EVALUATION OF CONSTRUCTED DEPRESSION STORAGE ON REDUCTION OF STORM RUNOFF FLOWS IN AN URBAN AREA

by

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CHAPTER I

INTRODUCTION

Though an old problem, the large volumes of storm runoff generated in developed urban areas are still a concern of engineers, city planners and homeowners. Bigger (1) stated that metropolitan development within the Los Angeles area has caused property damage and loss of life from periodic flood inundations to become successively more disastrous. In 1914, a flood in Los Angeles County caused $10 million in damages. Flood waters in 1934 devastated buildings, citrus groves, villages and highways and caused $40 million in damage; forty persons were reported killed. Still another flood in 1938 caused $62 million in damage and took fifty-nine lives. Bigger cited urbanization for this increase in the loss of life and property. By adding more impervious cover by roofs and paved streets, urbanization has increased amounts of runoff and its rate perceptibly. Lands that could safely store for a short time a portion of the runoff flood waters or allow it to percolate underground have been taken up by subdividers for more intensive use.

The highest percentages of impervious cover per unit area are in the business and commercial districts of the city. Buildings in these sections are constructed "wall to wall" and open directly onto walkways, paved parking areas, or paved streets. The flows from residential areas join with that from the commercial and business districts. Espey, et.al. (2) studied the effects of existing and future urbanization on the discharge hydrograph and runoff yield from the Waller Creek Watershed in Austin, Texas. They found that the peak discharge increased about 51% and the time of rise decreased 46% because of present urbanization as compared with rural conditions. They reported that if future development caused the impervious cover to increase to 50% of the watershed area, the peak discharge would increase by 62% and the time of flood peak rise would be reduced by 52% as compared with rural conditions.

Impervious coverage in residential subdivisions may approach that of the business districts in some instances. The impervious areas in the residential sections consists of roof areas of dwelling units, walkways, patios, driveways on the individual lots, and from the surfaces of street networks serving the subdivision. In the arid southwestern section of the country, one may encounter an entire lawn covered with concrete to eliminate the need for lawn upkeep and excessive use of water to maintain vegetation.

Current construction practices dictate that water from the residential site is usually directed by the shortest pathway to the nearest street or storm drain; these practices increase the flooding potential at downstream sites. Generally, in the design of storm runoff facilities for the residential area, runoff prediction calculations are at best approximations for the conditions in the watershed. Rarely is gaged rainfall and runoff data available for the area undergoing development.

Urban areas within the United States are projected to house nearly 90% of the country's population by the year 1990 (3). As existing urban centers continue to grow at a rapid rate and spread over adjacent lands, and as new urban centers come into existence, problems associated with storm water management will plague homeowners, city planners and engineers. Situations which will be encountered include property losses through flooding of homes and businesses, possible losses of life, disruption of work and transportation schedules, and possible health hazards as a result of contact with contaminated waters.

Beyond the inherent problems of flooding within the watershed, interest in recent years has been directed toward storm water quality. Thompson, et.al. (4) reported that in an average year in Lubbock, Texas, the total amount of Biochemical Oxygen Demand (BOD) discharged in runoff from a combined residential, commercial and industrial watershed was about 4% of the BOD discharge of sanitary sewage within the watershed. Typical sources of storm water pollutants are household and commercial litter, sediments from unpaved alleys and driveways, hydrocarbons from oil and grease deposits on streets, leaves from shrubbery and trees, chemicals used as pesticides, herbicides and fertilizers, and droppings from animals and birds (5). These indicate a significant source of pollution for receiving waters. Reductions in water flow from an area could decrease the volume of pollutants entering the receiving stream.

The growth of urban centers will inadvertantly increase amounts of impervious cover and result in increased storm runoff. Solutions to this dilemma may be found through the planning and incorporation of runoff management measures which can perhaps reduce the flows from areas being developed. Techniques which can be utilized are porous pavements, roof retention storage, vegetal measures, catchment ponding for roof runoff, and construction of level plans for storage on lawns and other pervious areas.

The objective of this study was to determine the degree of variation in the quantity of urban storm runoff which could result by increasing pervious area, retention and depression storage, and permeability of cover material over a small residential watershed. This objective was to be attained by varying the hydraulic and hydrologic characteristics of the watershed under the same precipitation regimes and comparing the results. Runoff values were determined with the use of the Environmental Protection Agency's (EPA) computer program, "Storm Water Management Model" (6,7,8,9). The study was treated as a simulation model since no previously monitored hydrologic or hydraulic data were available for the study area. The project utilized the hydraulic characteristics of a 154 acre watershed within Farrar Estates, a residential subdivision in southwest Lubbock, Texas. Historical rainfall data were obtained from the U.S. Weather Bureau at the Lubbock Regional Airport and the Texas Agricultural Experimental Station at Lubbock for the period of January 1974 to June 1976.

CHAPTER II

LITERATURE REVIEW

A search of the literature reveals a number of studies which have investigated the runoff process in urban areas. The purpose of this search was to gather information on the causes of runoff from a developing area. Emphasis is placed on the characteristics of the watershed and how these effect the rate and volume of runoff from the watershed. Runoff depletion techniques are presented next. Specific methods which have been used successfully to alleviate runoff are outlined, and the application of the method to the watershed, either during site construction or after completion of development, is discussed. Finally, methods of determining the runoff volume from a watershed which have been used are examined.

Watershed Characteristics

The volume of runoff from a watershed resulting from a given precipitation event has been attributed to several basic characteristics of the basin and rainfall event. Rainfall saturates the surface and the depressions of the surface are filled with water in excess of the current infiltration rate. When the depressions are filled, subsequent rainfall builds a layer of water on the surface. Upon reaching a particular depth, a flow of water moves to the nearest channel (10).

Lacey (11) stated that basin characteristics such as the ground slope, amount and nature of vegetation present, and the basin geology are major factors governing the runoff phenomenon. Other characteristics affecting runoff are size and shape of the watershed, soil permeability, land use, and the presence of lakes or swamps (12). If a tract of land consists of bare impervious and unfissured rock, all the rainfall discharged on it, less that held in depression storage and lost to evaporation will run off. Vegetative cover on a tract will aid in reducing runoff. Tilled land can temporarily increase the retentive power of the soil. The existence of surface depressions or dry lakes will act as flood moderators by capturing and holding surface runoff. In towns, the existence of impermeable cover such as roofs, pavements and paved roads largely influences runoff yield and intensity. Here, the rate of runoff may be greatly increased simply due to the absence of resistive and retentive cover, and by the accessibility of a more direct channel of flow. In contrast to urbanized lands, an area providing a maximum amount of vegetative or pervious cover is also providing a far greater resistance factor to the flow of water and an increased ability to store rainfall through soil infiltration.

Urban areas experience a continual increase in the frequency of flooding and degree of hazard and damage associated with floods as development progresses. A recent report cites the rate at which storm water runoff reaches the receiving steam from developments as an important contributor to this phenomenon (13). The findings of the report attribute this largely to an overall decrease in the runoff resistance factor of the surface cover and a larger contributing area resulting from more impermeability in the form of pavement and roof surfaces.

In a study by Pickels (14), the effects of watershed characteristics on flood discharge were investigated. The purpose of the study was to determine the relation of several parameters involved in a rainfall-runoff event to the actual effect that these parameters have on runoff quantities generated. The findings indicated that factors such as topography, geology, temperature and soil moisture content tend to be the most important in determining runoff rates and volumes.

It is apparent from the discussion presented thus far that a major runoff event may occur frequently and with eminent damage potential as a result of:

1. An increase of ground slope for overland flow
2. An increase in contributing area due to impervious cover
3. Provision of channels with low resistance to flow

Runoff Reduction Techniques

With the growth of urban centers, management and reduction of the large quantities of runoff generated have become a major interest. The techniques which may be used are those which may be installed prior to or in conjunction with construction, and methods which may be added at some time after construction. The former group includes such techniques as gradation of topography to flatten slopes and provide additional detention and storage, drainage into storage tanks or retention on roofs for gradual release of runoff at a lessened rate, infiltration enhancement by changing soil characteristics through addition of different types of soil or through the use of soil conditioners, and use of materials which exhibit greater infiltration capacity and moisture storage capacities than normal pavement for surface cover. Post construction methods may include such measures as increased vegetal cover, addition of recharge pits and infiltration basins, and parking lot storage.

There are basically two ways in which these runoff reduction techniques may be applied to a watershed. They are: (1) area methods: those which are incorporated into the development of a large basin and are part of an overall storm water management scheme which is applied as part of the urban plan, and (2) individual lot methods: those which are applied to the lot or singular piece of development rather than to a large area. The latter approaches may be built as part of the construction on individual parcels within the tract or applied by modifications to the individual parcels after construction.

Area Methods

Runoff reduction can be accomplished through the use of catchments and flow depletion devices over an area as it is being developed. Catchments are structures which are incorporated into the area during construction to catch and retain the rainfall and release the water slowly at a later time or through evaporation. Flow depletion is accomplished by inclusion of devices or techniques which will slow the flow rate of runoff or reduce it by retaining only a portion of the flow and allowing the remainder to continue to its nearest channel.

Catchments

Coleman (15) reports that there are essentially two types of structural devices which may be used to provide temporary storage for water: basins and terraces. Basins are designed to hold water and release it as seepage into the soil. Terraces generally are used more to slow the flow of water on a slope or deflect it than for storage.

Level terraces and flat channel terraces also function as basins and have been used extensively in control and collection of agricultural runoff. The surplus water collects behind the level, closed end terraces and backs over the land. Evaporation and seepage account for most of the water loss (16). Level terraces have been designed generally to hold runoff from a 10 year storm, whereas flat channels offer storage for storms of the 50 year frequency (17). The advantages of these terraces are that they eliminate the need for costly erosion control structures, and storage capacity for mechanical structures below the terraces may be substantially reduced. These terraces may also be used to change an inclined surface grade to that of an undulating slope with the result being surface storage for water where there was none (15).

A regular flood control reservoir may be used for storage. An example was the construction of the Melvina Ditch Detention Reservoir, a multipurpose detention basin in Oak Lawn, Illinois. The reservoir, which has a capacity of 165 acre-feet, was designed to serve as a recreation facility in addition to its primary function of reducing local flooding. Winter recreation activities include tobogganing and skiing on a large earth mound formed in one corner of the basin. A concrete paved area is used to eliminate erosion at the inlet. This area is flooded during winter months to serve as an ice skating rink, and during the summer, it is used for volleyball and basketball (18).

Flow Depletion Methods

Although the most obvious solution to runoff reduction is to construct catchment basins to completely retain the large quantities of rainfall, a somewhat more indirect means is to retard the runoff flow rate. Through techniques such as land grading, enhancement of infiltration, and increased vegetation, depletion of flows may be enhanced by allowing more time for seepage to occur. This in turn reduces the volume of water available for flooding.

Cleveland, et.al. (19) investigated the characteristics of runoff quantities and qualities resultant from various land use activities. Findings indicate that flow depletion techniques are basically two types: (1) practices which disperse flows and use the soil pore space as storage, and (2) practices which utilize structural forms to store the runoff for post storm release. The former practice is more applicable for land rich areas, and the latter for land poor (urban) areas. In land rich areas such as farms with open fields, graded terraces may be constructed to intercept surface runoff and convey it at slow, nonerosive velocities to a suitable outlet such as a grassed waterway. Where soils are highly permeable, absorptive terraces having no grade are used to impound the water allowing it to seep into the soil and prevent damage (12).

An increase in vegetal cover may also aid in depleting stormwater flows over an area. The added vegetation acts on surface flows by providing roughness for the surface, cross-slope diversions and interference to water movement. Vegetal interception is most effective during very small storms and decreases as rainfall intensity increases (15).

Another example of a storm water management program which provides flood damage reduction, open space, recreation and water supply benefits within an urban area is the Harvard Gulch Flood Control Project in southwest Denver, Colorado (20). Within this 6.9 square mile drainage basin, storm water runoff caused flood problems in the basin and downstream in the city. The project planners, hoping to gain the participation of communities in this densely populated part of Denver, formulated a green belt approach to solving the problem. The criteria established for the flood control project included: (1) the 4,000 downstream feet of the channel to be placed underground so as not to interrupt existing commercial activities or limit future planning by the city; (2) project monies spent not to exceed the $2.3 million bond issue; (3) new construction on the 26 acres of the state-owned property to result in an aesthetically pleasing park area and room for increased future building; (4) channel construction to lie on city right-of-ways whenever possible to avoid costly land and building acquisition; and (5) all new construction to be designed to improve the appearance of the neighborhood, so as to encourage new, well planned building and landscaping while also alleviating the flood hazard situation.

Construction of the project caused a low flow from infiltrating ground water which was previously lost to evaporation. Because of this, the Denver Water Board later filed a claim for 1/3 cubic foot per second (cfs) of the base flow of salvaged water. Projects of this type benefit the area by increased aesthetic appeal and greater storm water management without disrupting the urbanized area.

