A Storm-Sewer Flow Measurement and Recording System

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ABSTRACT

A comprehensive study and development of instruments and techniques for measuring all components of flow in a storm-sewer drainage system were undertaken by the U.S. Geological Survey under the sponsorship of FHWA. The study involved laboratory and field calibration and testing of measuring flumes, pipe insert meters, weirs, and electromagnetic velocity meters as well as the development and calibration of pneumatic bubbler and pressure transducer head-measuring systems. Tracer dilution and acoustic-flowmeter measurements were used in field verification tests. A single micrologger was used to record data from all the foregoing instruments as well as from a tipping-bucket rain gauge and also to activate on command the electromagnetic velocity meter and tracer dilution systems. A system was developed and suggested for use in measuring all components of flow in a typical storm-sewer system.

In recent years, with advances in modeling techniques for watershed rainfall runoff, there has been an emphasis on the modeling approach to storm-sewer design. The literature on this subject is full of statements about the need for more and better data bases to aid model development (1-3). For example, it was concluded by the American Society of Civil Engineers in 1965 that a technological hiatus exists largely because of an absence of suitable measuring devices. Progress has been made since then, and it was the objective of this study to evaluate existing devices and techniques as well as to consider new approaches and instruments. These would be tested and evaluated both in the laboratory and the field and an instrumentation package would be proposed that would accurately measure all of the flow components that make up a storm-sewer drainage system.

Figure 1 shows conceptually the total system chosen for the measurement of stormwater drainage. A detailed description of the development and testing of the system is described elsewhere (4); all figures are taken from that report. Head measurements are made by using a pneumatic bubbler with pressure transducers to convert sensed pressure to feet of water. There can be as many orifices and their respective pressure transducers serving as many measuring devices as required. Output from the transducers is sensed by the micrologger and stored if flow or change in head is indicated. Above a given threshold of stage in any of the measuring devices, such as the trunkline, an electromagnetic velocity meter is activated and then deactivated with falling stage. Data from other measuring devices, such as rain gauges, are stored by the micrologger.

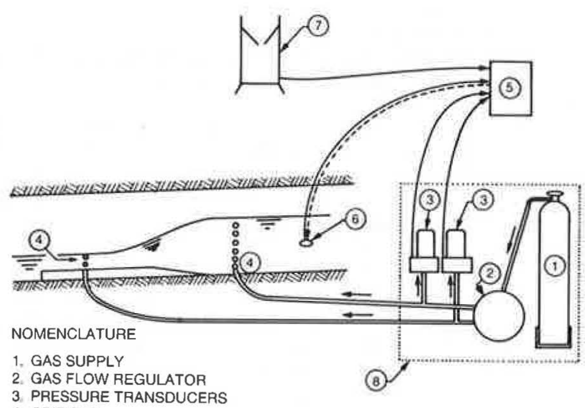

FIGURE 1 Conceptual diagram of storm-sewer flow measurement system.

APPROACH

This study consisted of laboratory testing and calibration followed by field verification of the various instruments and equipment selected for consideration in measuring storm-sewer flows. Laboratory tests were carried out at the U.S. Geological Survey (USGS) Hydrologic Instrumentation Facility located at the National Space Technology Laboratories, Mississippi. This was followed by field testing and verification of the instruments selected and, in some instances, in situ calibration of instruments and structures, which was accomplished at the field site by independently measuring selected flows from a nearby fire hydrant with an acoustic flowmeter. The hydrant flows were then diverted to the desired measuring device. Concurrent with the acoustic-flowmeter measurements, tracer dilution-discharge measurements (5,6) were made of each hydrant flow. This method involved the measurement of the degree of dilution of a known amount of water-soluble tracer following its injection into and mixture with the flow to be measured. The dilution-measuring system can be either manual or automatic (7); the dilution-discharge measurements were performed manually when steady hydrant flows could be utilized. In this study an automatic system also was installed to acquire discharge measurements with the occurrence of storm runoff (8). This system was activated by the micrologger on the basis of water stages in the storm-sewer system.

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Stormwater flows might be expected to be very unsteady, especially if the surface drainage area is small and largely paved. This approach to measurement, if successful, not only might be used to check various measuring devices at flows greater than those that can be obtained from the hydrant, but its possibilities for the measurement of stormwater flows in general might also be investigated. Such an installation offers the possibility of calibrating measuring devices or structures in situ and might also provide directly all the storm-runoff data desired, as has been suggested by Wenzel (9).

The various elements of a storm-drainage system and the approach or instrument selected in this study to perform and record the measurement were as follows:

1. Precipitation: Select a rain gauge for accuracy and compatibility with the data-recording system.
2. Catchment outflows: Design and calibrate a meter to be inserted in catchment outflow pipes.
3. Street-gutter bypass flows
   a. Rate in situ gutter and catchment as a unit,
   b. Design and rate, in situ, a weir for measuring gutter flows.
4. Trunkline flows
   a. Design and calibrate a modified Palmer-Bowlus type flume for both open and pipe-full flow,
   b. Test and determine velocity coefficients for an electromagnetic point-velocity meter installed in a trunkline to measure velocities near and during pipe-full flow conditions.
5. Head measurement system
   a. Combine pressure transducer and pneumatic-bubbler orifice into a working system,
   b. Test and calibrate pressure transducers.
6. Control and recording system: Test and evaluate microloggers to store and interpret data and to activate instruments on programmed command.

