SOAH DOCKET NO. 582-15-2082
TCEQ DOCKET NO. 2015-0069-MSW

APPLICATION OF 130	§	**BEFORE THE STATE OFFICE**
ENVIRONMENTAL PARK, LLC	§	
FOR PROPOSED PERMIT	§	**OF**
NO. 2383	§	
	§	**ADMINISTRATIVE HEARINGS**

PROTESTANTS' EXHIBIT 9

PREFILED TESTIMONY OF

ROBERT D. HARDEN

ON BEHALF OF PROTESTANTS TJFA & EPICC

TABLE OF CONTENTS

INDEX OF EXHIBITS

Exhibit No.	Description	Date
Exhibit 9-A	Resume of Robert. W. Harden	Not dated.
Exhibit 9-B	Unit Hydrograph	Not dated.
Exhibit 9-C	Natural Resources Conservation Service, "Urban Hydrology for Small Watersheds", TR-55, excerpt	June 1986
Exhibit 9-D	General Topographic Map (Drawing IA.3, p. 60 of Applicant's Ex. 130EP-1)	November 6, 2014
Exhibit 9-E	FEMA Floodplain Map (Drawing C2-A-1, p. 258 of Applicant's Ex. 130EP-2)	November 6, 2014
Exhibit 9-F	General Site Plan (Drawing IA.6, p. 63 of Applicant's Ex. 130EP-1)	March 4, 2015

I. INTRODUCTION

Q: Please state your name.

A: Robert Harden.

Q: What is your current profession?

A: I am currently a practicing engineer in the fields of groundwater and surface water hydrology.

II. QUALIFICATIONS

Q: What is your educational background?

A: I graduated with a B.S. in Civil Engineering from the University of Texas at Austin in 1988. In 1992 I graduated with a Master's Degree in Civil Engineering/Water Resources from the University of Texas at Austin.

Q: What practical engineering experience have you had since receiving your engineering degrees?

A: From 1988 to 1992, I was employed with the Railroad Commission of Texas in the Surface Mining Division as an Engineer in Training. This work experience involved permit application and construction plan review for surface mining activities. I worked on reviewing surface water control plans, sedimentation pond and diversion design plans, topographic analysis, land use, soil types, runoff volume and peak flow determinations, and probable hydrologic consequences on water quality and water quantity associated with surface mining and reclamation activities. From 1992 to present, I have been employed with R. W. Harden & Associates, Inc., and my work experience generally includes regional groundwater studies, availability analysis, water supply evaluation and development, dewatering and depressurization, water rights acquisition, water rights valuation, surface water drainage analysis, waste facilities, and property condemnation investigations.

Q: What type of work have you done in the water resources field directly applicable to a municipal solid waste Landfill?

A: I have reviewed and designed surface water control facilities including selection of design storm events, delineation of watersheds, estimated runoff volume and peak flow rates, determined flow velocities and hydraulic detention times, evaluated control of erosion and soil loss rates, evaluated the segregation of disturbed and undisturbed drainage, determined elevations of water surface profiles and the extents of flooding. This work involves determining applicable hydrologic analysis techniques based on regulatory standards and site specific considerations involving public safety and environmental protection. I have also designed and conducted surface and groundwater monitoring plans for purposes of demonstrating any off-site changes in water quality due to industrial, mining, and waste storage operations.

Q: Are you currently a licensed professional engineer?

A: Yes, I have been a registered professional engineer in Texas since the early 1990's and specifically practicing in the field of surface and groundwater hydrology.

Q: Please identify Protestants' Exhibit 9-A?

A: Protestants' Exhibit 9-A is a copy of my resume.

PROTESTANTS OFFER EXHIBIT 9-A.

III. SUMMARY OF OPINIONS

Q: Have you developed any opinions regarding the proposed 130 Environmental Park Landfill?

A: Yes.

Q: Please summarize your opinions briefly?

A: I have reviewed this application and developed opinions and concerns regarding the suitability of the site location with regard to risks from flooding, Applicant's approach to quantifying no impact to the hydrologic balance on surface water drainage in the immediate vicinity and just downstream of the site, the soil loss characteristics, and the potential for near surface leakage of leachate to drain into nearby streams. In some cases, it is my opinion that these concerns are significant and increase risks to human safety, welfare, and protection off the environment over the long term. I believe the application fails to meet the regulatory requirements of the Texas Commission on Environmental Quality for Landfill permitting.

IV. FAILURE OF APPLICATION TO COMPLY WITH TCEQ RULES REGARDING DRAINAGE

<u>REGULATORY BACKGROUND</u>

Q: Do the TCEQ rules contain requirements related to surface water drainage?

A: Yes.

Q: What do the rules require with regard to surface water drainage?

A: 30 Texas Administrative Code (TAC) § 330.63(c) requires that an Applicant provide a surface water drainage report, including a statement that the Facility complies with 30 TAC § 330.303. At 30 § 330.303, the TCEQ rules require that a Facility must be constructed, maintained, and operated to manage run-on and runoff during the peak discharge of a 25-year rainfall event and must prevent the off-site discharge of waste and feedstock material including in-process and processed materials. 30 TAC § 330.303 also requires that surface water drainage in and around a Facility shall be controlled to minimize surface water running onto, into, and off the treatment area. So, in short an application must include a surface water drainage report demonstrating that these requirements will be met. Additionally, § 330.63(c) requires that the drainage report demonstrate compliance with Subchapter G of Chapter 330. With regard to Landfills, that subchapter sets forth requirements, including: (1) existing or permitted drainage patterns must not be altered; (2) the owner or operator shall design, construct, and maintain a run-on control system capable of preventing flow onto the active portion of the Landfill during the peak discharge from at least a 25-year rainfall event; (3) The owner or operator shall design, construct, and maintain a runoff management system from the active portion of the Landfill to collect and control at least the water volume resulting from a 24-hour, 25-year storm; (4) The Landfill design must provide effective erosional stability to top dome surfaces and external embankment side slopes during all phases of Landfill operation, closure and post closure; and, (5) Embankments, drainage structures, and diversion channels must be sized and graded to handle the design runoff.

Q: What are the primary elements that the TCEQ rules require to be contained within the drainage analysis?

A: At 30 TAC § 330.63(c)(1), the rules establish that the drainage analysis must include depictions of the drainage areas, the design of all drainage facilities, sample calculations to verify that existing drainage patterns will not be adversely altered, and a description of the hydrologic method and calculations used to estimate peak flow rates and runoff volumes including justification of necessary assumptions.

Q: Do the rules contain any requirements related to the impact of a Landfill on existing drainage patterns?

A: Yes. The Facility surface water drainage report is required to contain discussion and analysis to demonstrate that existing drainage patterns will not be adversely altered as a result of the proposed Landfill development. This requirement is set forth at 30 TAC § 330.63(c)(1)(D)(iii). The Facility surface water drainage report is also required to demonstrate compliance with Subchapter G of Chapter 330, which at 30 TAC § 330.305(a) also sets forth a requirement that existing drainage patterns must not be adversely altered.

Q: Have you evaluated the hydrologic method and calculations used by the Applicant to estimate peak flow rates and runoff volumes?

A: Yes.

Q: What role do the peak flow rates and runoff volumes play in the drainage analysis for a Landfill?

A: To answer this, it is first important to understand that a Landfill Facility inherently alters the existing land surface topography, vegetation, and possibly surface soils. These changes have the potential to alter the way rainfall runs off the landscape from the native, baseline conditions to the post-developed Landfill condition. The ways that water runoff can be altered include changes in peak flow rate or total volume of runoff. Peak flow rates are a concern for flooding and erosion. If the Landfill Facility increases the peak flow rate in downstream, receiving streams then adverse flooding or erosion of soil can occur. If a Landfill Facility increases the total volume of runoff, then a pond or reservoir that is designed to capture a certain volume of runoff can be put at risk because the increased volume can cause water to rise above the reservoir dam and increase the chance the dam will fail. If the dam fails, then catastrophic type losses can ensue.

Q: Where, in the application, has the Applicant set forth the hydrologic method and calculations used to estimate peak flow rates and runoff volumes?

A: In Appendix C1-B of Attachment C1 to Part III of the application, the Applicant has provided existing condition hydrologic calculations, and Appendix C1-C contains the post-development hydrologic calculations.

Q: What general model has been used in the drainage analysis presented in the application?

A: The Applicant has used the HEC-HMS model.

Q: What are the primary factors considered by this model in determining the hydrologic conditions in an area?

A: Broadly speaking, the model considers the watershed characteristics and the amount of rainfall being considered. The watershed characteristics include the total area, the elevation change from the upstream sections to the downstream portion of the watershed, the length of slopes or creeks in a watershed, and the type of vegetation and soils present in the watershed. The vegetation (land use) and soils present are used to estimate what percentage of a rainfall event that is retained in a watershed and the resulting volume of water the runs off. The shape, slope, and stream lengths also determine the how the water runs off over time.

<u>LACK OF JUSTIFICATION FOR UNIT HYDROGRAPH USED IN DRAINAGE ANALYSIS</u>

Q: How does the application transform rainfall into runoff?

A: According to the application, the "Unit Hydrograph Method" was used.

Q: How does the Unit Hydrograph Method transform rainfall data into runoff amounts?

A: A unit hydrograph represents the flow rate at a watershed outlet resulting from 1 inch of excess precipitation distributed uniformly over a watershed. It is a graph of flow rate (gallons per minute or cubic feet per second) that occurs over the duration of the runoff. So, the unit hydrograph determines what flow rate occurs over time. If you think of rainfall as marbles being dropped onto the land, and then count how many marbles are running out of the watershed outlet per second, then the unit hydrograph determines whether they run out fast or slow. The unit hydrograph has an ascending limb where flow rate is increasing each time interval and a descending limb where flow rate is decreasing over time. The key point is the unit hydrograph determines the shape of the runoff curve.

Q: Let me present you with Protestants' Exhibit 9-B. Please identify this exhibit.

A: Exhibit Protestants' Exhibit 9-B is an example of a unit hydrograph.

Q: Can you explain how this graph can be used to transform rainfall data into a runoff amount?

A: The runoff unit hydrograph is combined with a rainfall hydrograph. The rainfall hydrograph is the shape of a rainfall event over time. Say an 8-inch rainfall over 24 hours. Both the runoff unit hydrograph and the rainfall hydrograph are divided into equal time intervals, say 5 minute intervals. Then the first five minutes of rainfall are multiplied by the first five minutes of the runoff hydrograph to get the flow rate and volume at the watershed outlet at time of five minutes. To estimate the flow rate ten minutes, two rainfall increments are added together. The incremental rainfall at ten minutes is multiplied by the runoff hydrograph at five minutes and added to the unit hydrograph at ten minutes times the increment of rainfall at five minutes. This tabulation continues over the course of the rainfall and runoff duration to get the total flow over time at the outlet of the watershed.

Q: Does the application provide the unit hydrographs utilized in the drainage calculations?

A: No.

Q: Why is it important to know the particular hydrograph utilized?

A: When using the unit hydrograph method, of primary importance is the justification for the unit hydrograph selected for the analysis and whether the unit hydrograph is appropriate considering the watershed areas, watershed shape, and potential for downstream hazards and safety considerations. Without seeing the unit hydrograph used by the Applicant, it is not possible to evaluate whether that hydrograph is appropriate in light of these considerations.

Q: What is the "peaking factor" for a unit hydrograph?

A: The peaking factor sets how high and quick the ascending limb of the unit hydrograph occurs.

Q: Why is the peaking factor important?

A: The peak flow at a watershed outlet is highly dependent upon the peaking factor of the unit hydrograph selected. The peaking factor controls the volume of runoff on the rising and receding limbs of the runoff hydrograph.

Q: What are the rising and descending limbs of a runoff hydrograph?

A: Exhibit 9-B shows the ascending and descending limbs of a unit runoff hydrograph.

Q: Does the application identify any peaking factor used in the drainage calculations?

A: No, and no justification for the unit hydrograph used is provided either.

Q: Does the use of an incorrect peaking factor have consequences for the design of a Facility?

A: Yes. The peaking factor selected for the unit hydrograph effects the required storage in storm water detention ponds to adequately suppress increases in peak runoff rate and associated flow velocities for erosion control. The unit hydrograph peaking factor also affects the extents of flooding.

PROTESTANTS OFFER EXHIBIT 9-B.

IMPROPER CHARACTERIZATION OF SURFACE FLOW CHANNELS

Q: In the field of hydrology, what is meant by the term "time of concentration"?

A: The time of concentration for a watershed is the time required for runoff to travel from the hydraulically most distant point in the watershed to the outlet. The hydraulically most distant point is the point with the longest travel time to the watershed outlet, and not necessarily the point with the longest flow distance to the outlet.

Q: Did the Applicant calculate the time of concentration watersheds on the site under post-development conditions?

A: Yes. The calculation of Total Time of Concentration for watersheds under post-development conditions is presented in the Postdevelopment Hydrologic Calculations, at page C1-C-10 (Applicant's Exhibit 130EP-2, p. 129).

Q: Why is The Natural Resource Conservation Service technical document TR-55 relevant to this analysis?

A: TR-55 is a reference document that specifies how the principles and assumptions of the Soil Conservation Method (SCS) method of hydrologic modeling are to be applied.

Q: Please identify Protestants' Exhibit 9-C?

A: Protestants Exhibit 9-C is a copy of TR-55, issued by the Natural Resource Conservation Service.

Q: Have you relied on this document in developing your opinions in this case?

A: Yes.

PROTESTANTS OFFER EXHIBIT 9-C.