Individual Lot Methods

Runoff reducing methods may be used in an urbanizing development on a lot-by-lot basis. The same basic principles and methods which are applied to large areas may be likewise used on individual lots. The scale of the application is much reduced, but the reduction in runoff volumes can be considerable. Ringenoldus (21) stated that runoff problems in urban areas are derived from reduction or elimination of the natural storage conditions. He points out that several methods are available for providing artificial storage to compensate for natural storage lost through urban activities. Some of the methods cited such as roof top storage, parking lot storage and excavation basins are the topics of the following discussion.

Catchments

This section deals with those approaches which have shown to be useful in providing storage capacity and can be easily applied to a single lot. Some of the methods are more easily adaptable in the initial stages of construction such as level pan excavation and roof storage; others may be applied after construction.

In a study conducted in Akron, Colorado, Mickelson (22) investigated the quantities of rainfall retained and running off of level pan construction. At the experiment station in Akron, a series of five level pans were constructed to zero grade within natural drainageways to intercept, spread and store the runoff that normally flowed through them. Each pan was equipped with Parshall or Type H runoff flumes and FW-1 waterstage recorders at the upper and lower ends of the pans to measure inflow and outflow. At each outflow flume a 6 inch plank was installed to allow 6 inches to water to collect in the pans. Water in excess of the 6 inch depth would flow into the next pan. Table 1

TABLE 1

ACREAGE INVENTORY OF CONTRIBUTING WATERSHED AND PAN AREAS

Pan Number	Pan Size, Acres	Watershed Size, Acres
1	6.4	357.3
2	6.6	18.4
3	3.0	138.3
4	2.5	63.5
5*	2.8	-----
Total	21.3	577.5

SOURCE: Mickelson, R. H. "Level Pan Construction for Diverting and Spreading Runoff." Trans. Am. Soc. of Agric. Engr. Vol. 9, No. 4, 1966.

*Pan 5 has no contributing watershed, but receives excess runoff from pans 3 and 4.

indicates the size of each level pan that was constructed and the watershed area contributing to the level pan. After construction of the level pans, rainfall and runoff were monitored for a three year test period. The average annual rainfall was 14.84 inches. Average runoff from the test site was 0.3 inches compared with 1.2-1.5 inches from unleveled areas. The results of the study are presented in Table 2.

Through the use of long range planning and an awareness of the need for storm water management, several reduction methods may be designed into a new development. An apartment development in Denver approached the storm water problem through the use of detention ponds, roof ponding, and ground water recharge through a recharge pit and infiltration basin.

Several ponds were located between the buildings with drainage into one which served as a groundwater recharge basin. The buildings were designed for up to 7 inches of rooftop ponding. The on-site storage provided recreational and aesthetic benefits, and reduced on-site and downstream flooding while providing a valuable addition to the groundwater resource (20).

Another apartment development in Arlington Heights, Illinois, uses a different variation in storm water management (20). Drainage channels convey runoff to a depressed tennis court which acts as a detention reservoir. During storms, the water from the apartment complex is temporarily stored in the depressed court. After the uncontrolled storm water has flowed into the court, it is discharged into the drainage system at a controlled rate. Although this scheme may not appear useful to an owner, there are instances where residential lots have tennis courts or swimming pools, and application of the same

TABLE 2

ANNUAL AND MONTHLY PRECIPATION AND RUNOFF DURING THE GROWING SEASON AT THE CENTRAL GREAT PLAINS FIELD STATION, AKRON, COLORADO

Month	57-Year Mean*	1962		1963		1964	
	Rainfall, Inches	Rainfall, Inches	Runoff,† Inches	Rainfall, Inches	Runoff,† Inches	Rainfall, Inches	Runoff,† Inches
MAY	2.94	5.08	0.04	1.01	0	2.23	TRACE
JUNE	2.41	4.83	0.08	2.08	TRACE	3.97	0.40
JULY	2.67	2.80	0.07	2.91	0.07	0.71	TRACE
AUGUST	2.08	0.84	0.01	3.75	0.15	1.47	TRACE
SEPTEMBER	1.37	0.49	----	3.23	0.03	0.13	0
OCTOBER	0.97	0.29	----	0.70	TRACE	0.16	0
CALENDAR YEAR	16.65	16.29	0.20	15.96	0.25	12.27	0.40

SOURCE: Mickelson, R. H. "Level Pan Construction for Diverting and Spreading Runoff." Trans. Am. Soc. of Agric. Engr. Vol. 9, No. 4, 1966.

*Runoff for years 1908 through 1961 is not available.

†Runoff measured from 23 contributing watersheds ranging from 1/4 to 357 acres in size. No runoff occurred during November through April.

principle could be made. On a much larger scale, such as in a shopping center complex, the parking lots could be constructed below ground level elevation to provide temporary storage for storm water before it is drained into a storm sewer.

Flow Depletion Methods

It is possible to reduce or deplete the rate of flow which occurs during a storm event by temporarily detaining on-site runoff from rain falling directly on an impervious area. By slowing the flow of storm water, especially from pervious areas, additional recharge of the ground water through percolation may occur. If depletion methods are coupled with runoff retention on pervious areas for percolation into the ground, the total volume of water available for runoff will be reduced.

A pioneering effort in reducing peak runoff rates during land development was made in Thomas Manor at El Paso, Texas (23). The design utilized captures about one half of the normal runoff and retains it on the individual lots. This development involved hundreds of lots, but required almost no storm sewers. The outfall was collected in a sump and pumped over a levee into the Rio Grande River. The use of individual lots for the storage of runoff reduced the need for storm drains and conserved rainfall where it would benefit the individual homeowners, all at a very low cost.

Another very widely used but often ignored and overlooked method for reducing runoff is to utilize the storage capacity offered by the street gutters during storm flows. Gutter storage generally has a greater peak reducing influence than the surface detention of overland flow, and requires a longer time to achieve equilibrium outflow. Gutters sometimes provide a surplus of storage above that required to accommodate the rainfall excess. This results in a maximum gutter outflow rate at the inlet less than the equilibrium rate (12).

Rospond (24) reported several examples where roof retention was used to limit the rate of runoff from a developed site so as not to exceed that of the site in its undeveloped state. A proposed building having 2.15 acres of roof space sat on a 3.92 acre site. By use of the Rational Method, the runoff from the undeveloped site was predicted to be 10.98 cubic feet per second (cfs), for a 4 inch per hour rain intensity and a runoff coefficient of 0.70. Through the use of control flow roof drains and roof retention with a maximum rise of 3 inches, the discharge from the developed site was only 7.41 cfs. The actual discharge from the building was only 1.07 cfs as compared to a potential of 7.7 cfs. The author reported that the method has proven effective on very large areas, but not on small individual roofs. It is believed, however, that flat roofs on a residential structure could also provide storage if the lot owner is attracted to flat roof design.

Diniz (25) reported on the use of porous pavement to reduce the volume of runoff resulting from urbanization. A test area consisting of a 12,120 square foot contributing area and a 27,300 square foot porous pavement parking area in The Woodlands, a new town being developed 30 miles north of Houston, Texas, had been studied extensively. The results of the study showed that 4 inches of storage or 8 inches of base (at 50% porosity) would suffice to control all of the 100 year frequency rainfall at The Woodlands porous pavement test area. It was concluded that the use of porous pavement is a viable approach to urban storm water management.

Runoff Models

Several models have been developed in recent years to predict the volume of runoff from a given watershed resulting from a rainfall event. The various techniques range from very simple singular equations to highly complex digital computer models. The amount of time and information required to use the models increases considerably as the complexity and precision of the model becomes more sophisticated. Listed below are a few of the models presently available and in use today:

1. Rational Method
2. Horton's Equation
3. British Road Research Laboratory Model
4. Storm Water Management Model

The use of each of these models will be discussed in the following sections.

Rational Method

By far, the most widely used technique in past years has been the Rational Method (26). The method is in the form of the equation:

$$Q = CIA$$

Where: Q - Peak discharge in cfs

C - Runoff coefficient based on the basin cover material

I - Average rainfall intensity in inches/hour

A - Area of watershed in acres tributary to the point of design

The method is relatively simple to apply, which counts for its attractiveness to design engineers. The runoff coefficient, "C", is a complex variable, having concealed within it numerous interdependent variables such as the character of land use, the extent of land coverage by impervious surface, ground slope, the infiltration capacity of pervious areas, the cumulative volume of major puddles and pools, length of overland flow, and the roughness coefficient of all overland flow surfaces and channels (27).

A major problem in predicting "C" is that in developing areas the future stage of development must be estimated; thus, considerable error is possible in predicting runoff from the area in the future. Also, the compositing of the many variables effecting the value of "C" does not lend itself to a methodical approach for determining its value. Consequently, determining the value of "C" in a particular locality must come from many years of experience. Another drawback to the method is that all too often the runoff coefficient is the only adjustable variable in the equation, and due to economic necessity it is adjusted to match the money available for a project.

For the purposes of this study, the Rational Method was not deemed adequate for use. This was due to a desire to enumerate and define more accurately many of the variables concealed in the runoff coefficient, "C", and to have greater flexibility than the equation possesses.

Horton's Equation

Foster (10) cites early work done by Horton which investigates the runoff from a very small watershed. Horton derived a runoff formula applicable to watersheds having lengths of a few hundred feet. The relationship takes the form:

$$q = \sigma \, \mathrm{TANH}^2 \{0.92 \, t(\frac{\sigma}{nL})^{0.5} \, S^{0.25}\}$$

Where: q - Rate of overland flow at the lower end of an elemental strip of turfed, bare or paved surface in cfs/acre of drainage area or inches/hour

σ - Effective rainfall in inches/hour

n - Retardance coefficient representing surface roughness

L - Effective length of flow in feet

S - Average surface slope in percent

t - Time or duration in minutes since rainfall began

Although the Horton equation is more encompassing than the Rational Method equation, it lends itself to inaccuracies due to the variability in the coefficient "n". Considerable experience and judgement is required to accurately determine its value. Like the runoff coefficient of the Rational equation, it is also subject to the same economic considerations and limitations. Recommended values of "n" are listed in Table 3. This method was not chosen for use in this study since it has limited diversity, and the study area was much larger that that recommended for use of the equation.

British Road Research Laboratory Method

Terstriep and Stall (28) tested the British Road Research Laboratory method (BRRL) on urban watersheds to compare computed hydrographs with those actually measured. The model was developed by the British Road Research Laboratory and reported by Watkins (29). The BRRL uses storm rainfall on an urban area as input and provides the storm runoff hydrograph as output. One important feature of the BRRL method is that

TABLE 3

RECOMMENDED VALUES FOR RETARDANCE COEFFICIENT IN HORTON'S EQUATION FOR RUNOFF

Type Cover	n
Smooth Pavement	0.02
Bare Packed Soil Free of Stones	0.10
Poor Grass Cover or Moderately Rough Bare Surface	0.30
Average Grass Cover	0.40
Dense Grass Cover	0.80

SOURCE: Foster, Edgar E. Rainfall and Runoff. (New York: The Macmillan Company, 1948).

This method was not chosen for use in this study since it has limited diversity, and the study area was much larger that that recommended for use of the equation.

it is readily applicable to basins before development takes place. By using plans for urban development, calculations can be made to predict the hydraulics of the proposed site.

Application of the method depends on the following five assumptions:

1. Only directly connected impervious area contributes runoff
2. Rainfall has a uniform spatial distribution over the basin area
3. Relationships between time and area contribution to runoff are constant and independent of intensity and duration of the event
4. A constant discharge - storage relationship is assumed to describe variation of discharge with storage for both rising and falling limbs of the hydrograph
5. Use of a one step storage routing technique is valid for converting precipitation to the outflow hydrograph

A unique feature of the BRRL method is that it derives the outflow hydrographs using only the impervious areas of a watershed directly connected to the storm drainage system. All other cover and impervious areas not directly connected to the drainage area are neglected. For this reason, the BRRL method would not be an effective method to use in this study, since the study involved varying the types and amounts of pervious and impervious cover material over the watershed and including the effect of pervious cover on the volume of runoff from the study area.

Storm Water Management Model

The Environmental Protection Agency, with the aid of Metcalf and Eddy, Inc., The University of Florida, and Water Resources Engineers, has developed the Storm Water Management Model (SWMM) (6,7,8,9). The comprehensive SWMM uses a high speed digital computer to simulate real storm events on the basis of rainfall (hyetograph) inputs and system (catchment, conveyance, storage/treatment, and receiving water) characterization to predict outcomes in the form of quantity and quality values. The program objectives are directed toward complete time and spatial effects, as opposed to simple maxima (such as the Rational Method) or only gross effects (such as total pounds of pollutant discharged in a given storm). The programming arrangement consists of a main control and service block, the executive block, a service block (combine), and four computational blocks: runoff, transport, storage, and receiving water. Activities in the blocks other than the main control and service block are as follows:

1. The executive block assigns logical units (tape/disk/drum), determines the block or sequence of blocks to be executed, and, on call, produces graphs of selected results. This block does no computation as such, while each of the other four blocks are set up to carry through a major step in the quantity and quality computations. All access to the computational blocks and transfers between them must pass through the executive block.

2. The combine block allows the manipulation of data sets (files stored on offline devices) in order to aggregate results of previous runs for input into subsequent blocks. This allows large, complex

drainage systems to be partitioned for simulation in small segments.

