ABSTRACT

KAYS, BARRETT L. Relationship of Soil Morphology, Soil Disturbance and Infiltration to Stormwater Runoff in the Suburban North Carolina Piedmont. (Under the direction of H. JOSEPH KLEISS and STANLEY W. BUOL).

A research study was conducted in 1976-78 to determine the significance of soil morphology, soil disturbance and infiltration in metropolitan storm water modeling. Three suburban and two rural sites in the Piedmont Province of North Carolina which are primarily of Cecil soils (Typic Hapludult, clayey, kaolinitic, thermic) were studied. A significant proportion of the suburban sites were composed of disturbed soil profiles. Excessively disturbed soils (Arents, Udorthents, Ochreptic Hapludults and some Typic Hapludults) had notably reduced infiltration rates, less volume of macroporosity and lower saturated hydraulic conductivities than undisturbed soil profiles.

One of the suburban sites, the 150 ha Sudbury (Briar Creek Tributary 6) watershed in Charlotte, NC has USGS 5-minute increment rainfall-runoff records from 1966-70. Final constant infiltration rates of excessively disturbed soils (35.8% of basin) were 1 to 5% of those for forest soil profiles, and 3 to 16% of those for the least disturbed urban soil profiles. Volume of macropores in subsoils of disturbed sites was 15.7 to 72.3% of that for forested sites, and saturated hydraulic conductivity was 0.5 to 24.2% of that for forest subsoils. The USGS monitoring indicates that watershed runoff varied between 17.5 and 80.4% for 1/2 to 1-hour duration high intensity summer storms. Percent total runoff was most sensitive to 1-day antecedent rainfall. Runoff from excessively disturbed soils appears to be an important to

dominant factor in the generation of mean maximum annual and larger floods. An infiltration excess method was used to estimate that 40 to 50% of the direct runoff was produced by soil surfaces for the most severe flood events recorded (approx. 5-year frequency floods). It appears that runoff from excessively disturbed soils sufficiently coincides in time and space with runoff from impervious surfaces (27.1% of basin) to produce the record flooding.

Soil morphology and infiltration data for two rural sites, the Schenck Forest (43 ha) and Pasture (10 ha) watersheds, Raleigh, NC were compared to weir stage data and 15-minute increment rainfall records. The pasture and forest mean final constant infiltration rates were sufficiently high (>8 cm/hr) to only rarely produce appreciable runoff. Percent total runoff for short duration intensive rainstorms varied from 0.7 to 21.5% for the forest and 0.1 to 24.6% for the pasture watershed. Percent total runoff was most sensitive to 5 to 10-day antecedent rainfall.

USDA soil hydrologic groups provided an inaccurate method to estimate infiltration and soil runoff characteristics of all sites studied. Soil hydrologic groups consistently under estimated infiltration of undisturbed forest, pasture and suburban soils. Suburban soil runoff appears to occur primarily from partial source areas consisting of disturbed soils. Reasonably accurate metropolitan storm water modeling for the Piedmont region requires deterministic soil hydrologic evaluations rather than use of USDA soil hydrologic groups and more detailed suburban soil mapping than that that occurs in SCS county soil surveys.

RELATIONSHIP OF SOIL MORPHOLOGY, SOIL DISTRIBUTION AND INFILTRATION TO STORMWATER RUNOFF IN THE SUBURBAN NORTH CAROLINA PIEDMONT

by

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INTRODUCTION

Human settlements in humid regions have always been plagued by drainage problems and flooding due to the impact of intense rainstorms. Traditionally the solution to urban drainage problems has been to collect and transport excess water away from the urban area. Little thought has been given to actually reducing the production of runoff. Suburban landscapes dominantly consist of soil surfaces that have an untapped potential for reducing the quantity of stormwater runoff. Soils offer a non-structural approach to the management of runoff; unfortunately soils have not been prudently conserved and managed for these urban benefits. Moreover, unnecessary disturbance of soils and destruction of their natural capabilities is common to modern metropolitan land development.

The USDA soil survey program in the United States has been established to (1) determine important characteristics of soils, (2) classify soils into defined types, (3) map soil boundaries, and (4) correlate and predict the behavior of soils for various uses. The early efforts of the soil survey program were almost exclusively applied to agricultural uses. Since World War II the primarily agricultural soil surveys have become increasingly used for non-agricultural applications. Soil interpretations for urban-related management decisions have become an important use of the modern soil survey program. However, the needs and approach of soil survey in urban and urbanizing areas is different from that in rural and agricultural areas.

In recent years pedologic research has been increasingly focused at various aspects of soil management in urban environs. Emphasis has been placed upon the description, mapping, characterization and interpretation of soils in unurbanized areas surrounding urban centers. Only limited attention has been given the appraisal of soils and soil conditions remaining after urbanization. In the early 1970's as part of the soil survey of the District of Columbia, the first major attempt was made to map, classify and characterize the resultant soils in Washington, DC. Previously soil mapping had generally been extended across cities without a sagacious examination of the urban soils.

The hydrology of suburban watersheds is greatly dependent upon the soil conditions present after urbanization. Analysis of the hydrologic impact of the conversion of rural to urban land uses is dependent upon, among other things, understanding the change in soil conditions.

The North Carolina Sedimentation Pollution Control Act of 1973 was established to prevent unnecessary soil erosion during urbanization, provide for soil and water conservation and to reduce downstream degradation of stream channels. Certain local ordinances pursuant to the state legislation have additionally been enacted to reduce stormwater runoff and downstream flooding. There is a real need to develop coordinated local programs to provide comprehensive plans of urban watersheds for the management of stormwater quality and quantity, sedimentation and erosion control, flood control and flood plain management (Stewart, 1978).