Q: On Page C1-C-10 (Applicant's Exhibit 130EP-2, p. 129), what is meant by the terms Sheet Flow, Shallow Concentrated Flow, and Channel Flow?

A: Sheet flow is the first type of flow in the uppermost portions of a watershed or sub-watershed. An example is rainfall flowing off a driveway. Shallow concentrated flow occurs next which is deeper in depth than sheet flow but is not contained within a defined drainage channel, ditch, or stream. Channel flow refers to flow which is contained within a defined drainage channel, ditch, or stream.

Q: Why are these different types of flow important?

A: At each step in these designations of flow type, the water is flowing at greater velocity.

Q: In your opinion, has the Applicant appropriately calculated the time of concentration for these watersheds in post-development conditions?

A: No. The transition from shallow concentrated flow to channel flow does not follow along specified standards for calculating time of concentration. The Natural Resource Conservation Service technical document TR-55 specifically states "*Open channels are assumed to begin where survey cross-section* *information has been obtained, where channels are visible on aerial photographs, or where blue lines (indicating streams) appear on United States Geologic Survey quadrangle sheets*." In calculating the time of concentrations, the application mistakenly uses shallow concentrated flow equations rather than open channel flow equations and this results in overestimating the time of concentration.

Q: Are there specific areas where the Applicant has mischaracterized the type of flow involved?

A: Yes.

Q: What are those areas?

A: In areas upstream of the Landfill site where the USGS maps show blue lines representing creeks or channel flow conditions. Drawing IA.3 of the application (page 60 of Applicant's Exhibit 130EP-1) is a USGS map of the Landfill site and surrounding vicinity. The dashed blue lines on this map upstream of the Landfill site represent intermittent streams, and yet the Applicant has improperly treated these areas as shallow concentrated flow.

Q: Let me present you with a copy of Protestants' Exhibit 9-D. Do you recognize this exhibit?

A: Yes. This is a copy of the General Topographic Map contained in the application (page 60 of Applicant's Ex. 130EP-1). On this exhibit, you can see the intermittent streams upstream of the Landfill site some of which the Applicant mischaracterized as shallow flow.

Q: What is the consequence of overestimating the time of concentration?

A: Longer times of concentration result in lower peak flow rates, slower flow velocities, and underestimating of flood plain delineations. Therefore, the calculation makes the surface water analysis less conservative and this increases the risks of flooding along the perimeter of the Facility boundary and downstream.

PROTESTANTS OFFER EXHIBIT 9-D.

V. FAILURE OF APPLICATION TO COMPLY WITH TCEQ RULES REGARDING FLOODING

REGULATORY BACKGROUND

Q: As we discussing issues related to flooding, can you clarify what is meant when the TCEQ rules refer to the "100-year flood"?

A: TCEQ rules define the "100-year flood" as a flood event with a 1.0% or greater chance of recurring in any given year or a flood of a magnitude equaled or exceeded once in 100 years on the average over a significantly long period.

Q: Is the Facility surface water drainage report also required to address flooding issues?

A: Yes. At 30 TAC § 330.63(c)(2), the rules require that the surface water drainage report identify whether the site is located within the 100-year floodplain. This regulation also provides that maps issued by the Federal Emergency Management Agency (FEMA) are considered prima facie evidence of floodplain locations. Information must also be provided addressing any special flooding factors that must be considered in designing, constructing, operating or maintaining the proposed Facility to withstand washout from a 100-year flood. The Facility surface water drainage report is also required to demonstrate compliance with Subchapter G of the TCEQ rules, which includes a requirement that the Facility shall be protected from a 100-year frequency flood by suitable levees. Such levees must be designed and constructed to prevent washout of solid waste from the Facility, and a freeboard of at least three feet must be provided by such levees.

Q: Do the TCEQ regulations elsewhere address floodplain issues?

A: Yes. Within Subchapter M of Chapter 330, related to Location Restrictions, at 30 TAC Section 330.547, the TCEQ rules provide that new municipal solid waste management units shall not restrict the flow of the 100-year flood, or result in washout of solid waste so as to pose a hazard to human health and the environment.

<u>IMPROPER METHODOLOGY FOR POST-DEVELOPED FLOODPLAIN DELINEATION</u>

Q: In your opinion did the application properly quantify the 100-year floodplain?

A: No.

Q: Why do you have this opinion?

A: The application contains a post-developed analysis of the extent of the 100-year floodplain. In this analysis, runoff conditions within the Facility boundary are assumed to be in the post developed condition. But the upstream watersheds upstream of this Facility are simulated in the present-day condition.

This is an unreasonable assumption because over the life of the Facility, the post-closure period, and decades beyond, the upstream watersheds will assuredly undergo additional urbanization with increases in impervious cover and landuse changes that will increase flood flows in receiving streams directly adjacent the Facility.

Q: What would this future increase in urbanization do to the floodplain?

A: The floodplain will likely expand as higher flood flows and higher flow elevations occur.

Q: Is it common for floodplains to be redefined?

A: Yes, they commonly grow as new flood events are experienced.

Q: Did the Applicant also determine the time of concentration for purposes of its floodplain analysis?

A: Yes.

Q: Do you agree with the Applicant's assumptions regarding time of concentration for purposes of the floodplain analysis?

A: No. The Applicant used the same assumptions for shallow concentrated flow and channel flow in its floodplain analysis, which resulted in the same errors discussed above.

Q: In the floodplain context, what are the potential consequences of this error?

A: This error would result in an underestimation of the floodplain. So, if the reaches involved had been properly characterized, the level of the modeled floodplain would have likely been higher.

<u>FAILURE TO ADDRESS PROXIMITY OF SITE TO 100-YEAR FLOODPLAIN</u>

Q: Do you believe this site has unique site hazards relative to hydrology?

A: Yes.

Q: What are your primary concerns regarding the unique hazards potential of this site?

A: My first concern is the proposed site location of the Facility presents heightened concerns for health, safety, welfare, physical property, and protection of the environment. Specifically, the Facility boundary sits atop a "point of land" that is topographically higher than drainage features directly to the west, south, and east of the Facility boundary. During large flood events, the 130 Environmental Park Facility boundary is located on land "that is bordered by water on three sides" or on "a piece of land nearly surrounded by water".

Q: Do the TCEQ regulations reflect these type of concerns?

A: Yes, 30 TAC § 330.561 indicates that municipal solid waste Landfills may not be located in areas described in 30 TAC § 335.584(b)(3). Correspondingly, 30 TAC §335.584(b)(3) prohibits locating a Landfill on a peninsula. Approximately 75% of the Facility boundary is surrounded and in close proximity to the present-day FEMA delineation of the 100- year floodplain.

Q: Do you feel this is just a coincidence?

A No, it appears that that the Facility was designed to purposefully "fit" precisely within long and extensive reaches of the current floodplain, rather than selecting a site with less topographic relief surrounding the Facility and that also has limited exposure to major flooding events. The present day, 100-year FEMA Zone A floodplain appears to be in direct contact or in very close proximity with the limits of Landfill grading including several of the storm water pond embankments.

Q: I will now present you with a copy of Protestants' Exhibit 9-E. Do you recognize this document?

A: Yes. This is a copy of Drawing C2-A-1 from the application (page 257 of Applicant's Exhibit 130EP-2). This map depicts the location of the Landfill footprint and the limits of Landfill grading to the location of the current 100-year FEMA Zone A floodplain.

PROTESTANTS OFFER EXHIBIT 9-E.

Q: Are there particular areas of concern for you on this map?

A: Yes, most importantly the area along the western side of the Facility boundary. This is where the floodplain encroaches most closely and appears to actually cover portions of the limits of grading. Along this western side, the access road is also located within the floodplain.

Q: Why is this a concern?

A: As I indicated earlier, future changes and expansions in the floodplain are to be expected as the area undergoes additional urbanization and increases in impervious cover occur.

Q: Has the application considered this?

A: No, the application has not considered the likely and impending expansion of the flood plain. The application considers future impacts from the Landfill plan. But these changes are combined with present day estimations of upstream watershed conditions to estimate the post-development conditions.

Q: What are the risk concerns regarding the proximity of the floodplain?

A: Increases in flood flow and the associated rise in flood flow elevation and expansion of extents of floodplain/flood flows would further encroach on the Landfill site and represent additional risks to the stability of the storm water pond embankments. If the base of one or more of these embankments were to be eroded and the embankment fail, further erosion, site stability and downstream flooding could occur. Additionally, during large flood events, the flood elevations will rise above the base of the Landfill and try to infiltrate or erode the soils directly between the bottom liner and adjacent flood waters. Overtime, if erosion, undercutting, or washout of these soils occurs, then the bottom liner itself could become exposed to floodwaters.

Q: Could these increases in flood flow, as a result of the proximity of the floodplain to the Landfill footprint, result in the washout of solid waste?

A: Over the long term, If the subgrade liner or the top cover liner were to fail because of flooding induced erosion, then yes.

Q: I will now present you with Protestants' Exhibit 9-F. Do you recognize this exhibit?

A: Yes. This is a copy of Drawing IA.6 from the application (page 63 of Applicant's Exhibit 130EP-1). This is the General Site Plan for the Facility.

Q: Is this site plan related to your concerns?

A: Yes. On this drawing, you can see that there is only one access road to the Facility from the connecting highway. This road runs across the 100-year floodplain. In the event the one road crossing to the Facility is washed away during a large flood event, then site access could be greatly impaired or not exist at all. This event could provide a real problem if emergency vehicle or fire department access were needed near this time. On this figure, you can also see that the leachate storage tanks are located to the west of the Facility. At that location, the leachate storage tanks are separated from the Landfill footprint by the 100-year floodplain.

PROTESTANTS OFFER EXHIBIT 9-F.

Q: Why is this location of the 100-year floodplain in between the leachate storage tanks and the Landfill footprint a concern?

A: The leachate is collected in the leachate collection system underlying the Landfill cells. The leachate is pumped out and leachate water levels are high and then transported via truck across the access road to the leachate storage tanks. If the access road is unpassable because of flood damage, then leachate cannot be pumped from the collection system and transported to the storage tanks. Oddly, leachate removal and storage is dependent upon the presence of the single access road which also crosses the floodplain.

<u>ADVERSE ALTERATION OF DRAINAGE PATTERNS INTO PLUM CREEK RESERVOIR 21</u>

Q: Is there an existing reservoir at the Landfill site?

A: Yes. If you look at the southern area of the Landfill property boundary shown on Exhibit 9-E, you will see that the Soil Conservation Service Site 21 Reservoir is located downstream of the Landfill site. This reservoir was originally constructed and classified as a NRCS low hazard dam. Recently, NRCS has now classified the reservoir as a high hazard dam due to additional home construction and human presence downstream of the reservoir. With this added hazard classification, the reservoir requires greater safety restrictions to protect human health and welfare.

Q: In your opinion, is there a potential for the Landfill to impact this reservoir?

A: Yes. The Landfill, as designed, will increase rainfall-runoff downstream of the Facility in a manner that contradicts the design standards of that reservoir.

Q: In your opinion, how does the potential impact of the Landfill on this reservoir constitute a hazard to human health and welfare?

A: Due to changes in land cover of the Facility, the total runoff volume increases. The storm water ponds are not designed to retain this volume increase in runoff. The increased runoff from the Landfill will potentially cause the floodwaters stored in the reservoir to more frequently flow over the top of the dam, and also increase the time it takes to drain the floodwater to be ready for a new flood event. Each of these issues is a specific design standard for the reservoir. So, the increased runoff from the Landfill Facility increases the chance of a dam breach and dam failure with subsequent potential loss of human life downstream of the reservoir. In my opinion, the lack of retaining runoff volumes does not comply with TAC §330.63(c)(1)(D)(iii) which requires an analysis to demonstrate that existing drainage patterns will not be adversely altered as a result of the proposed Landfill development.

Q: Does the application address the Landfill effects on the design standards of Reservoir 21?

A: No, the application contains no discussion or analysis that addresses this concern.

POTENTIAL ADVERSE IMPACTS UPON WATER QUALITY

Q: Do you have any water quality concerns regarding the design of the Landfill Facility?

A: Yes. The site layout increases the potential for discharge of leachate or other problematic water quality directly into receiving streams.

Q; Why is this?

A: As I indicated earlier, the Facility boundary is "perched" atop a point of land that is surrounded in close proximity with short, downhill slopes to local drainages. A geology map prepared by the University of Texas, Bureau of Economic Geology indicates alluvium material is present at the surface. Test borings provided by the Applicant indicate the gravel is remnant and contained within the underlying Midway clay. During a site visit, I witnessed considerable amounts of gravel lying and scattered on the land surface. My concern is that the presence of alluvial gravels surrounding the Facility may not be fully quantified. If a channel of alluvium were present and leachate leaked into a localized zone of preferential permeability, then even a small gravel channel could readily transmit the leachate off site. The application also describes the weathering of the underlying clay increases near land surface and possibility a near surface weathering feature could transmit leachate. If such a release were to occur, then the release could occur undetected by the proposed groundwater monitoring system which monitors deeper zones.

VI. CONCLUSIONS

Q: So, what are your overall conclusions with regard to the application?

A: The design of the Landfill Facility appears to be an overly "fit" or overly calculated design relative to the natural surface water system. What I mean by this is the Facility uses as much space as is possible up to and near the boundary of the existing floodplain over a large portion of the perimeter of the Facility. It appears to be an attempt at a calculated solution rather than a careful approach.