RESULTS AND CONCLUSIONS

From the inception of rainfall to flow in roadways and gutters, collection via curb inlets and drop structures or catchments, and final conveyance from the area via lateral and trunkline pipes, the whole gamut of flow hydraulics can occur in a storm-sewer drainage system. In this section, each of the measuring devices or techniques considered part of an overall storm-sewer drainage collection and recording system will be briefly described and the results of laboratory and field tests presented.

Precipitation Measurements

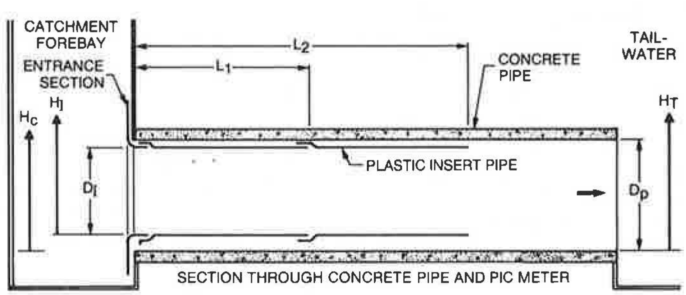
The rapidity of runoff in response to rainfall in predominantly paved areas such as highways makes it vital that the rain gauges being used have rapid responses (10). For this reason various investigators have recommended the use of tipping-bucket rain gauges (11). Furthermore, the tipping feature is also the most suitable for digital recording of rainfall volumes and intensities.

Several manufacturers currently produce tipping-bucket rain gauges, but the market is continuously changing, and final selection should depend on the quality of construction and on laboratory tests of accuracy and responsiveness and compatibility with the data-recording system.

Catchment Outflows

It was found that most pipes draining catchments were seldom larger or smaller than 12 to 24 in. in diameter. Flow in catchments typically is very turbulent, making it difficult to measure head in this location. If head could be measured, it might be possible to rate the existing outlet or calibrate a structure to be placed in the outflow pipe. Their size precluded the ready construction of measuring flumes or other devices in the outflow pipes. For this reason a pipe insert contraction (PIC) meter was designed that could be placed in the outflow pipe away from the catchment (see Figures 2 and 3). Two meters, 10 and 15 in. in diameter, were designed to nest inside 12- and 18-in. concrete pipes, respectively.

Both the 10- and 15-in. PIC meters were successfully calibrated in the laboratory; only a 15-in. one was field tested. Figure 4 shows the calibration curves for the 15-in. PIC meter for both free-surface and pipe-full flow (see Figure 2 for definition of



DIMENSIONS OF PIC METER

TEST METER	DIAMETERS: PLASTIC PIPE, D_P (1)	DIAMETERS: INSERT PIPE, D_I (2)	LENGTHS: ONE INSERT TUBE, L_1 (7)	LENGTHS: TWO INSERT TUBES, L_2 (8)
12 INCH	1.00	0.833	1.67	3.00
18 INCH	1.50	1.250	3.00	5.67

ALL DIMENSIONS ARE IN FEET EXCEPT AS NOTED

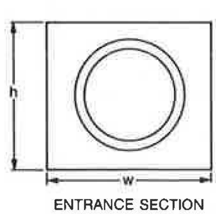


FIGURE 2 Sketch and dimensions of PIC meter.

FIGURE 3 Placement of 15-in. insert pipe through 18-in. manhole into catchment; 20-in.-long pipe subsequently turned 90 degrees and inserted into 18-in. sewer line.

terms). Although there is a slight scatter in the data for the different barrel lengths, it is not significant. The flow conditions in the long barrel configuration appeared more stable. The long barrel PIC meter could not be made to flow full except by artificially raising the tailwater in the laboratory. Despite the agreement of the data at low values of $\Delta H_{IT}/D_I$ (ΔH_{IT} is the difference between the head on the insert in the catchment and the tailwater head), the calibration should probably not be used at relative heads less than 0.05 because sizable errors are likely with such small differences (0.062 ft).

To verify the calibration of the 15-in. PIC meter installed at the field test site, eight hydrant discharges were measured through the meter. Figure 4B compares the field rating with the laboratory calibration for the condition of free surface flow below the crown of the PIC meter. As can be seen, there is close agreement between the tracer dilution and acoustic-flowmeter measurements; a curve fitted to both is to the right of the laboratory calibration at lower heads and both converge at higher heads. The discrepancy is considerable at the lower heads but not surprising considering the violent and skewed flow conditions in the catchment. As heads increase, the flow conditions in the catchment smooth out.

The tests point to the need to place any measuring device away from the immediate catchment and to also measure head away from the catchment.

