3. Basic Concepts

3.1 Geographic Information Systems

The goal of this work is to use GIS to reduce the effort required for map manipulation, table referencing, and repetitious computations for the determination of hydrologic parameters. The intent is not to replace the need for hydrologists but to increase the ability of the hydrologist to make responsible decisions based on the most detailed data available. Hydrologic analyses must still rely in part on judgement and experience. Use of GIS can allow a designer to accommodate more detailed appraisal of the spatial variations in hydrologic parameters than would be feasible using manual procedures. However, first, the hydrologist must obtain some knowledge in the field of GIS. This section provides an introduction to the concepts that are applicable to the Hydrologic Data Development System as well as to GIS in general.

Geographic information systems have been described as computer-assisted systems for the capture, storage, retrieval, analysis, and display of spatial data (Clarke, 1986). A definition that is more appropriate to the applications contained herein is a collection of interactive computer hardware and software tools and data that allow translation of spatially referenced (georeferenced) data into quantitative information which can aid in decision making. Originally developed as a cartographic tool, GIS offers capability for spatial data management. A GIS is characterized by the unique ability of a user to overlay data layers and perform spatial queries to create new information, the results of which are automatically mapped and tabulated. Graphical elements describing the location and shape of features are dynamically linked to databases which describe the properties of the features.

The goal of a GIS is to take observations of the real world and simplify and scale the data into graphical elements to which are related descriptive features termed attributes. The attributes are maintained in a database management system (DBMS) while the graphical elements are described in one of two general types of spatial structure: vector and tessellation. Vector structures are those in which discrete elements, points, lines, and polygons, are represented digitally by a series of two-dimensional coordinates (x and y) which imply magnitude and direction. Tessellation refers to the representation of spatial data with a network (or mesh) of elements. Many types of tessellation are possible including rectangles, squares, equilateral triangles, irregular triangles, and hexagons.

Generally, vector methods are suitable for mapping and performing spatial queries, while tessellation is used to represent continuous surfaces such as topography. Rectangular tessellation may be used for modeling involving mathematical functions and logical operators. The following discusses two structures, vector and square tessellation (grid), which are employed by Arc/Info, a widely used commercial package of GIS software.

3.1.1 Arc/Info Vector Modelling

Three basic elements, a point, a line, and a polygon, can be used to describe discrete features: a point is defined by one set of Cartesian coordinates (x and y). A line, termed an arc in Arc/Info, is defined by a string of Cartesian coordinates in which the beginning and end points are defined as nodes, and intermediate points along the line are defined as vertices. A straight line can be defined by two nodes and no vertices. A curve is defined by two nodes and a multitude of vertices. A polygon is defined by an arc or a series of arcs in which the terminal nodes join to create an enclosed area.

Spatial relationships between features (termed topology) are defined using three basic parameters - connectivity, area definition, and contiguity. Connectivity is established using arc-node topology in which each arc has a unique numerical identifier, a beginning identifier (from-node), and an end identifier (to-node). Joining arcs share a common node. Polygon-arc topology defines areas by assigning a unique numerical identifier to the series of arc identifiers that make up a polygon. In doing so, an arc identifier may appear in more than one polygon (where two or more areas abut each other), however, the coordinates defining the arc require definition only once. This minimizes storage requirements and avoids overlapping of polygon boundaries.

Contiguity is established by the combination of arc direction (described by the from and to-nodes) and by identifying the polygon on either side of the arc. This is termed left-right topology. The area outside the defined features but within the map boundary is identified as a universal polygon (ESRI, 1994).

In typical computer-aided design, specific feature types are established as individual graphical layers which are displayed simultaneously. Similarly, in GIS, topologically-defined feature types are organized in layers or themes of information which are often termed coverages. Features are described in database tables which are linked to the topological data using the feature numerical identifier. Three table types are of particular relevance to HDDS: arc attribute tables (AAT's), polygon attribute tables (PAT's), and

INFO tables. Descriptive data that apply to lines (arcs) in a theme are assigned to an arc attribute table and include the following:

- from-node
- to-node
- arc length
- internal arc numerical identifier
- user-defined or default arc numerical identifier, and
- user supplied feature descriptions (attributes).

Area features are described in polygon attribute tables which include:

- area,
- perimeter,
- internal polygon numerical identifier,
- user-defined or default polygon numerical identifier, and
- user supplied feature descriptions (attributes).

A Point feature is described using a PAT in which no area is defined.

In HDDS, and for many other applications, the majority of attribute data can be assigned to PAT's or AAT's. However, for conditions in which one-to-many or many-to-one relationships exist, definition of all attributes in a PAT or AAT can require repetition. Use of INFO database tables can eliminate redundancy by assigning attributes to a table which is index-linked to the PAT or AAT.

Geographic Analysis

The power of vector processing is the ability to perform geographic analyses using overlays of different coverages and applying conditions to establish new information with new topology and attributes. The most common processes include:

- creation of buffer zones,
- intersection of coverage features,
- joining of maps, and
- clipping of one coverage using another coverage.

Figure 3-1 indicates the general nature of these processes. Other variations of these basic processes exist but are not detailed here.