Soil scientists have conducted extensive research concerning the management of soils, infiltration, runoff and erosion control of agricultural lands. Soil-water and pedologic principles and related research techniques that have been developed by soil scientists have not been applied to the study of soil conditions of suburban lands, nor to the study of soil infiltration and runoff factors that govern suburban watershed processes.

The intent of this research program is to extend soil science research techniques to the evaluation of suburban lands. The research program was developed to provide a preliminary assessment of suburban soil-water and runoff relationships for the Piedmont region of North Carolina. The objectives of the research program were:

(1) To define the type of soil data requirements necessary for suburban watershed hydrologic modeling;

(2) To describe, map and characterize soils present after urbanization including man-made soils;

(3) To investigate the type of changes in soil physical properties which accompany suburban land use conversion and influence stormwater runoff; and

(4) To assess the general frequency of occurrence of the major types of soil disturbance which have the greatest impact on watershed runoff and downstream flooding.

The study of soil infiltration runoff relationships of suburban watersheds is different from that of agricultural watersheds. Short duration high intensity rainstorms are the important rainfall events in the study of small suburban watersheds. Studies of agricultural watersheds have placed more emphasis on longer duration and less intensive rainstorms as well as seasonal soil moisture changes. Due to the complex pattern of impervious surfaces and soil conditions on suburban lands, there is extreme spatial and temporal variability in infiltration and runoff rates. Runoff waters take such a multiplicity of routes across various surfaces that the separation of the influences of soils, impervious surfaces, man-made drainage structures and stream channel flow is virtually impossible. The study of suburban lands is complicated by the problems of obtaining access onto numerous private land parcels and use of private lands for the location of soil sampling pits.

It has been well recognized that runoff from impervious surfaces significantly contributes to runoff volumes and downstream flooding. It has been assumed that runoff from soil surfaces does not significantly contribute to the peak discharge rates of urban and suburban watersheds. If this assumption is true, then runoff from soil surfaces must be rather limited or it must come too late in the rainfall-runoff event to contribute to the principal portion of the flood. However, if runoff from soil surfaces does contribute to suburban watershed discharge peaks, then the management of soils to promote infiltration could theoretically aid in urban stormwater management.

Watershed planning and engineering studies rely upon methods that estimate the infiltration and runoff characteristics of proposed land uses. The USDA soil hydrologic groups have been commonly used to estimate suburban watershed hydrologic changes. Implementation of stormwater management regulations requires considerable financial obligations by both the local governments and the private land developers. The increased costs of storm runoff controls has produced a greater interest in understanding urban hydrologic phenomena, hydrologic estimates and cost effective planning and design solutions.

2. LITERATURE REVIEW

The relationship of soils in urban environs to runoff and flooding is distinctly different than that in agricultural areas. The factors governing suburban watershed runoff are not limited to soil-water movement and soil runoff phenomena. Therefore, a review of literature necessitates the inclusion of our current understandings of urbanization and urban flooding.

2.1 Urbanization

The population of the State of North Carolina has grown from 3.57 million in 1940 to 5.45 million in 1975 (Clifford, 1977; U. S. Dept. of Commerce, 1973). The urban population which was 27.3% of the total population in 1940, became 45.3% of the States population in 1975. The larger metropolitan centers in the Piedmont crescent account for the largest portion of this growth.

The conversion of land to urban and suburban uses is a drastic land use change and physical alteration. Large metropolitan areas have a variety of land uses which, according to Clawson (1971), occur in the following distribution:

	102 cities of U.S. of 100,000 plus population	
Type of land use	% of land area	Acres/1,000 population
Total	100.0	130.1
Public streets	17.5	22.8
Total excluding public streets	82.5	108.3
Privately owned, total	67.4	89.2
Residential	31.6	44.3
Commercial	4.1	5.4
Industrial	4.7	6.1
Railroads	1.7	2.4
Undeveloped	22.3	26.9

Type of land use	102 cities of U.S. of 100,000 plus population: % of land use	Acres/1,000 population
Public and semipublic		
(excluding streets)	13.7	15.8
Recreational areas	4.9	5.6
Schools and colleges	2.3	3.3
Airports	2.0	3.1
Cemeteries	1.0	1.2
Public housing	0.5	0.5
Other (by subtraction)	3.0	2.2

The values will vary significantly depending upon the specific city. The distribution of land uses between the central city and the suburbs differs appreciably. For example, the amount of privately owned undeveloped land would be higher than 22.3% in the suburban fringe and lower towards the central city. The largest single category (31.6%) is that of privately owned residential land. The percent of residential land in the suburbs will normally exceed 50%. Undeveloped land in the suburbs is primarily a temporal land use due to the incremental process of urbanization.

The percent of imperviousness, the amount of buildings, streets and other urban impervious cover, is an indicator of the extent of the urban physical change. The Soil Conservation Service (1975) estimated imperviousness ranges for typical land uses:

Land use	% Imperviousness
Low density residential	20-30
Medium density residential	25-35
High density residential	30-40
Business-commercial	40-90
Light industrial	45-65
Heavy industrial	50-70

The percent of impervious area or impervious-area index is determined using aerial photographs and city maps (Anderson, 1970; Martens, 1968; Carter, 1961). The percent reported by many researchers includes the impervious cover of roof tops, streets and parking lots for suburban residential areas (Putnam, 1972) but appears not to include sidewalks, driveways, patios and other miscellaneous pavement on residential lots and urban developments. The method of calculation of impervious area determined by various researchers or agencies can yield significantly different values.

As the land use conversion from rural to suburban to urban development proceeds, the natural drainage network is slowly replaced by urban storm drainage systems. McPherson (1974) noted that only 42% of the natural stream channels remained in the Rock Creek watershed adjacent to Washington, D. C. Other researchers (Hammer, 1971, 1972; Fox, 1976; Graf, 1976; Shanks and Rao, 1977) have attributed significant hydrologic impacts to suburban stream channel improvements. The construction of impervious material, storm sewerage, improved open stream channels and other drainage modifications all combine to produce a structural urban drainage system significantly different from the rural or natural watershed system.