Gutter Bypass Flows

The difficulties of measuring bypass flow in the gutters are primarily due to the adverse conditions created by vehicular traffic and debris. The placement of sophisticated measuring instruments in the gutter or curb adjacent to inlets was judged to have a limited chance of success. Two approaches were tested: (a) an in situ rating of the inlet and catchment as a unit to distinguish the flow components and (b) an in situ rating of a weir structure placed in the street gutter.

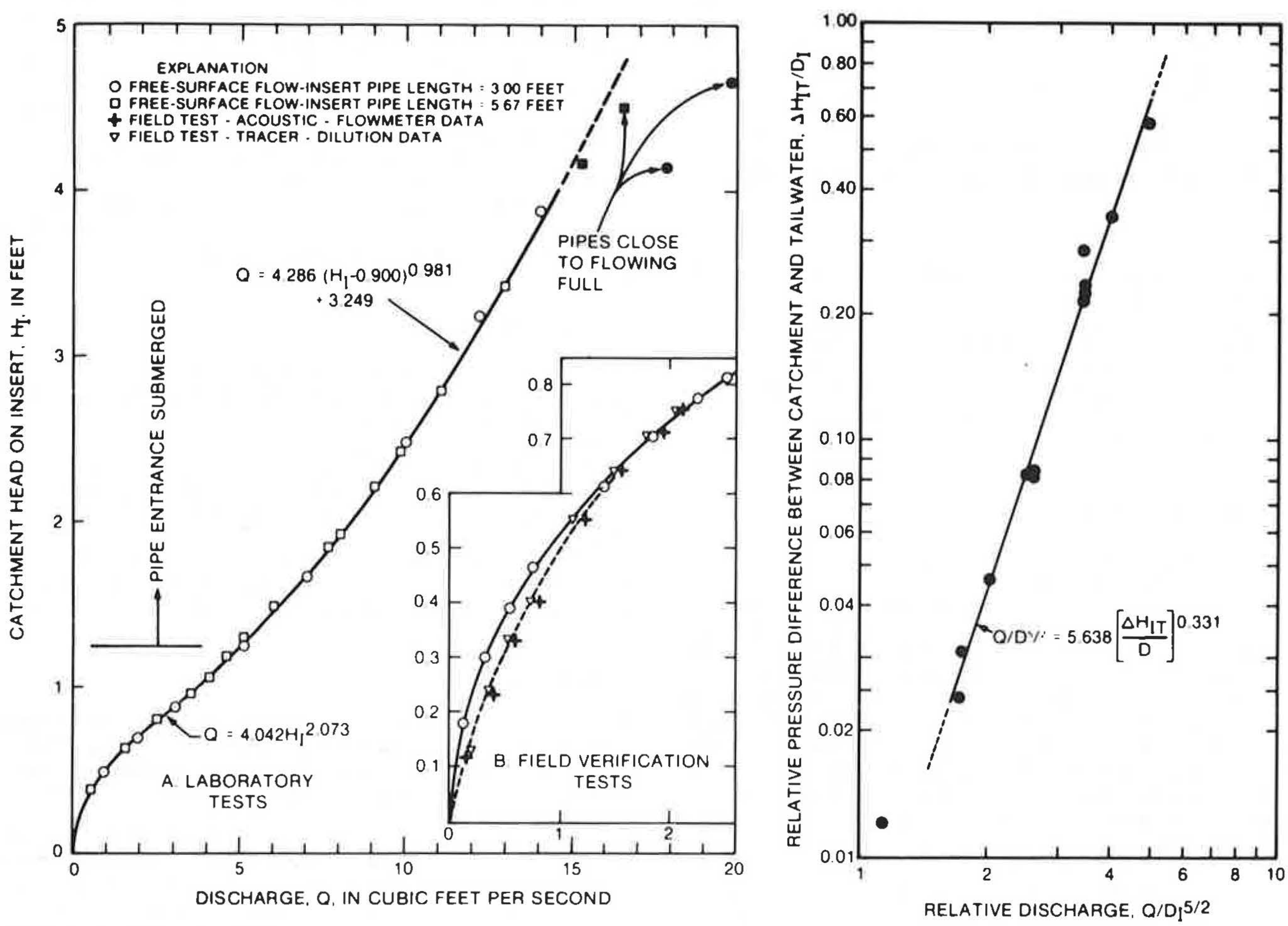


FIGURE 4 Fifteen-inch PIC meter calibration: left, free surface flow; right, pipe-full flow (laboratory tests only).

Inlet In Situ Rating

Conceptually for each catchment and inlet design and configuration a unique relationship existed between the flow into and out of the catchment and that bypassing the inlet. This unique relationship was determined in the field for a single inlet by measuring, for selected discharges, the total flows from the fire hydrant up to and past the point at which a portion of the flow bypassed the inlet. Flows out of the catchment were measured with the PIC meter. Once the rating was established, the outlet flow was a measure of the flow bypassing the inlet. The unique discharge relationship for this inlet is shown in Figure 5 in which the bypass discharge is plotted versus the catchment outlet discharge. The results are good, although it was not possible to extend the rating as high as might have been desired because of the limited hydrant discharges available.