Tabular Analysis

The functionality of most database systems are applicable to attribute tables and other INFO tables. Since attribute tables are linked to graphical features, conditional queries may be applied to the data. The features meeting the specified conditions can then be displayed and used for subsequent geographic analysis. Some of the basic tabular operations employed in HDDS are (1) selection of a subset of active data with user-specified conditions, (2) adding of data to subsets with user-specified conditions, and (3) assignment of new values to a specified item calculated from a user-defined function of existing attributes.

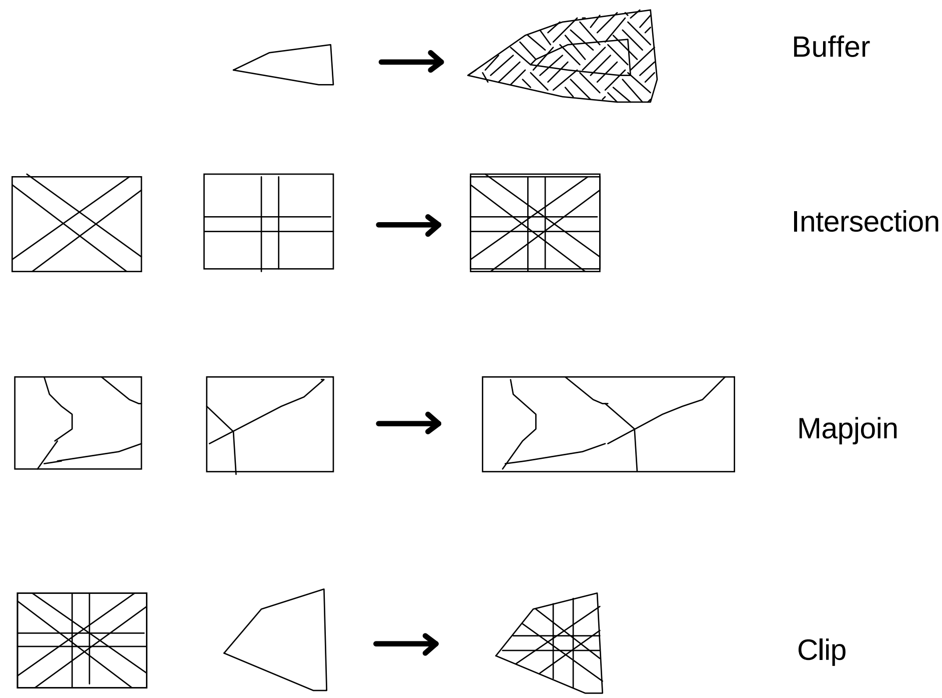

Figure 3-1： Basic vector processes

3.1.2 Cell-Based Processing with GRID

This section provides an introduction to some basic features of GRID, a cell-based geoprocessing facility that operates within Arc/Info versions 6 and 7. Cell-based, or raster, processing is the mainstay of HDDS so specific attention to GRID processes is warranted.

Generally, cell-based geographic information systems employ a grid data structure in which a rectangular domain is divided into an array of uniformly-sized, square cells. Each cell is assigned a value which defines the condition of any desired spatially-varied quantity. This contrasts with vector coverages in which map features are represented using a vector topological model and thematic attributes are represented in tabular data. GRID provides an extensive set of functions and operators, collectively termed Map Algebra Language, which allow manipulation of existing gridded data to produce new data.

GRID Data Model and Structure

A grid database consists of a set of grids each of which represents a spatial variable or theme. Rows and columns are defined in a Cartesian coordinate system which may have an associated map projection. (The map projections available to Arc coverages are also applicable to GRID). Values assigned to each cell may be integer or floating point numbers representing nominal, ordinal, interval, or ratio measurements. Null data, such as would exist outside the domain of valid cell values, are assigned NODATA.

If the grid is defined as an integer grid, a Value Attribute Table (VAT) is assigned. Primarily, this comprises a record number, the cell value, and the number of such values in the grid. Each value in the grid corresponds to one record in the VAT. Additionally, the VAT may contain supplemental attributes the use of which may be compared to an Arc Attribute Table (AAT) or a Polygon Attribute Table (PAT). Supplemental items are not limited to integer values. Grid operations may be performed using a defined item in the VAT but the default item is the cell value. The supplemental attributes must be added to the VAT using standard Arc/Info tabular database procedures: they cannot be added directly from GRID functions. GRID functions assign data to the value and count items of the VAT.

As long as grids are spatially registered, they may be considered as layers between which or on which mathematical or logical operations may be formed. Spatial registration implies that all grids must be in the same map projection. Each grid contains registration information that includes the map projection as well as the location of the grid within the Cartesian coordinate system. Summary statistics are also contained in the registration data.

Representation of Geographic Features in GRID

A grid may represent a continuous surface such as topography or discrete elements such as points lines and polygons and regions. In reality, a grid does not differentiate between continuous or discrete data. A point, for example, is merely represented by a single cell having a unique value. A line is represented as a string of cells containing the same value. A polygon is represented by a contiguous block of cells each with the same value. A zone in GRID is defined as the collection of cells containing identical cell values. As such, a zone is not necessarily contiguous. Since a zone need not be contiguous but all cells within a zone have the same cell value, a GRID zone may represent a region. GRID has specific features that allow conversion of vector coverages into grid coverages and vice versa. These are:

- POINTGRID - converts points to grid cells,
- LINEGRID - converts lines to grid cells,
- POLYGRID - converts polygons to grid cells,
- GRIDPOINT - converts grid cells to points,
- GRIDLINE - converts grid cells to lines, and
- GRIDPOLY - converts grid cells to polygons.

