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Drainage Control Through Vegetation and Soil Management

EDWARD J. KENT, SHAW L. YU, AND DAVID C. WYANT

A procedure is developed that promotes the use of soil infiltration capacity and available soil profile storage in the design of highway drainage systems. By considering a design volume represented by the soil profile storage, the dependence on constructed runoff detention basins or other drainage structures can be reduced. This design volume is selected as the antecedent available storage in the soil that produces the T-year runoff from the T-year design rainfall. Data requirements of the overall methodology are commonly available soils, vegetation, and climatic parameters. The influence of antecedent moisture on the relation between rainfall and runoff frequency was tested by using 5 years of daily soil moisture and hourly rainfall and 10 years of hourly runoff data from the Calhoun Experimental Forest near Union, South Carolina. Equations that estimate the design antecedent moisture and its associated storage for ungaged sites are developed. Vegetation and soil management techniques that increase the volume of soil profile storage and soil infiltration capacity are reviewed. In addition, the Calhoun soil moisture data are fitted to frequency distributions to assess the risk involved in using soils-based drainage designs.

Traditional drainage design is usually based on (a) an estimate of peak design storm runoff for a given area and (b) man-made facilities that can accommodate and transport these peak flows away from developed sites. In recent years, however, the trend has shifted toward using on-site or source control to reduce flow rates leaving developed areas and thus prevent increased risk of downstream flooding. This change in philosophy has resulted in part from the excessive cost of building detention facilities but mostly from the growing concern over the effects of storm runoff downstream.

Engineers who design urban drainage systems often choose to use paved, open drainage channels and curb and gutter because of their high efficiency and stability in transporting runoff. Unfortunately, the efficiency that makes paved channels and curb and gutter desirable for removing runoff can cause detrimental effects downstream, including increased potential for flooding, erosion of natural waterways, and sediment pollution. Consequently, grassed roadside ditches or swales, infiltration pits and trenches, and porous pavements have been suggested for use in urban drainage design. All of these facilities rely on the use of soil infiltration capacity and soil profile storage to reduce the volume of storm runoff. This paper concentrates on the development of a methodology that allows the water storage capabilities of the soil profile to be explicitly included in the design of on-site drainage systems for handling storm water.

RAINFALL FREQUENCY VERSUS RUNOFF FREQUENCY

In the design of facilities for managing storm water, it is common practice to assume that the peak discharge from some selected design storm has the same return period as the rainfall depth in some "critical" duration. However, numerous studies of watersheds have concluded that the return frequency of runoff produced by a given storm is not fixed but varies over a wide range and depends on antecedent conditions in the catchment (1).

The runoff response on natural watersheds is highly sensitive to antecedent soil moisture or surrogate measures of wetness, such as five-day antecedent precipitation. This means that the proper selection of antecedent moisture is necessary to produce the desired T-year design runoff from the T-year rainfall. In a study of the density function of the difference between gross rainfall and the antecedent soil moisture deficit, Beran and Sutcliffe (2) concluded that for a given location and season the mean soil moisture deficit produces the rainfall excess of T-year return period from the rainfall of the same return period.

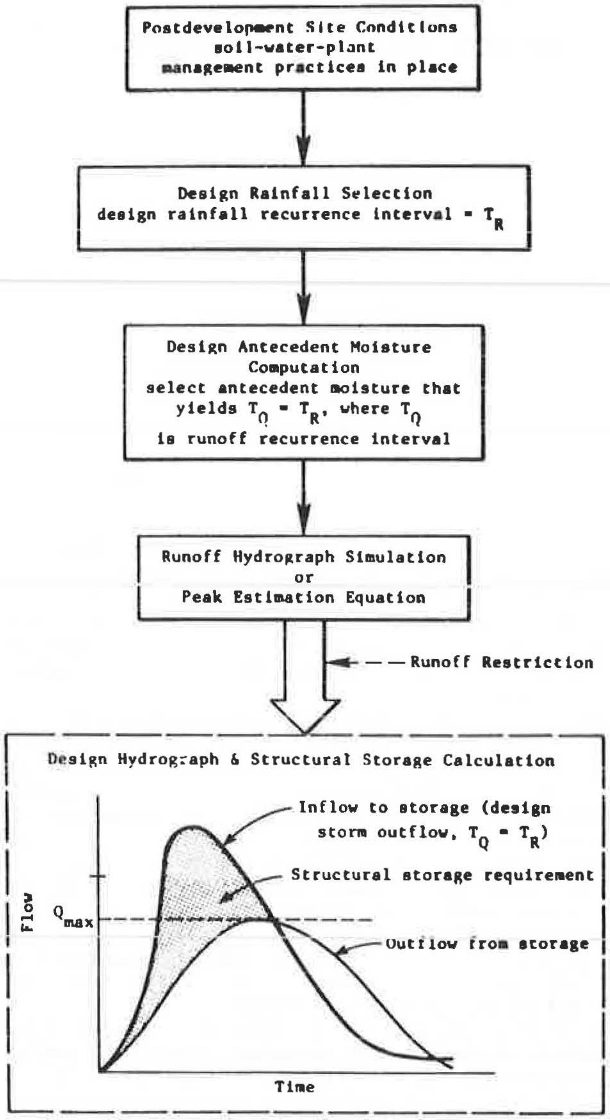
In critiquing a paper by Larson and Reich (3), Laurenson addressed the question, When the design storm-loss-rate unit hydrograph method of flood estimation is being used, what loss rate should be selected to produce equality of rainfall and runoff recurrence interval? He suggested that the correct value is the median of all values of loss rate that have been derived for the catchment.