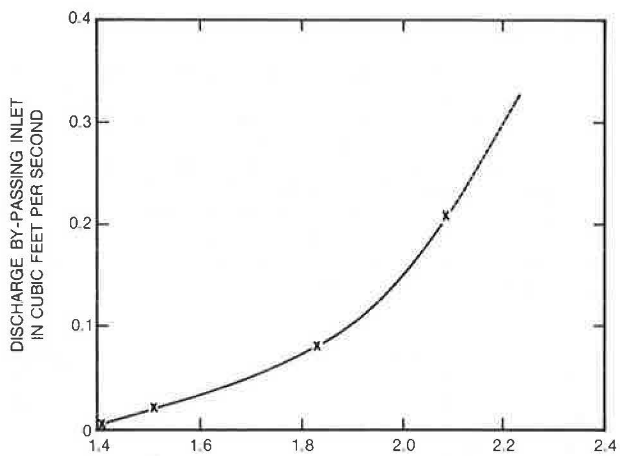


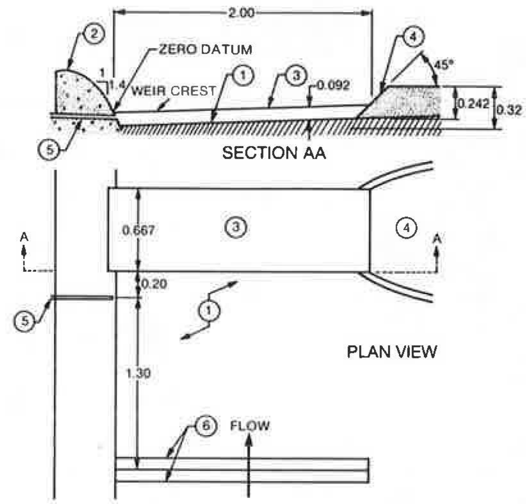
FIGURE 5 In situ bypass discharge rating for inlet at field test site.

Although this method is accomplished with considerable effort, it is the ultimate in assessing the hydraulics of a given storm-drainage system. It can be expected that in practice every inlet will have different physical and hydraulic characteristics regardless of similarity in design. The in situ rating of each would resolve this problem, though with considerable effort.

Curb Weir In Situ Rating

An alternative to the inlet rating technique was desirable. It was decided to try a broad-crested weir structure located in the street gutter to intercept and measure bypass flows. The structure was to have a low profile and be sturdy, capable of withstanding vehicular traffic, and preferably self-cleaning. Figure 6 shows the design of the curb dual weir that was field rated. It consists of a section of aluminum channel 8 in. wide, 1 in. thick, and 2 ft long secured and sealed to the street gutter.

The initial tests using hydrant flows diverted down the street gutter and through the weir structure indicated that supercritical flow was occurring in the gutter with a hydraulic jump forming just upstream of the weir. To produce subcritical flow in the approach to the measuring weir, a second weir was placed 2.0 ft upstream, hence the name "dual weir." The hydraulic jump then formed upstream of



NOMENCLATURE

1 STREET GUTTER
2 CURB
3 RECTANGULAR BROAD-CRESTED WEIR
4 WEIR ABUTMENT, SHAPED OF ASPHALT
5 PNEUMATIC BUBBLER TUBE ORIFICE
6 UPSTREAM TRIANGULAR WEIR

NOTE: ALL DIMENSIONS ARE IN FEET UNLESS OTHERWISE INDICATED

FIGURE 6 Curb dual weir installation.

this second weir with subcritical flow between the two weirs, providing reasonably good head-measuring conditions in the approach to the broad-crested measuring weir. The field rating for this curb dual weir is shown by the solid curve in Figure 7.

As noted in Figures 6 and 7, the curb dual weir is not horizontal and the abutment and curb are not vertical; as a result, the top width (B_t) increases with head. For the same reason, the effective head (H_e) is not the same as the head measured from zero datum at the low point next to the curb (H_{cw}). If the effective width (B_e) is determined for each flow as the mean width for that head and H_e, computed as a mean head, the discharge equation for this broad-crested weir becomes

$$Q = C_b \times 2/3\ B_e (2g)^{1/2} H_e \qquad (1)$$

The theoretical rating curve for $C_b = 0.86$ is also shown in Figure 7 and agrees closely with the field rating. The coefficient C_b for the normally higher broad-crested weir is about 0.50 to 0.57. As pointed out by Vennard (12), C_b will be larger for a low-profile weir with a high velocity of approach; obviously that is the case for this broad-crested weir.

These tests, although limited, lend credibility to using this kind of curb dual weir installation and the theoretical rating to measure bypass flows.

Trunkline Flows

Trunklines are typically 3 ft in diameter and larger and hence it is feasible to install flumes, weirs, and other measuring devices in them. Despite their size, trunklines are accessible only through small manholes, which is usually a limiting factor.