Although there is extensive use of integrated storm sewerage in suburban areas of the northern states, it is of limited use in the southern United States (McPherson, 1974; Tucker, 1969). Normally storm runoff is routed as overland flow to the nearest ditch or tributary stream, or is collected into a conduit, transported and released in the nearest stream or improved open channel. Therefore because only a minimal stormwater collection facility is constructed, the timing of runoff from soil surfaces can be expected to more closely coincide with runoff from impervious surfaces given appropriate climatic conditions.

2.2 Urban Flooding

The problem of urban flooding is and will continue to be a major engineering, land planning and soil and water conservation problem. About one-sixth of all urban areas in the United States are within the 100-year flood plains and about half of the land area in these metropolitan flood plains is occupied by urban development (Goddard, 1973). Schneider and Goddard (1974) determined the amount of flood plains and. urban area in flood plains for selected metropolitan areas. Data for 13 of the eastern-most cities are:

	Extent of 100-year flood plains		Urbanized portion of flood plain	
Metropolitan areas	Area sq mi	% of urban area	Area sq mi	% of flood plain urbanized
Asheville, NC	1.6	4.4	1.0	65.0
Boston, MA	62.4	9.4	11.9	19.1
Charleston, SC	39.8	40.1	21.2	53.3
Chicago, IL	131.8	10.3	75.1	57.0
Dallas, TX	146.1	21.7	28.0	19.2
Harrisburg, PA	9.7	12.4	8.1	83.5
Lansing, MI	4.8	6.5	0.9	18.8
Monroe, LA	32.5	81.0	26.8	82.4
Norfolk-Portsmouth, VA	59.2	19.8	15.5	26.2
Richmond, VA	12.9	8.9	1.7	13.2
St. Louis, MO-IL	136.1	29.6	91.7	67.4
Tallahassee, FL	3.1	10.4	2.6	83.9
Texarkana, TX-AR	4.7	13.8	2.1	44.2

A 100-year frequency flood would extend over 1.6 square miles or 4.4% of Asheville, NC. One square mile or 65.0% of the flood plain in Asheville is urbanized. The extent of flood plains and the potential for flood damages varies greatly between cities. Monroe, LA has 81.0%

of the urban area in 100-year flood plains. Each metropolitan area probably has a unique set of terrain, type of flood plains, climatic and man-made conditions that govern the potential for flood damages.

Application to the National Flood Insurance Program (Public Law 90-448, Title XII, August 1, 1968) has recently been completed. In North Carolina, 265 municipal, town and county governments have joined the program by establishing local flood plain ordinances. One of the major unresolved problems is that considerable urban flooding occurs outside of the major flood plains pursuant to the National Flood Insurance Program. Flooding also occurs upstream along small tributaries, upstream of road crossings served by culverts, in and upstream of under-ground storm drainage systems and in upland positions around developed areas when the drainage systems are overtopped. "Somewhere around half of all urban annual flooding damages occur on the large segment of urban land outside of 100-year flood plains" (McPherson, 1975).

The control of flooding along small urban tributaries in North Carolina is dependent upon the local governments ability and willingness to enact stormwater and flood plain management. Flood plain management along small tributaries is not included in the National Flood Insurance Program model local ordinances, therefore few local governments have legislation that deal with these problems in small watersheds. The Sedimentation Pollution Control Act of 1973, N.C.G.S. 113A-50 et seq. and local legislation[1] pursuant to the Act provides limited means of

[1]The N. C. Sedimentation Control Commission has to date approved 38 local ordinances pursuant to the Sedimentation Pollution Control Act of 1973.

reducing stormwater velocities for newly developed lands. However, no urban stormwater and watershed management legislation has been established in North Carolina primarily due to the lack of technical knowledge sufficient to implement an effective program. While the relationship of stormwater runoff and flooding to urbanization is not sufficiently understood, less is known about what management techniques and procedures are effective in reducing stormwater runoff and downstream flooding (Stewart, 1978).

2.3 Relationship of Urbanization to Storm Runoff and Flooding

The process of urbanization produces a profound disruption of the previous conditions on a watershed. The construction of impervious material and the destruction of the soils capacity to infiltrate rainfall creates a completely new hydrologic balance. The construction of paving, culverts, storm sewers, ditches and open channels allow for a more rapid removal of runoff waters and in doing so produces greater flood magnitudes. Thus urbanization increases the total volume of runoff and the peak flows of the watershed. The increased peak flows on the urban basin over its rural counterpart means that overbank flooding conditions will occur more often on the urban basin. Thus the frequency of flooding will increase (Leopold, 1968).

The amount of total runoff or coefficient of runoff is governed primarily by the amount of infiltration and surface detention. The reduction in the watershed infiltration has been correlated with the percent of imperviousness of numerous urban watersheds (Carter, 1961; Martens, 1966; Anderson, 1970; Putnam, 1972). The basin lag time significantly governs the peak discharge rate. Lag time is defined as the time between the center of mass of the storm precipitation and the center of mass of the resultant hydrograph. The construction of impervious surfaces and artificial channels decreases the lag time. The volume of direct runoff (that which contributes directly to the peak flow) comes sooner and over a shorter time period, thus creating a greater flood magnitude. Thus the stream is said to be artificially "flashy." The change in lag time is assumed to be due to physical changes in the watershed. Numerous relationships of lag time to watershed or urbanization parameters have been presented (Snyder, 1958; Carter, 1961; Viessman, 1966, 1968; Espey et al., 1966; Martens, 1968; Anderson, 1970; Putnam, 1972).