Map Algebra Language

The structural framework within which grid processing operations are organized is termed map algebra. The following four classes of operations are identified and available in GRID:

- local or per-cell,
- focal or per-neighborhood,
- zonal or per-zone, and
- global or per-layer.

Local Operators and Functions

Local operators and functions perform on each cell individually. That is, the function or operation is performed on a cell and the resulting value is assigned to the same cell location in an output grid and the same process is performed on all cells in the grid as indicated in **Figure 3-2**. Input grid cells with NODATA will yield output grid cells with NODATA unless the operation specifically defines how to manipulate NODATA. Local operators include arithmetic, Boolean, relational, bitwise, logical and assignment operators. Local functions include trigonometric, exponential, logarithmic, tabular reclassification, selection, statistical and conditional evaluation functions. Decision making and iteration capabilities are provided using a DOCELL feature in which cell by cell computations may be performed within a loop while or until specific conditions are satisfied.

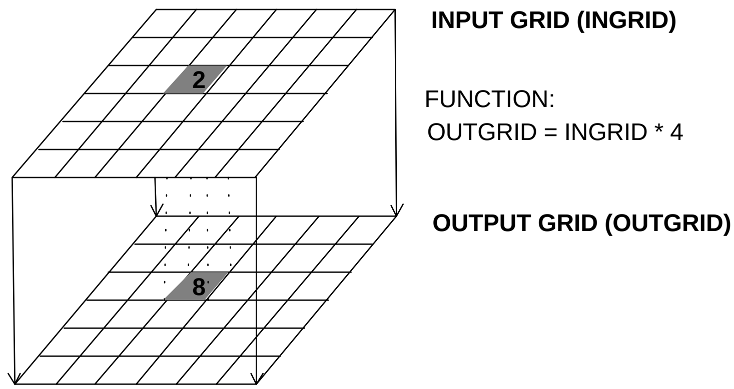

Figure 3-2: Example of a local function

Focal Functions

The value of an output grid cell may be derived as a function of the cells in a defined neighborhood. A neighborhood could consist of the eight cells abutting the cell or defined shapes such as rectangular, circular, annular, wedged shaped or a user-defined shape. **Figure 3-3** shows a focal function in which the output cell is the sum of the cells in a 3-cell by 3-cell neighborhood.

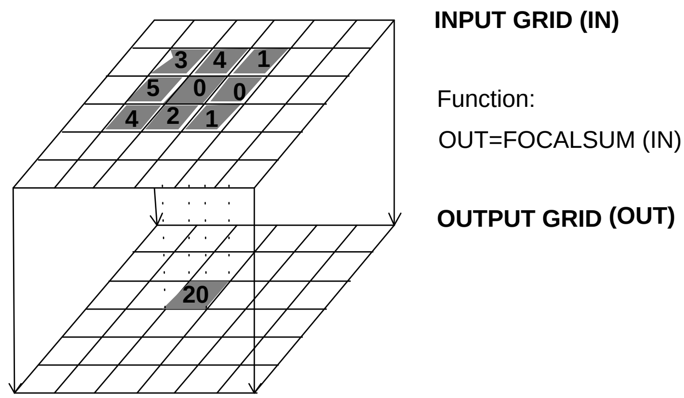

Figure 3-3: Example of a focal function

Zonal Functions

A zonal function returns the value of an output grid cell as a function of the values in a source input grid that are identified as zones by an input zone grid. An example is shown in **Figure 3-4**.

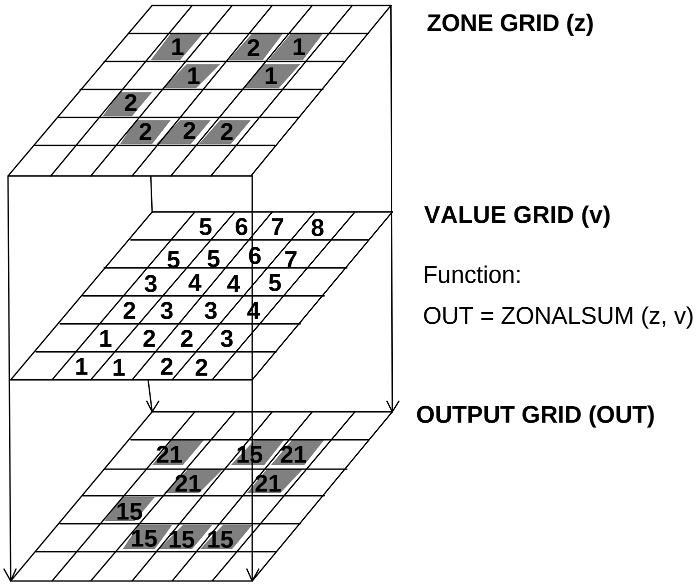

Figure 3-4: Example of a zonal function

Global Functions

Global functions, see **Figure 3-5**, operate on input grids to produce output grids in which the value in each cell may possibly be a function of all the cells in the input grids. Such functions include, but may not be limited to:

- euclidean distance measurement,
- cost distance measurement,
- shortest path,
- nearest neighbor,
- grouping of zones into connected regions,
- geometric transformations,
- raster to vector conversion, and
- interpolation.