3. The runoff block computes the storm water runoff and its characteristics for a given storm for each subcatchment and stores the results in the form of hydrographs and pollutographs at inlets to the main sewer system.

4. The transport block sets up pre-storm conditions by computing dry weather flow and infiltration and distributing them through the conveyance system. The block then performs its primary function of flow and quality routing by picking up runoff results and producing combined flow hydrographs and pollutographs for the total drainage basin at selected points.

5. The storage block uses the transport output and modifies flow and characteristics at a given point or points according to the predefined storage and treatment facilities provided. Costs of construction of storage/treatment facilities may also be computed.

6. The receiving water block accepts output of the transport or runoff blocks directly, or the modified output of the storage block, and computes the resultant hydrodynamics and concentration in the receiving river, lake, estuary or bay. In principle, all blocks may be run together in a single computer execution, but from a practical standpoint only one or two blocks are usually used.

The SWMM was the runoff model used in this study. Through the use of the block, "Runoff", surface runoff is generated from a predescribed watershed based on arbitrary rainfall hyetographs, antecedent conditions, land use, and topography. The model simulates both the quantity and quality runoff phenomena of a drainage basin, and routes the flows and contaminants into the major sewer lines. From the rainfall hyetographs, the program makes a step accounting of rainfall infiltration losses in pervious areas, surface detention, overland flow, gutter flow, and contaminants washed into inlet manholes, and produces hydrographs and pollutographs from the flows.

Graham, Costello and Mallon (30) performed a sensitivity analysis of the model in an application to the Washington, D.C., metropolitan area. They found that the greatest effect on quantity and quality results was due to land use and characteristics of the impervious areas. In general, the model is sensitive to the following quantity input parameters:

1. Surface roughness for impervious areas
2. Detention depth for impervious areas
3. Maximum or minimum values of infiltration

Assuming a thorough evaluation of the basin's physical data (such as ground slope, area, percent imperviousness), the user has the flexibility to adjust seven quantity input parameters:

1. Resistance factor for impervious areas
2. Resistance factor for pervious areas
3. Surface storage on impervious areas
4. Surface storage on pervious areas
5. Maximum infiltration rate
6. Minimum infiltration rate
7. Decay rate of infiltration

The model has been extensively tested and verified on watersheds at several locations in the U.S. which include Lancaster, Pennsylvania, and San Francisco, California.

CHAPTER III

EXPERIMENTAL PROCEDURES

The following is a discussion of the approach taken to formulate and conduct the analysis done in this study. Included is a description of the watershed characteristics such as type of land use, hydraulic properties, and the climate which predominates in the study area. The parameters required for use of the SWMM will be detailed, and their importance in the model pointed out. As an integral part of this discussion, the methods used to quantify the parameters and their values as measured from the watershed will be presented. Another topic discussed is the test sequence determination and a description of the application of the testing methodology to the model. This includes an outline of the rationale used to consider the future growth within the watershed, the patterns by which the area will develop, and the approach used to apply this growth to the SWMM model.

Characterization of the Watershed

The watershed used in this study was a 154 acre residential subdivision located in southwest Lubbock, Texas. The study area was developed in 1972. It consists of single family housing units and some duplex dwelling units adjacent to the commercial and municipal parcels in the lower watershed area. Most of the lots in the area have been developed, and only a few vacant lots remain. A few acres of land in the lower watershed will be developed for commercial activities, and some will be a city park. Neither of these two uses are considered in this study.

Although the majority of the basin is fully developed, there are several undeveloped and vacant lots toward the far western boundary and at random locations within the watershed. These lots have been sold and will probably have houses constructed on them by January 1978. The boundaries of the study area are represented by the area outlined in Figure 1. At present the population density for the study area based on the City of Lubbock Planning Department's population factor of 3.16 persons per single family residence is reported to be 15.72 persons per acre.

Houses in the basin range in value from approximately $40,000 to $80,000, as reported by a representative of Jim Turner Enterprises, a major realtor/construction contractor operating in the subdivision. Houses in the area must have a minimum floor cover of 1800 square feet, a two car attached garage, brick veneer siding, and wooden roof shingles.

Surface drainage occurs in the area as overland flow from the lots to the streets, and then proceeds as curb and gutter flow to an earthen channel which leads to a playa lake directly east of the subdivision. The streets in the area are all paved with Texas Highway Department Type "C" asphalt and have concrete curbs and gutters. Average slopes of the streets range from 0.62 to 0.81 percent.

There is no storm sewer drainage within the basin. Before draining into the curbs and gutters, storm water falling on the lots first runs off of the roofs and impervious areas such as patios and sidewalks.

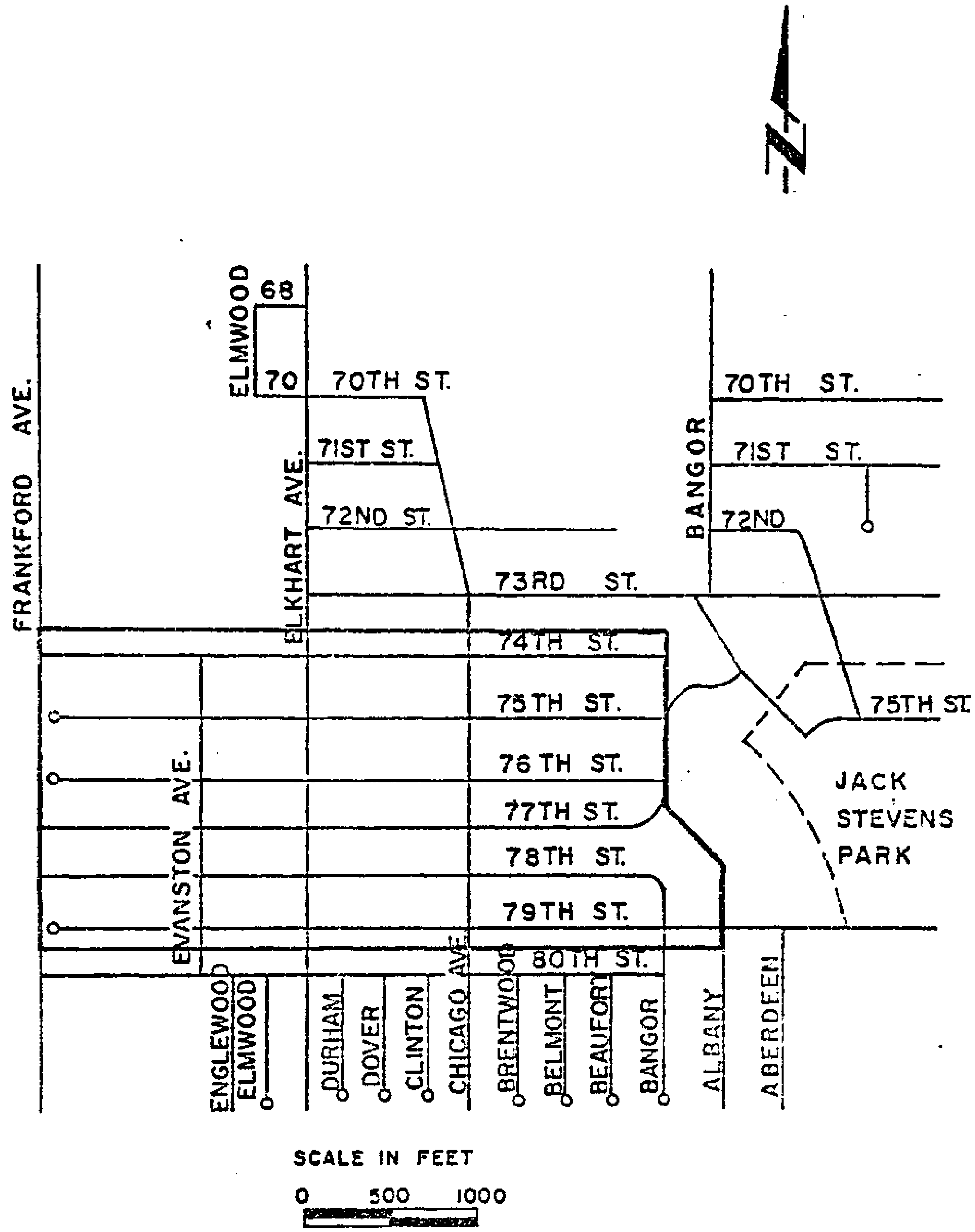


Fig. 1. Location map of the subcatchment study area in Farrar Estates.

It then flows by the slope of the yard to either the curbs in the front of the lots or to nonpaved alleys in the rear. In the curbs and alleys, the water flows by gravity into the streets until it finally reaches the playa lake.

Lubbock has the semiarid, warm, continental climate characteristic of the Southern High Plains of Texas. The climate of the area is transitional between desert conditions on the west and humid climates to the east and southeast (31). The normal annual precipitation is 18.41 inches with the maximum rainfall usually occurring during the months of May through October as shown in Figure 2. Precipitation in these months is caused by warm, moist tropical air carried inland from the Gulf of Mexico. The condition produces moderate to heavy afternoon and evening convective thunderstorms. Precipitation in the area is characterized by its erratic nature varying from as much as 13.93 inches to none in a single month. Rainfall intensities range from less than 0.50 inches per hour to more than 3 inches per hour. Snow occurs occasionally in the winter months, but remains on the ground only a short time.

The normal annual temperature for the area is 59.7°F. The warmest months are June, July and August, with a normal daily maximum in July of 92°F. About 79 days a year have temperatures above 90°F with about 98 days a year recording minimum temperatures less than 32°F.

Data Determination

A land use study was conducted in the area to determine the physical parameters which were used to describe the watershed in the computer model. Aerial photographs of the area taken in 1975 and obtained from the City of Lubbock Planning Department and actual physical

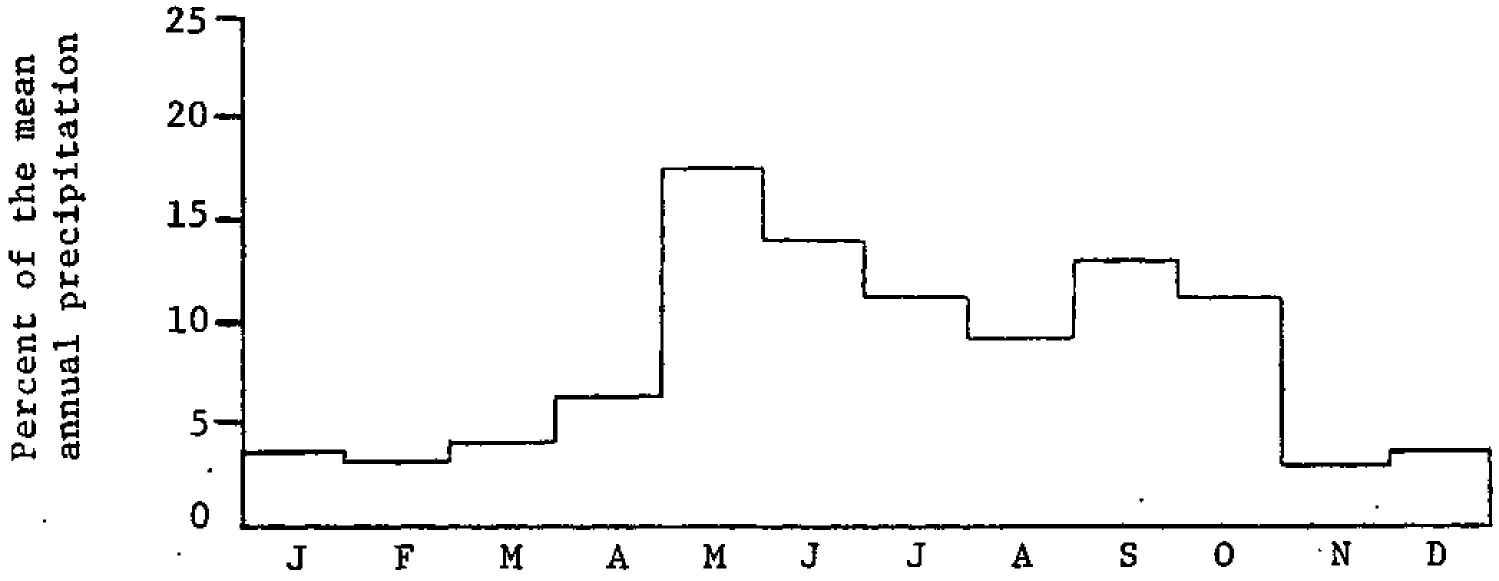


Fig. 2. Monthly Distribution of Rainfall for Lubbock, Texas.

measurement of several representative housing units within the basin were used to determine the land uses. A summary of the major land uses in the watershed is given in Table 4.

Four basic parameters needed to describe the watershed are the following:

1. A description of the subcatchment arrangement
2. The width of each subcatchment
3. The length of each subcatchment
4. The area of each subcatchment

The initial step in determining the data began by defining the study area on an aerial map and describing the subcatchment arrangement within the watershed. The watershed was divided into seven subcatchments, each one draining by overland flow into the street gutters. The watershed subcatchment division is shown in Figure 3. Once the arrangement of the subcatchments was determined, their widths, lengths and areas were measured and recorded. These parameters remained fixed throughout the duration of the study and as such are not considered as variables.