Carter (1961), studying 20 streams near Washington, DC, correlated percent impervious and percent of area served by storm sewerage to the increased magnitude of discharges for the urban streams. Anderson (1970) completed a rather extensive study of 64 gaging stations in the vicinity of Fairfax County, VA. He concluded that urbanization may triple average-flood magnitudes over that for rural areas. The lag time was determined to be the basin characteristic most affected by urbanization and accounting for the flood magnitudes. Anderson (p. 21) found that

> the lag time for a completely storm-sewered system is about one-eighth that of a comparable natural system, while storm sewering of only tributaries (main channels unlined) reduces the lag time to about one-fifth that of a comparable natural system.

Martens (1966), in a study of flood conditions in Charlotte, NC developed a ratio to the mean annual flood for various degrees of imperviousness. He determined flood profiles and extent of inundation for a 20-year flood (p. 1):

> Seventy-five percent of the channels in metropolitan Charlotte will reflect an increase of about 3 1/2 feet in the elevations of the 20-year flood as a result of the change in the basin from undeveloped to urbanized conditions.

Basin lag time for fully developed basins was found to be one-fourth that for comparable rural basins.

Putnam (1972) completed an extensive study of the effects of urban flooding in the Piedmont region of North Carolina. Putnam (p. 60) found that the

> lag time for an urban basin having an impervious cover of about 25 percent is one-seventh that of a comparable natural watershed, whereas the lag time for a basin completely covered with impervious surfaces is about one-sixteenth that of the same area under natural (undeveloped) conditions.

He determined that (p. 60) that

> for the type of urban development expected in the Piedmont area of North Carolina, the peak discharge can be expected to increase by a factor of about two to four depending upon the recurrence interval of the flood and the anticipated conditions of development.

Although the amount of impervious material commonly has been used as a parameter of urbanization, the percent of impervious material does not have the same effect upon the amount of runoff produced for all storms. Snyder (1970) proposed that the peak discharge for more severe rainstorms can be appreciably governed by runoff from pervious soil surfaces. In his analysis of Four Mile Run basin in Arlington County, VA he proposed "that soil moisture capacity of appreciable portions of pervious areas my be exhausted prior to the occurrence of the critical" storm. Direct runoff would tend to occur from pervious surfaces and aggregate with runoff from impervious areas. The Four Mile Run watershed was considered to be 20% impervious (Anderson, 1970). Snyder (p. 1628) stated that

> runoff for the larger floods on Four Mile Run averages about 60% of the effective rainfall. This difference between percentage of impervious area and percentage of direct runoff speaks for itself.

2.4 Rainfall

The average annual precipitation for the Piedmont region of North Carolina ranges from 110 to 122 cm. The precipitation is more or less uniformly distributed throughout the year (Hardy et al., 1967). Three types of storms can cause major urban flooding problems. Summer convective rainstorms having short duration and high intensity precipitation are the most frequent cause. Tropical storms and longer duration, lower intensity precipitation from frontal storms also cause problems (Putnam, 1972).

Rainfall frequency data are used for the design of urban developments, drainage systems and watershed management. Point rate-duration-frequency curves are normally used for selection of appropriate rainfall conditions (U.S. Weather Bureau, 1955). The rainfall frequency data cover durations of 5 minutes to 24 hours and return periods from 2 to 100 years.

Meterological data for a period of 50 years may be insufficient in predicting a return frequency of high intensity, low probability rainstorms. The determination of the return period for high magnitude, low frequency events can be difficult (Myers, 1969) due to the insufficiency of data for these rare storm events.

Low frequency rainstorms do not necessarily occur randomly through time. Severe thunderstorms which were of 50-year and over 100-year recurrence intervals occurred in the Maryland Piedmont in the summer of 1971. In June 1972 the tropical storm Agnes again produced well over 100-year frequency rainfall. All three rainstorms produced record flooding (Gupta and Fox, 1974). The maximum 3-day total of rainfall from tropical storm Agnes which was recorded in Maryland was 37.29 cm. The greatest daily rainfall recorded which was 31.12 cm occurred in Baltimore County, MD (Costa, 1974; DeAngelis and Hodges, 1972).

Recent studies have demonstrated precipitation anomalies in metropolitan areas. Attention has focused upon summer convective precipitation. The city environs create different atmospheric conditions than occur in rural areas. This difference is brought about by a number of physical factors of which the most important is the concentration of man-made surface materials; concrete, asphalt, metal, brick, gravel, wood and glass over the landscape (Marotz and Coiner, 1973). The urban physical conditions provide an extra increment of heating supplied to convective rain clouds. Marotz and Coiner presented data from a detailed spatial study of five cities in eastern Kansas. The amount of man-made surface materials in Kansas City and Lawrence, Kansas were 47 and 37% of the land surface, respectively. The percentages for three small towns—Baldwin, Fudora and Tonganoxie—were 15, 18 and 21%.

Normally the convective precipitation anomalies affect an area of the city and down wind of the city creating 5 to 15% more precipitation than the non-affected area (Harnack and Landsberg, 1975). Natural rainstorms have been found to build over a city via a so-called "heat island" effect (Parry, 1956; Atkinson, 1971; Canfield and Woollum, 1968; Changnon, 1968; Huff and Changnon, 1972; Changnon and Huff, 1973; Harnack and Landsberg, 1975). Huff and Changnon (1972) found an urban-induced increase in the average summer rainfall from 6 to 15% for distances up to 25 miles downwind of St. Louis, MO. The urban influence was most active on days of moderate to heavy intensities of natural rainfall. The "heat island" effect appears to intensify the natural rainstorms, as well as creating storms.

Canfield and Woollum (1968) conducted climatological studies for Washington, DC and determined that the city created a 13% increase in summer precipitation. Changnon and Huff (1973) estimated a 5 to 15% urban induced effect for summer storms at Washington, DC.