CURRENT DESIGN PROCEDURE

Current drainage design practices can be summarized as follows:

1. Postdevelopment site conditions, such as slope, vegetation, and replacement of disturbed soils, are planned and minor attention is given to hydrologic impacts.
2. The runoff hydrograph or peak flow produced by some design rainfall of return frequency T_r is calculated. Antecedent soil moisture conditions are arbitrarily set, maybe at saturation, to yield a conservative runoff hydrograph of peak-flow estimate.
3. If no runoff restriction is in force, then outlet pipes from the site are sized to carry the predicted peak flow (Q_p). If restrictions are in force and they are exceeded by Q_p, then a detention structure with a controlled outlet must be sized so that Q_{max} allowed by the restrictions is not exceeded.

Figure 1. Flowchart of proposed drainage design procedure.



PROPOSED APPROACH

Two major changes in the current drainage design procedure are proposed. First, vegetation and soils management techniques are to be used to maintain or improve postdevelopment opportunity for on-site storage of storm water in the natural soil profile. This action will reduce postdevelopment runoff volumes and flow rates. Second, the design antecedent moisture and its associated storage will be calculated based on the soils and vegetation of the catchment, and they will be the proper moisture to produce the T-year flood from the T-year rainfall. Figure 1 shows these modifications in the context of the total drainage design procedure.

The findings of Beran and Sutcliffe (2) and others indicate that the seasonal, or perhaps annual, mean value of antecedent moisture should be selected to produce a runoff peak with a recurrence interval approximately equal to that of the design rainfall. The validity of their results was first investigated by using data collected for a forested watershed in South Carolina.

WATERSHED DESCRIPTION AND DATA BASE

The data used in this study were collected at the Calhoun Experimental Forest in South Carolina. A detailed description of the project is given by Metz and Douglass (4).

One of the catchments studied in the Calhoun project, referred to here as catchment 3, was selected for this investigation because data on antecedent soil moisture, peak stream flow, and rainfall were all available for it. The catchment had an area of 21.8 acres and was covered with a 20- to 26-year-old stand of loblolly pine. No soil moisture data were collected on the catchment, but it was located within 2 miles of instrumented pine plots that had very similar soils, cover, and rainfall. Antecedent soil moisture on the catchment was therefore assumed to be equal to that recorded for the instrumented loblolly pine plot. The daily soil moisture record extended from May 1950 through March 1956.

Hourly rainfall data were available for the period 1950-1961 from rain gages located in the Calhoun Experimental Forest. Information on the frequency of rainfall for the site was found in a technical memorandum of the National Oceanic and Atmospheric Administration (5) and was also determined from 23 years of records for a recording gage at nearby Lockhart, South Carolina.

Instantaneous flow records for runoff from catchment 3 were available for the 10-year period from 1951 to 1961.

The antecedent soil moisture values showed a strong seasonal trend under all cover conditions at the experimental plots. High moisture levels were observed in winter, when gentle storms of long duration are common and evapotranspiration rates are low. These are contrasted with summer conditions, when convectional storms of short duration and high intensity predominate and evapotranspiration rates are greatly increased by plant activity and high temperatures. Seasonal antecedent moisture histograms for barren, broomsedge, and loblolly pine plots are shown in Figure 2. Two seasons were assumed: summer, lasting from May 1 through October 14, and winter, from October 15 through April 30 each year. The histograms also indicate the seasonal mean antecedent moisture ($\overline{EMC}_a$) for each cover type.

Results for barren and broomsedge plots are included to show how, within a season, the frequency of dry antecedent conditions is increased with the increasing evapotranspiration capabilities of the cover type. Approximate maximum or potential rates of evapotranspiration (ET_p) under the three cover types shown in Figure 2 are given below:

Cover	ET_p (in/day)
Forest	0.20-0.30
Grass	0.15-0.25
Barren	0.10

ANALYSIS OF RAINFALL VERSUS RUNOFF FREQUENCY

Rainfall Frequency

Based on a duration of 1 h, which corresponds closely to the time of concentration of the watershed, the rainfall intensities for various recurrence intervals were obtained from the work of Frederick and others (5). Point rainfall values were selected because of the small size of catchment 3.

Stream-Flow Frequency

The 10-year stream-flow record restricted the fre-

Figure 2. Seasonal antecedent soil moisture histograms for various cover types at Calhoun Experimental Forest: (a) barren, October 1950 through December 1954; (b) broomsedge, October 1950 through April 1955; and (c) loblolly pine, October 1950 through April 1955.