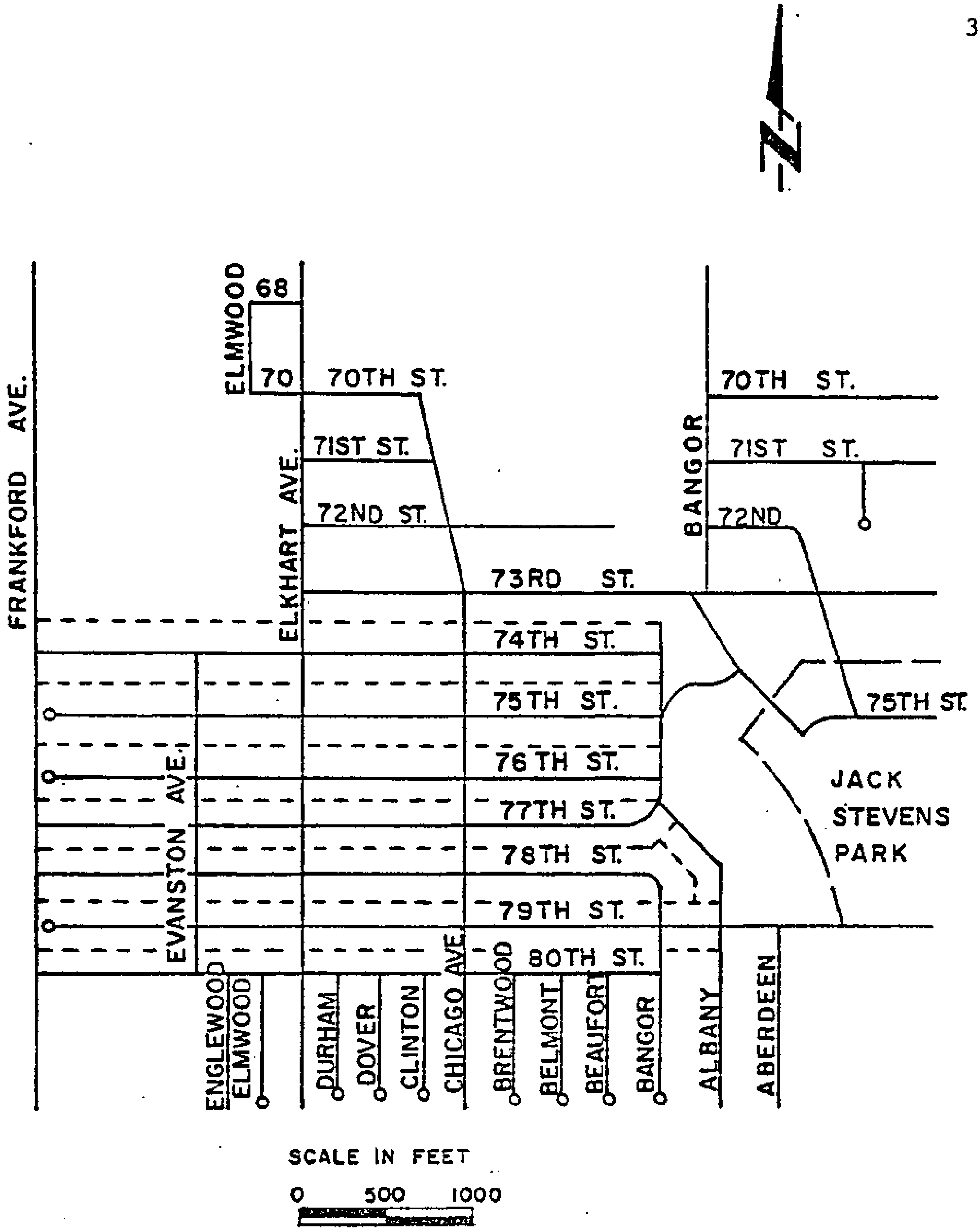
A good deal of detailed information was needed to describe the individual subcatchments. This information had to be physically measured in the field. These parameters included:

1. Percent impervious cover with zero retention
2. Percent impervious cover of the subcatchment
3. Ground slope of the subcatchment
4. Street invert slope
5. Depth of street gutters when full

TABLE 4

LAND USE SURVEY, FARRAR ESTATES SUBDIVISION, LUBBOCK, TEXAS

Type	Area (Acres)	Percent of Total Area
Streets	23.92	15.56
Sidewalks and Driveways	13.4	8.72
Roofs	33.04	21.5
Grass (Lawns)	41.63	27.1
Vacant Lots and Alleys	41.68	27.12



— — — — — Indicates subcatchment boundaries.

Fig. 3. Map showing the subcatchment division of the watershed.

6. Side slopes of the gutters
7. Impervious area retention storage
8. Pervious area retention storage

In order to determine these values, several houses within the watershed which were representative of the majority of the home sites were selected. The lot layouts which appeared to be most prevalant were of four types: (a) conventional corner lots, (b) corner lots with circular driveways, (c) conventional interior lots, and (d) interior lots with circular driveways. Sketches were made of each type lot showing the complete layout from street to alley and side boundary to side boundary. Dimensions were then added to indicate the length and width of all sidewalks, driveways, porches, patios and roof areas. The measurements of all the concrete areas were used to determine the percent impervious cover of the subcatchment which would provide no retention of water. This value was variable and will be discussed in detail later.

As a second requirement, the total impervious cover of the subcatchment was determined. This was done by measuring the concrete areas on each type lot, the roof area of each house, and the paved street area within the subcatchment. Although not required as input to the model, other areas such as lawns, gardens, and flower beds were also measured in order to do an area coverage balance over the entire watershed. Once these measurements were made for each type house, the number of similar houses within the subcatchment was noted. The percentages of pervious and impervious coverage for the entire subcatchment were then calculated by multiplying the coverage for each type house by the number of similar houses within the subcatchment.

The final measurement taken from each lot was the ground slope from the house foundation to the street. This was needed to define the slope of overland flow of water to the gutters. The layouts of two typical interior lots are shown in Figures 4 and 5.

Certain measurements were also taken from the streets and gutters within each subcatchment. At several locations, the invert slope of the streets was profiled. Also included was a cross-sectional profile of the street, used to determine the side slopes of the gutters and the depth of water in the gutters when flowing full. All of these measurements were made by standard surveying techniques and instruments such as a transit, Philadelphia rod, steel tape, and level.

Other parameters required by the model but not directly measured from the watershed were the amount of retention storage provided by impervious and pervious surfaces. These values, like the percent impervious cover, were variables, and could be defined at the user's discretion.

The only other major piece of input data required was the description of a desired rainfall event. This storm could be a theoretical design storm or an actually recorded occurrence. The storm event was described in the model as a rainfall hyetograph. Rainfall data was collected from the Texas Agricultural Experimental Station in Lubbock, and a storm hyetograph constructed from the data. Several storms were investigated, and the one finally chosen depicted the high intensity thunderstorm lasting about 2 hours which is typical of the area. The rainfall hyetograph used throughout the study is shown in Figure 6. All of the previously discussed data was recorded as the original case

Impervious cover-46.7% of total lot area

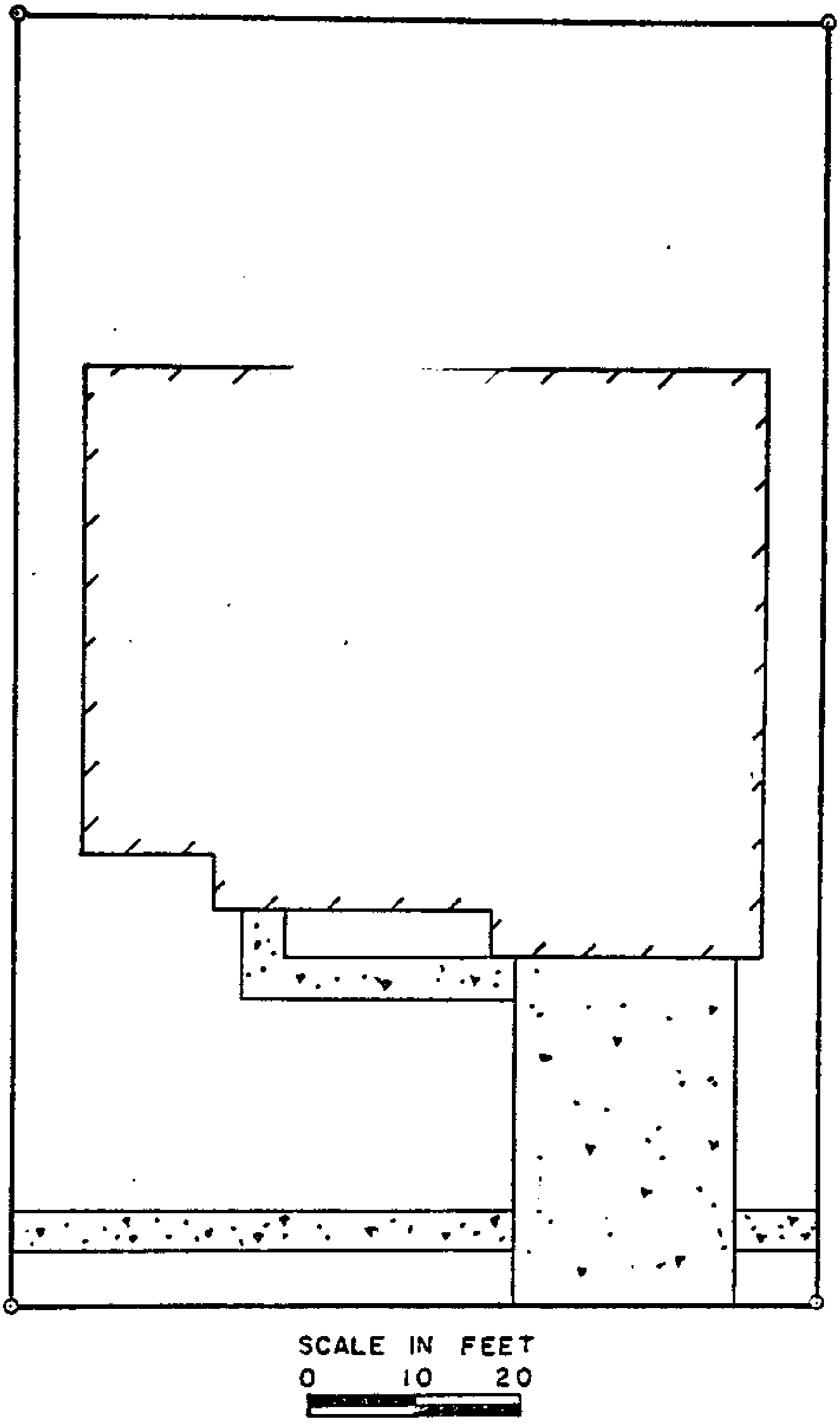


Fig. 4. Lot layout of a typical home within the watershed.

Impervious cover-73.4% of total lot area

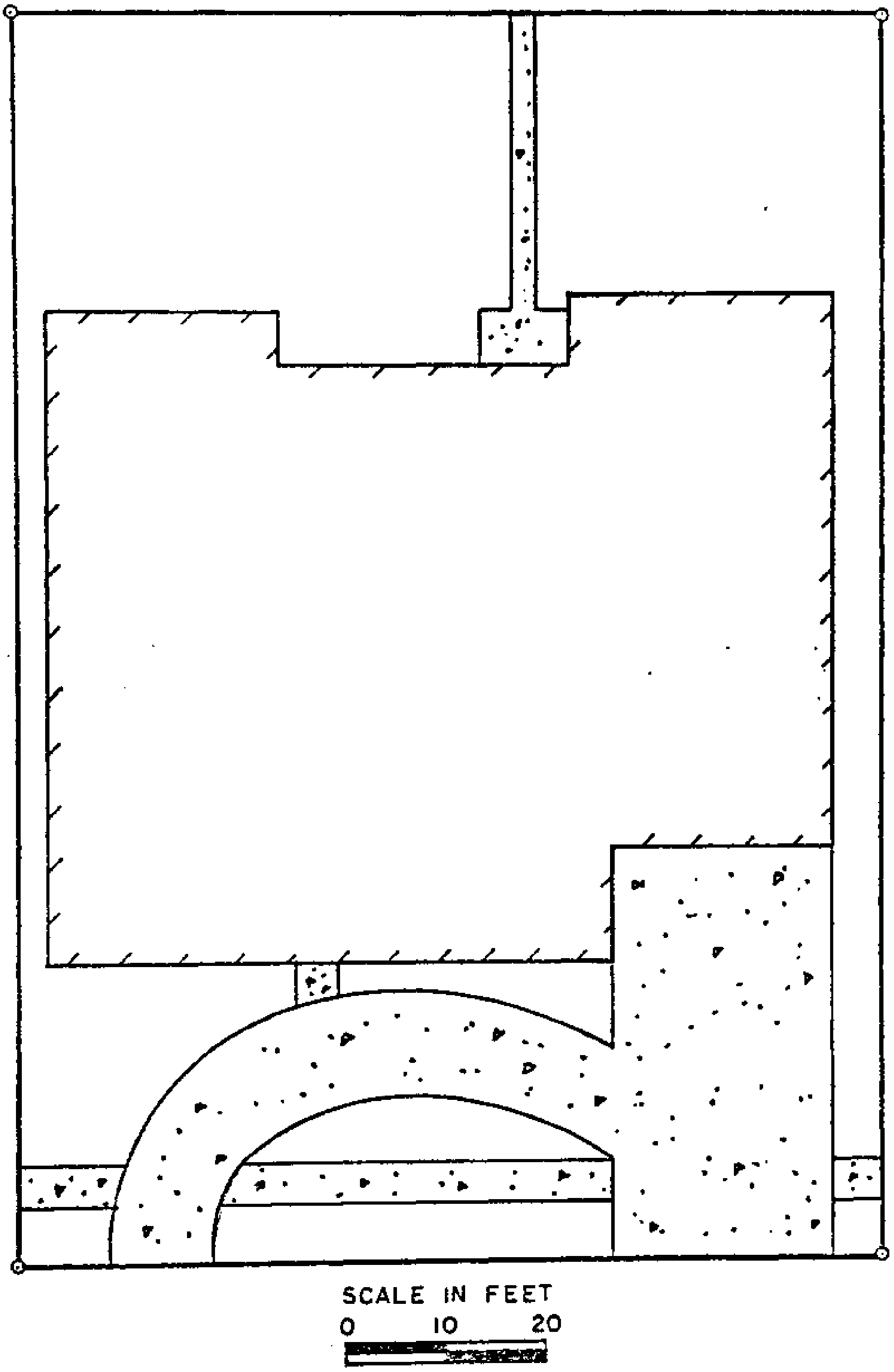


Fig. 5. Lot layout of a typical home within the watershed having a circular driveway.

describing the watershed as it actually exists. The study was conducted by varying certain parameters such as retention storage, impervious cover, and ground slopes.