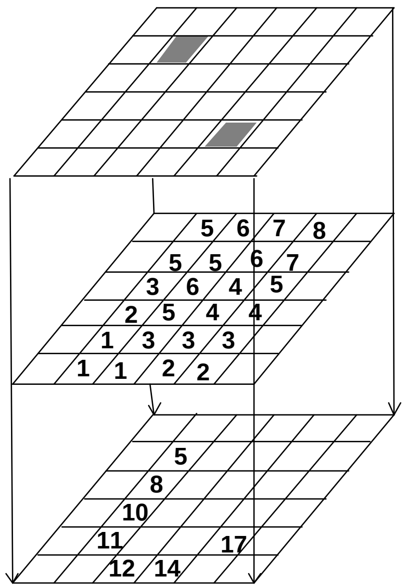

Figure 3-5: Example of a global function

DOCELL Blocks

GRID provides an impressive array of pre-defined functionality, however, this may not suffice. DOCELL blocks allow user-defined functionality similar to "DO" loops in FORTRAN. As the name implies, a DOCELL performs a user-defined operation on a cell-by-cell basis. In this respect, it is similar to a local function. The primary difference is that mathematical, logical, and conditional operators can be incorporated so that operations may differ by cell as opposed to the same operation being performed on every cell in a grid. Such differential treatment of spatial data is not available in vector-based processing. HDDS makes extensive use of such capability.

3.1.3 Vector Analysis versus Cell-based Processing

Figure 3-6 contrasts the ways in which vector and grid schemes represent features. The arc-node topology system and associated attribute database in Arc/Info produce new information (coverages and attributes) by computation on the records resulting from Boolean queries. The same operation is performed on all selected records. It is difficult to perform operations on individual records in such a way as to combine both the location and descriptive attributes of a feature. The GRID map algebra language and cell-based representation of features allow almost limitless manipulation in a relatively efficient manner.

Attribute data representation can be more efficient in a vector system than a raster system. For example, the value code for a contiguous zone of land use must appear in every cell within the zone of a grid. The same zone is represented in a vector system by one polygon and one value code. On the other hand, a grid system is easily represented geographically: in addition to the projection parameters, a grid can be completely defined by a point of origin, the cell dimensions, and array size. A vector element can require extensive strings of coordinates.

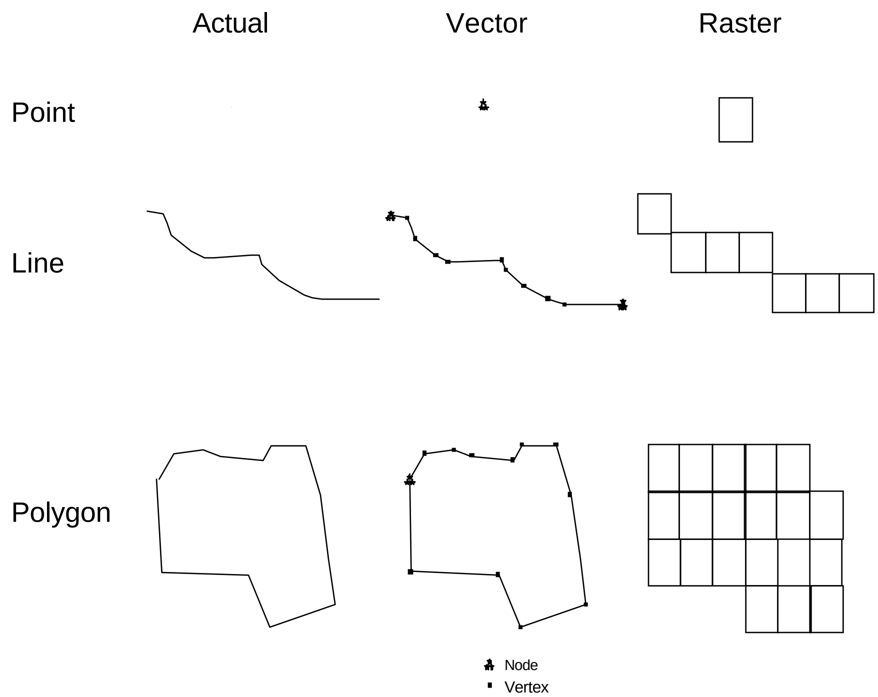

Figure 3-6: Representation of features in ARC and GRID

3.1.4 Triangular Irregular Networks (TIN)

A triangular irregular network is a tessellation scheme in which a continuous surface is represented by a mesh of triangles which need not be regular. This type of system is not employed in HDDS.

3.1.5 Arc Macro Language (AML) and Interface Programming

Arc/Info is command-line driven. That is, commands are typed in by the user to which the software responds. This may seem archaic, however, a high-level programming language, Arc Macro Language (AML), is available with which a user can automate command sequences, establish conditional statements and looping routines, request user input, create menu-driven interfaces, read and write files, and run external programs.