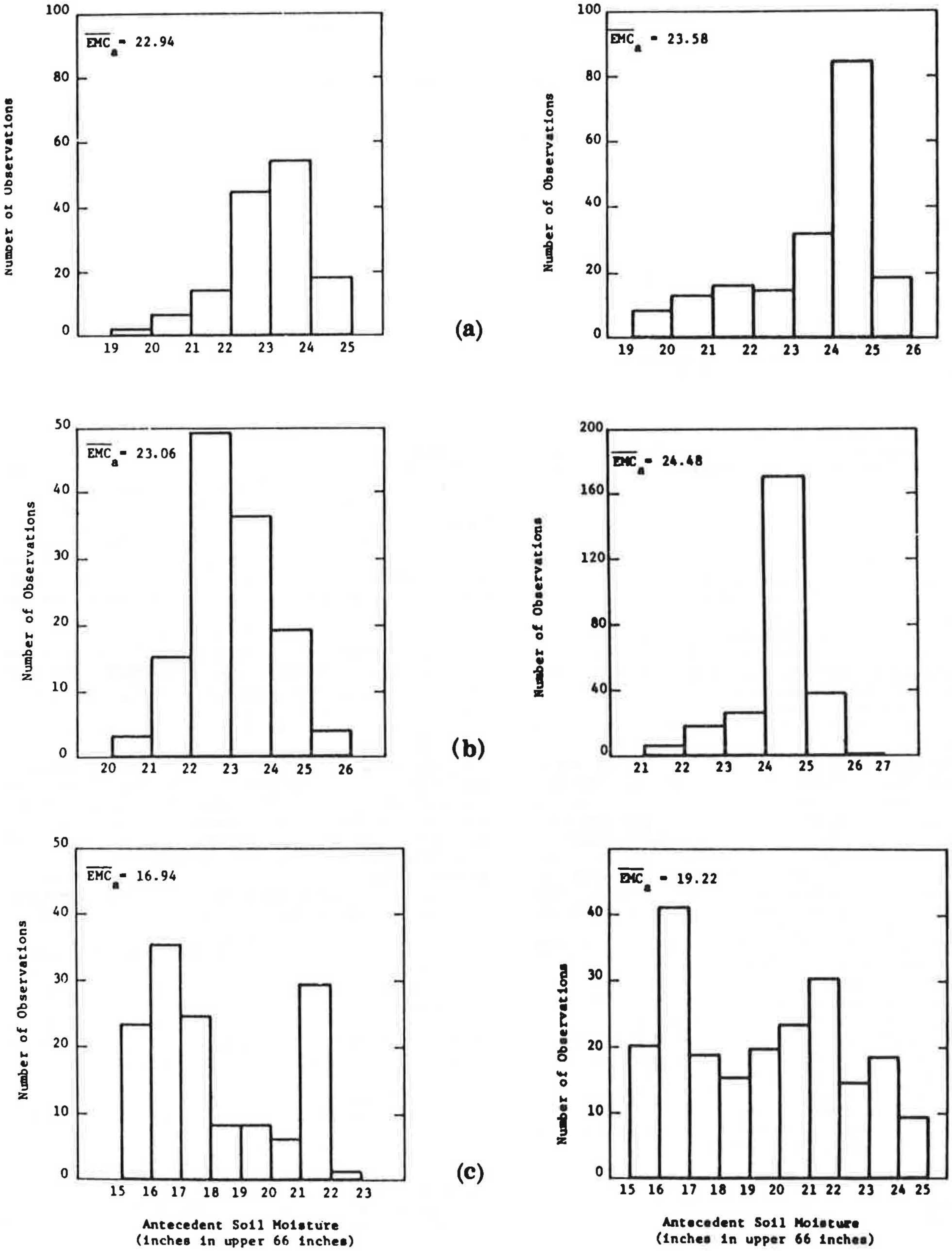


Table 1. Rainfall versus runoff frequency relations for catchment 3.

Storm No.	Date	Peak Flow (ft^3/s)	One-Hour Maximum Rain (in)	T_Q (years)	T_R (years)	T_{RW} (years)	$EMC_a - \overline{EMC_a}$ (in in upper 66 in)
1	12-20-51	4.55	0.40	1.4	<<1.0	1.1	-2.62
2	3-3-52	8.86	0.50	2.6	<<1.0	1.2	1.55
3	3-24-52	3.42	0.20	1.2	<<1.0	1.0	4.79
4	2-15-53	3.41	0.30	1.2	<<1.0	1.0	-0.62
5	2-20-53	2.91	0.40	1.1	<<1.0	1.1	2.68
6	1-16-54	8.77	0.80	2.6	<1.0	3.0	1.45
7	3-31-54	3.76	0.10	1.3	<<1.0	1.0	4.81
8	2-6-55	4.21	0.35	1.3	<<1.0	1.0	2.38
9	4-14-55	5.38	0.25	1.6	<<1.0	1.0	0.78
10	3-16-56	6.60	0.25	1.9	<<1.0	1.0	3.81
11	7-7-52	0.58	2.05	<<1.0	3.0	-	-
12	6-19-54	0.04	1.50	<<1.0	1.5	-	-
13	7-14-54	0.002	1.60	<<1.0	1.4	-	-
14	8-14-55	0.27	1.85	<<1.0	2.1	-	-
15	3-29-60	12.52	0.95	4.2	1.0	6	-
16	3-30-60	27.20	1.30	21.0	1.2	33	-
17	7-20-59	1.74	1.50	1.1	1.5	-	-
18	6-20-60	0.23	1.95	<<1.0	2.5	-	-
19	9-21-60	15.80	2.15	3.7	8.0	-	-

Note: T_Q = annual peak runoff recurrence interval, T_R = annual 1-h rain recurrence interval, T_{RW} = winter season 1-h rain recurrence interval, and ($EMC_a - \overline{EMC_a}$) = antecedent moisture differential.

quency analysis to recurrence intervals of 10 years or less. Frequency analyses were performed on the annual peaks by using the log-Pearson Type III analysis.

Analysis

The objective of the analysis of rainfall versus runoff frequency was to compare the recurrence interval of runoff with the recurrence interval of rainfall for selected storm events on catchment 3. The events initially selected for analysis were those that produced runoff peaks of at least one-year recurrence interval. Estimates of the peak-flow frequency for the selected events were based on analysis of the annual peaks.