Test Sequence

The objective of the study was to determine the effectiveness of using various runoff reducing plans over a residential watershed. In order to do this, three basic techniques discussed in Chapter 2 were investigated. These techniques were roof retention of water, the construction of level pans on pervious areas, and the use of porous pavement in the streets. It was assumed that basically three approaches could be taken to apply these techniques to the basin.

The first approach assumed the possibility that 100 percent of the lots within the watershed would for one reason or another be constructed providing roof retention, or that 100 percent of the streets within the area would provide runoff reduction using porous pavement. In this approach, there was no combination of the two techniques. As developed, each lot would be constructed providing roof retention, or all the streets in the subdivision would be constructed with porous pavement.

It is believed that to expect 100 percent of the lots to provide level pan lawns would be somewhat unrealistic. A few homeowners might be convinced that panning their lawns is worthwhile, but generally, most would not desire to use such landscaping. Level pan lawns were investigated only when less than 100 percent of the lots would provide them.

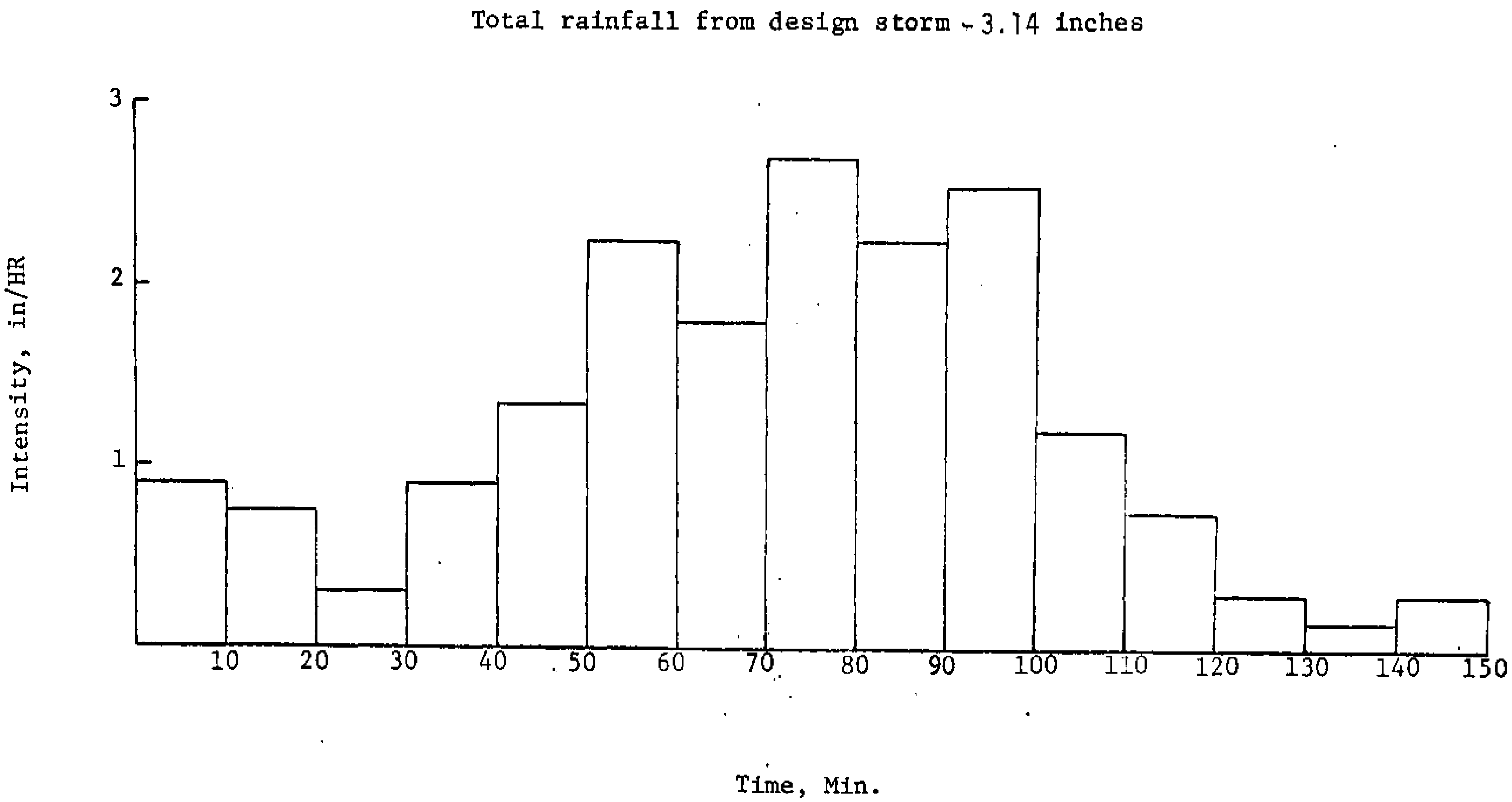


Fig. 6. Design rainfall hyetograph.

The second approach allowed for combining the different types of reduction methods. It was felt that this would be somewhat more realistic than the idea of everybody utilizing the same technique. In combining the methods, it was assumed that all of the lots would be built providing roof retention and 100 percent of the streets would have porous pavement. Naturally, both of these approaches are somewhat hypothetical, but it was felt that through tax incentives, stipulations by land developers, deed restrictions, city ordinances, or whatever means, the area could develop in this manner.

The third and most realistic approach assumed that the area would develop in a very random manner. As the lots were developed, certain owners would choose to provide roof retention, some would provide level pan lawns, and some might not provide either method. This approach could also occur where a presently developed residential area exists, and a certain portion of the residents might decide to modify their lots to provide one or more of the methods. In this case, application of the reduction techniques would occur in an even more random fashion than in a newly developing area. To account for this randomness, cases were studied where 25 to 50 percent of the lots provide roof retention, and 25 to 50 percent of the lots provide level pan lawns.

This randomness of development was not considered to include the application of porous pavement to the streets within the watershed. Generally, as a subdivision is developed, the streets are paved in entire block sections and often several blocks at a time. For this reason, the porous pavement method was considered to be used either exclusively throughout the watershed or not used at all. Also, for this study, porous pavement was only provided on the streets, and not to any paved areas on the individual lots. Porous pavement could, however, be used to a limited extent on the individual lots. Homeowners could use porous pavement instead of concrete to construct driveways, walkways, and alleys. The use of porous pavement would probably be undesirable for items such as patios due to the absence of aesthetic appeal. Patios could be constructed with materials such as tiles or sand-filled bricks which are not bound together by mortar or cement. This type of construction would provide retention storage capacity for water very similar to that of porous pavement.

By using the randomness scheme of 0, 25, 50 and 100 percent of the lots providing the runoff reduction techniques, it was felt that a combination could be obtained which would give maximum runoff reduction. This scheme would also provide a cost comparison for optimum reduction at least cost. A complete listing of the various cases studied is shown in Table 5.

SWMM Usage

A considerable amount of input data is necessary in order to apply the SWMM to a watershed. Some of the more important parameters have been discussed in the previous section. Others have been omitted due to the lengthy description required to define them. For a complete outline of the model capabilities and input requirements, the SWMM Users Manual (8) should be consulted. The purpose of this section is to describe the parameters which were variable and instrumental in this study, and the primary runoff reduction method in which they were

TABLE 5

STORM RUNOFF RETENTION METHODS INVESTIGATED

Case	Description of Retention Methods
1	Residential area as it actually exists
2	25% of lots provide roof retention
3	50% of lots provide roof retention
4	100% of lots provide roof retention
5	25% of lots provide level pans
6	50% of lots provide level pans
7	100% of lots provide streets with porous pavement
8	100% of lots provide both roof retention and porous pavements

used.

Five of the model variables which were of importance in this study are:

1. The percent impervious cover with zero retention
2. The percent impervious cover over the watershed
3. The subcatchment ground slope (overland flow)
4. The pervious area retention storage
5. The impervious area retention storage

Each of these parameters was only varied in their relation to the original case representing the watershed as it exists. In this case, it was assumed that none of the three study methods, roof retention, porous pavement, or level pans, existed. Therefore, any modification from the present condition would involve some or all of the variables.

The following discussion outlines the procedures used to define the watershed as it actually exists, and the cases where the parameters varied. Only the concrete cover was considered to have zero retention storage capability. Thus, the percent impervious cover with zero retention was defined as the concrete area divided by the total impervious cover over the watershed. Total impervious cover included all roof tops, the entire concrete area within the watershed, and all asphaltic pavement. This value changed each time the porous pavement method was investigated. Although the concrete coverage remained constant, the porous pavement was not considered to be impervious. Therefore, the concrete area would become a larger portion of the impervious cover within the watershed, and the percent cover with zero retention was adjusted upward. Likewise, whenever the porous pavement method was used, the percent impervious cover of the watershed was adjusted downward since the pavement cover was no longer considered impervious. It should be kept in mind that these values were adjusted only when the porous pavement method was investigated. In all other cases, the impervious coverage remained the same as it was in the original case defining the watershed as it actually exists.

There was only one method studied in which the ground slope for overland flow was varied. This was in the cases where level pan lawns were provided. The lawns actually have a slope of about 3.5 percent. In the case where pans were provided, lawns were leveled to zero slope. It was assumed that the lawns would also be provided with small berms around their periphery or sunken below the sidewalk and driveway surfaces enough to provide 3-4 inches of rainwater storage.

Practically everytime a different runoff reducing method was investigated the pervious and impervious area retention storage value was affected. Whenever the level pan method was used, the desired 3-4 inches of storage needed only to be specified for the lawn area since no change in surface cover was made. However, in the case of porous pavement, some extra computation was required. As previously mentioned, the porous pavement was not considered as impervious cover. Whenever porous pavement was provided alone as a reduction method, the volume of water which could be held in the pavement due to the porosity was calculated (25). The literature indicated that a base coarse having a porosity of 50 percent would provide storage approximately equal to one half (1/2) the thickness of the base. For this study, a standard 8 inch base coarse at 50 percent porosity was used to provide 4 inches of storage in the porous pavement. The water volume retained in the porous pavement was calculated by multiplying the 4 inches of storage by the total porous pavement area. The resulting volume of water was then evenly distributed over the total pervious area, lawns and streets, by dividing the water volume by the pervious area. The linear depth of water storage could then be defined as the pervious area retention storage value in the program. This procedure was not followed, however, whenever porous pavements and level pans were investigated together as a combined reduction method. In that case, both areas were assigned equal storage capacities since the two combined to provide the total pervious area cover available.

Impervious area retention storage was assigned only when the roof retention method was used. It was desired to provide approximately 3 inches of storage capacity on the roof tops as suggested in the literature (24). Here, as with the porous pavement method, a specific value for a certain amount of storage solely on the roof tops could not be set. This necessitated calculating the volume of water that could be held on the roof tops and distributing it over the impervious area of the subcatchment. In this case, only the streets and roof tops were used as the distribution area, since the concrete area was designated to have zero retention capacity. The depth of storage capacity on the roof area needed only to be defined whenever porous pavement was used in conjunction with roof retention. In this case, the pavement was not considered as impervious cover. The roof area in this case was the only area providing storage, and the desired storage was simply specified. Throughout the study, whenever any combination of these methods was used, these same procedures were followed.

