEST GUTTER SLOPE : 0.54 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
857	2.35	10.75	0.80	458	873	415	460	—	—	442	—	—	410	148	531	383	143	—	—	149	—	—	440
735	1.55	10.75	0.80		766	308		764	304		758	316	270		444	296		436	293		430	281	300
663	1.18	10.75	0.80		718	260		720	260		708	266	150		409	261		398	255		395	246	270
583	0.84	10.75	0.80		680	220		670	210		672	230	110		375	227		379	236		370	221	230
493	0.55	5.50	0.57		642	184		627	167		618	176	110		321	173		311	168		324	175	140
408	0.33	1.75	0.33		587	129		583	123		581	139	020		270	122		272	129		274	125	050
830	2.15	10.75	0.80		826	368		—	—		—	—	350		506	358		—	—		—	—	380
790	1.90	10.75	0.80		798	340		792	332		790	348	330		474	326		466	323		468	319	360

INLET: COMBINATION

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 1.00 %

DATE TESTED : /71

WEST GUTTER SLOPE : 1.00 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
845	2.25	11.00	0.82	455	850	395	453	—	—	438	—	—	360	144	537	393	138	—	—	138	—	—	390
731	1.55	11.00	0.82		740	285		737	284		730	292	260		420	276		407	269		411	273	340
685	1.30	11.00	0.82		700	245		698	245		709	271	210		398	254		390	252		391	253	260
611	0.96	11.00	0.82		674	219		666	213		680	242	190		375	231		354	216		360	222	220
555	0.74	9.00	0.74		641	186		632	179		624	186	120		344	200		342	204		341	203	150
513	0.61	6.25	0.61		620	165		611	158		613	175	060		312	168		310	172		312	174	090
457	0.44	3.50	0.45		595	140		590	137		590	152	—		280	136		279	141		283	145	—
420	0.36	2.00	0.35	↓	580	125	↓	574	121	↓	575	137	—	↓	264	120	↓	262	124	↓	264	126	—

INLET: COMBINATION

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 2.06 %

DATE TESTED : /71

WEST GUTTER SLOPE : 2.01 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
630	1.02	11.00	.81	447	650	203	438	636	198	423	640	217	210	139	334	195	128	335	207	120	340	220	240
840	2.20	11.00	0.81		747	300		760	322		768	345	310		519	380		484	360		490	370	340
595	0.89	11.00	0.81		611	164		615	177		616	193	190		328	189		330	202		327	207	220
551	0.73	8.75	0.73		573	126		565	127		590	167	150		307	168		308	180		307	187	180
492	0.56	5.50	0.57		567	120		565	127		512	089	060		290	151		287	159		286	166	110
445	0.41	3.00	0.41		540	093		541	103		506	083	030		270	131		269	141		256	136	060
395	0.30	1.50	0.31		535	088		533	095		496	073	—		246	107		237	109		240	120	—
760	1.70	11.00	0.81	↓	677	230	↓	—	—	↓	—	—	290	↓	455	316	↓	—	—	↓	—	—	320

INLET: COMBINATION

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 3.08 %

DATE TESTED : /71

WEST GUTTER SLOPE : 2.99 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
638	1.06	10.50	0.80	438	528	090	428	534	106	408	500	092	210	137	335	198	118	333	215	102	340	238	210
605	0.93	10.50	0.80		527	089		532	104		500	092	190		330	193		333	215		334	232	190
553	0.70	8.00	0.70		525	087		533	105		492	084	110		321	184		329	211		325	223	140
511	0.60	6.00	0.60		520	082		534	106		490	082	150		316	179		315	197		303	201	120
465	0.47	3.80	0.47		508	070		521	093		489	081	040		297	160		297	179		277	175	070
435	0.39	2.75	0.40	↓	507	069	↓	517	089	↓	488	080	020	↓	282	145	↓	275	157	↓	250	148	040

INLET: COMBINATION

CROWN SLOPE: 0.25 IN/FT

EAST GUTTER SLOPE : 4.01 %

DATE TESTED : /71

WEST GUTTER SLOPE : 4.03 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
870	2.40	10.00	0.79	432	740	308	421	—	—	403	—	—	410	137	530	393	108	—	—	087	—	—	440
759	1.67	10.00	0.79		622	190		597	176		602	199	240		266	129		275	167		336	249	270
708	1.40	10.00	0.79		493	061		508	087		478	075	210		240	103		300	192		340	253	240
600	0.90	10.00	0.79		490	058		507	086		478	075	160		355	218		359	251		352	265	190
539	0.68	7.75	0.79		489	057		506	085		477	074	190		348	211		328	220		344	257	040
475	0.49	4.25	0.50		485	053		492	071		473	0.70	110		316	179		320	212		319	232	090
425	0.37	2.50	0.38		488	056		490	069		470	067	030		297	160		283	175		270	183	060
810	2.00	10.00	0.79		730	298		—	—		—	—	360		396	259		—	—		—	—	390
840	2.20	10.00	0.79		705	273		—	—		—	—	310		480	343		—	—		—	—	340