2.5 Source Area Concept of Storm Runoff

The basic approach to watershed hydrology which has dominated the field for nearly a half century is the Hortonian concept of infiltration and production of runoff (Horton, 1933). Horton (1945) proposed a "technology of overland flow" which was based upon a concept of spatially uniform rainfall excess. Attention was placed upon the processes of overland flow which was considered to be the dominant mechanism accounting for stream flow. A watershed was thought to have a "time of concentration" that time after the beginning of the storm event when all areas of the watershed are contributing to overland flow.

The infiltration rate is rarely, if ever, uniform across a watershed, therefore rainfall excess occurs in a multiplicity of rates, times and space. Betson (1964) proposed the concept of "partial area" of storm runoff. The concept simply recognizes that only a portion of the drainage basin contributes to storm runoff.

The storm runoff phenomena is further complicated by the fact that direct precipitation into the stream, subsurface or base flow, quick return subsurface flow, lateral hillside interflow and overland flow are a continuum of water movement processes that in some proportionality account for the stream rise. In humid regions overland flow rarely occurs on forested watersheds (Hewlett and Nutter, 1970). Rainfall intensity may have a limited effect on forest watershed discharge (Hewlett et al., 1977). Overland flow does not occur in forested watersheds except where the soils have been severely disturbed (Dunne et al., 1975). Those researchers that prescribe to the concept of partial area or variable source area of runoff production are firmly opposed to the Hortonian concept as the dominant mechanism to explain runoff.

Hewlett and Hibbert (1967) proposed the "variable source area" concept. Runoff production is primarily restricted to zones of saturation that vary in location and extent of the watershed with seasonal or temporal changes in subsurface soil-water movement (Dunne and Black, 1970a, 1970b; Dunne et al., 1975). Relatively flat permeable upland portions of Piedmont basins tend to be an original source of infiltration, deep seepage and slow lateral subsurface flow (Nutter, 1973; Ligon, 1972). Hillslope portions of the basins generally account for the processes of quick return subsurface flows, interflow and through-flow (Beasley, 1976; Kirkby and Chorley, 1967; Nutter, 1973; Dunne et al., 1975). Only a limited portion of the Piedmont watershed, along the foot of hillslopes and throughout the saturated valley bottomlands, contributes to stream flows during and following a rainfall event (Hewlett and Nutter, 1970; Hewlett, 1961; Tischendorf, 1969). This emphasis on subsurface flows has led to a greater appreciation, investigation and understanding of the role of soil—water movement between storm events.

The concept of "variable source area" has not been applied to urban watershed hydrology. The Hortonian concept of uniform infiltration and surface runoff generation is still dominant in the study and practice of urban hydrology. Reduced infiltration rates for disturbed urban soil conditions (Kelling and Peterson, 1975; Felton and Lull, 1963) logically should create even more variable infiltration rates and production of runoff than before urbanization.

2.6 Infiltration Processes

Since the 1930's (Horton, 1933) the infiltration approach to the understanding of surface runoff phenomena and runoff estimation has dominated the field of hydrology. Horton defined infiltration capacity as the "maximum rate at which rain can be absorbed by a given soil when in a given condition." The infiltration capacity curve normally takes the form of a depletion rate approaching a more or less steady state rate. The depletion portion of the curve is generally thought to be governed by the rate of surface entry, the transmission rate through the soil and the rate of filling of the porosity in the upper portion of the profile (Musgrave and Holtan, 1964). The depletion is due to the filling of the "initial soil detention" or "storage capacity," however there is no clear point at which the processes of filling of the porosity gives way to the processes of transmission. The latter part of the infiltration capacity curve is thus governed by the transmission through the profile by saturated (or unsaturated) flow. After saturation the rate of infiltration is limited by the volume and continuity of the largest macropores in the most restrictive horizon the wetting front has encountered. These large pores represent a negligible proportion of most soil profiles but contribute greatly to infiltration (Dixon, 1966).

It is to be expected that large pores would greatly govern flow rates since according to Poiseuille's equation flow through a theoretically ideal pore would be proportional to the fourth power of the pore diameter. Therefore, the downward flow through an ideal tubular pore of 1-mm diameter would be 10,000 times as great as for a pore of 0.1-mm diameter.

Dixon and Peterson (1971, p. 969) proposed a channel system concept for infiltration:

> The channel system concept contends that a network of large soil pores, when functional, provides a subterranean arterial system for rapidly distributing free surface water to locations within the soil mass (or matrix) and for exhausting soil air displaced from this mass.

The channel system would thus allow for the transfer of water to areas of greater soil water tension (unsaturated smaller pores) and the escape of air. The channel system would not be functional if the large pores were not connected to the surface, opened and sufficiently interconnected into a network to allow the escape of entrapped air.

The large channels when connected and open to an irregular soil surface provide a means to more rapidly achieve saturated flow. Dixon and Peterson (1971) demonstrated that the time required to achieve positive soil moisture pressure heads (pressures necessary for saturated flow) within the profile was significantly delayed when the channels were blocked, constricted, poorly interconnected, unopen to the surface or without a rough soil surface. This delay produced significantly lower mass infiltration. Thus in a general sense, the time required to fill the storage capacity is extended and the transmission rate after saturation is lower due to the lack of an effective channel system.

Horton (1933) recognized the fact that the runoff coefficient is not a constant. The coefficient would vary not only with rainfall intensity but also with antecedent soil moisture and other soil properties. The infiltration capacity of a soil was at that time considered to be a single value that represented all soil properties except for antecedent moisture. Thus Horton assumed that the steady state infiltration rate could be estimated from soil texture when he established relative runoff coefficients for fine and coarse textured soils. This overly simplified approach has produced countless runoff coefficient charts dependent upon soil texture rather than macroporosity. These charts are in common usage today. Most of the charts do not even allow for consideration of the antecedent soil moisture conditions as did the early Hortonian "depletion-curve" and runoff coefficient methods.