When modeling a surface water system, the models employed have degrees of uncertainty in the model inputs that are assumed by the engineer. More conservative assumptions lead to larger storm water ponds, greater flood elevations and greater flood plain delineations, while less conservative assumptions lead to less safety factor in Facility design. As I have discussed, the Applicant has not justified several of its assumptions in its drainage analysis and flooding analysis, including its assumptions regarding the nature of contributing flow channels and the unit hydrograph utilized. Considering that the Applicant has not justified the assumptions underlying its analysis, the Applicant has not demonstrated compliance with the TCEQ regulations related to drainage and flooding.

But, what is far more important in hydrologic design and Facility siting is to consider the potential for unknown events, changed conditions in the future, the hazard potential, and inherent variability in hydrology to arrive at a hydrologic design that provides a suitable level of protection for safeguarding the health, welfare, property, and the environment. Often, it is best to design for "what could go wrong" rather than trying to "exactly calculate" a hydrologic model to fit regulatory requirements.

In this case, there are several natural conditions present that give rise to greater concerns. These include:

(1) just downstream, the presence of Plum Creek Reservoir 21 and the associated and documented safety concerns of this reservoir,

(2) The greater rainfall runoff volumes from the Facility that do not comply with the design standards of the reservoir and increase the chance of dam failure.

(3) The large extent of the Facility boundary adjacent to the existing floodplain,

(4) the inevitability of the floodplain to expand over time with greater degrees of urbanization,

(5) Landfill site access is limited to only one road that would be at risk in a large future flood event and associated safety concerns for emergency personnel accessibility to the site,

(6) the close proximity of drainages located downhill of the Landfill, and

(7) the potential for pollution into these drainages to occur and be unmonitored by the groundwater monitoring system.

In this case, the site selection and engineering design should consider the natural conditions present to the degree necessary to provide adequate levels of protection for the associated hazard conditions. A Landfill that is "perched" above directly adjacent creeks and a floodplain is located on a peninsula during large flood events. In addition, a major reservoir with safety concerns is located immediately downstream.

These facts demand a higher safety standard than a Landfill that is located on flat topography with no direct, or limited, connection to flooding and no downstream concerns of increased runoff. The specific provisions of the TCEQ rules addressing drainage and flooding reflect the important nature of these concerns and the need to address these issues in the permitting process. This is why I, as a registered professional engineer who has practice in design of surface water control facilities and assessing effects on the hydrologic balance, feel the application does not meet several cited rules in the Texas Administrative Code.

Q: Anything else you would like to provide?

A: Not at this time. I do reserve the right to timely supplement or amend my prefiled testimony if warranted based on ongoing discovery.

Mr. Harden has over 27 years of specialized practice in the field of hydrology. His experience spans both surface water and groundwater hydrology including resource management, availability, hydrologic design, regulatory review, supply development, expert witness, and regulatory experience in Texas, throughout the United States, and overseas. His experience includes work for industry, landowners, river authorities, water supply corporations, and local and state governments. Specific work experience involves local and regional surface water and groundwater studies, rainfall-runoff and flooding studies, control structure design, availability analysis, water supply evaluation and development, aquifer studies, water quality contamination evaluations, water rights assessments, and expert witness testimony.

Mr. Harden has presented results of analysis to public stakeholders including local governments, groundwater conservation districts, state agencies, regional water planning groups, the Texas Legislature. Expert witness experience includes involvement in contested cases before local and state regulatory authorities, providing testimony in depositions, as well as testimony in federal court.

Education

- B.S., Civil Engineering, 1988,
  The University of Texas at Austin,
- M.S., Civil Engineering/Water Resources, 1992,
  The University of Texas at Austin

Registration/Certification

- Licensed Professional Engineer, State of Texas
- Registered Professional Engineer, State of Mississippi
- Registered Professional Engineer, State of Indiana

Professional Affiliations

- National Society of Professional Engineers
- Texas Society of Professional Engineers
- National Groundwater Association
- Texas Groundwater Association
- Association of Groundwater Scientists and Engineers

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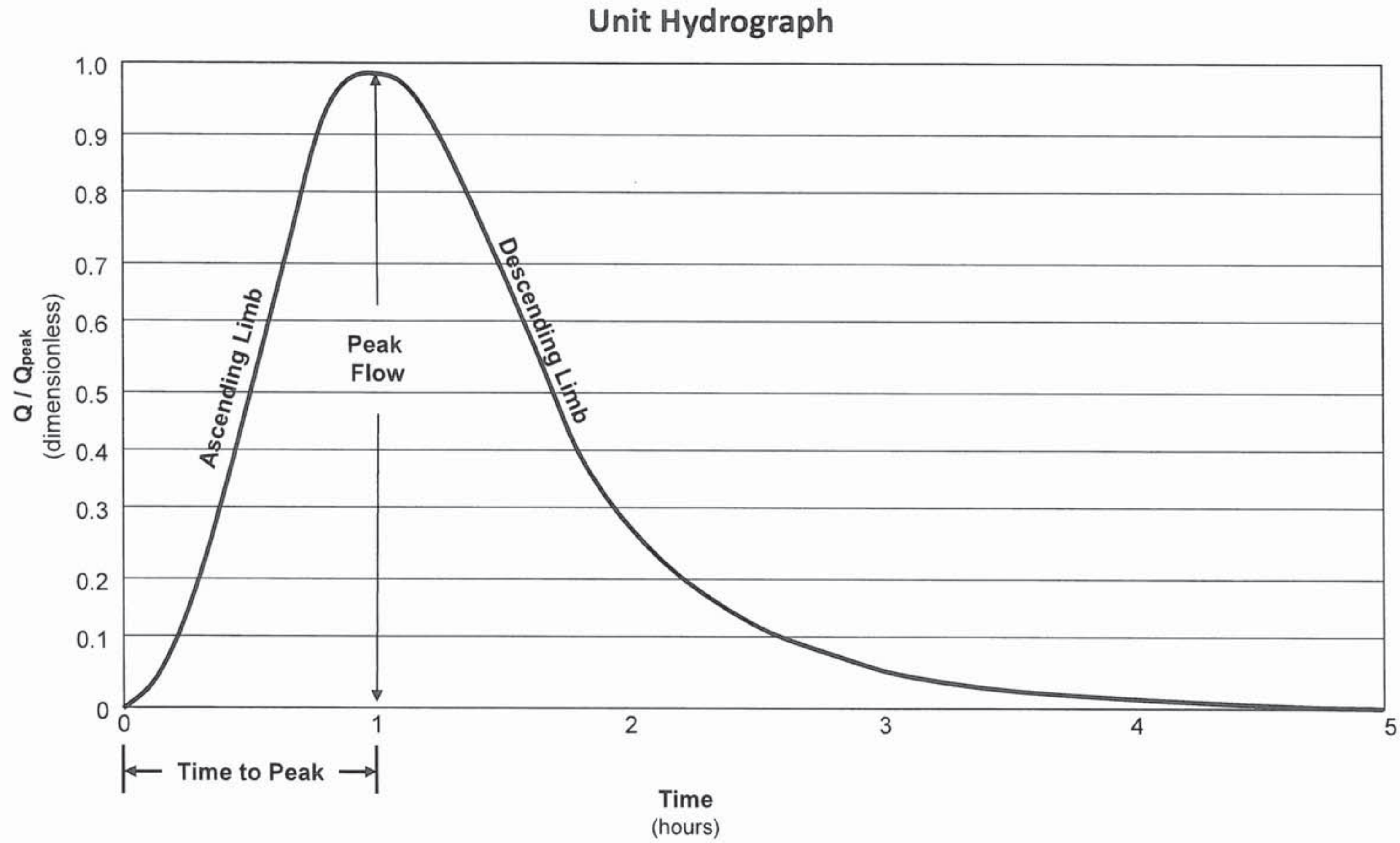
Unit Hydrograph
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Q / Qpeak
(dimensionless)
Ascending Limb
Peak
Flow
Descending Limb
0
1
2
3
4
5
Time to Peak
Time
(hours)

United States
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**Natural
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Engineering
Division**

Technical
Release 55

June 1986

Urban Hydrology for Small Watersheds

TR-55

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Click the show/hide navigation pane button, and then click the bookmarks tab. It will navigate you to the contents, chapters, rainfall maps, and printable forms.

United States
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TR-55

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Preface

Technical Release 55 (TR-55) presents simplified procedures to calculate storm runoff volume, peak rate of discharge, hydrographs, and storage volumes required for floodwater reservoirs. These procedures are applicable in small watersheds, especially urbanizing watersheds, in the United States. First issued by the Soil Conservation Service (SCS) in January 1975, TR-55 incorporates current SCS procedures. This revision includes results of recent research and other changes based on experience with use of the original edition.

The major revisions and additions are:

- A flow chart for selecting the appropriate procedure;
- Three additional rain distributions;
- Expansion of the chapter on runoff curve numbers;
- A procedure for calculating travel times of sheet flow;
- Deletion of a chapter on peak discharges;
- Modifications to the Graphical Peak Discharge method and Tabular Hydrograph method;
- A new storage routing procedure;
- Features of the TR-55 computer program; and
- Worksheets.

This revision was prepared by Roger Cronshey, hydraulic engineer, Hydrology Unit, SCS, Washington, DC; Dr. Richard H. McCuen, professor of Civil Engineering, University of Maryland, College Park, MD; Norman Miller, head, Hydrology Unit, SCS, Washington, DC; Dr.Walter Rawls, hydrologist, Agricultural Research Service, Beltsville, MD; Sam Robbins (deceased), formerly hydraulic engineer, SCS, South National Technical Center (NTC), Fort Worth, TX; and Don Woodward, hydraulic engineer, SCS, Northeast NTC, Chester, PA. Valuable contributions were made by John Chenoweth, Stan Hamilton, William Merkel, Robert Rallison (ret.), Harvey Richardson, Wendell Styner, other SCS hydraulic engineers, and Teresa Seeman.

Revised June 1986
Update of Appendix A January 1999

Contents

Figures

Protestants' Exhibit 9-C, Page. 6

Tables

Exhibits

Worksheets

Metric conversions

The English system of units is used in this TR. To convert to the International System of units (metric), use the following factors:

From English unit	To metric unit	Multiply by
Acre	Hectare	0.405
Square mile	Square kilometer	2.59
Cubic feet per second	Cubic meters per second	0.0283
Inch	Millimeter	25.4
Feet per second	Meters per second	0.3048
Acre-foot	Cubic meter	1233.489
Cubic foot	Cubic meter	0.0283

Perform rounding operations as appropriate to indicate the same level of precision as that of the original measurement. For example:

1. A stream discharge is recorded in cubic feet per second with three significant digits.
2. Convert stream discharge to cubic meters per second by multiplying by 0.0283.
3. Round to enough significant digits so that, when converting back to cubic feet per second, you obtain the original value (step 1) with three significant digits.

Definitions of symbols

Symbol	Unit	Definition
a	ft^2	Cross sectional flow area
Am	mi^2	Drainage area
CN		Runoff curve number
CN_c		Composite runoff curve number
CN_p		Pervious runoff curve number
E_{max}		Maximum stage
F_p		Pond and swamp adjustment factor
H_w	ft	Head over weir crest
I_a	in	Initial abstraction
L	ft	Flow length
L_w	ft	Weir crest length
m		Number of flow segments
n		Manning's roughness coefficient
P	in	Rainfall
P_{imp}		Percent imperviousness
P_2	in	Two-year frequency, 24-hour rainfall
p_w	ft	Wetted perimeter
q	ft^3/s (cfs)	Hydrograph coordinate
q_i	ft^3/s (cfs)	Peak inflow discharge
q_o	ft^3/s (cfs)	Peak outflow discharge
q_p	ft^3/s (cfs)	Peak discharge
q_t	csm/in	Tabular hydrograph unit discharge
q_u	csm/in	Unit peak discharge
Q	in	Runoff
r	ft	Hydraulic radius
R		Ratio of unconnected impervious area to total impervious area
s	ft/ft	Slope of hydraulic grade line
S	in	Potential maximum retention after runoff begins
t	hr	Hydrograph time
T_c	hr	Time of concentration
T_p	hr	Time to peak
T_t	hr	Travel time
V	ft/s	Average velocity
V_r	acre-ft, ft^3 or watershed-inch	Runoff volume
V_s	acre-ft, ft^3 or watershed-inch	Storage volume

Chapter 1 Introduction

The conversion of rural land to urban land usually increases erosion and the discharge and volume of storm runoff in a watershed. It also causes other problems that affect soil and water. As part of programs established to alleviate these problems, engineers increasingly must assess the probable effects of urban development, as well as design and implement measures that will minimize its adverse effects.

Technical Release 55 (TR-55) presents simplified procedures for estimating runoff and peak discharges in small watersheds. In selecting the appropriate procedure, consider the scope and complexity of the problem, the available data, and the acceptable level of error. While this TR gives special emphasis to urban and urbanizing watersheds, the procedures apply to any small watershed in which certain limitations are met.

Effects of urban development

An urban or urbanizing watershed is one in which impervious surfaces cover or will soon cover a considerable area. Impervious surfaces include roads, sidewalks, parking lots, and buildings. Natural flow paths in the watershed may be replaced or supplemented by paved gutters, storm sewers, or other elements of artificial drainage.

Hydrologic studies to determine runoff and peak discharge should ideally be based on long-term stationary streamflow records for the area. Such records are seldom available for small drainage areas. Even where they are available, accurate statistical analysis of them is usually impossible because of the conversion of land to urban uses during the period of record. It therefore is necessary to estimate peak discharges with hydrologic models based on measurable watershed characteristics. Only through an understanding of these characteristics and experience in using these models can we make sound judgments on how to alter model parameters to reflect changing watershed conditions.