Flows in trunklines may be subcritical or supercritical. The presence of constrictive flow measurement devices such as flumes will almost invariably cause subcritical flow to occur upstream, if it is not subcritical already, and rapid transition to pipe-full flow when discharge and heads become large

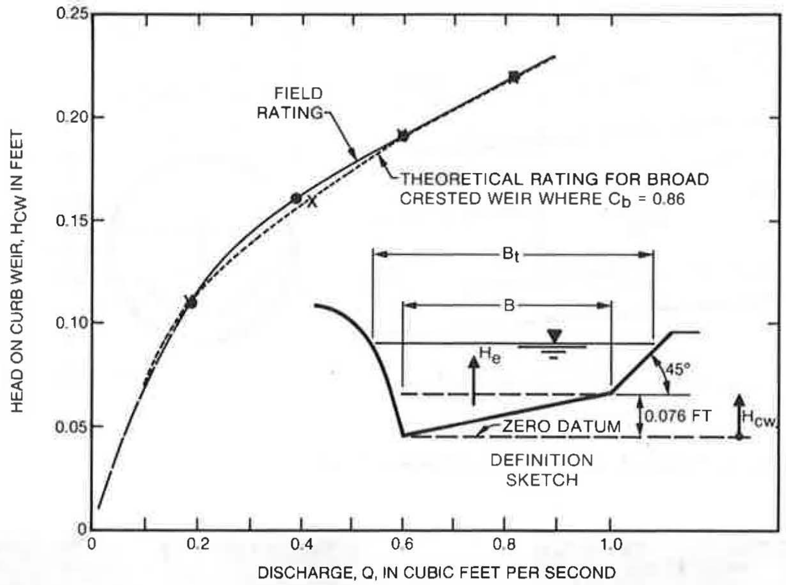


FIGURE 7 Discharge ratings for curb dual weir.

enough. Establishing a discharge rating in the transition zone between open-channel and pipe-full flow is a particular problem.

Surcharge conditions occur when piezometric heads are above the pipe crown elevations and the system is experiencing pipe-full pressure flow.

Backwater conditions, such as when trunklines discharge into nearby streams, may further complicate the hydraulics. Typically, trunkline pipes become submerged as the receiving stream reaches flood stage, thus causing the trunklines to fill as free flow in the pipes ceases to exist. In extreme cases, negative flow may exist in which flow enters from the stream. Flow-measuring devices in these trunklines that depend on only head measurements and free flow are no longer valid under such conditions.

The decision in this study was to rate a Palmer-Bowlus flume modified to function as a venturi meter for pipe-full flow and as both a subcritical and a supercritical flume during open-channel flow. An electromagnetic velocity meter was to be installed upstream of the flume to aid in measuring transition flows as well as flows during backwater conditions. Head would be measured upstream of the flume and in the throat, allowing the applicable calibration to be chosen.

Design and Calibration of a Modified Palmer-Bowlus Flume

The most common type of device used for measurement of flow in larger trunklines is the Palmer-Bowlus flume (13-15). The decision in this study was to design and rate a modified type of Palmer-Bowlus flume (MPB) for both open-channel flow and as a venturi meter with the occurrence of pipe-full flow. It was also intended that the flume perform as a supercritical-flow flume when head was measured in the throat. To accomplish this, the typical Palmer-Bowlus flume design was modified as shown in Figure 8 by making it longer with flatter side slopes and a greater floor thickness. This MPB flume was also designed so that its components could be passed through small manhole openings as shown in Figure 9 for assembly in a trunkline (Figure 10). The 1:1 side slopes were to make construction of concrete possible without having to employ forms.

An 18-in. MPB flume was calibrated in the laboratory for four pipe slopes--0, 1, 2, and 3 percent--for both the approach and the throat. A 48-in. MPB flume was installed at the field test site and rated for low discharges by using hydrant flows measured with tracer dilution and the acoustic velocity meter. Dilution-type discharge measurements were also obtained in the 48-in. MPB flume during several runoff events.

Generalized calibrations for the MPB flume were successfully obtained for both open-channel and pipe-full flow conditions and are shown in Figure 11 (terms are defined in Figure 8; ΔH_{at} is the head difference between the approach and the throat when the system is flowing full). In addition, satisfactory calibrations for the MPB flume functioning as a supercritical flowmeter were obtained (Figure 11B), which extended the measurement range capability because the throat does not fill as quickly as the approach., Nevertheless a transition zone exists between open-channel and pipe-full flow during which flow may pulsate because of alternate filling and opening.

As soon as pipe-full flow exists throughout the MPB flume, pressurized flow exists, and the flume can be treated as a venturi meter. At the steeper slopes considerable difficulty was experienced in getting the 18-in. MPB flume to flow completely full without raising the tailwater and creating backwater. Discharges on the order of 20 ft^3/sec would just barely cause the pipe and the flume to fill. Most of the data in Figure 11C are based on tests in which tailwater was increased to force the system to flow full. Data are also shown for those tests where pipe-full flow occurred or almost occurred without tailwater. As can be seen, most of the scatter is for those measurements where pipe-full flow was not definitely established. These data are purposely shown to emphasize that fully pressurized flow must exist through the MPB flume for this calibration to apply.