All vector processing, GRID expressions and DOCELL blocks may be embedded in scripts using AML. AML allows:

- variable substitution,
- control of flow,
- iteration,
- development of user interface menus and slider bars, and
- access to external programs.

Use of AML's becomes essential for building complex applications and repetitive processes. HDDS comprises an extensive set of AML routines which incorporate vector analysis and cell-based processing. One initially confusing issue when using AML is that the syntax for mathematical operations in AML differs from the GRID Map Algebra Language, but MAL may be incorporated in AML.

The simplest use of AML is to link a string of commands that would usually be entered individually. Such an AML is a file containing the same commands in the same order that they would have been issued manually. The provision of a wide array of special commands (termed directives) specific functions, and menus allows much more complex programming than basic command sequence repetition. Macro routines can invoke menus and other macro routines, and menus can invoke macro routines and other menus. HDDS is dependent on this capability.

User input via keyboard, mouse, or other devices can be requested to establish variables. Also, data can be read from existing attribute and information tables to be set as variables for subsequent use. Variables can be integer number, real number, character, or Boolean. They may be assigned as global or local: local variables are active only within the routine in which the variables were set, whereas global variables remain active from initiation until the particular Arc session is ended. HDDS employs local variables wherever the variables are not needed in subsequent routines to save random access memory. Global variables are used extensively where needed between routines and to save processing time. (Data could be written to files or tables and subsequently read when needed, but this increases processing time, though memory use would be reduced).

The above provides only a brief discussion of AML. For detail, the user is referred to ESRI (1993).

3.2 Elements of Geodesy

A particular point on the Earth's surface is defined by its geographic coordinates of latitude (ϕ) and longitude (λ), and elevation (z) above mean sea level. Latitude and longitude are angles measured in degrees, minutes, and seconds on a reference geometric model of the curved Earth surface. Elevation is measured in feet or meters above a surface which is defined by a gravitational model of the Earth.

Most engineering computation is done on a simplified Cartesian system with mutually perpendicular axes (x, y, and z). In fluid mechanics, it is customary to identify a "datum" which is drawn as a horizontal line but in fact is a curved line following a constant gravitational potential.

Translation from a geographic coordinate system to a Cartesian system is a complex process involving consideration of the shape of the Earth and its gravitational field.

By definition, a GIS relies on the ability to define position and spatial relationships accurately. Generally, GIS is two-dimensional, representing the horizontal plane referenced to a horizontal datum. A horizontal datum is a mathematical representation of the Earth, usually a sphere or an ellipsoid. Elevations are referenced to a vertical datum and may be represented in GIS as attributes of spatial elements. Geodesy is the subject in which the definition of location and elevation are addressed. This subject is no discussed.

Guralnik (1982) provides the following definition of geodesy.

The branch of applied mathematics concerned with measuring , or determining the shape of, the Earth or a large part of its surface, or with locating exactly points on its surface.

Traditionally, there has been no distinction made between geodesy and surveying but today, many consider surveying to be the practice of positioning while geodesy provides the theoretical foundation for surveying. The National Research Council of Canada (NRC, 1973) employs the following definition.

Geodesy is the discipline that deals with the measurement and representations of the Earth, including its gravity field, in a three-dimensional time varying space.

3.2.1 Geometry of the Earth's Shape

There is a common misconception that the Earth was considered flat until Copernicus angered the church by contradicting its Earth-centered universe tenet with the theory of a spherical Earth in orbit around the sun.

As early as 600 BC, Thales of Miletus hypothesized a spherical Earth and by 550 BC, the School of Pythagoras believed in a spherical Earth. Eratosthenes (270-195 BC) is credited with being the founder of geodesy having made the first recorded estimate of the Earth's radius at approximately 7,350 km versus today's estimates of about 6,370 km (Dragomir et al., 1982).

In 1660, on behalf of the Academy of Sciences in Paris, Jean Picard determined the length of quarter of a meridian to be 10,009 km (which is equivalent to a radius of 6372 km) the methods and accuracy of which are deemed comparable to present results.

Until the 17th century, consideration of the Earth's shape had focused on geometrical attributes. In 1687, Newton set forth his theory of universal attraction from which he deduced that the Earth must be an oblate spheroid flattened at the poles. Measurements made by the Paris Academy of Sciences between 1735 and 1744 supported Newton's concept (Dragomir et al, 1982). Newton deduced that mean gravity increases from the Equator to the poles.

Contemporary knowledge is that the Earth is an irregular shape, the description of which presents severe difficulties when performing mathematical calculations on its surface. Therefore, it is necessary to define a regular solid figure that most nearly fits the topography of the Earth. To date, the most practical shape considered has been the oblate spheroid or ellipsoid. Though there are several estimates in use today, the major axis is in the plane of the Equator with a radius of about 6378 km and the minor axis is in the plane of the polar axis with a radius of about 6357 km.