Urbanization changes a watershed's response to precipitation. The most common effects are reduced infiltration and decreased travel time, which significantly increase peak discharges and runoff. Runoff is determined primarily by the amount of precipitation and by infiltration characteristics related to soil type, soil moisture, antecedent rainfall, cover type, impervious surfaces, and surface retention. Travel time is determined primarily by slope, length of flow path, depth of flow, and roughness of flow surfaces. Peak discharges are based on the relationship of these parameters and on the total drainage area of the watershed, the location of the development, the effect of any flood control works or other natural or manmade storage, and the time distribution of rainfall during a given storm event.

The model described in TR-55 begins with a rainfall amount uniformly imposed on the watershed over a specified time distribution. Mass rainfall is converted to mass runoff by using a runoff curve number (CN). CN is based on soils, plant cover, amount of impervious areas, interception, and surface storage. Runoff is then transformed into a hydrograph by using unit hydrograph theory and routing procedures that depend on runoff travel time through segments of the watershed.

For a description of the hydrograph development method used by SCS, see chapter 16 of the SCS National Engineering Handbook, Section 4—Hydrology (NEH-4) (SCS 1985). The routing method (Modified Att-Kin) is explained in appendixes G and H of draft Technical Release 20 (TR-20) (SCS 1983).

Rainfall

TR-55 includes four regional rainfall time distributions. See appendix B for a discussion of how these distributions were developed.

All four distributions are for a 24-hour period. This period was chosen because of the general availability of daily rainfall data that were used to estimate 24-hour rainfall amounts. The 24-hour duration spans most of the applications of TR-55.

One critical parameter in the model is time of concentration (T_c), which is the time it takes for runoff to travel to a point of interest from the hydraulically most distant point. Normally a rainfall duration equal to or greater than T_c is used. Therefore, the rainfall distributions were designed to contain the intensity of any duration of rainfall for the frequency of the event chosen. That is, if the 10-year frequency, 24-hour rainfall is used, the most intense hour will approximate the 10-year, 1-hour rainfall volume.

Runoff

To estimate runoff from storm rainfall, SCS uses the runoff curve number (CN) method (see chapters 4 through 10 of NEH-4, SCS 1985). Determination of CN depends on the watershed's soil and cover conditions, which the model represents as hydrologic soil group, cover type, treatment, and hydrologic condition. Chapter 2 of this TR discusses the effect of urban development on CN and explains how to use CN to estimate runoff.

Time parameters

Chapter 3 describes a method for estimating the parameters used to distribute the runoff into a hydrograph. The method is based on velocities of flow through segments of the watershed. Two major parameters are time of concentration (T_c) and travel time of flow through the segments (T_t). These and the other parameters used are the same as those used in accepted hydraulic analyses of open channels.

Many methods are empirically derived from actual runoff hydrographs and watershed characteristics. The method in chapter 3 was chosen because it is basic; however, other methods may be used.

Peak discharge and hydrographs

Chapter 4 describes a method for approximating peak rates of discharge, and chapter 5 describes a method for obtaining or routing hydrographs. Both methods were derived from hydrographs prepared by procedures outlined in chapter 16 of NEH-4 (SCS 1985). The computations were made with a computerized SCS hydrologic model, TR-20 (SCS 1983).

The methods in chapters 4 and 5 should be used in accordance with specific guidelines. If basic data are improperly prepared or adjustments not properly used, errors will result.

Storage effects

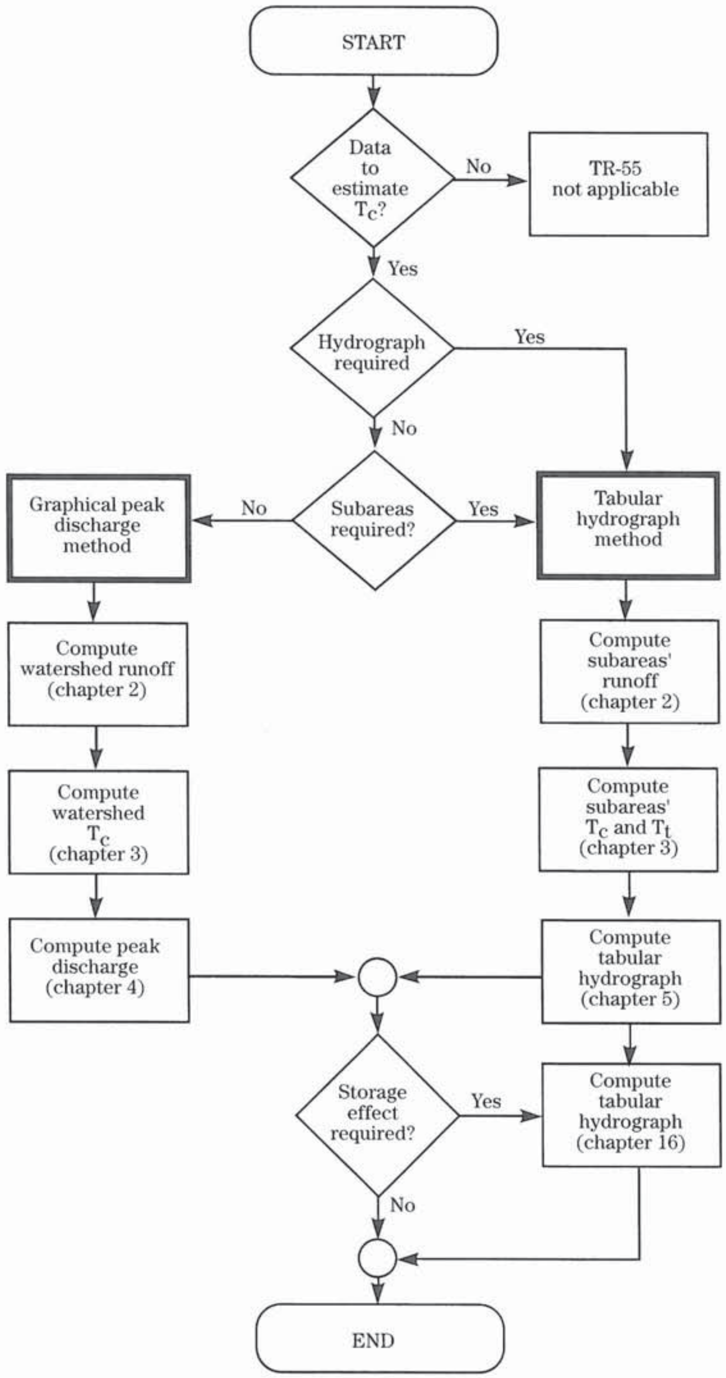
Chapter 6 outlines procedures to account for the effect of detention-type storage. It provides a shortcut method to estimate temporary flood storage based on hydrologic data developed from the Graphical Peak Discharge or Tabular Hydrograph methods.

By increasing runoff and decreasing travel times, urbanization can be expected to increase downstream peak discharges. Chapter 6 discusses how flood detention can modify the hydrograph so that, ideally, downstream peak discharge is reduced approximately to the predevelopment condition. The shortcuts in chapter 6 are useful in sizing a basin even though the final design may require a more detailed analysis.

Selecting the appropriate procedures

Figure 1-1 is a flow chart that shows how to select the appropriate procedures to use in TR-55. In the figure, the diamond-shaped box labeled "Subareas required?" directs the user to the appropriate method based on whether the watershed needs to be divided into subareas. Watershed subdivision is required when significantly different conditions affecting runoff or timing are present in the watershed—for example, if the watershed has widely differing curve numbers or nonhomogeneous slope patterns.

Figure 1-1 Flow chart for selecting the appropriate procedures in TR-55.



Protestants' Exhibit 9-C, Page. 11

Limitations

To save time, the procedures in TR-55 are simplified by assumptions about some parameters. These simplifications, however, limit the use of the procedures and can provide results that are less accurate than more detailed methods. The user should examine the sensitivity of the analysis being conducted to a variation of the peak discharge or hydrograph. To ensure that the degree of error is tolerable, specific limitations are given in chapters 2 through 6. Additional general constraints to the use of TR-55 are as follows:

- The methods in this TR are based on open and unconfined flow over land or in channels. For large events during which flow is divided between sewer and overland flow, more information about hydraulics than is presented here is needed to determine T_c. After flow enters a closed system, the discharge can be assumed constant until another flow is encountered at a junction or another inlet.

- Both the Graphical Peak Discharge and Tabular Hydrograph methods are derived from TR-20 (SCS 1983) output. Their accuracy is comparable; they differ only in their products. The use of T_c permits them to be used for any size watershed within the scope of the curves or tables. The Graphical method (chapter 4) is used only for hydrologically homogeneous watersheds because the procedure is limited to a single watershed subarea. The Tabular method (chapter 5) can be used for a heterogeneous watershed that is divided into a number of homogeneous subwatersheds. Hydrographs for the subwatersheds can be routed and added.

- The approximate storage-routing curves (chapter 6) should not be used if the adjustment for ponding (chapter 4) is used. These storage-routing curves, like the peak discharge and hydrograph procedures, are generalizations derived from TR-20 routings.

Chapter 2 Estimating Runoff

SCS runoff curve number method

The SCS Runoff Curve Number (CN) method is described in detail in NEH-4 (SCS 1985). The SCS runoff equation is

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \text{[eq. 2-1]}$$

where

- Q = runoff (in)
- P = rainfall (in)
- S = potential maximum retention after runoff begins (in) and
- I_a = initial abstraction (in)

Initial abstraction (I_a) is all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but generally is correlated with soil and cover parameters. Through studies of many small agricultural watersheds, I_a was found to be approximated by the following empirical equation:

$$I_a = 0.2S \quad \text{[eq. 2-2]}$$

By removing I_a as an independent parameter, this approximation allows use of a combination of S and P to produce a unique runoff amount. Substituting equation 2-2 into equation 2-1 gives:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{[eq. 2-3]}$$

S is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100, and S is related to CN by:

$$S = \frac{1000}{CN} - 10 \quad \text{[eq. 2-4]}$$

Figure 2-1 and table 2-1 solve equations 2-3 and 2-4 for a range of CN's and rainfall.

Factors considered in determining runoff curve numbers

The major factors that determine CN are the hydrologic soil group (HSG), cover type, treatment, hydrologic condition, and antecedent runoff condition (ARC). Another factor considered is whether impervious areas outlet directly to the drainage system (connected) or whether the flow spreads over pervious areas before entering the drainage system (unconnected). Figure 2-2 is provided to aid in selecting the appropriate figure or table for determining curve numbers.

CN's in table 2-2 (*a* to *d*) represent average antecedent runoff condition for urban, cultivated agricultural, other agricultural, and arid and semiarid rangeland uses. Table 2-2 assumes impervious areas are directly connected. The following sections explain how to determine CN's and how to modify them for urban conditions.

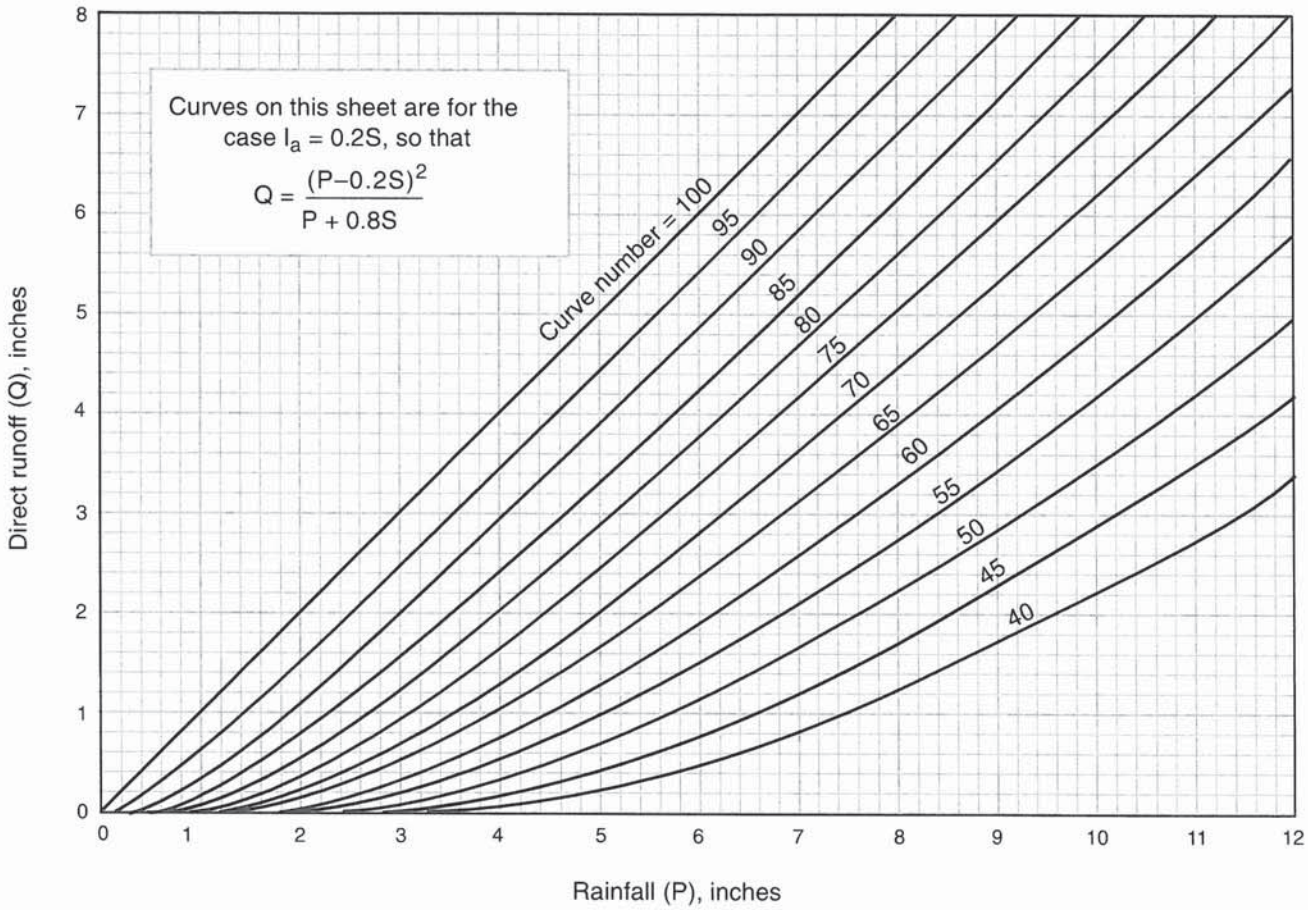
Hydrologic soil groups

Infiltration rates of soils vary widely and are affected by subsurface permeability as well as surface intake rates. Soils are classified into four HSG's (A, B, C, and D) according to their minimum infiltration rate, which is obtained for bare soil after prolonged wetting. Appendix A defines the four groups and provides a list of most of the soils in the United States and their group classification. The soils in the area of interest may be identified from a soil survey report, which can be obtained from local SCS offices or soil and water conservation district offices.