Soil properties including texture, structure, antecedent moisture, temperature and porosity were found to affect infiltration (Horton, 1937b, Baver, 1936; Musgrave, 1955; Musgrave and Free, 1936). Baver found that the type, rate and amount of water movement was related to properties affecting the noncapillary porosity (porosity drained from 0 to -1/3 bar tension). The size of the structural aggregates was thought to influence infiltration. Lutz (1934) found that 45.4% and 83.3% of the aggregates in the subsoil of the Iredell and Davidson series, respectively, to be larger than 0.1 mm and concluded that the higher percent in Davidson was the most important factor in producing greater percolation through the profile.

Based upon these early pedologic infiltration studies, an extensive survey of the infiltration rates and numerous soil series was conducted (Free et al., 1940). The procedure for the infiltration tests consisted of using a 9-inch diameter single ring 18 or 24 inches in length. The tube was jacked into the soil sufficient to penetrate the subsoil. A 1/4-inch constant head of water was maintained. The surface vegetation was removed and an initial infiltration test was conducted for 180 minutes. Twenty-four hours later a wet antecedent soil moisture infiltration test was conducted. Sixty-eight various soil series were studied. The final constant infiltration rate at 180 minutes was best correlated to various subsoil properties: (r^2) -0.42 for percent clay, -0.33 for volume weight, 0.36 for total porosity, 0.54

for noncapillary porosity, and 0.40 for organic matter. One of the conclusions was that techniques to measure the actual size distribution of soil pores should be developed. The investigators established the fact that further studies of the relationship of soil texture to infiltration, which had consumed much of the earlier literature, should be relegated to a low priority. Techniques to estimate or measure soil pores and pore size distribution were developed soon thereafter (Learner and Lutz, 1940; Nelson and Baver, 1940).

The difference in pore size distribution (0 to 500 cm^{-1} water tension) was found to correlate well to the differences in infiltration and runoff between Muskingum silt loam and Keene silt loam soils (Schiff and Dreibelbis, 1949). It was concluded that (1) the subsoil pore size distribution and transmission rates of the subsoil were the main reasons for greater runoff, (2) there was sufficient available storage so that runoff was not produced for most storm events, and (3) runoff only occurred under high rates of rainfall or when sufficient surface sealing took place.

Significant differences in infiltration and surface runoff are known to exist between forest, pasture and cultivated land uses (Dreibelbis and Post, 1943, 1940; Hursh and Hoover, 1942; Hursh, 1944; Holtan and Kirkpatrick, 1950). The Hortonian concept of uniform infiltration and runoff production becomes increasingly complex with the inclusion of land use factor(s). Due to the complexity of these land use problems and the rainfall-infiltration-runoff processes, it was generally agreed that the hydrograph remains as the single most valuable tool in relating storm runoff to the hydrologic characteristics of the soil profile (Hursh and Hoover, 1942; Horner and Lloyd, 1940; Horton, 1937a).

One of the most intensive studies of soil infiltration phenomena involved the study of two agricultural watersheds near Edwardsville, IL from 1940 to 1943 (Sharp et al., 1949; Holtan and Minshall, 1968). The type F infiltrometer, rainfall simulator (Parsons, 1939; Sharp and Holtan, 1942) was utilized to evaluate the soil, vegetational and topographic relationships of 54 plots on the watersheds. A system of soil-cover groups was developed as a basis for estimating land areas of similar infiltration capacity. It was concluded that there was good agreement between total runoff from plots and the watershed as a whole. In a later analysis of these data (Minshall and Jamison, 1965), it was determined that there was not sufficient agreement between the plots and the watershed discharges. The relationships were not the same for all storms because it was dependent upon the antecedent moisture condition of the soil preceding the storm. Not all the flow measured as runoff from plots or watersheds could be attributed to surface runoff.

The system of hydrologic soil groups was developed to provide a pedologic basis of estimating infiltration from agricultural watersheds across the United States (Soil Conservation Service, 1954; Musgrave, 1955). Musgrave established the soil groups to represent a seepage constant or final constant infiltration rate, the rate of infiltration after prolonged wetting. Research data or correlated estimates or judgement were used to rate all soil series into one of the four hydrologic groups: Group A, 0.76 to 1.15 cm/hour; Group B, 0.38 to 0.76 cm/hour; Group C, 0.13 to 0.38 cm/hour; or Group D, 0.00 to 0.13 cm/hour. The literature is unclear as to the number of soil series hydrologic ratings which were based upon research data and how many were determined by judgment, but it should be assumed that the vast majority of rating decisions were made without infiltration data of any kind.

Holtan (1958, 1961) proposed a linear relationship to express an infiltration curve or to estimate a curve from soil hydrologic groups. The function of soil moisture storage exhaustion with time is determined by the relationship:

$$f = 0.69\ A\ S_a^{1.4} + f_c$$

where:

f is the infiltration rate at a given time increment in cm/hour,

f_c is the seepage rate or saturated hydraulic conductivity through the impeding horizon in cm/hour,

S is the porosity above the impeding horizon that is available for storage in cm of water,

S_a is the porosity above the impeding horizon that is available for storage in the time increment in cm of water,

A is an index of surface connected porosity, and

0.69 is a constant with metric units.

The S value is estimated from soil porosity and soil moisture tension data. The f_c is actually the final constant infiltration rate, but it is taken to be the saturated hydraulic conductivity of the most impeding horizon to be encountered by the wetting front.