Ellipsoid vs. Spheroid

The terms ellipsoid and spheroid are often used interchangeably: a spheroid may be generated by rotating an ellipse about either its major axis or its minor axis. A solid in which all plane sections through one axis are ellipses and through the other axis are ellipses or circles is defined as an ellipsoid. If two of the axes of an ellipsoid are equal, the shape can be described as spheroidal but is also described as an ellipsoid of revolution. Of course, if all three axes are equal, the shape is a sphere. If an ellipse is rotated about its minor axis it is described as being oblate. Prolate refers to an ellipse rotated about its major axis.

The term biaxial ellipsoid is also used to refer to a spheroid. A further refinement of the geometrical shape of the Earth would be a triaxial ellipsoid in which none of the axes is equal. i.e. a section through the Earth at the Equator would be an ellipse also. Though the deformation would only be of the order of 20 m. While such a shape would provide a better fit of the Earth's shape, the added mathematical complexity has limited its use.

The geometrical parameters of a reference ellipsoid are as follows and refer to **Figure 3-7**.

a = semi-major axis

b = semi-minor axis

f = (a-b)/a = geometrical flattening (approximately 1/300)

$$e = \sqrt{\frac{a^2 - b^2}{a^2}} \text{ = numerical eccentricity} \qquad \textbf{(3-1)}$$

The eccentricity may be determined as a function of the flattening as:

$$e^2 = 2f - f^2 \qquad \textbf{(3-2)}$$

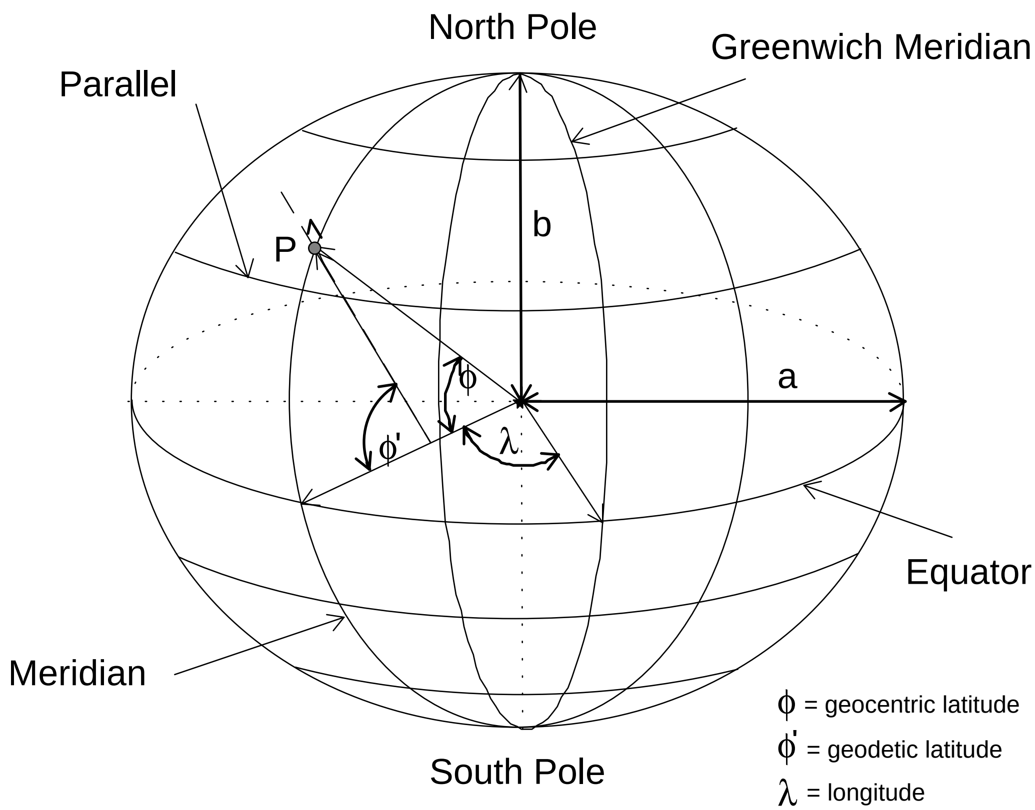

Figure 3-7: The graticule and parameters of the ellipsoid

3.2.2 Gravity and the Geoid

To date, the instruments with which the land has been surveyed are gravity dependent e.g. levels and theodolites, electronic distance measurement devices and total station instruments. Even global positioning system (GPS), which employ radio signals emitted from artificial satellites, rely on gravity since the orbit of each satellite is a function of Earth's gravity.

Initially, it may appear that, by defining a reference ellipsoid that reasonably well represents the shape of the Earth the information should be available to define spatial relationships. Analysts are used to dealing with Cartesian coordinates and linear orthogonal planes in which a level surface is considered to be parallel to the horizontal plane. However, in terrestrial terms, a level surface is neither linear nor is it necessarily parallel to the reference surface (ellipsoid). A level surface is a function of the Earth's gravity potential. That is, a level surface represents the locus of points having the same value of gravity potential and as such is also called an equipotential surface. (Dragomir et al., 1982, pp. 63) The physical surface that most closely approximates any terrestrial equipotential surface is the sea surface: although sea level varies temporally, its mean level provides a suitable reference. In geodesy, the equipotential surface which best approximates mean sea level over the whole Earth is called the geoid (Vanicek et al., 1986, pp. 87).