CHAPTER 4

RESULTS OF ANALYSIS

The following discussion is a presentation of the findings of this study. Highlights which may lead to a better understanding and add meaning to the analysis are presented. In Table 5, a summary description of the various retention methods described in Chapter 3 is listed. A recall of the cases examined during the study will help avoid later confusion in the discussion of the results.

Table 6 and Figure 7 indicate that providing retention storage over a suburban watershed results in a noticeable reduction in runoff volume. Methods which employ the greatest amount of area coverage, such as level pans and porous pavement, necessarily lead to a more appreciable amount of reduction than the more point specific methods such as roof retention. Notably, these methods provide greater reduction at a lesser cost.

Individual Case Results

Particular instances will be identified in the following discussion which have bearing on the objective of the study. A case by case analysis is not presented. Instead, only important highlights are noted.

An interesting observation can be noted in the results listed in Table 6. Case 1 is an analysis of the runoff characteristics of the watershed as it existed at the time of the study. Cases 2, 3 and 4

TABLE 6

HYDROLOGIC RESULTS OF ANALYSIS

Case	Description	Runoff Volume (ft^3)	Time of Rise to Peak (Min.)	Peak Rate (CFS)	% Reduction of Rate	% Reduction in Volume
1	Existing Watershed	1,164,980	99.6	320.0	-----	----
2	25% Roof Retention	1,087,830	100.8	320.0	0	6.6
3	50% Roof Retention	997,977	100.8	320.0	0	14.3
4	100% Roof Retention	818,095	99.6	320.0	0	29.8
5	25% Level Pans	984,022	103.5	260.0	18.8	15.5
6	50% Level Pans	772,303	93.6	172.5	46.0	33.7
7	100% Porous Pavement	520,627	90.0	120.0	62.5	55.3
8	100% Porous Pavement & Roof Retention	167,879	89.4	33.8	89.4	85.6

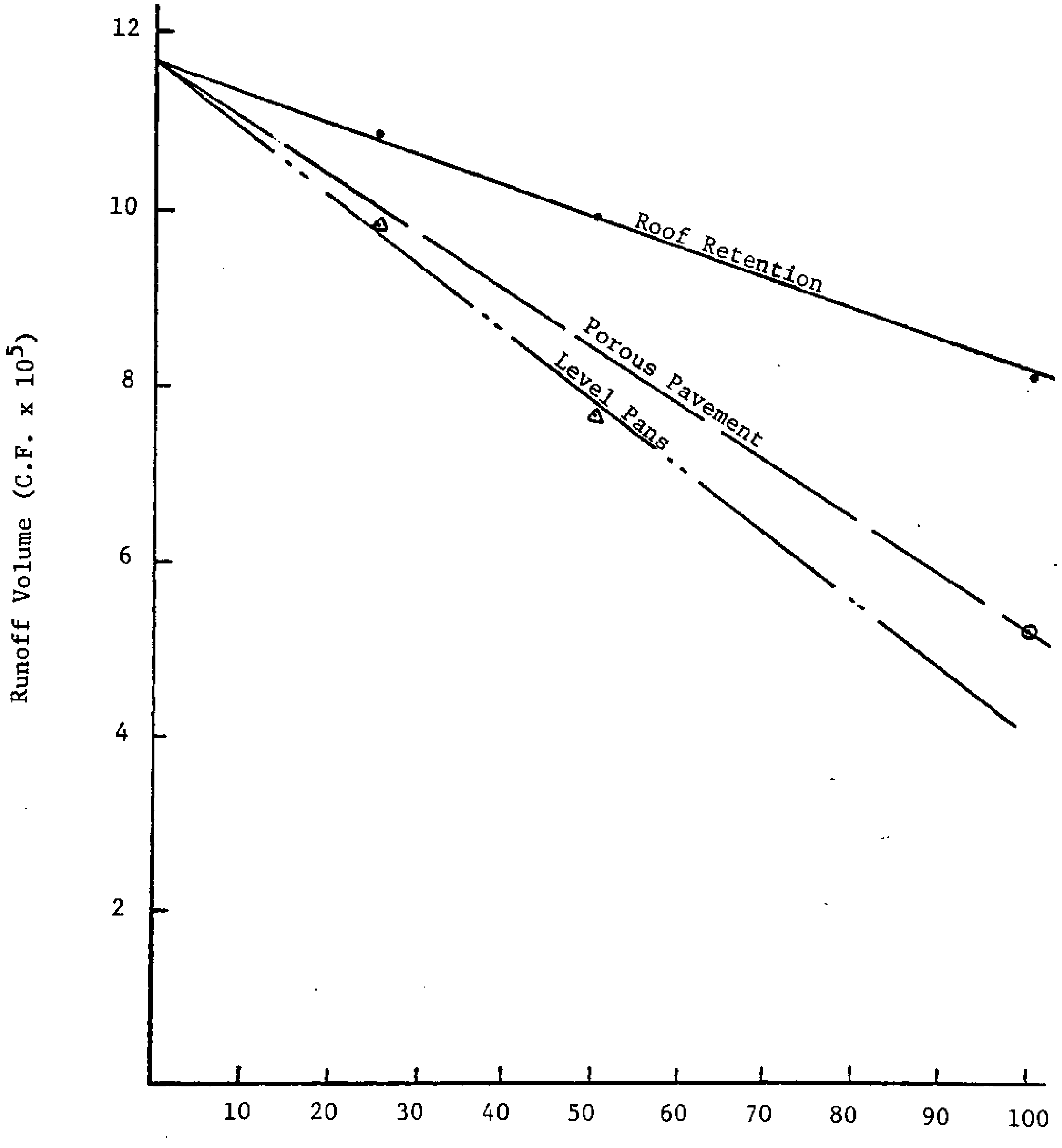


Fig. 7. Runoff volume resulting by varying the number of lots providing the indicated reduction method.

are an analysis of the runoff occurring by varying the percentages of lots which provide the roof retention method of runoff reduction. As the percentage of homes providing roof retention is increased, the percent reduction in runoff volume increases, and the actual volume decreases as expected. However, the time of rise to the peak runoff rate and the peak rate itself remain relatively constant. Three possible explanations which would account for this unexpected occurrence are:

1. There was an error or some other problem in the input data which caused the peak rate to remain unchanged

2. A smaller percentage of the area covered which is actually controlled by this technique does not appreciably effect the rate of runoff

3. There exists some inherent deficiency in the program itself

Of the possible explanations, it is believed that "2" is most likely to be correct.

In these cases, the control storage area (roof tops) is about 25% of the total watershed area (55% of the total impervious area). A maximum water depth of 3 inches was provided on each roof top before runoff began. It is believed that the storage capacity of the roofs is satisfied very quickly since the percentage of runoff volume reduction is not great for these cases. Rain which falls on the roof tops in excess of the storage capacity then flows from the roofs to the lot grade and overland in its usual shortest pathway to the gutters. In a very short period of time the gutter flow reaches its normal peak rate. The hydrographs for cases 2, 3 and 4 are shown in Figures 8, 9, and 10.

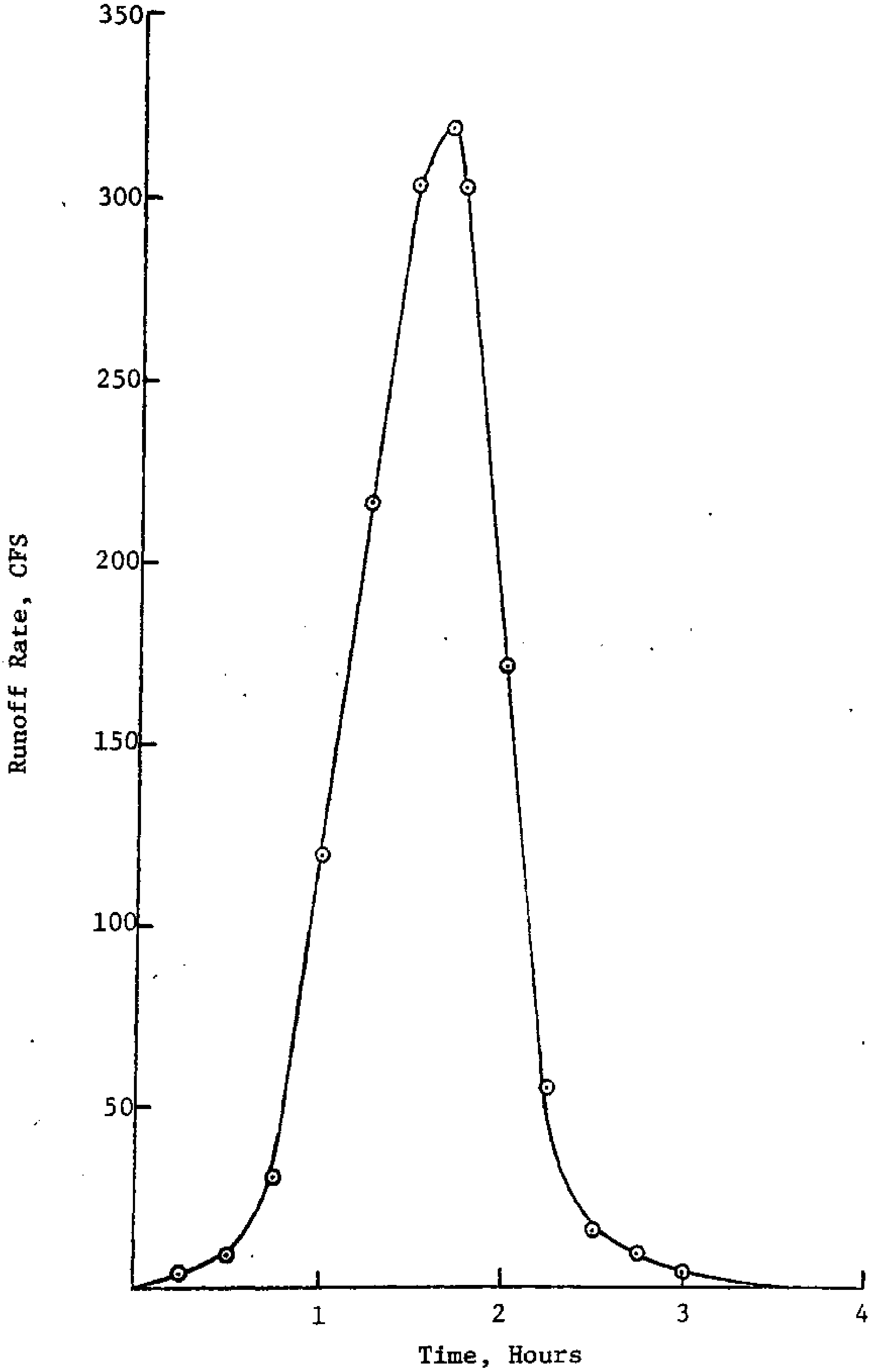


Fig. 8. Runoff hydrograph for 25% roof retention

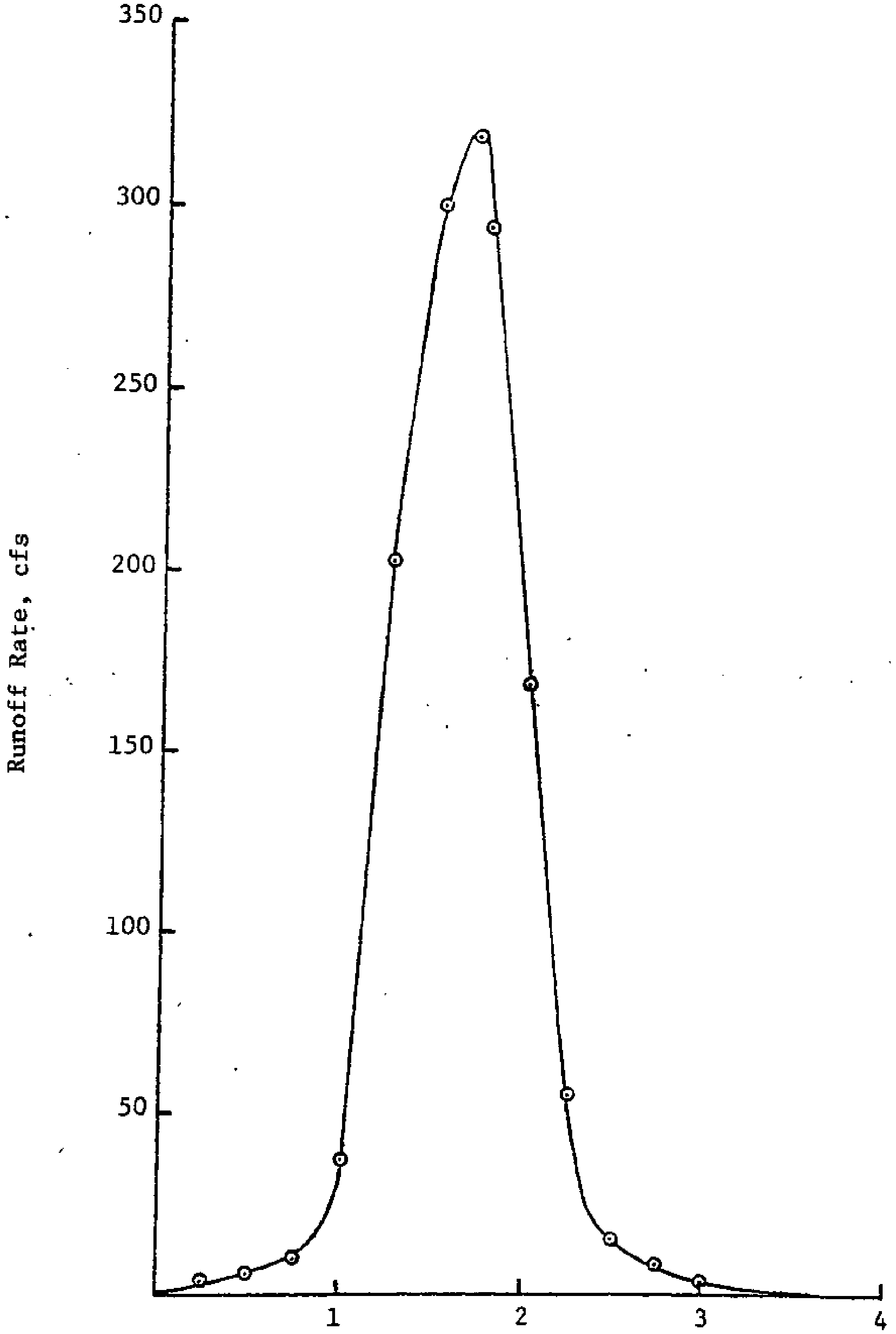


Fig. 9. Runoff hydrograph for 50% of the lots providing roof retention.