From a practical standpoint, it is suggested that the throat calibrations using the MPB as a supercritical-flow flume in conjunction with the venturi calibration when the flume is flowing full will yield good results with a limited transition zone. Care must be taken to determine which flow condition exists. The advantages of using the MPB flume as a

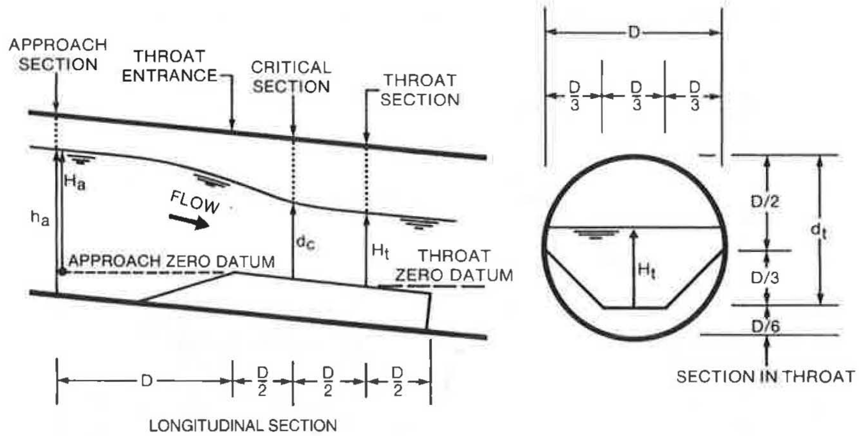


FIGURE 8 Design of modified Palmer-Bowlus flume.

FIGURE 9 Passage of part of modified Palmer-Bowlus flume form through 18-in. manhole.

FIGURE 10 Framework for forming modified Palmer-Bowlus flume of concrete.

supercritical-flow flume are the improved self-cleaning characteristics and the greater range in discharge available before the pipe nears flow-full conditions (about 10.5 ft^3/sec compared with 7.5 ft^3/sec for the 18-in. MPB flume). The chief disadvantage is the less sensitive throat calibration.

Electromagnetic Velocity Meter

It was recognized that measuring the flows in pipes with meters such as the MPB flume was apt to be poor in the transition range. In order to measure discharges in the transition range, an electromagnetic point velocity meter (EVM) was installed in the approach to the MPB flume (16). The EVM was to be activated when stages approached the crown of the trunkline to measure velocities as flow went from free surface to pipe full and back. With known velocities, it would be possible to compute discharges through the transition.

In conjunction with the laboratory calibration of the 18-in. MPB flume, an EVM was calibrated to determine what velocity coefficients should apply to different flows and flow conditions in the approach to the flume. These tests were less than satisfactory because it was found that approach conditions to the flume (a hydraulic jump formed upstream when flow in the upstream pipe was initially supercritical) probably affected the velocity distributions in an unpredictable manner. Furthermore, in the transition zone, pulsating flow resulted, which added uncertainty to the applicable velocity coefficients. Only with pipe-full flow did the EVM velocity coefficients appear to be reasonably stable at about 1.00, regardless of pipe slope. Uncertainty exists as to what, if any, coefficient should be used at other than pipe-full flow. Therefore it would appear that the scheme of using an EVM located in the approach to the MPB flume to measure transition flows is of questionable value.

Field Tests of the MPB and EVM

Fire hydrant discharges were directed into the 48-in. trunkline leading to a 48-in. MPB flume installed at the field site. Once each flow had stabilized, it was measured by both tracer dilution and acoustic meter; these discharges were in close agreement and also agreed closely with the calibration curves shown in Figure 11A and 11B. No attempt has been made to show these data in Figure 11A or 11B.