Data were available on 12 winter storm events that met the previously mentioned criteria for the peak-flow recurrence interval, and antecedent moisture data were available for 10 of these. The results for these 12 storms are given in Table 1 (storms 1-10 and 15-16). It is readily apparent that each of the rainstorms had recurrence intervals less than the floods they produced. In addition, the results suggest that using the T-year rainfall in drainage design calculations may produce a flood peak with a recurrence interval greater than T, which would lead to overdesign.

Because all of these events occurred in the winter season, it was decided to select some summer events for analysis. Seven rainfall events of at least one-year recurrence interval were selected. The results are given in Table 1 (storms 11-14 and 17-19). For each of these storms, the assumption of equivalence of rainfall and runoff return frequency is rejected. This time, each of the rainfall events had a recurrence interval greater than that of the runoff peak it produced. For example, storm 19, with an 8-year recurrence interval, produced a runoff peak with a recurrence interval of less than 4 years.

The lack of equivalence of rainfall and runoff peak recurrence interval results from the seasonal nature of both rainfall intensity and antecedent moisture in catchment 3.

The occurrence of lower antecedent moisture levels in summer than in winter is shown in Figure 2. The information on rainfall and runoff peak frequency was derived from annual maximums and does not reflect the seasonal nature of either precipitation intensity or runoff peaks.

All of the high-runoff events in Table 1 occurred in the winter, as did 9 out of 10 observed annual peaks at catchment 3. A check of the stream-flow records at a U.S. Geological Survey gaging station on nearby Fairforest Creek revealed that 31 of 39 recorded annual peaks occurred in winter. These facts suggest that for catchment 3 the flood frequency based on annual peaks is equivalent to the winter season flood frequency.

In the last column of Table 1 the antecedent moisture differential for each storm is expressed as the difference between the antecedent moisture (EMC_a) and the winter season mean ($\overline{EMC_a}$) for a loblolly pine area (19.22 in).

Given that the peak flows occur in winter, the designer needs to know what recurrence interval of rainfall will produce the T-year (winter season) design runoff. Beran and Sutcliffe (2) found that for a given location and season the mean antecedent moisture produces equivalence between T_Q and T_R. Their results were tested for catchment 3 by computing the 1-h rainfall frequency for the winter season. This was accomplished by using 23 winter seasons of rainfall recorded at nearby Lockhart. The frequency curve for 1-h winter storms (based on NOAA data) is shown in Figure 3.

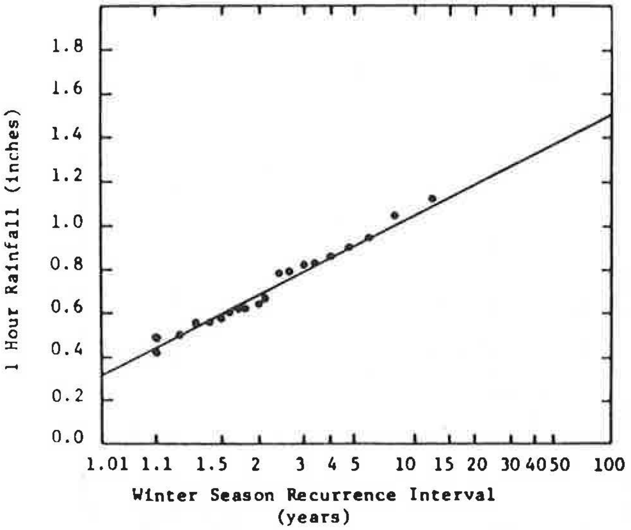
Winter season recurrence intervals for the winter storm events are given in Table 1. There is now a close relation between the winter values of T_R and the values of T_Q.

The analysis described above seems to verify the findings of Beran and Sutcliffe. The difference between rainfall and runoff peak recurrence interval for the 12 winter storms was reduced through the use of seasonal rather than annual frequency analysis. The last column of Table 1 indicates that the antecedent moisture did not differ more than 30 percent from the seasonal mean of 19.22 in for any of the 12 winter storms. The mean antecedent moisture appears to be a reasonable design assumption for producing the T-year runoff from the T-year rainfall, but additional storms on other catchments must be analyzed to further verify such an assumption.

Design Implications

The preceding analysis of rainfall, runoff peaks,

Figure 3. Rainfall frequency curve for 1-h winter season maximum storms at Lockart, South Carolina: 1951-1974.



and antecedent moisture on catchment 3 may be translated into the following general procedure for drainage design.

1. Analyze runoff data for the catchment region to determine whether runoff peaks occur mostly in one season.
2. Select some design runoff recurrence interval T.
3. If runoff peaks are seasonal, perform a frequency analysis on rainfall data for the season in which runoff peaks usually occur. If runoff is not seasonal, use frequencies based on annual maximums and skip step 4.
4. Use the results of step 3 to select T-year seasonal rainfall for design use.
5. When a runoff simulation model or a peak estimation equation requires an antecedent soil moisture assumption for the design rainfall, use the mean seasonal antecedent moisture for the runoff at the site in question. If runoff is not seasonal, use the mean annual antecedent moisture for design.

APPLICATION OF FINDINGS TO DRAINAGE DESIGN

Estimation of Seasonal Average Antecedent Moisture

Drainage design is often applied to catchments for which few or no soil moisture data are available. If antecedent moisture is to be routinely considered in drainage design in such catchments, then a technique is needed for estimating seasonal values of $\overline{EMC}_a$.

The Calhoun Forest has typical Piedmont soils and vegetative covers. The antecedent moisture information from the plots (Figure 2) is therefore assumed to be typical of that for the Piedmont region. The seasonal values of $\overline{EMC}_a$ from the various Calhoun plots were analyzed to provide estimates of $\overline{EMC}_a$ for catchments in the Piedmont region.