Graphical representation of solutions of this relationship by Holtan and Creitz (1967) indicates that the infiltration rates approach the final constant infiltration rate only after 3 to 4 hours. Typical infiltration curves and data presented by other authors demonstrate that the time to the final constant infiltration rate may be substantially shorter than that indicated by the Holtan equation (Bertoni *et al*., 1958; Bruce and Whisler, 1973). Bruce et al. (1976) found that the subsoil condition in a Cecil profile regulated infiltration after 30 minutes into the event, and that the time may be as short as 10 minutes for high intensity storms with wet antecedent conditions. The form of the Holtan infiltration equation which is a slow positive decay function may not represent various types of soils and land use conditions common to the southeastern Piedmont.

Earlier Horton had proposed a similar equation based upon studies of hydrographs from small plots (Horton, 1933, 1940). Horton calculated a "normal depletion-curve" for the catchment to represent soil moisture storage during the rainfall event. The curve exponentially decays in 1 to 3 hours approaching a final constant rate. The equation with later modifications is defined as:

$$f = 0.69\ f_c + (f_o - f_c)e^{-kt}$$

where:

f is the infiltration rate at given time increment in cm/hour,

f_c is the ultimate or final constant infiltration rate in cm/hour,

f_o is the initial maximum infiltration rate in cm/hour,

k is an empirical constant,

t is the time from start of rainfall event, and

0.69 is a constant with metric units.

Horton derived the f_c, f_o and k values from hydrograph analysis, although they are defined herein as deterministic values. The exponent is negative rather than positive as for Holtan's equation, thereby allowing for a more rapid decay in the early portion of the infiltration curve.

2.7 Infiltration Measurement

Infiltration can be measured by two general approaches, using infiltrometers or by analysis of watershed rainfall-runoff data. Infiltrometers are used to determine rates on small plots, while hydrograph analysis yields an infiltration function for a small catchment or plot, or yields an average moisture storage or infiltration rate for all soil land use conditions in a large drainage basin (Musgrave and Holtan, 1964).

Flooding type infiltrometers and rainfall simulator infiltrometers are the two basic types of infiltrometers. The flooding type which is more commonly used for pedologic studies consists of the application of water in double concentric rings (Ahuja et al., 1976; Johnson, 1963; Musgrave and Holtan, 1964; Swartzendruber and Olson, 1961) or ponding in a plot size constructed basin (Klute, 1972; Nielsen et al., 1973). The double rings or the size of the ponding plot are intended to minimize lateral movement of water such that measurement is principally of the vertical component. The flooding type infiltration measurements are only practical on relatively flat terrain. However, these methods are sufficiently versatile to allow for numerous measurements on different soils and land use conditions.

Rainfall simulators employ the application of an artificial rainfall to plots so that surface runoff can be measured. The infiltration rate is taken to be the difference between the rainfall and runoff rates after abstraction for surface detention, interception and depression storage. The mass infiltration curve is derived by a graphical method described by Sharp and Holtan (1940, 1942). Rainfall simulators provide three major advantages over flooding type infiltration measurements in that (1) the simulators can be operated on a variety of terrain, (2) they provide values that resemble natural rainfall infiltration (values tend to be lower than that for flooding) and (3) they provide the measurement of runoff rates.

Determination of infiltration rates by hydrograph analysis can be achieved on small plots or on the watershed as a whole. The infiltration curve through time can be estimated on small plots. Hydrograph analysis of a watershed provides an estimate of an average infiltration rate for a given storm event. The range of average infiltration rates can be determined by analysis of the average infiltration rates for numerous storm events. Due to the complexities of rainfall variability and time of travel of runoff to the point of measurement, the entire infiltration curve cannot be estimated except for extremely small catchments. The detention-flow relationship method (Horton, 1945) of calculating the infiltration rates are applicable to plots and small catchments, while the average infiltration method (Horner and Lloyd, 1940; Sherman, 1940) can be utilized on larger watersheds.

2.8 Soil-Water Movement

The theory of water movement during infiltration has been described in detail by, for example, Hillel (1971), Phillip (1969), Nielsen *et al*. (1972) and Klute (1973). The theory which is the subject of many books will not be repeated herein, but reference will be made to important aspects of the process. The theory of soil-water movement has been developed with experimentation of primarily non-swelling, uniform, low colloidal content soils.

Steady state saturated flow of water in soil is described as a flux equation, Darcy's law, due to a driving force(s):

$$v = -(k\rho/\eta)\nabla\phi$$

where:

v = velocity of flow,

k = permeability of the soil,

ρ = water density,

η = water viscosity, and

$\nabla\phi$ = force(s) per unit mass of water (after Klute, 1965).

and written whereby:

$$q = \frac{Q}{At} = -K\frac{\Delta H}{\Delta x}$$

where:

q = instantaneous soil water flux,

Q = volume of water flowing through,

A = unit cross-sectional area in,

t = time,

H = hydraulic head, and

x = soil depth.

And solving for K, the hydraulic conductivity:

$$K = -\frac{Q}{At}\frac{\Delta x}{\Delta H}$$ (after Matzdorf *et al*., 1975)

The force required to move the water is considered to be governed by the gravitational potential gradient, the soil matrix potential and the soil osmotic potential. The Darcy based theory is restricted to water flow in saturated soils, due to the fact that the unsaturated hydraulic conductivity is a function of the volumetric soil-water content. The theory modified in varying manners to take into account the change in the matrix potential with water content, can be used to describe unsaturated flow (Nielsen et al., 1964). The hydraulic conductivity for small changes in soil-water content, $\theta(cm^3/cm^3)$, is estimated to be:

$$\overline{K}(\overline{\theta}) = \frac{\Delta Q}{\Delta t} \frac{\Delta x}{\Delta H}$$

Unsaturated flow during infiltration would occur in non-surface connected porosity prior to saturation, during a rainfall event insufficient to produce steady state saturated flow, and after the rainfall event when a saturated zone becomes unsaturated due to the redistribution of water along the wetting front. In a layered soil with a coarse-textured soil over a fine-textured subsoil, the hydraulic conductivity of the upper profile would initially control the wetting or infiltration front. However, as the wetting front approaches the fine-textured subsoil, the hydraulic conductivity of this zone would begin to control the infiltration rate of the profile (Hillel, 1971). Assuming saturated flow in the most hydraulically limiting horizon the wetting front encounters, the quasi-steady state infiltration rate should approach the saturated hydraulic conductivity of that horizon.