Most urban areas are only partially covered by impervious surfaces: the soil remains an important factor in runoff estimates. Urbanization has a greater effect on runoff in watersheds with soils having high infiltration rates (sands and gravels) than in watersheds predominantly of silts and clays, which generally have low infiltration rates.

Any disturbance of a soil profile can significantly change its infiltration characteristics. With urbanization, native soil profiles may be mixed or removed or fill material from other areas may be introduced. Therefore, a method based on soil texture is given in appendix A for determining the HSG classification for disturbed soils.

Figure 2-1 Solution of runoff equation.



Cover type

Table 2-2 addresses most cover types, such as vegetation, bare soil, and impervious surfaces. There are a number of methods for determining cover type. The most common are field reconnaissance, aerial photographs, and land use maps.

Treatment

Treatment is a cover type modifier (used only in table 2-2b) to describe the management of cultivated agricultural lands. It includes mechanical practices, such as contouring and terracing, and management practices, such as crop rotations and reduced or no tillage.

Hydrologic condition

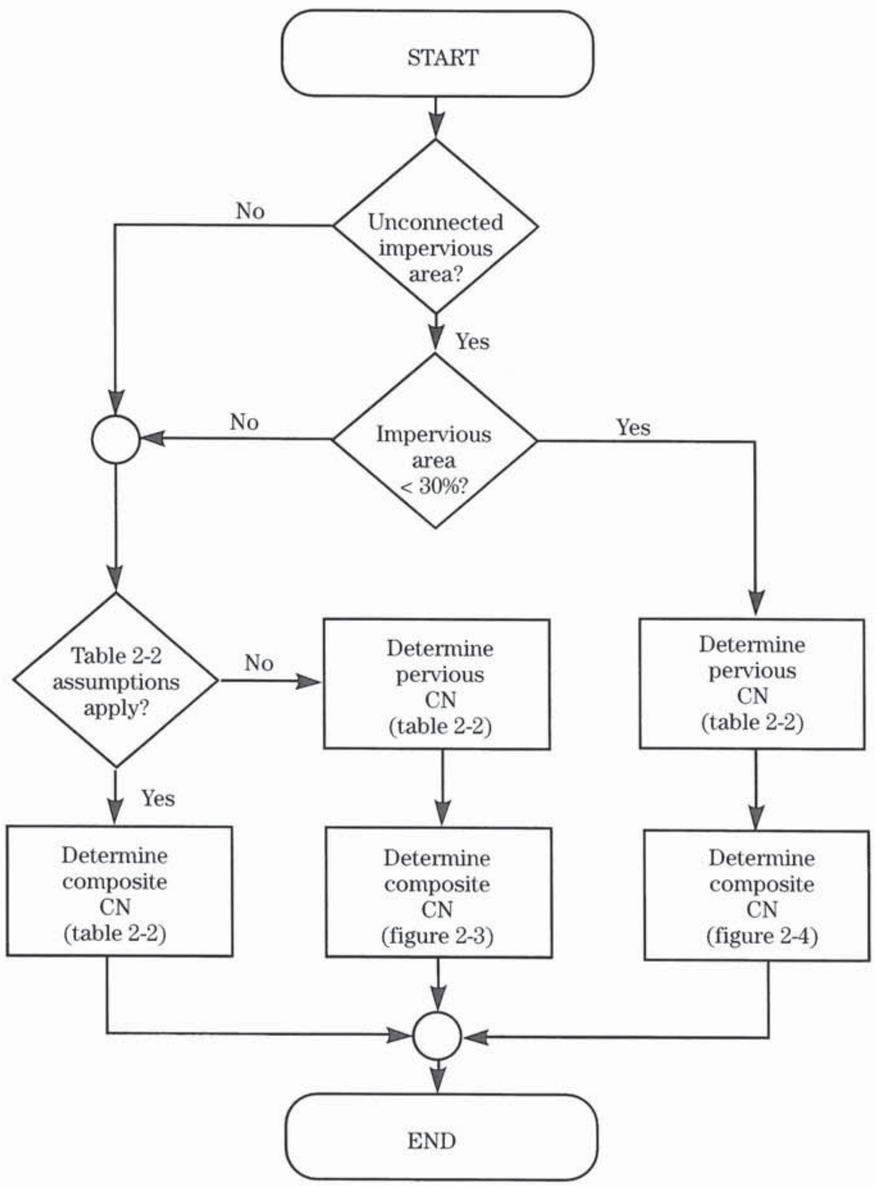
Hydrologic condition indicates the effects of cover type and treatment on infiltration and runoff and is generally estimated from density of plant and residue cover on sample areas. *Good* hydrologic condition indicates that the soil usually has a low runoff potential for that specific hydrologic soil group, cover type, and treatment. Some factors to consider in estimating the effect of cover on infiltration and runoff are (a) canopy or density of lawns, crops, or other vegetative areas; (b) amount of year-round cover; (c) amount of grass or close-seeded legumes in rotations; (d) percent of residue cover; and (e) degree of surface roughness.

Table 2-1 Runoff depth for selected CN's and rainfall amounts 1/

Rainfall	Runoff depth for curve number of—												
	40	45	50	55	60	65	70	75	80	85	90	95	98
	inches												
1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.08	0.17	0.32	0.56	0.79
1.2	.00	.00	.00	.00	.00	.00	.03	.07	.15	.27	.46	.74	.99
1.4	.00	.00	.00	.00	.00	.02	.06	.13	.24	.39	.61	.92	1.18
1.6	.00	.00	.00	.00	.01	.05	.11	.20	.34	.52	.76	1.11	1.38
1.8	.00	.00	.00	.00	.03	.09	.17	.29	.44	.65	.93	1.29	1.58
2.0	.00	.00	.00	.02	.06	.14	.24	.38	.56	.80	1.09	1.48	1.77
2.5	.00	.00	.02	.08	.17	.30	.46	.65	.89	1.18	1.53	1.96	2.27
3.0	.00	.02	.09	.19	.33	.51	.71	.96	1.25	1.59	1.98	2.45	2.77
3.5	.02	.08	.20	.35	.53	.75	1.01	1.30	1.64	2.02	2.45	2.94	3.27
4.0	.06	.18	.33	.53	.76	1.03	1.33	1.67	2.04	2.46	2.92	3.43	3.77
4.5	.14	.30	.50	.74	1.02	1.33	1.67	2.05	2.46	2.91	3.40	3.92	4.26
5.0	.24	.44	.69	.98	1.30	1.65	2.04	2.45	2.89	3.37	3.88	4.42	4.76
6.0	.50	.80	1.14	1.52	1.92	2.35	2.81	3.28	3.78	4.30	4.85	5.41	5.76
7.0	.84	1.24	1.68	2.12	2.60	3.10	3.62	4.15	4.69	5.25	5.82	6.41	6.76
8.0	1.25	1.74	2.25	2.78	3.33	3.89	4.46	5.04	5.63	6.21	6.81	7.40	7.76
9.0	1.71	2.29	2.88	3.49	4.10	4.72	5.33	5.95	6.57	7.18	7.79	8.40	8.76
10.0	2.23	2.89	3.56	4.23	4.90	5.56	6.22	6.88	7.52	8.16	8.78	9.40	9.76
11.0	2.78	3.52	4.26	5.00	5.72	6.43	7.13	7.81	8.48	9.13	9.77	10.39	10.76
12.0	3.38	4.19	5.00	5.79	6.56	7.32	8.05	8.76	9.45	10.11	10.76	11.39	11.76
13.0	4.00	4.89	5.76	6.61	7.42	8.21	8.98	9.71	10.42	11.10	11.76	12.39	12.76
14.0	4.65	5.62	6.55	7.44	8.30	9.12	9.91	10.67	11.39	12.08	12.75	13.39	13.76
15.0	5.33	6.36	7.35	8.29	9.19	10.04	10.85	11.63	12.37	13.07	13.74	14.39	14.76

1/ Interpolate the values shown to obtain runoff depths for CN's or rainfall amounts not shown.

Figure 2-2 Flow chart for selecting the appropriate figure or table for determining runoff curve numbers.



Protestants' Exhibit 9-C, Page. 16

Table 2-2a Runoff curve numbers for urban areas [1]

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) [5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

1 Average runoff condition, and $I_a = 0.2S$.

2 The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.

3 CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.

4 Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.

5 Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

Table 2-2b Runoff curve numbers for cultivated agricultural lands [1]

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment [2]	Hydrologic condition [3]	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

1 Average runoff condition, and I_a=0.2S

2 Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

3 Hydraulic condition is based on combination factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness.

Poor: Factors impair infiltration and tend to increase runoff.

Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Table 2-2c Runoff curve numbers for other agricultural lands [1]

Cover description: Cover type	Hydrologic condition	Curve numbers for hydrologic soil group: A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. [2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. [3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 [4]	48	65	73
Woods—grass combination (orchard or tree farm). [5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. [6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 [4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

1 Average runoff condition, and $I_a = 0.2S$.

2 *Poor:* <50%) ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: > 75% ground cover and lightly or only occasionally grazed.

3 *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.

4 Actual curve number is less than 30; use CN = 30 for runoff computations.

5 CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.

6 *Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

Table 2-2d Runoff curve numbers for arid and semiarid rangelands [1/]

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition [2/]	A [3/]	B	C	D
Herbaceous—mixture of grass, weeds, and low-growing brush, with brush the minor element.	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush.	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon-juniper—pinyon, juniper, or both; grass understory.	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sagebrush with grass understory.	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub—major plants include saltbush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

1 Average runoff condition, and I_a, = 0.2S. For range in humid regions, use table 2-2c.
2 Poor: <30% ground cover (litter, grass, and brush overstory).
Fair: 30 to 70% ground cover.
Good: > 70% ground cover.
3 Curve numbers for group A have been developed only for desert shrub.

Antecedent runoff condition

The index of runoff potential before a storm event is the antecedent runoff condition (ARC). ARC is an attempt to account for the variation in CN at a site from storm to storm. CN for the average ARC at a site is the median value as taken from sample rainfall and runoff data. The CN's in table 2-2 are for the average ARC, which is used primarily for design applications. See NEH-4 (SCS 1985) and Rallison and Miller (1981) for more detailed discussion of storm-to-storm variation and a demonstration of upper and lower enveloping curves.

Urban impervious area modifications

Several factors, such as the percentage of impervious area and the means of conveying runoff from impervious areas to the drainage system, should be considered in computing CN for urban areas (Rawls et al., 1981). For example, do the impervious areas connect directly to the drainage system, or do they outlet onto lawns or other pervious areas where infiltration can occur?

Connected impervious areas — An impervious area is considered connected if runoff from it flows directly into the drainage system. It is also considered connected if runoff from it occurs as concentrated shallow flow that runs over a pervious area and then into the drainage system.

Urban CN's (table 2-2a) were developed for typical land use relationships based on specific assumed percentages of impervious area. These CN vales were developed on the assumptions that (a) pervious urban areas are equivalent to pasture in good hydrologic condition and (b) impervious areas have a CN of 98 and are directly connected to the drainage system. Some assumed percentages of impervious area are shown in table 2-2a

If all of the impervious area is directly connected to the drainage system, but the impervious area percentages or the pervious land use assumptions in table 2-2a are not applicable, use figure 2-3 to compute a composite CN. For example, table 2-2a gives a CN of 70 for a 1/2-acre lot in HSG B, with assumed impervious area of 25 percent. However, if the lot has 20 percent impervious area and a pervious area CN of 61, the composite CN obtained from figure 2-3 is 68. The CN difference between 70 and 68 reflects the difference in percent impervious area.

Unconnected impervious areas — Runoff from these areas is spread over a pervious area as sheet flow. To determine CN when all or part of the impervious area is not directly connected to the drainage system, (1) use figure 2-4 if total impervious area is less than 30 percent or (2) use figure 2-3 if the total impervious area is equal to or greater than 30 percent, because the absorptive capacity of the remaining pervious areas will not significantly affect runoff.