The seasonal value of $\overline{EMC}_a$ for each Calhoun Forest plot was normalized for application in Piedmont catchments by expressing $\overline{EMC}_a$ as a fraction of the field capacity (FIELDC) of the upper 66 in of soil on each plot. When a soil is at field capacity, all of its capillary pores are full. Much of this capillary water is available to plants for evapotranspiration, so that the fraction of FIELDC represented by $\overline{EMC}_a$/FIELDC for a particular season and cover type reflects the soil-drying potential of the cover type.

$\overline{EMC}_a$ is then computed by

$$\overline{EMC}_a = C \times FIELDC \tag{1}$$

where C is a multiplier that depends on cover type and season. From the Calhoun soil moisture data and the FIELDC as determined by Ramsey (6), values for C were obtained for various cover types and seasons in the Piedmont region. The C-values ranged from 0.70 for loblolly pine (summer) to 1.00 for broomsedge (winter).

This technique has yet to be verified. It should yield usable results for deep, well-drained Piedmont soils in locations that have a climate similar to that at the Calhoun Experimental Forest.

Available Storage

In any particular soil, the level of EMC_a determines the volume of empty pore space available to store any portion of the design rainfall that infiltrates. This volume of empty pore space is defined here as the antecedent available storage (AS_a). If EMC_a is at the wilting moisture, then the volume of AS_a in the soil profile is at a maximum for the soils and vegetative cover at the site. This maximum storage volume represents the total storage capacity (TSC) of the soil profile. When EMC_a is at some moisture above the wilting point, AS_a can be computed as

$$AS_a = TSC - EMC_a \tag{2}$$

or

$$as_a = tsc - emc_a \tag{3}$$

All upper-case terms are expressed in units of inches of water contained within a specified depth (e.g., the upper 66 in) of soil profile, whereas lower-case terms refer to inches of water per inch of soil.

England (10) used soil moisture tension and texture data compiled by Holtan and others (7) to estimate the volume of water held in excess of the wilting point (15-bar moisture retention) at saturation and at FIELDC for various soil texture classes. The volume of moisture held in excess of the wilting point will be referred to as M_w for units of total inches in the profile or m_w for units of inches per inch. England's results are shown in Figure 4. This figure can be used to obtain estimates for any combination of soil texture and level of moisture m_w. The curves were fitted by eye to England's data points.

The upper curve in Figure 4 represents the driest soil condition where available storage is at a maximum (as = tsc) for all texture classes. The available storage corresponding to higher levels of moisture is read from the vertical scale by moving vertically downward from the wilt line a distance equal to m_w and using the available storage scale.

For example, if it is desired to find the available storage provided by a silt loam with an m_w = 0.20 in/in, Figure 4 is entered at point A. Next, to account for the m_w of 0.20 in/in, move vertically downward from point A a distance of 0.20 in/in, as indicated by the ordinate scale, to point B. Finally, to find the corresponding level of available storage for m_w = 0.20 in/in, move horizon-

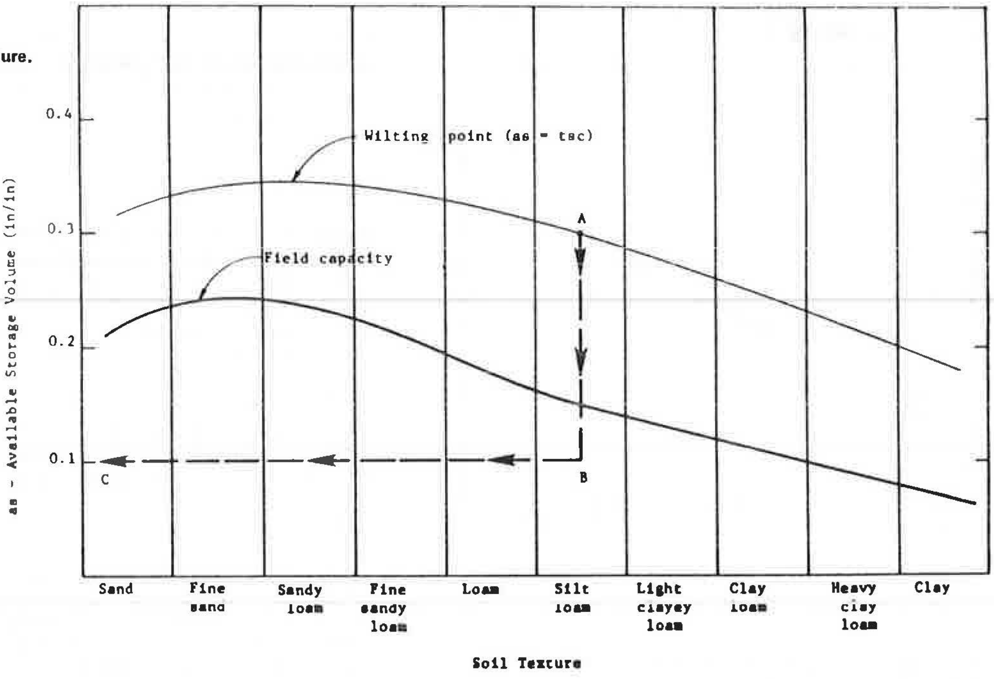


Figure 4. Variation in available storage at wilting point and field capacity as a function of soil texture.

tally to point C and read the answer: as = 0.1 in/in. This value is the average for the silt loam texture class. Because the wilting point for the silt loam ranges from 0.29 to 0.31 in/in, the estimate of available storage may range from 0.09 to 0.11 in/in.