Gravity Field

Gravity (force) is the sum of gravitational and centrifugal forces. Newton's law of universal gravitation states that a body of mass (M) attracts another body of mass (m) by a force (F) whose magnitude is proportional to the product of the two masses and inversely proportional to the square of their separation distance (r):

$$F = \frac{GmM}{r^2} \tag{3-3}$$

G is described as the gravitational constant and represents the ratio between the behavior of mass as a source of gravitation and behavior of the same mass as a responder to gravitation. Its value is determined to be 6.672 E-11 kg^{-1} m^3 s^{-2} (Vanicek, 1988, p71).

The dimensions of the Earth cannot be considered as negligible. Also, the distribution of mass within the Earth is not uniform. Since gravitational forces are additive, the force exerted by an Earth of nonuniform density can be obtained by considering the Earth as a series of infinitesimally small volumes of a particular density distribution and integrating over the body of the Earth. However, the distribution of density of the Earth is only approximately defined at present such as to negate any benefit of performing an integration.

Considering the mean radius of the Earth to be 6371.009 km and GM to be 3.986005E20 cm^3 s^{-2}, **Eq. (3-3)** yields a mean value of gravitational attraction on the surface of the Earth of F = 9.82022 [ms^{-2}] x m, or g = 9.82022 ms^{-2}.

Since the distribution of density is both radially varied and laterally irregular and the Earth is not spherical, the gravitational field is not perfectly radial. Additionally, the Earth's density distribution varies with time. Conventional treatment of the Earth's gravitational field ignores these variations.

The centrifugal component of Earth's gravity is a result of the rotation of the Earth about the polar axis. The magnitude of the centrifugal force acting on an Earthbound body is quantified by **Eq. (3-4)**:

$$f = pw^2 m \tag{3-4}$$

where:

p is the perpendicular distance of the body to the spin axis,

w is the Earth's angular velocity of spin, and

m is the mass of the particle.

Using a radius at the Equator of 6378.137 km and w = 72.92115 E-6 rad s^{-1} , the centrifugal force is:

$$f = 3.392\ [\text{cm s}^{-2}] \times m$$

This is about 0.35 % of the gravitational force. At the poles, the force will be zero. The angular velocity varies temporally thus inducing variations in the magnitude of centrifugal force. Furthermore, a phenomenon described as the wobble of the Earth affects the direction of centrifugal force.

The gravity force, then, is a vector quantity that is the resultant of the gravitational force and centrifugal force. The resulting force is:

$$F_R = F_{B-A} + f_a = [GM / r^2 + p_A w^2]m \tag{3-5}$$

It is more convenient to work in terms of accelerations rather than forces. From Newton's second law, F_R = ma, the term in brackets can be described as the vector of acceleration denoted as g. Thus, in order to determine the geometrical properties of the gravity force field, it is sufficient to focus on the acceleration (g). The units of the magnitude of g are gal (after Galileo) where 1 gal = 1E-2 m/s^2. The mean value of g is of the order of 980.3 Gal (Vanicek et al., 1986, pp. 75). Since the component forces vary spatially, the magnitude and direction of gravity varies spatially and temporally. Generally, the direction of gravity is neither towards the mass centroid of the Earth nor perpendicular to the reference ellipsoid.

The geoid is an irregular surface that is only approximated by a reference ellipsoid. The distance between the geoid and the reference ellipsoid is termed the geoid undulation (N) and is measured perpendicular to the ellipsoid surface.

Gravity Potential

The gravity force, by definition is a vector property. Therefore, the gravity field is a vector field. It is also an irrotational field and thus can be represented by a scalar field so requiring only one value at each location rather than a triplet of numbers. The gravity field can then be expressed by **(3-6)**.

$$F = mg = \nabla V = m\nabla W \text{ or } g= \nabla W \qquad \textbf{(3-6)}$$

W is called the gravity potential and V is the potential energy. Since the differential operator (∇) is a linear operator, the gravity potential W can be evaluated as the sum of the gravitational potential W_g and the centrifugal potential W_c:

$$g= g_g + g_c = \nabla W_g + \nabla W_c = \nabla(W_g + W_c)= GM/r + 0.5\ pw^2 \qquad \textbf{(3-7)}$$

From **Eq. (3-7)**, it can be seen that W_g decreases above the Earth while W_c increases **(**Vanicek et al., 1986, pp. 83). Though W_c only applies while the mass of interest is Earthbound.

By defining specific values of gravity potential, equipotential surfaces can be defined. Lines of force can be described as being the curves to which the gradient of the potential is tangent at every point. These lines are known as plumb lines. Since the distribution of density and angular velocity vary with location the equipotential surfaces undulate and are not parallel.

Sections through equipotential surfaces closely resemble series of concentric ellipsoids. By definition, the magnitude of gravity is directly related to the spacing of equipotential surfaces. Close spacing represents a stronger gravity field. Since the gravity potential is constant over an equipotential surface, and in the absence of any other external forces, there can be experienced no work on a particle along the surface.