The hydraulic conductivity and permeability are a function of the pore size distribution of the soil (Marshall, 1958; Green and Corey, 1971; Bouma and Hole, 1965, 1971; Bouma and Anderson, 1973). The relationship between pore diameter and conductivity for planar and tubular pores is described by Childs (1969) and Bouma and Anderson (1973). The velocity of flow through a single tubular pore would be:

$$v = \eta\rho g\pi r^4/8\pi \cdot \text{grad } \phi$$

where:

v = velocity,

η = water viscosity,

ρ = water density,

g = gravitational constant,

r = pore radius, and

grad ϕ = hydraulic gradient.

Therefore, the hydraulic conductivity, K, would be written as:

$$K = \eta\rho g\pi r^4/8\pi$$

Given a soil with a series of identical pores that are also the only pores, $\eta\rho r^4 = f$, where f = total porosity of soil, the hydraulic conductivity would be:

$K = \eta\rho g r^2 f/8\pi$ (after Bouma and Anderson, 1973).

The determination of theoretical water flow through a continuum of different sized pores has been developed (Bouma and Anderson, 1973). The soil moisture characteristic curve procedure has been developed as a standard experimental method for estimating effective pore size distribution (Hillel, 1971). The soil moisture characteristic curve is useful for estimating the hydraulic conductivity as various volumetric water contents near saturation.

Extreme spatial variability of hydraulic conductivity and infiltration rates occur in nature (Nielsen et al., 1973; Carvallo et al., 1976). The variability in soil-water movement is commonly observed between different soils (Lutz, 1970), however, variation across a field, macroheterogeneity, or within a small area, microheterogenity, is common. The maximum degree of variability in any one horizon across a field can in some soils be found in any square meter in the field. This degree of microheterogenity can occur due to the microvariability in the pore size distribution, pore network patterns and degree of connectivity between pores.

2.9 Micromorphology of Soil Pore System

A significant portion of the volume of a soil is occupied by voids or pores. The total void space generally consists of a subpopulation of uniquely arranged large pores that are connected to a subpopulation of smaller pores, and so forth down to submicroscopic sized pores. More specifically, soil pore networks are seldom an ideal system like arteries and veins of an animal, but rather are commonly an apparent disarray of a poorly connected highly irregular population of tubular, planar, chamber and packing voids, as well as, vughs and vesicules that may not connect to the network, except in a most discordant manner. Not withstanding these problems, a standard terminology for the description of large pores in a soil profile has been developed (Johnson et al., 1960). Brewer (1976) has developed a standard nomenclature and set of procedures for the description of soil voids, as well as, the entire soil fabric. Brewer proposed the following size terminology for soil voids:

Size classification of voids

Class name	Subclass	Class limits
Macrovoids		>75 µm
	Coarse macrovoids	>5000 µm
	Medium macrovoids	2000-5000 µm
	Fine macrovoids	1000-2000 µm
	Very fine macrovoids	75-1000 µm
Mesovoids		30-75 µm
Microvoids		5-30 µm
Ultramicrovoids		5 µm
Cryptovoids		<0.1 µm

This system of classification of void sizes should not be confused with the terms "macropore" and "micropore." The latter terms are defined in relationship to soil moisture characteristic data and are terms of effective pore size (Marshall, 1958). A currently recognized arbitrary point of -60 cm H_20 soil moisture tension or approximately 52 µm effective pore diameter is the boundary between macropores and micropores.

Soil peels have been used to provide a means of analyzing horizontal or vertical sections of soil fabric (Bouma and Hole, 1965, 1971; Bouma and Anderson, 1973). A similar system of preparing soil profile samples to study "biopores" has been developed by Van der Plas and Slager (1964). Rogaar (1974) presented procedures for preparing three-dimensional polyester casts of pore networks. By far the most commonly used procedures for accurate examination of soil pores has been through the use of thin sections of impregnated soil material (Brewer, 1976). Extravagant means of thin section study of soils has led to the development of advanced electronic visual analysis equipment, which can provide rapid counting and measurement of voids (Murphy *et al*., 1977a, 1977b).

Thin sections have been used to study the relationship between change in soil surface micromorphology and infiltration rates for 16 Australian soils (Beckmann and Smith, 1974). The soils were classified as to their relative decrease in rainfall acceptance due to the effects of wetting and drying cycles and trampling. The micromorphological infilling of soil pores has been compared to differences in hydraulic conductivity of stream channel alluvium (Qashu and Buol, 1967).

The development of argillans coating the sides of soil pores has been thought to inhibit plant growth and restrict moisture movement (McCracken et al., 1971; Khalifa and Buol, 1969). Micromorphological and mineralogical study of the genesis of argillans in the argillic horizons of Cecil soils (Khalifa and Buol, 1968) has indicated that many of the clay coatings are relative young features and that they consist of translocated clays from the upper horizons. Soil turbation by freezing and thawing, plant root growth, desiccation and wetting, soil expansion and contraction, soil organisms and by tillage and other forms of disturbance, destroys the argillans along the pore networks. Orientated clays in the soil matrix are thought to be remnants of previous argillans (Buol and Hole, 1959, 1961).