A set of curves like those in Figure 4 could provide rapid estimates of TSC when the soil texture and depth are given. Such curves could also be used to find the average antecedent available storage ($\overline{as}_a$) for design use after $\overline{emc}_a$ has been determined and the wilting point moisture has been substracted to yield m_w.

In calculating TSC, EMC$_a$, or AS for drainage design, the depth of soil profile should be set at the rooting depth for the planned vegetative cover. This is because plant roots influence both the infiltration capacity and permeability during rain events and also regulate the antecedent moisture frequency, as indicated in Figure 2. Soil layers below the rooting depth are usually near capacity and provide insignificant storage during rain events.

Prediction of Design Rainfall Excess

The time distribution and magnitude of the design rainfall excess can be determined by using a modified Φ-index technique. After the design storm excess rain hyetograph has been determined, then the runoff hydrograph can be calculated. Finally, with the design hydrograph known, it is possible to size required detention structures if Q_p is exceeded as it was in Figure 1.

Figure 5 shows the details of this modified, physically based Φ-index. It traces the series of events for a hypothetical 10-year, 6-h rainfall on a site. AS_a for this hypothetical site is 1 in, and typical values have been assigned to other parameters. During the initial rain interval (t_i), all rainfall infiltrates at a rate equal to the rainfall rate. During the depression storage interval (t_d), the rainfall rate exceeds the infiltration rate (f_c) and all rainfall is captured in depression storage. After t_d, all rain in excess of f_c becomes runoff until, at the end of the soil storage interval, the soil profile is saturated. Once the soil profile is full, the rain can enter the soil only as fast as percolation and lateral drainage occur.

Rainfall and soil storage data for use in the modified Φ-index approach are the design rainstorm and the average antecedent available storage, respectively. Other parameters such as interception storage, depression storage, and final infiltration rate must be evaluated by field experiments or estimated from the literature based on the soil-water-plant characteristics of the site.

SOIL AND VEGETATION MANAGEMENT PRACTICES

The management of soils and vegetation can maintain or improve soil storage capabilities in two ways: (a) maintaining high infiltration and percolation rates and (b) maintaining a high total storage capacity.

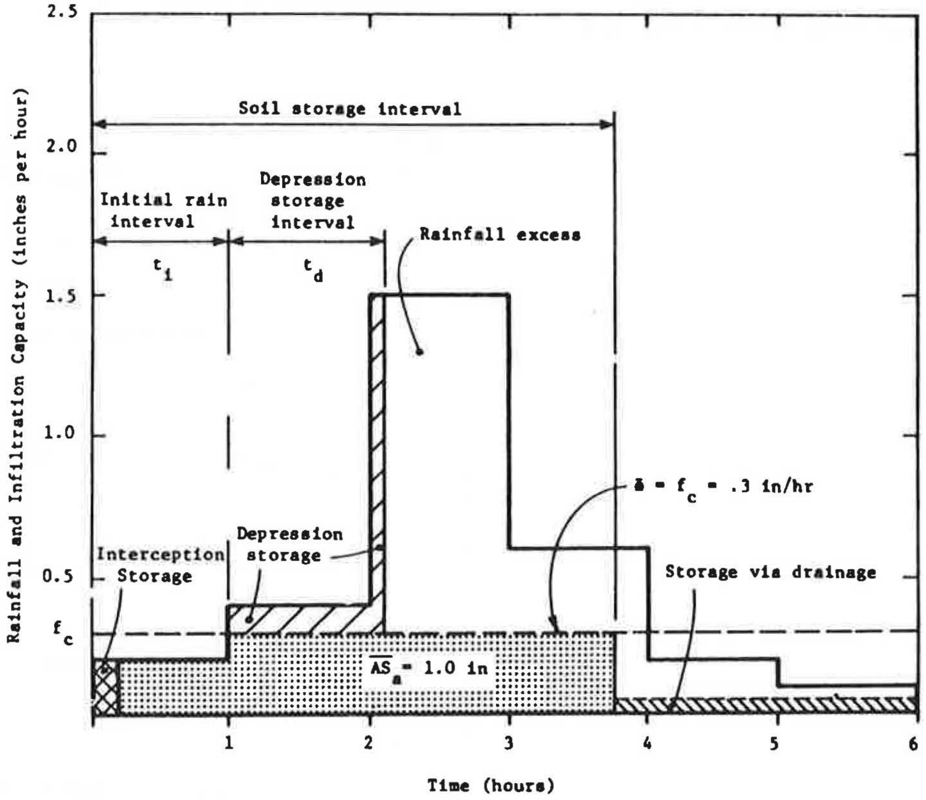
Infiltration Management

Practices that maintain a rough, open, stable structure at the soil surface and a high noncapillary porosity throughout the profile are the key to high infiltration capacities. Roughness refers to the microrelief that produces depression storage, whereas openness refers to the macroporosity visible at the soil surface ($\underline{\theta}$). An open-surface structure allows water in while letting air out with very little pressure buildup. Structural stability prevents the surface sealing associated with the breakdown of surface aggregates and in-washing of fines. High noncapillary porosity permits fast percolation through the dominance of gravity drainage.

The soil surface should be left in a rough and uncompacted state as much as possible. A smooth, compact surface will not only impede infiltration but will also encourage high runoff velocities and result in erosion, washout of new vegetation or seeds, and the siltation of drainage works.