INLET: COMBINATION

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 0.99 %

DATE TESTED : /71

WEST GUTTER SLOPE : 0.97 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
910	2.75	11.00	0.82	460	895	435	456	—	—	444	—	—	—	158	602	444	152	—	—	152	—	—	—
783	1.85	11.00	0.82	↓	780	320	↓	790	334	↓	780	336	350	↓	480	322	↓	476	325	↓	467	315	380
720	1.47	11.00	0.82	↓	745	285	↓	732	276	↓	716	272	270	↓	424	266	↓	410	258	↓	408	256	300
579	0.83	11.00	0.82	↓	680	220	↓	676	220	↓	677	233	180	↓	343	186	↓	340	188	↓	330	178	230
475	0.49	4.00	0.48	↓	617	157	↓	613	157	↓	572	328	040	↓	310	152	↓	312	160	↓	300	148	070
850	2.28	11.00	0.82	↓	813	353	↓	—	—	↓	—	—	410	↓	545	387	↓	—	—	↓	—	—	390

INLET: COMBINATION

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 2.02 %

DATE TESTED : /71

WEST GUTTER SLOPE : 1.96 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
815	2.05	11.00	0.82	452	745	293	449	—	—	430	—	—	370	154	463	311	140	—	—	137	—	—	400
751	1.65	11.00	0.82		690	238		690	241		680	250	260		414	260		415	275		391	254	290
695	1.34	11.00	0.82		673	221		675	226		672	242	220		390	236		400	260		395	258	250
565	0.78	11.00	0.82		649	197		638	189		607	177	160		305	151		306	166		283	146	220
435	0.39	2.75	0.40		597	145		584	135		549	119	090		252	098		242	122		226	089	140
640	1.08	11.00	0.82		647	195		640	191		608	178	210		334	180		342	202		320	183	240
865	2.40	11.00	0.82	↓	785	333	↓	—	—	↓	—	—	440	↓	532	378	↓	—	—	↓	—	—	340

INLET: COMBINATION

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 3.07 %

DATE TESTED : /71

WEST GUTTER SLOPE : 2.97 %

WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
c																							
865	2.40	10.50	0.80	440	710	270	430	—	—	413	—	—	440	146	450	304	126	—	—	112	—	—	470
785	1.85	10.50	0.80		648	208		670	230		697	284	340		334	188		366	240		305	193	370
725	1.50	10.50	0.80		636	196		632	202		594	181	260		330	184		332	206		309	197	340
645	1.10	10.50	0.80		635	195		625	195		593	180	230		329	183		338	202		300	188	260
545	0.71	8.00	0.80		625	185		619	189		584	171	100		300	154		309	193		264	152	230
461	0.46	3.50	0.80		595	155		585	155		546	133	030		266	120		266	140		228	116	160
830	2.15	10.50	0.80	↓	690	250	↓	700	270	↓	710	297	410	↓	351	205	↓	343	217	↓	320	208	360