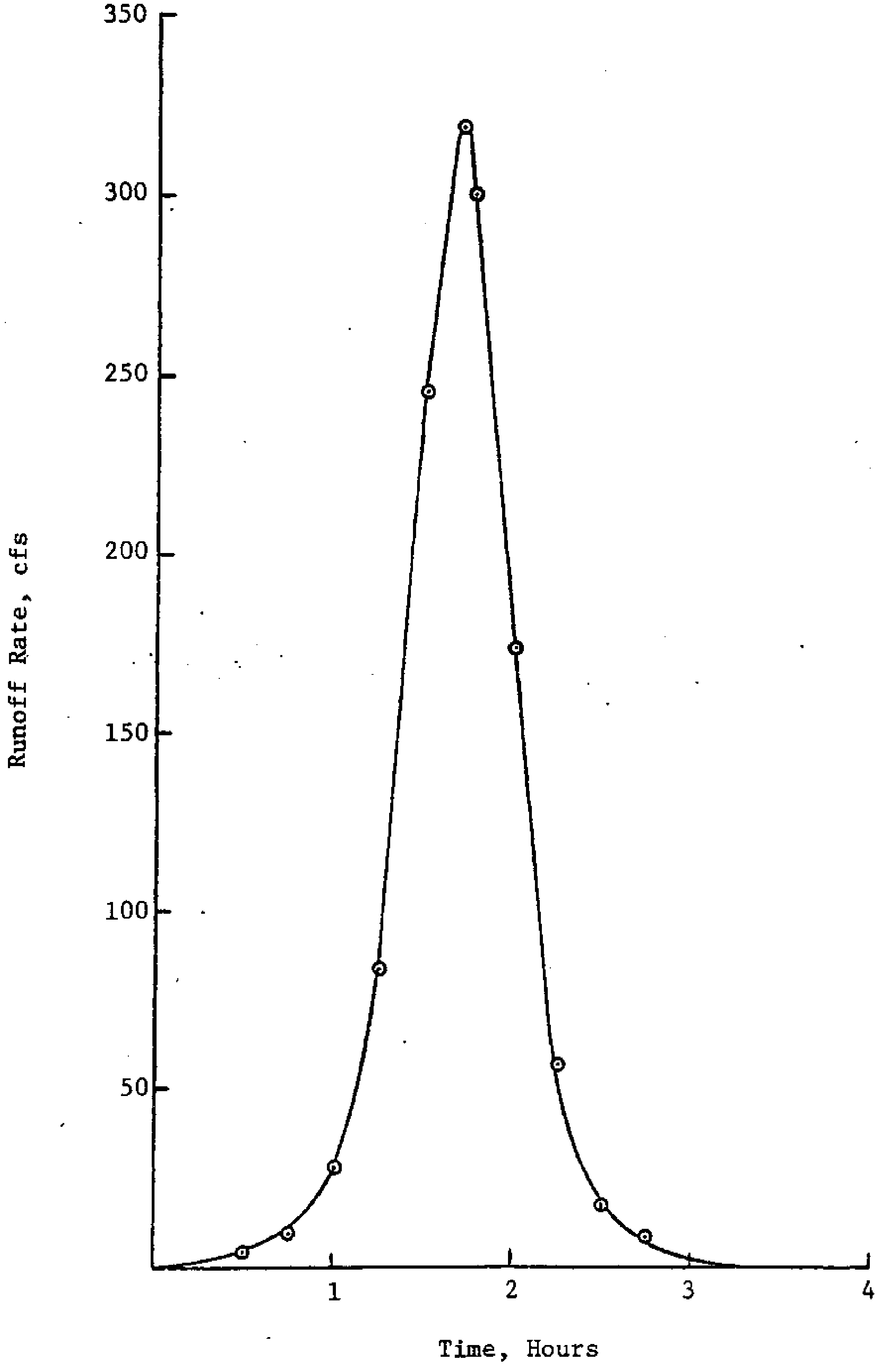


Fig. 10. Runoff hydrograph for 100% of the lots providing roof retention.

Comparing the early minutes of the rising limb of each hydrograph indicates that increased storage capacity does delay the time of rise of the limb. However, at the point where rise begins, the curve becomes very steep and the peak rate is quickly achieved.

Comparing the information in Table 6 aids in drawing further conclusions from the results. Cases 3 and 5 indicate that approximately the same volume reduction occurs when 50 percent of the lots use roof retention as when 25 percent of the lots use the level pan method. The same trend is observed in cases 4 and 6 when 100 percent of the homes provide roof retention and 50 percent of the lots provide level pan construction. This indicates that level pan construction is a considerably more effective runoff reduction method than roof retention. A comparison of case 7 with case 4 shows that constructing the streets within the watershed with porous pavement would also provide greater runoff storage capacity than roof retention of rainwater. The case was not investigated where 100 percent of the lots were constructed with level pans. However, the line corresponding to level pan construction in Figures 7 and 11 was extrapolated linearly to approximately where the point would have been located. This clearly indicates that when individually considered, level pan construction exhibits greater runoff reducing capability than either roof retention or porous pavement.

By use of Figure 11 and Table 7, a particular combination of methods for runoff reduction could be selected. The desired percentage of homes providing the method, and the expected runoff volume depletion that could occur over the watershed as well as the cost of implementation can be determined. According to Figure 11, the three methods

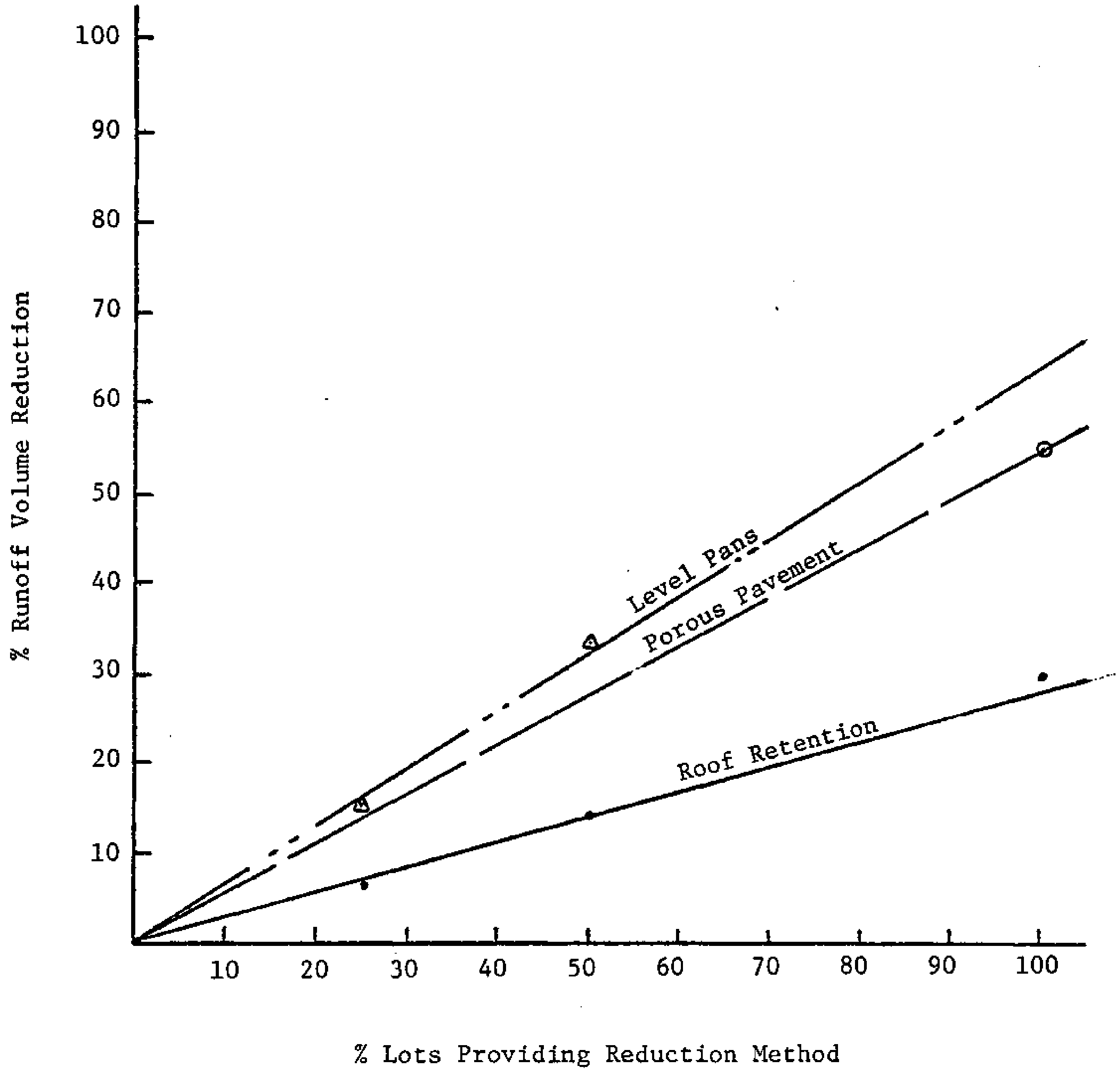


Fig. 11. Reduction of runoff volume resulting by varying the number of lots providing the indicated reduction method.

TABLE 7

COST OF APPLYING VARIOUS RUNOFF REDUCTION METHODS

Method	Cost
Roof Retention	$ 533/house
Porous Pavement	$1,355/house
Level Pans	$ 478/house

investigated all result in increasing amounts of runoff reduction. Observations thus far indicate that porous pavement and level pans provide a greater capacity for runoff reduction than the roof retention method. This is in close agreement with literature cited earlier in the text. Rospond (24) also stated that roof retention is probably most effective when used on very large roof surface areas such as shopping centers and office buildings.

Cost Effectiveness

Costs of applying each method were determined and used in a comparative analysis of the methods. Rospond (32) was contacted about the cost of applying roof retention. He stated that the cost was virtually the same as that of conventional roof drain systems. These prices were obtained from a vendor of roof drain systems and are summarized in Table 7 (33).

Diniz (34) was contacted about the cost of applying the porous pavement method. He stated that porous pavement is comparably priced to standard asphaltic pavement. The cost was calculated using a 2.5 inch binder, 4 inch base course, and a 1.5 inch surface for the pavement. This 8 inch thick pavement would provide the 4 inches of water storage specified throughout the study if constructed at a porosity of 50 percent as reported in the literature (25). The prices for the pavement items were determined from the 1977 Dodge Guide (35). The cost to provide porous pavement is listed in Table 7.

The cost of providing level pan lawns was calculated as being the same as standard earthwork furnished during the initial developmental stages of the subdivision rather than added after completion of construction. The price for such earthwork was determined from the 1977 Dodge Guide, and the cost is listed in Table 7 (35).

With the aid of Figures 12 and 13, it can be determined that level pans and porous pavement, respectively, yield greater runoff volume reduction than roof retention, and at a propitious capital investment. Figure 12 indicates that roof retention is far less expensive than porous pavement and comparable to level pan construction. However, Figure 13 shows that level pans are the most economical approach to runoff reduction and porous pavement is competitive with roof retention.