In backfilling, the most permeable, arable soil should be placed on top. This will ensure obtaining the highest infiltration capacities and allow for

Figure 5. Use of a physically based index to predict rainfall excess.



the establishment of vegetative cover.

Vegetation should be established as soon as possible. In addition to traditional erosion control and aesthetic value, a good cover shields the surface soil from direct impact of raindrops and thus preserves the open, rough surface structure created earlier. In addition, plant roots act to bind the surface structure and create deep macropores into less permeable layers. Plants also act as mulch formers, adding organic material to lighten and increase the noncapillary porosity of surface layers.

Special attention should be given to the maintenance of high infiltration capacities in upland areas. These areas have the driest soils, are seldom saturated, and can store large volumes of storm water.

Available Storage Management

At a given site, AS fluctuates daily with the soil moisture, which in turn is determined by infiltrated rainfall, gravity drainage, and losses due to evapotranspiration. AS is maximized when the soil moisture is minimized. Thus, the key objective in AS management is to drain the soil between rain events as quickly as possible through gravity drainage and evapotranspiration.

A high rate of gravity drainage or permeability is largely associated with a high noncapillary porosity. Where soils are not to be disturbed during development, no increase in existing permeability can be achieved. However, when earthwork is necessary, there is an opportunity for maintaining or increasing noncapillary porosity and, thereby, permeability.

An effective way to increase the noncapillary porosity of fine soils is to add organic matter. Organic matter binds small soil particles to form larger stable aggregates.

Excessive compaction destroys the noncapillary pores while usually having little effect on the capillary or plant-available porosity (9). Backfill soils should be only lightly compacted where bearing strength or slope stability is not a controlling factor. Care should be taken during construction to avoid compacting existing undisturbed soils.

The action of plant roots can greatly improve gravity drainage rates. As roots penetrate the soil, they often provide enough space for water to move alongside and downward into the profile. Root senescence and death leave a long, continuous noncapillary pore. During a rain event these extensive macropores provide access to a large wall area of relatively dry soil deep within the profile. In established vegetated areas, the noncapillary porosity caused by such root action is a major contributing factor to soil permeability.

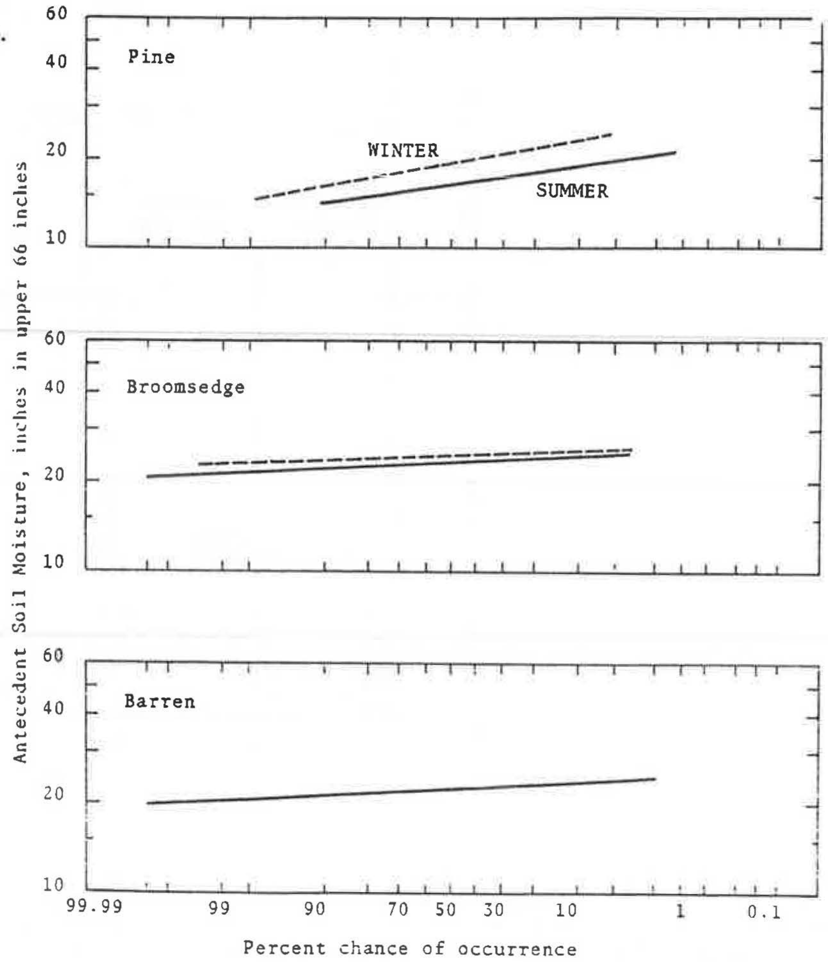
Plant species should be selected and placed in the watershed so as to withdraw soil water at the maximum feasible rate. Criteria for plant selection include the suitability of the soil, hardiness, rooting depth, evapotranspiration rate, maintenance, and the seasonal variability of the evapotranspiration rate. The best plant cover is one with good resistance to drought, a high evapotranspiration rate per unit depth throughout the year, a large total root depth, and inexpensive maintenance.

The placement of vegetation greatly affects its effectiveness as a soil moisture pump. Plants have access to more water and can create more new storage more rapidly when they are located in moist areas as opposed to dry areas. Such moist areas are usually located at low areas or near the toe of a slope. Field inspections and final grade plans should be used to detect or predict such moist areas, and water-using vegetation should be concentrated in these areas when the project is completed.