When impervious area is less than 30 percent, obtain the composite CN by entering the right half of figure 2-4 with the percentage of total impervious area and the ratio of total unconnected impervious area to total impervious area. Then move left to the appropriate pervious CN and read down to find the composite CN. For example, for a 1/2-acre lot with 20 percent total impervious area (75 percent of which is unconnected) and pervious CN of 61, the composite CN from figure 2-4 is 66. If all of the impervious area is connected, the resulting CN (from figure 2-3) would be 68.

Figure 2-3 Composite CN with connected impervious area.

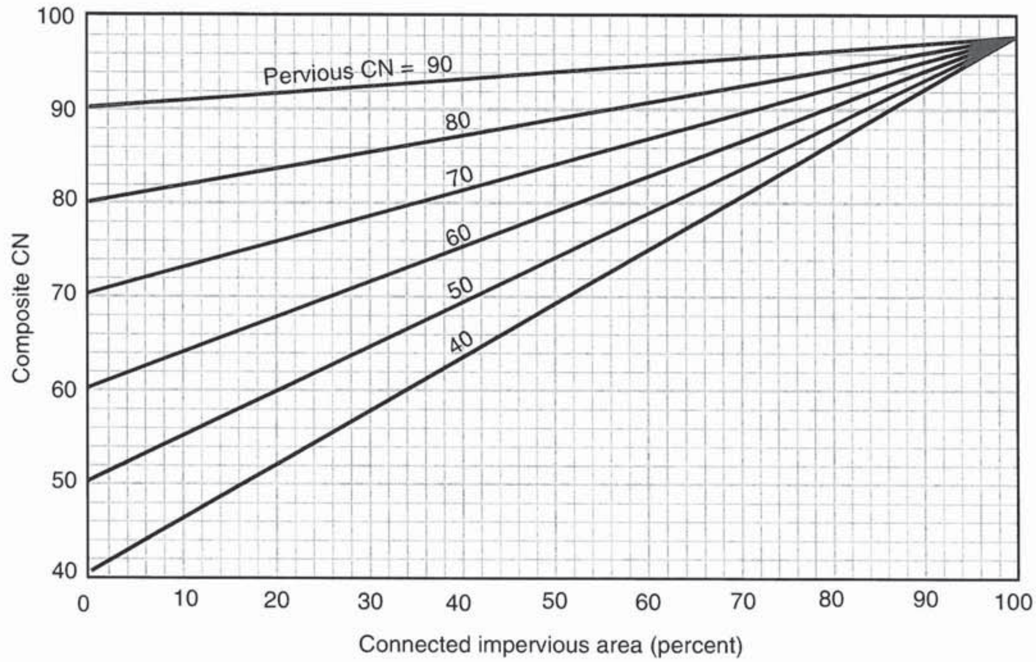
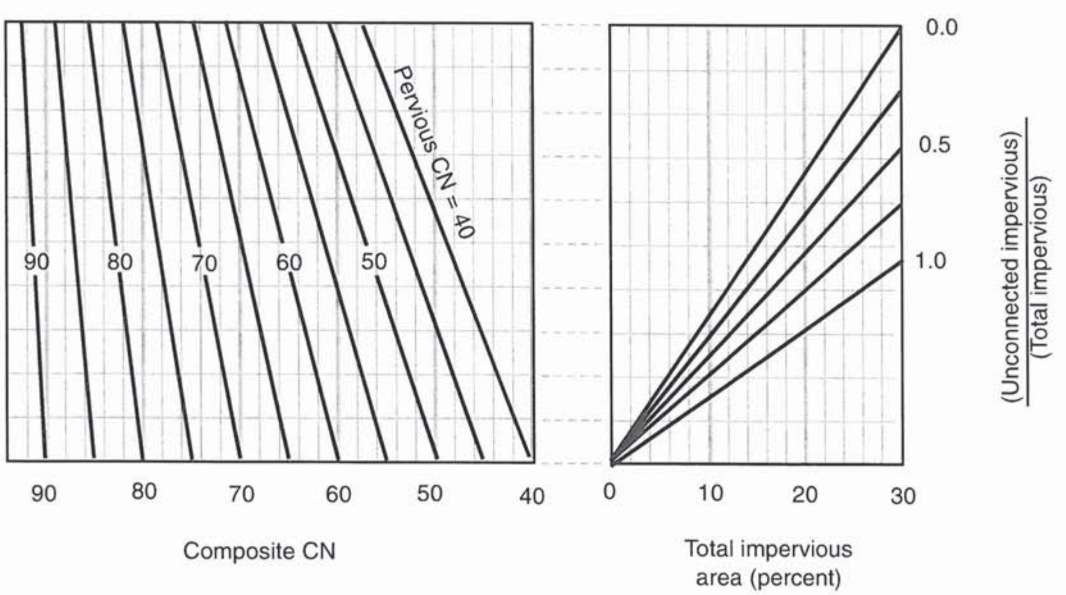


Figure 2-4 Composite CN with unconnected impervious areas and total impervious area less than 30%



Runoff

When CN and the amount of rainfall have been determined for the watershed, determine runoff by using figure 2-1, table 2-1, or equations 2-3 and 2-4. The runoff is usually rounded to the nearest hundredth of an inch.

Limitations

- Curve numbers describe average conditions that are useful for design purposes. If the rainfall event used is a historical storm, the modeling accuracy decreases.
- Use the runoff curve number equation with caution when re-creating specific features of an actual storm. The equation does not contain an expression for time and, therefore, does not account for rainfall duration or intensity.
- The user should understand the assumption reflected in the initial abstraction term (I_a) and should ascertain that the assumption applies to the situation. I_a, which consists of interception, initial infiltration, surface depression storage, evapotranspiration, and other factors, was generalized as 0.2S based on data from agricultural watersheds (S is the potential maximum retention after runoff begins). This approximation can be especially important in an urban application because the combination of impervious areas with pervious areas can imply a significant initial loss that may not take place. The opposite effect, a greater initial loss, can occur if the impervious areas have surface depressions that store some runoff. To use a relationship other than $I_a = 0.2S$, one must redevelop equation 2-3, figure 2-1, table 2-1, and table 2-2 by using the original rainfall-runoff data to establish new S or CN relationships for each cover and hydrologic soil group.
- Runoff from snowmelt or rain on frozen ground cannot be estimated using these procedures.
- The CN procedure is less accurate when runoff is less than 0.5 inch. As a check, use another procedure to determine runoff.
- The SCS runoff procedures apply only to direct surface runoff: do not overlook large sources of subsurface flow or high ground water levels that contribute to runoff. These conditions are often related to HSG A soils and forest areas that have been assigned relatively low CN's in table 2-2. Good judgment and experience based on stream gage records are needed to adjust CN's as conditions warrant.
- When the weighted CN is less than 40, use another procedure to determine runoff.

Examples

Four examples illustrate the procedure for computing runoff curve number (CN) and runoff (Q) in inches. Worksheet 2 in appendix D is provided to assist TR-55 users. Figures 2-5 to 2-8 represent the use of worksheet 2 for each example. All four examples are based on the same watershed and the same storm event.

The watershed covers 250 acres in Dyer County, northwestern Tennessee. Seventy percent (175 acres) is a Loring soil, which is in hydrologic soil group C. Thirty percent (75 acres) is a Memphis soil, which is in group B. The event is a 25-year frequency, 24-hour storm with total rainfall of 6 inches.

Cover type and conditions in the watershed are different for each example. The examples, therefore, illustrate how to compute CN and Q for various situations of proposed, planned, or present development.

Example 2-1

The present cover type is pasture in good hydrologic condition. (See figure 2-5 for worksheet 2 information.)

Example 2-2

Seventy percent (175 acres) of the watershed, consisting of all the Memphis soil and 100 acres of the Loring soil, is 1/2-acre residential lots with lawns in good hydrologic condition. The rest of the watershed is scattered open space in good hydrologic condition. (See figure 2-6.)

Example 2-3

This example is the same as example 2-2, except that the 1/2-acre lots have a total impervious area of 35 percent. For these lots, the pervious area is lawns in good hydrologic condition. Since the impervious area percentage differs from the percentage assumed in table 2-2, use figure 2-3 to compute CN. (See figure 2-7.)

Example 2-4

This example is also based on example 2-2, except that 50 percent of the impervious area associated with the 1/2-acre lots on the Loring soil is "unconnected," that is, it is not directly connected to the drainage system. For these lots, the pervious area CN (lawn, good condition) is 74 and the impervious area is 25 percent. Use figure 2-4 to compute the CN for these lots. CN's for the 1/2-acre lots on Memphis soil and the open space on Loring soil are the same as those in example 2-2. (See figure 2-8.)

Figure 2-5 Worksheet 2 for example 2-1

Worksheet 2: Runoff curve number and runoff

Project: Heavenly Acres	By: WJR	Date: 10/1/85
Location: Dyer County, Tennessee	Checked: NM	Date: 10/3/85

Check one: [X] Present [ ] Developed

1. Runoff curve number

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN 1/ Table 2-2	CN 1/ Figure 2-3	CN 1/ Figure 2-4	Area [ ] acres [ ] mi² [X] %	Product of CN x area
Memphis, B	Pasture, good condition	61			30	1830
Loring, C	Pasture, good condition	74			70	5180
				Totals ➡	100	7010

1/ Use only one CN source per line

CN (weighted) = $\frac{\text{total product}}{\text{total area}} = \frac{7010}{100} = 70.1$; Use CN ➡ 70

2. Runoff

		Storm #1	Storm #2	Storm #3
Frequency	yr	25		
Rainfall, P (24-hour)	in	6.0		
Runoff, Q (Use P and CN with table 2-1, figure 2-1, or equations 2-3 and 2-4)	in	2.81		

Figure 2-6 Worksheet 2 for example 2-2

Worksheet 2: Runoff curve number and runoff

Project: Heavenly Acres	By: WJR	Date: 10/1/85
Location: Dyer County, Tennessee	Checked: NM	Date: 10/3/85

Check one: ☐ Present ☒ Developed   175 Acres residential

1. Runoff curve number

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN [1/] Table 2-2	CN Figure 2-3	CN Figure 2-4	Area ☒ acres ☐ mi² ☐ %	Product of CN x area
Memphis, B	25% impervious 1/2 acre lots, good condition	70			75	5250
Loring, C	25% impervious 1/2 acre lots, good condition	80			100	8000
Loring, C	Open space, good condition	74			75	5550
				Totals ➡	250	18,800

[1/] Use only one CN source per line

CN (weighted) = $\frac{\text{total product}}{\text{total area}} = \frac{18,800}{250} = 75.2$; Use CN ➡ 75

2. Runoff

		Storm #1	Storm #2	Storm #3
Frequency	yr	25		
Rainfall, P (24-hour)	in	6.0		
Runoff, Q (Use P and CN with table 2-1, figure 2-1, or equations 2-3 and 2-4)	in	3.28		

Protestants' Exhibit 9-C, Page. 26

Figure 2-7 Worksheet 2 for example 2-3

Worksheet 2: Runoff curve number and runoff

Project: Heavenly Acres	By: WJR	Date: 10/1/85
Location: Dyer County, Tennessee	Checked: NM	Date: 10/3/85

Check one: ☐ Present ☒ Developed

1. Runoff curve number

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN [1/] Table 2-2	CN [1/] Figure 2-3	CN [1/] Figure 2-4	Area ☒ acres ☐ mi^2 ☐ %	Product of CN x area
Memphis, B	35% impervious 1/2 acre lots, good condition		74		75	5550
Loring, C	35% impervious 1/2 acre lots, good condition		82		100	8200
Loring, C	Open space, good condition	74			75	5550
				Totals ➡	250	19,300

1/ Use only one CN source per line

CN (weighted) = total product / total area = 19,300 / 250 = 77.2 ; Use CN ➡ 77

2. Runoff

		Storm #1	Storm #2	Storm #3
Frequency	yr	25		
Rainfall, P (24-hour)	in	6.0		
Runoff, Q (Use P and CN with table 2-1, figure 2-1, or equations 2-3 and 2-4)	in	3.48		

Figure 2-8 Worksheet 2 for example 2-4

Worksheet 2: Runoff curve number and runoff

Project: Heavenly Acres	By: WJR	Date: 10/1/85
Location: Dyer County, Tennessee	Checked: NM	Date: 10/3/85

Check one: ☐ Present ☒ Developed

1. Runoff curve number

Soil name and hydrologic group (appendix A)	Cover description (cover type, treatment, and hydrologic condition; percent impervious; unconnected/connected impervious area ratio)	CN [1/] Table 2-2	CN [1/] Figure 2-3	CN [1/] Figure 2-4	Area ☒ acres ☐ mi² ☐ %	Product of CN x area
Memphis,B	25% connected impervious 1/2 acre lots, good condition	70			75	5250
Loring, C	25% impervious with 50% unconnected 1/2 acre lots, good condition			78	100	7800
Loring, C	Open space, good condition	74			75	5550
				Totals	250	18,600

[1/] Use only one CN source per line

CN (weighted) = $\frac{\text{total product}}{\text{total area}} = \frac{18,600}{250} = 74.4$; Use CN ➡ 74

2. Runoff

		Storm #1	Storm #2	Storm #3
Frequency	yr	25		
Rainfall, P (24-hour)	in	6.0		
Runoff, Q (Use P and CN with table 2-1, figure 2-1, or equations 2-3 and 2-4)	in	3.19		

Chapter 3 Time of Concentration and Travel Time

Travel time (T_t) is the time it takes water to travel from one location to another in a watershed. T_t is a component of time of concentration (T_c), which is the time for runoff to travel from the hydraulically most distant point of the watershed to a point of interest within the watershed. T_c is computed by summing all the travel times for consecutive components of the drainage conveyance system.