Figure 12 indicates that if 40 percent of the lots provided porous pavement, the cost would be $207,000. Figure 13 shows this would result approximately in a 22 percent reduction in runoff volume. However, if 40 percent of the lots provide roof retention, this would cost $77,000. Figure 13 shows this would result in a runoff volume reduction of only 11.5 percent. Table 8 lists the costs of 40 percent of the lots providing each of the runoff reducing methods. Table 9 indicates that a 20 percent reduction in runoff volume can be attained whenever 71 percent of the houses provide roof retention of stormwater. When compared on a lot-by-lot basis, the same reduction in runoff volume can be achieved when approximately one-half (1/2) as many lots provide porous pavement streets. A cost comparison shows that a 20 percent reduction in runoff volume can be achieved using porous pavement for about 24 percent ($45,000) more than the cost of providing roof retention. It is believed that the benefits realized through reduced property damage and repairs would merit the additional initial capital

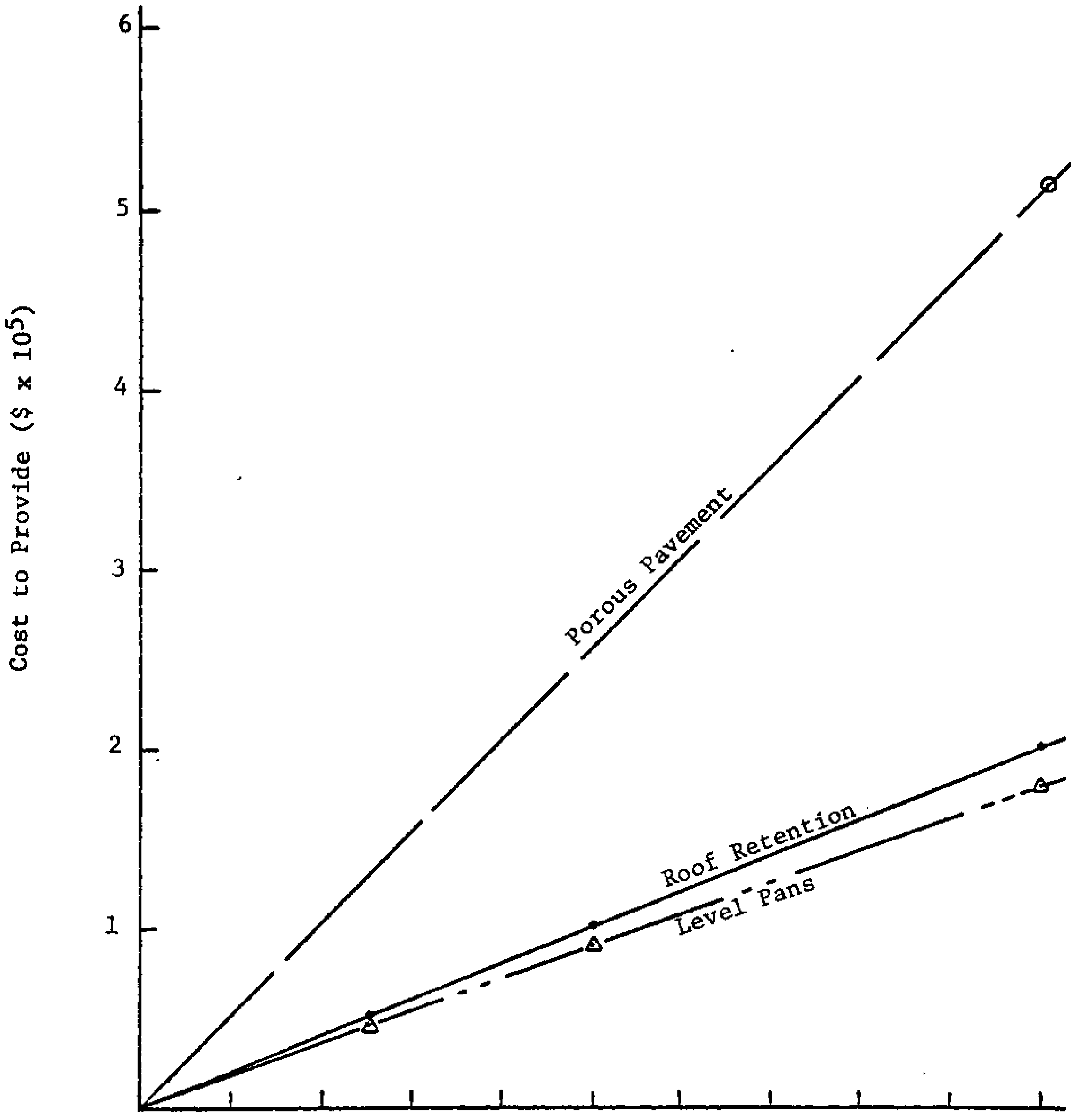


Fig. 12. Cost to provide each reduction method by varying the number of lots using the method.

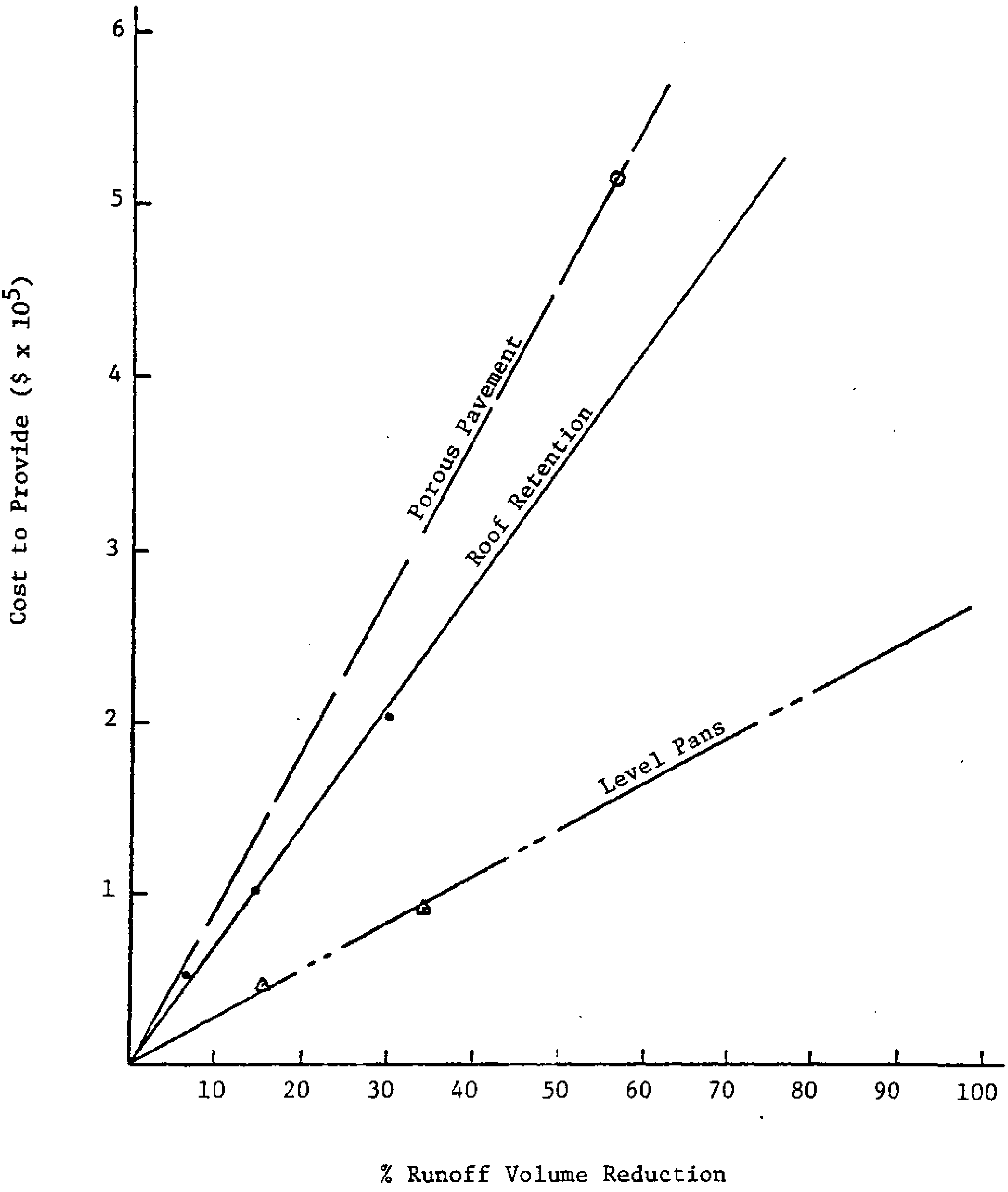


Fig. 13. Cost of providing each method to attain a desired reduction in runoff volume.

investment by homeowners and/or city officials. However, this should be verified by further investigation. Such investigation was out of the scope of work for this study.

Level pan construction is the least expensive and most effective runoff reducing method considered. The results listed in Table 8 clearly confirm this observation. Whenever an equal number of lots provide each of the techniques (level pans, roof retention, and porous pavement), a greater runoff volume reduction occurs with level pan construction than with either roof retention or porous pavement. Notably, this is accomplished with a more favorable capital expenditure.

The results in Table 9 also indicate that level pans are the most beneficial and cost effective method. While providing approximately equal runoff volume reduction (20%), level pans cost less than one-third (1/3) the price and require fewer lots than either of the two alternatives.

In summary, the intent of this study was not necessarily to rate one of the investigated methods as superior to another. Moreover, it was to determine whether implementing these techniques could result in appreciable reduction in runoff volume. It has clearly been shown that all the methods investigated do indeed provide runoff reduction. In addition, the results indicate that level pans and porous pavement are somewhat more effective at reducing runoff than roof retention. The cost analysis further shows that level pans are most desirable due to their low cost of construction and high reductive capacity.

It is believed that the most feasible approach to reducing runoff from a developing residential area is to incorporate into the

TABLE 8

COST AND RUNOFF REDUCTION COMPARISON FOR 40% OF THE LOTS PROVIDING INDICATED METHODS OF REDUCTION

Method	Level Pans	Roof Retention	Porous Pavement
Cost to Provide	$73,000	$76,500	$207,000
% Volume Reduction	26	11.5	22

TABLE 9

COST COMPARISON TO ATTAIN A 20% REDUCTION IN RUNOFF VOLUME

Method	Level Pans	Roof Retention	Porous Pavement
Cost to Provide	$55,000	$142,000	$187,500
% Lots Required	31	71	36

initial planning phase area methods such a porous pavement, grading for flow retardation, and construction of level pans at strategic locations. Not only are they the most cost effective, but they could also be included as part of the development program prior to the layout of the street and utility networks at minimal additional expense. Area methods would not be attrative as additions to the urban watershed after development. This is due to the need to remove old existing landscape features and pavement, and replace them with the new runoff reducing features.

Incorporating these techniques into the planning phase might necessitate some policy changes. Instead of relying on addition of the methods after construction has been undertaken, developers could landscape so that those areas most suited for flow reduction and storage could be utilized. On a lot-by-lot basis, builders could be encouraged to include techniques which enhance flow detention and reduction in the construction of homes and in the landscaping of lawns.

One or all of these techniques could easily be applied to any residential area whether in the planning stages or fully developed. Certain of the methods would be more easily applied in each phase of development.

The best choice for providing rainwater storage capacity and runoff reduction from a developing residential area is the construction of level pans. Level pans have been shown to be the most beneficial and cost effective method investigated. However, the low cost of level pan construction was based on providing the necessary earthwork and landscaping during the initial stages of construction. The cost to remove old lawns and established foliage, and replace them with level pans would be considerably higher than that determined during the study. Innovations in planning policy might need to be enacted to assure maximum usage of level pan construction by homeowners. Such innovations as deed restrictions which specify level pan lawns could be enforced on a lot-by-lot basis. On a much larger scale, city zoning restrictions could require level pans within a new subdivision either on individual lots or in green belt areas.

As for the porous pavement approach, most subdivision developers must provide paved streets. With only a slight change in pavement design, this runoff reducing scheme could easily be included as an initial step in the development.

Retrofitting of runoff reducing techniques would probably have to be implemented on an individual preference or need basis, since construction would be necessary in a previously well established area. The simplest application would be retention of rainwater on the roofs of houses to be constructed on undeveloped lots in the area. Some foresight during the planning stages would be necessary to apply this method in-that roof tops would need to be constructed flat and reinforced with the required load carrying capacity. In semiarid areas such as the southwestern United States, houses are often built with flat roofs so that the roof retention technique could be easily adapted.

To encourage homeowners to provide the necessary equipment for roof retention of storm water, tax breaks could be written into existing laws, or subsidies granted for purchase of the required equipment.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

From the results of this study, it can be concluded that:

1. Runoff volumes are appreciably reduced by providing constructed depression storage over a residential watershed

2. Area methods which are implemented during the development and construction phases of a subdivision are the most cost effective methods for reducing runoff

3. Grading and the construction of level pans are the most effective of the area methods in reducing runoff

4. Roof retention is a useable approach if flat roof construction is acceptable to the homeowner

This study has shown that constructed depression storage does offer a means of reducing storm water runoff from a residential watershed. The results presented in Chapter Four support the theory that runoff can be reduced by applying the methods used in this study. Some of the results indicate the need for further in-depth investigation. It is believed that future work would be better substantiated and supported by including the following recommendations:

1. Make use of the updated SWMM which now includes a subroutine describing the porous pavement method

2. Investigate further the cause for no reduction of peak rate and time of rise to peak rate for the roof retention method

3. Investigate thoroughly the long term economic benefits to homeowners and cities providing depression storage to reduce storm water runoff damage

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