INLET: COMBINATION

CROWN SLOPE: 0.50 IN/FT

EAST GUTTER SLOPE : 4.01 %

DATE TESTED : /71

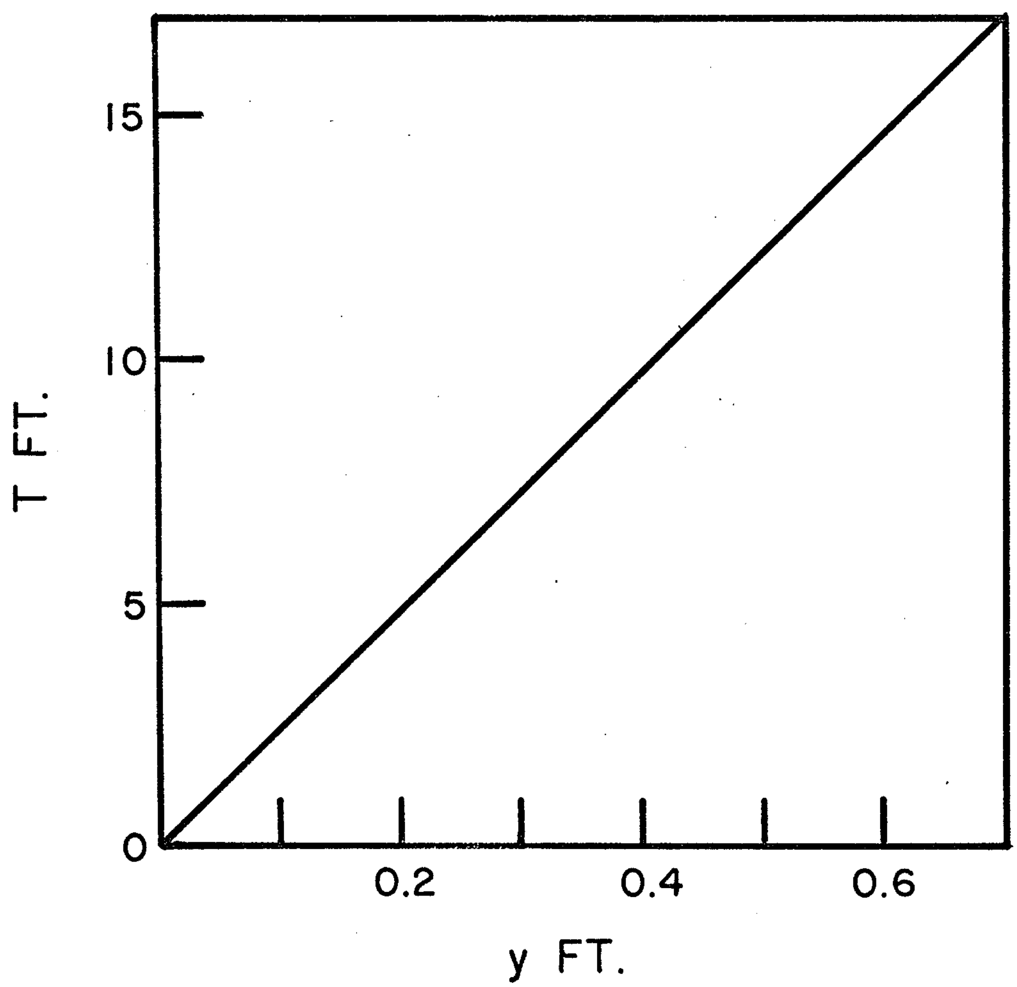
WEST GUTTER SLOPE : 4.03 %

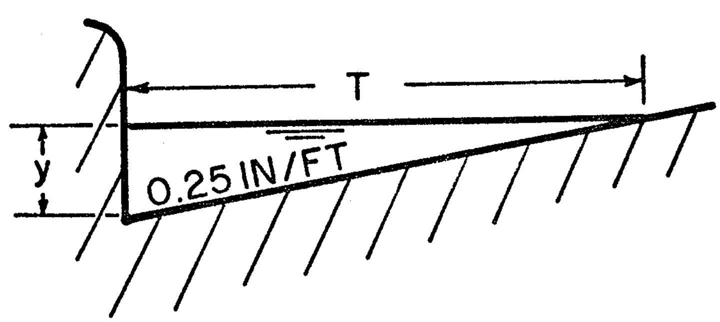
WEST FLOW		EAST FLOW		EAST y_1			Ey_2			Ey_3			Ey_4	WEST y_1			Wy_2			Wy_3			Wy_4
H	Q_1	P	Q_2	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4	Z_1	R_1	y_1	Z_2	R_2	y_2	Z_3	R_3	y_3	y_4
909	2.70	11.00	0.82	432	746	314	421	—	—	403	—	—	440	137	322	185	108	—	—	087	—	—	470
772	1.77	11.00	0.82	↓	616	184	↓	610	189	↓	585	182	350	↓	320	183	↓	338	230	↓	290	203	380
715	1.44	11.00	0.82	↓	613	181	↓	608	187	↓	583	180	290	↓	313	176	↓	313	205	↓	337	250	320
607	0.93	11.00	0.82	↓	610	178	↓	612	191	↓	580	177	250	↓	313	176	↓	317	209	↓	267	180	280
555	0.74	9.00	0.74	↓	607	175	↓	603	182	↓	578	175	060	↓	296	159	↓	295	087	↓	250	163	310
452	0.43	3.25	0.43	↓	580	148	↓	580	159	↓	538	135	020	↓	267	130	↓	257	049	↓	211	124	200
400	0.31	1.50	0.31	↓	551	109	↓	551	130	↓	513	110	010	↓	235	098	↓	227	019	↓	180	093	140

APPENDIX C

CHARTS SHOWING FLOW SPREAD vs. DEPTH OF FLOW FOR CITY OF WINNIPEG STREETS

C-1 DEPTH VS SPREAD FOR S_x = 0.25 IN/FT





C-2 DEPTH VS SPREAD FOR S_x = 0.50 IN/FT