T_c influences the shape and peak of the runoff hydrograph. Urbanization usually decreases T_c, thereby increasing the peak discharge. But T_c can be increased as a result of (a) ponding behind small or inadequate drainage systems, including storm drain inlets and road culverts, or (b) reduction of land slope through grading.

Factors affecting time of concentration and travel time

Surface roughness

One of the most significant effects of urban development on flow velocity is less retardance to flow. That is, undeveloped areas with very slow and shallow overland flow through vegetation become modified by urban development: the flow is then delivered to streets, gutters, and storm sewers that transport runoff downstream more rapidly. Travel time through the watershed is generally decreased.

Channel shape and flow patterns

In small non-urban watersheds, much of the travel time results from overland flow in upstream areas. Typically, urbanization reduces overland flow lengths by conveying storm runoff into a channel as soon as possible. Since channel designs have efficient hydraulic characteristics, runoff flow velocity increases and travel time decreases.

Slope

Slopes may be increased or decreased by urbanization, depending on the extent of site grading or the extent to which storm sewers and street ditches are used in the design of the water management system. Slope will tend to increase when channels are straightened and decrease when overland flow is directed through storm sewers, street gutters, and diversions.

Computation of travel time and time of concentration

Water moves through a watershed as sheet flow, shallow concentrated flow, open channel flow, or some combination of these. The type that occurs is a function of the conveyance system and is best determined by field inspection.

Travel time (T_t) is the ratio of flow length to flow velocity:

$$T_t = \frac{L}{3600V} \qquad \text{[eq. 3-1]}$$

where:

T_t = travel time (hr)
L = flow length (ft)
V = average velocity (ft/s)
3600 = conversion factor from seconds to hours.

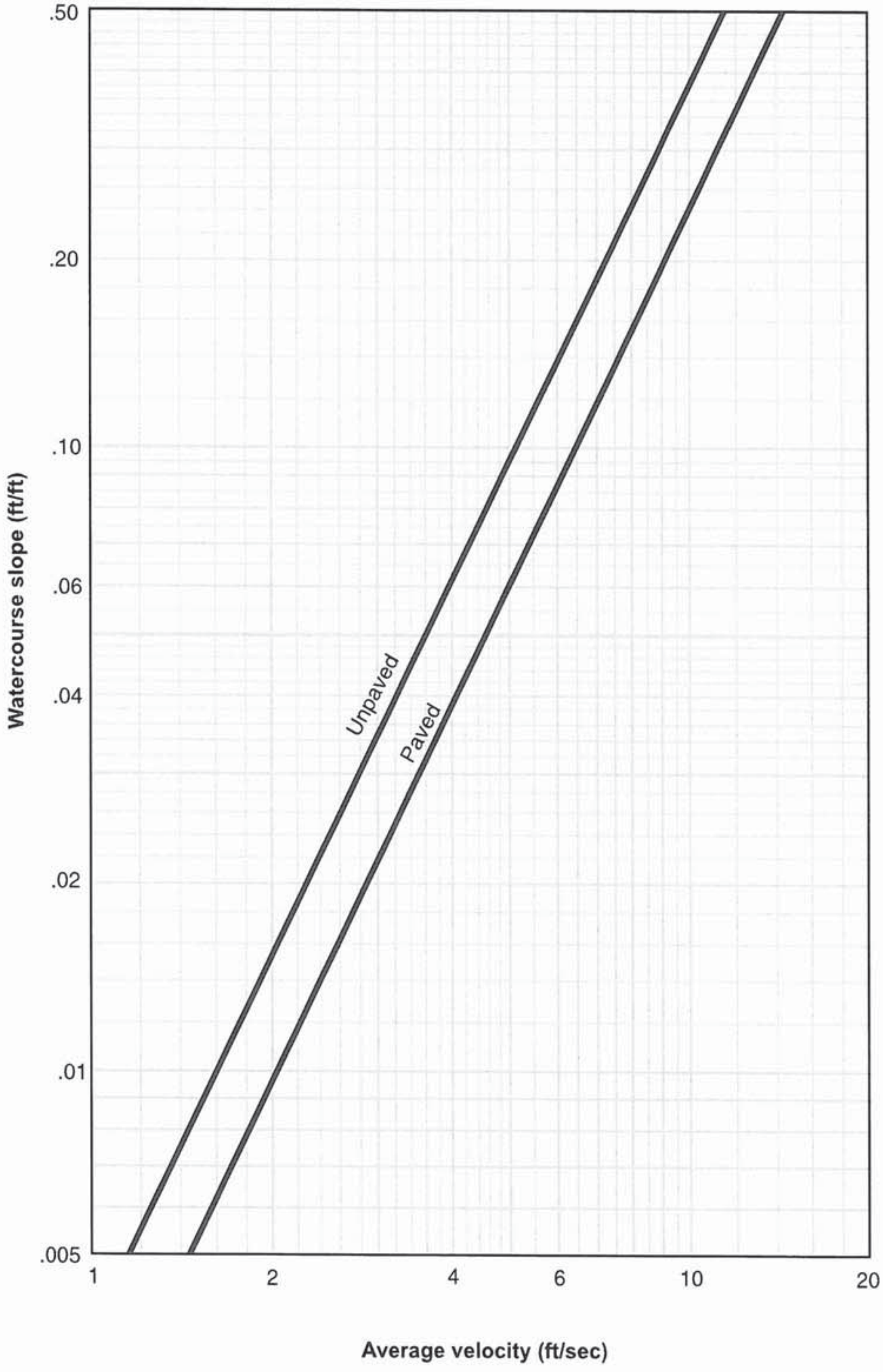
Time of concentration (T_c) is the sum of T_t values for the various consecutive flow segments:

$$T_c = T_{t_1} + T_{t_2} + \dots T_{t_m} \qquad \text{[eq. 3-2]}$$

where:

T_c = time of concentration (hr)
m = number of flow segments

Figure 3-1 Average velocities for estimating travel time for shallow concentrated flow



Protestants' Exhibit 9-C, Page. 30

Sheet flow

Sheet flow is flow over plane surfaces. It usually occurs in the headwater of streams. With sheet flow, the friction value (Manning's n) is an effective roughness coefficient that includes the effect of raindrop impact; drag over the plane surface; obstacles such as litter, crop ridges, and rocks; and erosion and transportation of sediment. These n values are for very shallow flow depths of about 0.1 foot or so. Table 3-1 gives Manning's n values for sheet flow for various surface conditions.

Table 3-1 Roughness coefficients (Manning's n) for sheet flow

Surface description	n [1]
Smooth surfaces (concrete, asphalt, gravel, or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated soils:	
Residue cover ≤20%	0.06
Residue cover >20%	0.17
Grass:	
Short grass prairie	0.15
Dense grasses [2]	0.24
Bermudagrass	0.41
Range (natural)	0.13
Woods:[3]	
Light underbrush	0.40
Dense underbrush	0.80

1 The n values are a composite of information compiled by Engman (1986).

2 Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.

3 When selecting n , consider cover to a height of about 0.1 ft. This is the only part of the plant cover that will obstruct sheet flow.

For sheet flow of less than 300 feet, use Manning's kinematic solution (Overtop and Meadows 1976) to compute T_t:

$$T_t = \frac{0.007(nL)^{0.8}}{(P_2)^{0.5} s^{0.4}} \quad \text{[eq. 3-3]}$$

where:

T_t = travel time (hr),
n = Manning's roughness coefficient (table 3-1)
L = flow length (ft)
P_2 = 2-year, 24-hour rainfall (in)
s = slope of hydraulic grade line (land slope, ft/ft)

This simplified form of the Manning's kinematic solution is based on the following: (1) shallow steady uniform flow, (2) constant intensity of rainfall excess (that part of a rain available for runoff), (3) rainfall duration of 24 hours, and (4) minor effect of infiltration on travel time. Rainfall depth can be obtained from appendix B.

Shallow concentrated flow

After a maximum of 300 feet, sheet flow usually becomes shallow concentrated flow. The average velocity for this flow can be determined from figure 3-1, in which average velocity is a function of watercourse slope and type of channel. For slopes less than 0.005 ft/ft, use equations given in appendix F for figure 3-1. Tillage can affect the direction of shallow concentrated flow. Flow may not always be directly down the watershed slope if tillage runs across the slope.

After determining average velocity in figure 3-1, use equation 3-1 to estimate travel time for the shallow concentrated flow segment.

Open channels

Open channels are assumed to begin where surveyed cross section information has been obtained, where channels are visible on aerial photographs, or where blue lines (indicating streams) appear on United States Geological Survey (USGS) quadrangle sheets. Manning's equation or water surface profile information can be used to estimate average flow velocity. Average flow velocity is usually determined for bankfull elevation.

Manning's equation is:

$$V = \frac{1.49 r^{\frac{2}{3}} s^{\frac{1}{2}}}{n} \quad \text{[eq. 3-4]}$$

where:

- V = average velocity (ft/s)
- r = hydraulic radius (ft) and is equal to a/p_w
  - a = cross sectional flow area (ft^2)
  - p_w = wetted perimeter (ft)
- s = slope of the hydraulic grade line (channel slope, ft/ft)
- n = Manning's roughness coefficient for open channel flow.

Manning's n values for open channel flow can be obtained from standard textbooks such as Chow (1959) or Linsley et al. (1982). After average velocity is computed using equation 3-4, T_t for the channel segment can be estimated using equation 3-1.

Reservoirs or lakes

Sometimes it is necessary to estimate the velocity of flow through a reservoir or lake at the outlet of a watershed. This travel time is normally very small and can be assumed as zero.

Limitations

- Manning's kinematic solution should not be used for sheet flow longer than 300 feet. Equation 3-3 was developed for use with the four standard rainfall intensity-duration relationships.
- In watersheds with storm sewers, carefully identify the appropriate hydraulic flow path to estimate T_c. Storm sewers generally handle only a small portion of a large event. The rest of the peak flow travels by streets, lawns, and so on, to the outlet. Consult a standard hydraulics textbook to determine average velocity in pipes for either pressure or nonpressure flow.
- The minimum T_c used in TR-55 is 0.1 hour.
- A culvert or bridge can act as a reservoir outlet if there is significant storage behind it. The procedures in TR-55 can be used to determine the peak flow upstream of the culvert. Detailed storage routing procedures should be used to determine the outflow through the culvert.

Example 3-1

The sketch below shows a watershed in Dyer County, northwestern Tennessee. The problem is to compute T_c at the outlet of the watershed (point D). The 2-year 24-hour rainfall depth is 3.6 inches. All three types of flow occur from the hydraulically most distant point (A) to the point of interest (D). To compute T_c, first determine T_t for each segment from the following information:

Segment AB: Sheet flow; dense grass; slope (s) = 0.01 ft/ft; and length (L) = 100 ft. Segment BC: Shallow concentrated flow; unpaved; s = 0.01 ft/ft; and L = 1,400 ft. Segment CD: Channel flow; Manning's n = .05; flow area (a) = 27 ft^2; wetted perimeter (p_w) = 28.2 ft; s = 0.005 ft/ft; and L = 7,300 ft.

See figure 3-2 for the computations made on worksheet 3.

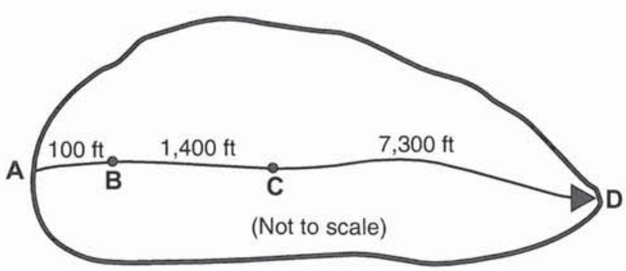


Figure 3-2 Worksheet 3 for example 3-1

Worksheet 3: Time of Concentration (T_c) or travel time (T_t)

Project: Heavenly Acres	By: DW	Date: 10/6/85
Location: Dyer County, Tennessee	Checked: NM	Date: 10/8/85

Check one: ☐ Present ☒ Developed

Check one: ☒ T_c ☐ T_t through subarea

Notes: Space for as many as two segments per flow type can be used for each worksheet.
Include a map, schematic, or description of flow segments.