Several periods of storm runoff were experienced

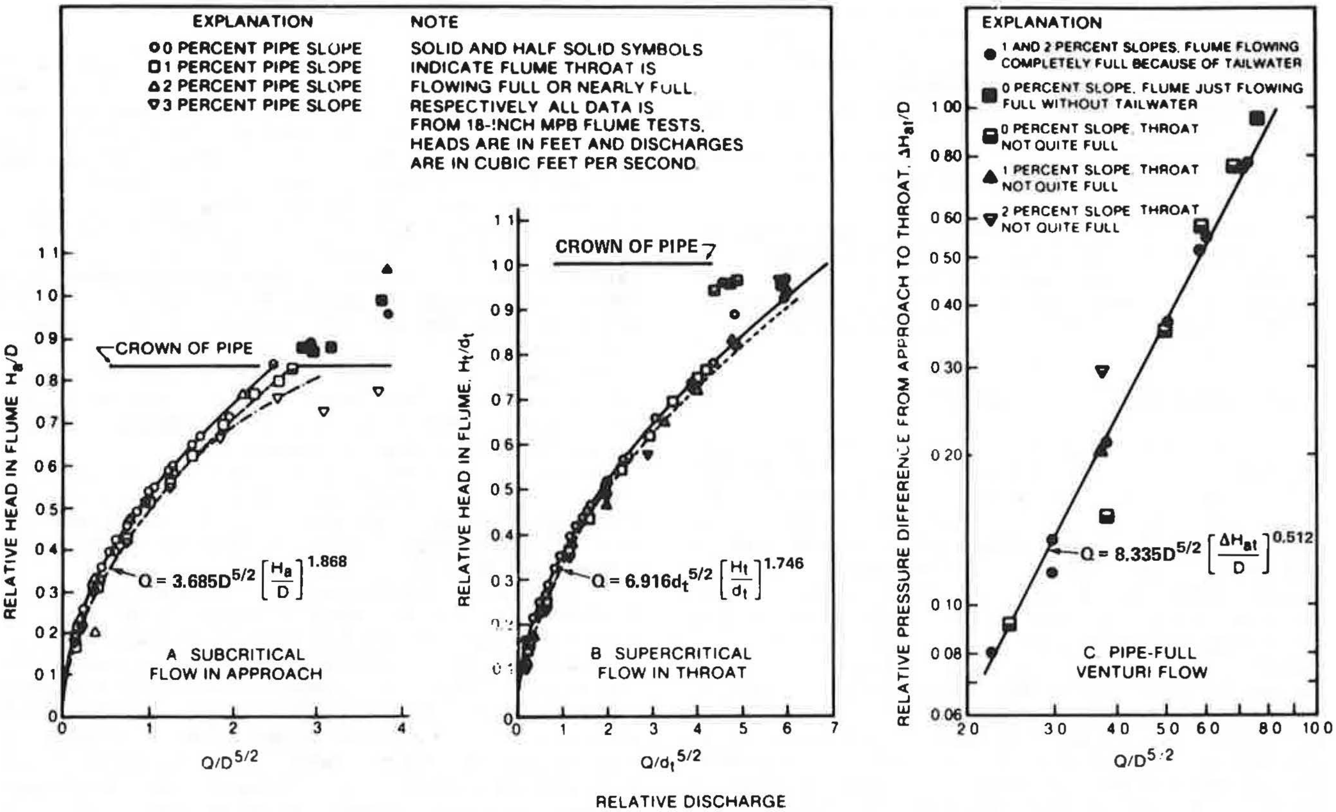


FIGURE 11 Calibrations for modified Palmer-Bowlus flume.

during the field test period. A total of 12 dilution measurements was obtained automatically, some on the rapidly rising limbs of the hydrographs and others on the slower recessions. As might be expected, these measurements scatter more than the dilution measurements made during the steady-flow hydrant tests. Nevertheless, agreement was good and verified the laboratory calibrations. Normally the dilution measurements made on the slower-changing recessions would be expected to give the most accurate results. In this case no distinction could be made, probably because mixing was so nearly instantaneous. Factors causing such good mixing were the turbulence in a junction box at the point of injection and the hydraulic jumps above and possibly below the MPB flume; sampling was downstream of the MPB flume.

At the field site the EVM was installed on a vertical support rod in the approach to the 48-in. MPB flume 0.4D above the invert and 1D upstream of the entrance. It was activated only when the micrologger sensed that sufficient stage existed during a given flow event. The voltage output was then recorded on the micrologger.

The system worked without flaw during all field tests. The EVM was adequately submerged only at head values at and above 1.2 ft. Unfortunately, the field site was found to experience backwater at about this stage, so a direct comparison of discharges computed from the EVM velocity data and the MPB flume calibration could not be made. Unfortunately too, the highest dilution-discharge measurements thus far obtained are at approximately the same head as that when the EVM is activated; thus the validity of the EVM-based discharges cannot be confirmed at this time. Field tests are continuing in hopes that higher dilution-discharge measurements will confirm this backwater effect. If so, the validity of using the EVM to measure flows under backwater conditions would be confirmed.

Stage and Head Measurement System

In the normal storm-sewer drainage system, it is impractical, if not impossible, in most instances to employ fluid intake systems with stilling wells and floats or other such direct means of measuring water stage or pressure heads in connection with flow measurement devices. It was elected in this study to use the gas purge or pneumatic-bubbler and orifice system because of the flexibility and reliability it offered. With this system, a gas is bubbled out through an orifice and the pressure exerted by the overlying fluid column is measured and converted to head in feet of water (17). Various types of manometers have been developed to convert gas pressure to feet of water. Although not new, pressure transducers were tested to measure gas pressures and relay the corresponding voltage output to a micrologger recorder.

Five pressure transducers were initially calibrated in the laboratory before installation at the field test site. These ranged from 10-in. to 100-in. water-stage sensing units. They were tested from -25°C to +50°C. The calibrations of the five transducers were then periodically checked at the field test site by using a water-filled standpipe. Three of the five transducers were then retested in the laboratory following 6 months of use.