RISK ASSESSMENT

A constructed storage facility (e.g., a detention

Figure 6. Antecedent soil moisture probability analysis for various Calhoun Forest cover types (lognormal distribution).



basin) provides a fixed quantity of storage. This is in contrast to drainage designs, which incorporate the variable storage capability of the soil profile and thus involve risk. This risk is associated with the possibility that, when a design storm actually occurs, the antecedent soil moisture will be higher than the level assumed in the design.

The risk involved in such a soils-based drainage design can be calculated as the joint probability of the design storm event occurring simultaneously with various levels of antecedent moisture. The short period of record at catchment 3 makes the use of such a joint probability approach for that site impossible.

An alternative method of risk analysis requires the use of conditional probability concepts. The problem can then be expressed as follows: What is the probability that $\overline{\mathrm{EMC}}_a$ will be exceeded, given that a rain event greater than or equal to the design storm occurs? In the symbols of probability analysis, it is desired to find the value of

$$P[X \geq x \mid Y \geq y]$$

where

X = antecedent soil moisture (in),
x = EMC_a (in),
Y = volume of the t-hour rain event (in), and
y = volume of the t-hour design rain event (in).

If X and Y are independent, a reasonable assumption for a given location and season is

$$P[X \geq x \mid Y \geq y] = P[X \geq x] \tag{4}$$

The above equation indicates that the probability of $\overline{\mathrm{EMC}}_a$ being equaled or exceeded prior to a design storm is $P[X \geq x]$. It is important to note that this equation holds for any design storm recurrence interval (T_R). Estimates of $P[X \geq x]$ for the three cover types at the Calhoun Experimental Forest were obtained by fitting observed antecedent soil moisture data to probability distributions. The data used in the analysis were antecedent moistures preceding the 30 largest rain events of the 4- to 5-year period of record for each season and type of vegetation. The results are shown in Figure 6.

The plots for antecedent moisture frequency indicate, for each season and type of vegetation, the probability that any given antecedent moisture will be equaled or exceeded. As an example, assume a design situation in which winter season soil moisture conditions are to be used and the vegetative cover is loblolly pine. If $\overline{\mathrm{EMC}}_a$ is used for design, then Figure 2 indicates that $\overline{\mathrm{EMC}}_a$ = 19.22 in for pine in winter. The middle plot in Figure 6 indicates that for an $\overline{\mathrm{EMC}}_a$ = 19.22 in the chance of occurrence is approximately 52 percent. All cover types and seasons, except barren-winter, were found to be lognormally distributed by using the chi-square goodness-of-fit test at a 5 percent level of significance. The barren-winter results exhibited a large standard deviation and a severe skew that prevented a good fit to any distribution.

If one compares moisture frequency on a seasonal basis, Figure 6 indicates that the frequency of dry antecedent moisture is highest in summer (solid line) for pine and broomsedge. In comparing vegetative covers, the highest frequency of dry moisture conditions is maintained by pine followed by broomsedge and barren. Pine cover exhibits the greatest range of antecedent moisture. The greatest difference between winter and summer antecedent moisture for the full range of frequencies was observed under the pine cover.

The objective of drainage design is to size facilities to handle some T-year runoff peak. This study and others have shown that the best antecedent soil moisture assumption for predicting the T-year runoff peak from a T-year rainfall is seasonal antecedent moisture.

The risk analysis has shown, by using probability theory, that cover types that have high evapotranspiration rates (e.g., pine) can provide a drier antecedent soil moisture more frequently than can cover types that have lower evapotranspiration rates (e.g., broomsedge). In addition, seasonal antecedent soil moisture data probably fit a lognormal distribution for Piedmont cover types in other basins where soil and climatic conditions are similar to those found at the Calhoun Forest. Finally, the risk of experiencing a level of $EMC_a > \overline{EMC}_a$ when a design rainfall occurs does not represent a risk of a design failure but simply describes antecedent moisture probability.

CONCLUSIONS

1. Future drainage design work should incorporate source control of runoff through the management of postdevelopment soils and vegetation. This practice will reduce runoff peaks and thereby decrease the need for constructed detention facilities and other costly flood control measures.

2. The design storm concept of sizing drainage facilities is a valid technique only when used with hydrologic assumptions that will facilitate prediction of the T-year runoff peak from the T-year design rainfall. In locations where flood peaks are strongly seasonal, the seasonal rainfall frequency should be used for design. Flood peaks are seasonal if the annual frequency analysis yields the same frequency relation as one of the seasonal frequency analyses. If antecedent soil moisture is a parameter of the method for design peak-flow estimation and flood peaks in the watershed are seasonal, then the seasonal average antecedent moisture should be used for design. If flood peaks in the watershed are not typically seasonal, then the annual average antecedent moisture should be used in design.

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Effects of Dredged Highway Construction on Water Quality in a Louisiana Wetland

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A research effort to determine, by physical and chemical means, the effect of current bridged highway construction techniques on water quality in a wetland is summarized. Selected water-quality parameters were monitored before, during, and after construction activities. The data show increases in turbidity and color during construction and a gradual returning to the preconstruction ambient in areas where construction was completed. Other parameters also followed this trend, but these changes were not as directly related to the construction activities as were turbidity and color. Local isolated activities other than highway construction were shown to produce more severe and longer-lasting effects on water quality. The information obtained may be useful in predicting the degree and duration of impacts of future construction projects on wetland environments.

The effects of highway construction on the water quality of wetland areas have been studied only to a limited degree. The apparent signs of water degradation, such as siltation and sedimentation, have