Sheet flow (Applicable to T_c only)

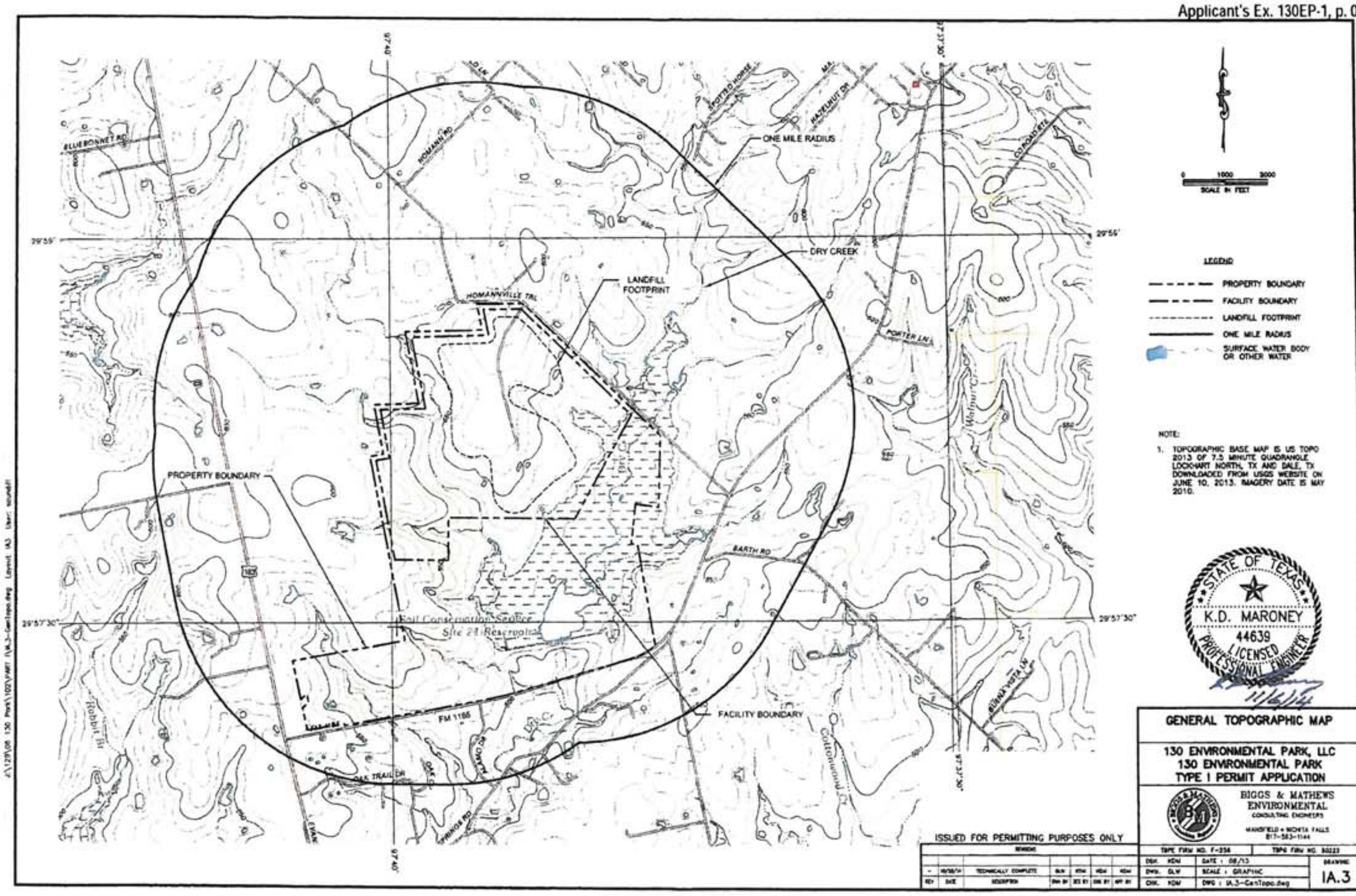
Segment ID	AB		
1. Surface description (table 3-1)	Dense Grass		
2. Manning's roughness coefficient, n (table 3-1)	0.24		
3. Flow length, L (total L ≤ 300 ft) ... ft	100		
4. Two-year 24-hour rainfall, P_2 ... in	3.6		
5. Land slope, s ... ft/ft	0.01		
6. $T_t = \frac{0.007\,(nL)^{0.8}}{P_2^{0.5}\,s^{0.4}}$ Compute T_t ... hr	0.30	+	= 0.30

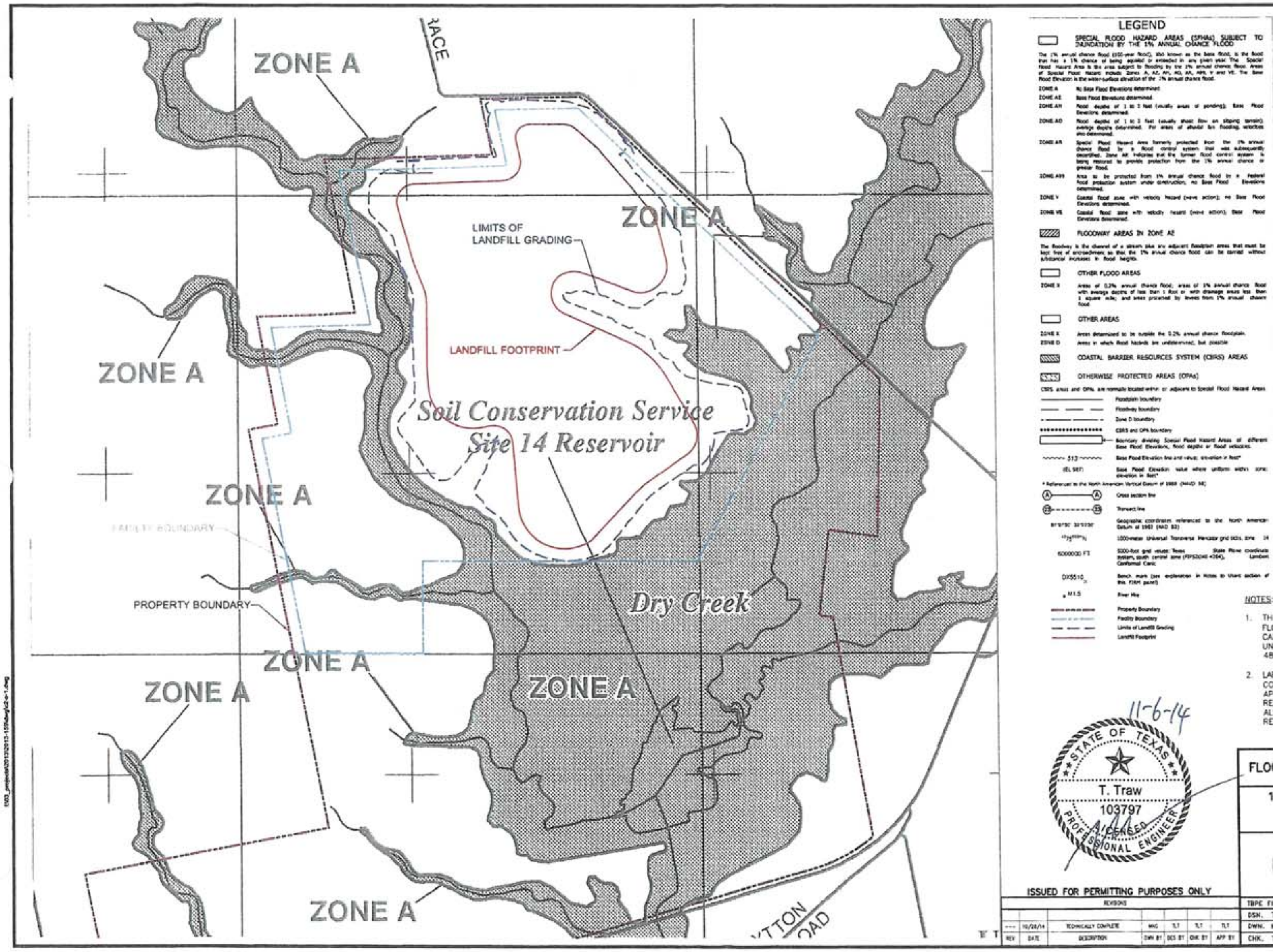
Shallow concentrated flow

Segment ID	BC		
7. Surface description (paved or unpaved)	Unpaved		
8. Flow length, L ... ft	1400		
9. Watercourse slope, s ... ft/ft	0.01		
10. Average velocity, V (figure 3-1) ... ft/s	1.6		
11. $T_t = \frac{L}{3600\,V}$ Compute T_t ... hr	0.24	+	= 0.24

Channel flow

Segement ID	CD		
12. Cross sectional flow area, a ... ft^2	27		
13. Wetted perimeter, p_w ... ft	28.2		
14. Hydraulic radius, $r = \frac{a}{p_w}$ Compute r ... ft	0.957		
15 Channel slope, s ... ft/ft	0.005		
16. Manning's roughness coefficient, n	0.05		
17. $V = \frac{1.49\,r^{2/3}\,s^{1/2}}{n}$ Compute V ... ft/s	2.05		
18. Flow length, L ... ft	7300		
19. $T_t = \frac{L}{3600\,V}$ Compute T_t ... hr	0.99	+	= 0.99
20. Watershed or subarea T_c or T_t (add T_t in steps 6, 11, and 19) ... Hr			1.53


BLUEBONNET RD
HOMANN RD
SPOTTED HORSE
HAZELNUT DR
ONE MILE RADIUS
29°59'
DRY CREEK
LANDFILL FOOTPRINT
HOMANNVILLE TRL
PORTER LN
PROPERTY BOUNDARY
EARTH RD
29°57'30"
Soil Conservation Service Site 21 Reservoir
FACILITY BOUNDARY
FM 1185
OAK TRAIL DR
BUENA VISTA LN
0 1000 2000
SCALE IN FEET
LEGEND
PROPERTY BOUNDARY
FACILITY BOUNDARY
LANDFILL FOOTPRINT
ONE MILE RADIUS
SURFACE WATER BODY OR OTHER WATER
NOTE:
1. TOPOGRAPHIC BASE MAP IS US TOPO 2013 OF 7.5 MINUTE QUADRANGLE LOCKHART NORTH, TX AND DALE, TX DOWNLOADED FROM USGS WEBSITE ON JUNE 10, 2013. IMAGERY DATE IS MAY 2010.
STATE OF TEXAS
K.D. MARONEY
44639
LICENSED PROFESSIONAL ENGINEER
11/6/14
GENERAL TOPOGRAPHIC MAP
130 ENVIRONMENTAL PARK, LLC
130 ENVIRONMENTAL PARK
TYPE I PERMIT APPLICATION
BIGGS & MATHEWS ENVIRONMENTAL
CONSULTING ENGINEERS
MANSFIELD • WICHITA FALLS
817-563-1144
ISSUED FOR PERMITTING PURPOSES ONLY
TECHNICALLY COMPLETE
DATE : 08/13
SCALE : GRAPHIC
DWG : IA.3-GenTopo.dwg
IA.3



NOTES:

1. THIS MAP HAS BEEN COMPILED FROM FEMA FLOOD INSURANCE RATE MAPS (FIRM) OF CALDWELL COUNTY, TEXAS AND UNINCORPORATED AREAS COMMUNITY PANEL: 48055C1025E EFFECTIVE DATE: 6-19-2012
2. LABELING OF THE RESERVOIR SITE AS "SOIL CONSERVATION SITE 14 RESERVOIR" IS AN APPARENT ERROR ON THE FIRM. THE RESERVOIR SITE SHOWN IS ACTUALLY SITE 21, ALSO KNOWN AS PLUM CREEK WATERSHED RETARDING STRUCTURE No. 21.

11-6-14

STATE OF TEXAS
T. Traw
103797
LICENSED PROFESSIONAL ENGINEER

ISSUED FOR PERMITTING PURPOSES ONLY

REV	DATE	DESCRIPTION	DWN BY	DES BY	CHK BY	APP BY
---	10/28/14	TECHNICALLY COMPLETE	MNG	TLT	TLT	TLT

FLOOD INSURANCE RATE MAP (FIRM)

130 ENVIRONMENTAL PARK, LLC
130 ENVIRONMENTAL PARK

BIGGS & MATHEWS ENVIRONMENTAL
CONSULTING ENGINEERS
MANSFIELD • WICHITA FALLS
817-563-1144

TBPE FIRM NO. F-256 & F-834 | TBPG FIRM NO. 50222
DSN. TLT | DATE : 2/14
DWN. MNG | SCALE : GRAPHIC
CHK. TLT | DWG : C2-A-1.DWG
DRAWING C2-A-1

NOTES:

1. CONTOURS AND ELEVATIONS PROVIDED BY DALLAS AERIAL SERVICE FROM AERIAL PHOTOGRAPHY FLOWN MAY 13, 2013. HORIZONTAL DATUM IS TEXAS STATE PLANE COORDINATE SYSTEM, SOUTH CENTRAL ZONE (NAD 83). ELEVATIONS ARE RELATIVE TO NAVD88 - GEOID 12A.
2. REFER TO PART I, APPENDIX 1C FOR FACILITY BOUNDARY LEGAL DESCRIPTION.
3. THERE ARE NO WASTE DISPOSAL ACTIVITIES WITHIN THE FACILITY BOUNDARY THAT ARE NOT INCLUDED IN THIS PERMIT APPLICATION.
4. THERE ARE NO INTAKE/DISCHARGE STRUCTURES LOCATED WITHIN OR ASSOCIATED WITH THE FACILITY.
5. PERMANENT BENCHMARK INFORMATION:
   COORDINATES (NAD 83): N 13905896.44, E 2393722.33
   LATITUDE: N 29°58'43.75"
   LONGITUDE: W 97°39'24.76"
   ELEVATION: 592.37 FT-MSL

STATE OF TEXAS — K.D. MARONEY — 44639 — LICENSED PROFESSIONAL ENGINEER — 3/4/15

ISSUED FOR PERMITTING PURPOSES ONLY

REV	DATE	DESCRIPTION	DRN BY	DES BY	CHK BY	APP BY
-	10/28/14	TECHNICALLY COMPLETE	GLW	KDM	KDM	KDM

GENERAL SITE PLAN

130 ENVIRONMENTAL PARK, LLC
130 ENVIRONMENTAL PARK
TYPE I PERMIT APPLICATION

BIGGS & MATHEWS ENVIRONMENTAL
CONSULTING ENGINEERS
MANSFIELD • WICHITA FALLS
817-563-1144

TBPE FIRM NO. F-256		TBPG FIRM NO. 50222
DSN. KDM	DATE : 8/13	DRAWING
DWN. GLW	SCALE : GRAPHIC	IA.6
CHK. KDM	DWG :	