The following conclusions were drawn from laboratory and field tests of the five transducers:

1. Each transducer should be tested and calibrated in the laboratory over a range of depths and temperatures.
2. Calibrations should exclude the use of data extremes and transducers should be installed if possible to avoid their use at very low heads (0.1 to 0.2 ft of water).

3. Temperature effects are not normally significant but high temperatures significantly over 100°F should be avoided or the transducer should be insulated from extremes in temperature.
4. Hysteresis is not significant and is lowest at lower temperatures.
5. Transducers may experience an aging process and should be periodically calibrated in the field.

In general it was concluded that the combination of the pressure transducer and pneumatic bubbler and orifice into a head-measuring system can be very successful if used with the foregoing precautions, in particular the avoidance of shallow depths.

Control and Data Recording System

In recent years (18) numerous solid-state digital recorders have become available. Certain of the data loggers or microloggers have been tailored for the collection, storage, and processing of hydrologic data. The Campbell Scientific CR-21 micrologger is such a unit. The CR-21 is an extremely low-power, battery-operated, temperature-stable data logging and system control device. The unit uses a 12-V power supply and has nine input channels and four output control ports. This micrologger can be programmed to sense and process data and emit commands to activate various instruments. This latter feature was important because the power consumption of an electromagnetic velocity meter would be excessive for prolonged battery operation alone unless it could be turned on only when needed. Furthermore, the CR-21 can be programmed to store data only if runoff occurs. This unit stores data internally and unloads it automatically to cassette or solid-state storage.

The single CR-21, shown in Figure 12, was used at the field test site to record pressure-transducer data from five measuring devices: a curb weir, four voltages from a 15-in. PIC meter and a 48-in. MPB flume, the voltage output from an EVM, and the counts from a tipping-bucket rain gauge. Furthermore, the same micrologger was programmed to activate the EVM and two automatic tracer dilution-discharge measurement systems above selected heads.

The CR-21 unloads its data to a solid-state recorder that can interface with most computers. Suitable programs may be used to query the storage module and output the data as desired.

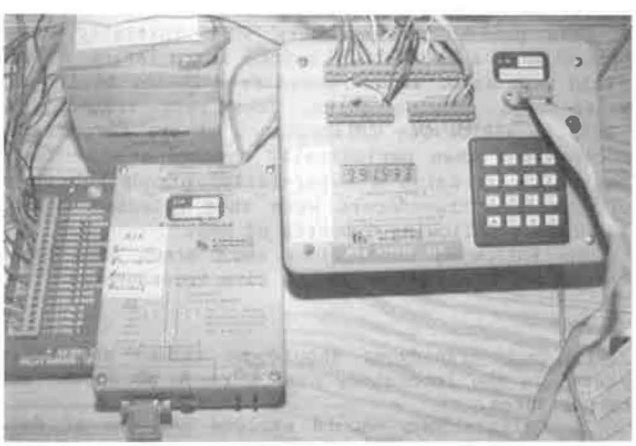


FIGURE 12 Micrologger unit in center with relay board on left and data storage module at lower center.

SUMMARY AND SUGGESTIONS

This study has been successful in identifying certain measuring devices and techniques that can be suggested for inclusion in any storm drainage measurement system. The MPB flume can be relied on for measuring flows in trunklines whether open channel or pipe full; the electromagnetic velocity meter can be used for measuring pipe-full flow caused by backwater conditions; the in situ rating of catchment inlets, although difficult, can be used to evaluate gutter bypass flows; and quality tipping-bucket rain gauges are available commercially that will yield quick response and accurate measurement of rainfall. The pneumatic bubbler and transducer system is a reliable means of measuring head as long as the transducers are kept calibrated. The micrologger can serve all of the devices, both recording data and activating instruments as needed.

Additional work needs to be performed on developing a device to measure flows out of catchments. The PIC meter developed as part of this study was not wholly satisfactory because it depends on the measurement of head in the catchment.

Furthermore, the dilution-gauging approach should be considered in any study if mixing conditions appear favorable. It is suggested that this approach to rating existing catchments in situ be used without any modifications except the addition of pneumatic bubblers and stilling wells. Consideration also should be given to using dilution gauging to measure entire runoff events in catchments; these data are used alone without resorting to adding measurement devices, rating existing catchments, or making any changes in the existing storm-sewer system except to sample the tracer.

The acquisition of comprehensive storm precipitation-runoff data sets for selected segments of highway systems could involve instrumenting several miles of highway. The first attempt might be to try to make such a monitoring system a single, interconnected, centrally controlled network. Instead, it is recommended that a highway system under consideration for study be divided into small units in which one or more inlets, trunkline gauges, and a rain gauge are served by one transducer-pneumatic network, which in turn interfaces with its own micrologger recorder. This is suggested because experience with microloggers indicates that they have good timing accuracy; hence the primary argument for centralized control and the expense and complexity of a central system are eliminated.

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