The above discussion on geodesy allows one to realize that the surface of an homogeneous fluid in equilibrium coincides with an equipotential surface. Only minor deviations exist due to nonhomogeneity of the water in addition to external forces such as wind and thermal gradients. Thus when considering a static sea of uniform density, the surface would coincide with an equipotential surface. Mean sea level, then, represents the equipotential surface termed the geoid, at least to an approximation of a few meters. Static waters at levels other than sea level, such as tarn lakes, retention pools etc., approximate the shape of other equipotential surfaces.

In order for water to flow, external energy must be applied to the water. The primary source of such energy is gravity. (Wind and the Coreolis effect are minor). The existence of gravimetric potential difference between two points provides the potential energy. However, in order for the potential energy imparted to water to be converted into kinetic energy, the Earth's topography must provide unobstructed pathways between higher and lower equipotential surfaces.

Although it is feasible to define locations on the Earth as sets of three-dimensional geometric coordinates, any hydrologic study must incorporate both the spatial relations of topographical features and the gravimetric features as indicated by height.

Gravity Anomaly

Equation (3-5) allows computation of the theoretical value of gravity assuming the Earth to be a regular surface without undulations, or without variations in rock densities or crust thickness. Actual measurements of gravity often vary from theoretical values. The differences are termed anomalies.

3.2.3 Horizontal Positioning and Horizontal Datum

The North and South poles approximate the ends of an axis about which the Earth revolves. An imaginary circle, halfway between the poles is called the Equator. A network of imaginary lines of latitude and longitude (graticule) is used to define locations on the Earth's surface. Lines of latitude, or parallels, are formed by equally-spaced circles surrounding the Earth parallel to the Equator. The spacing is one degree such that there are ninety spaces from the Equator to each pole, numbered from 0 at the Equator to 90 at the poles. North is considered positive and the South referenced as negative. For a spherical Earth model, the arc length of one degree of latitude is invariant. The length of one degree of latitude increases toward the poles of an ellipsoidal Earth model.

Lines of longitude, or meridians, are formed as half circles or half ellipses about a polar axis and which are orthogonal to the Equator. The Equator is divided into 360 spaces such that there are 360 meridians at one degree spacing. The meridian passing through Greenwich, England was established internationally as the Prime Meridian (0 degrees) in 1884

(Snyder, 1987, pp. 9). The convention is to measure eastward locations as positive up to 180 degrees from the Greenwich Meridian, and westward locations as negative. The length of a degree of longitude decreases with increasing latitude since the radius of a line of latitude decreases towards the poles.

A typical horizontal datum of the Earth comprises longitude and latitude of an initial point (origin), an azimuth, the semi-major radius, the flattening, and the geoid separation at the origin. Horizontal datums based on artificial satellite data use the center of mass of the Earth as origin. Several horizontal datums are in use in the United States:

- North American Datum of 1927 (NAD 27),
- North American Datum of 1983 (NAD 83),
- World Geodetic System of 1972 (WGS 72), and
- World Geodetic System of 1984 (WGS 84).

The North American Datums are civilian systems while the World Geodetic Systems were developed by the military but are now being used by civilian entities. Consideration of the datum employed is of paramount importance because the location of origin, axes of rotation and other defining parameters differ from one system to the next. As a result, the latitude and longitude of any point on the Earth's surface changes when moving from one datum to another. Most GIS and other mapping software accommodate translation of data from one datum to another.

North American Datum of 1927

Early reference ellipsoids relied on terrestrial measurements and astronomic observations necessitating use of locations on the Earth's surface to define an origin. NAD 27 is defined with an initial point at Meades Ranch, Kansas, (lat 39°13'26.686", long 261°27'29.494") and employs the Clarke 1866 ellipsoid, the parameters of which are shown in **Table 3-1**. The Clarke 1866 ellipsoid is not Earth-centered and its minor axis does not coincide with the polar axis, though it is considered to be parallel to the polar axis. This datum was established to minimize error in representation of locations in North America and so does not represent the best global fit.

North American Datum of 1983

NAD 83 was derived from measurements using modern geodetic, gravimetric, astrodynamic, and astronomic instruments. It is an Earth-centered datum and uses the Geodetic Reference System 1980 (GRS 80) ellipsoid, the parameters of which appear in **Table 3-1**. The minor axis approximates the polar axis and the major axis is parallel to the Equator. As a result, the NAD 83 surface deviates from the NAD 27 surface.

World Geodetic System of 1972

WGS 72 was based on satellite, surface gravity, and astrogeodetic data available through 1972. It was established by the Defense Mapping Agency (DMA) for the Department of Defense's navigation and weapon system guidance requirements. The system provided a reference frame within a geometric figure and gravimetric model of the Earth. The coordinate system is Earth-centered and Earth-fixed and provides a means of relating positions described in various local geodetic systems to be represented in one contiguous system. Reference ellipsoid data appears in **Table 3-1**.

World Geodetic System of 1984

The WGS 84 is a conventional terrestrial coordinate system that was developed by the DMA as a replacement for WGS 72 as a result of newer, more accurate instrumentation and more comprehensive control networks. The WGS Earth Gravitational Model and geoid were replaced with more accurate models based on new and more extensive data sets and improved software. Improvements were made to the accuracy of datum shifts from other geodetic systems errors. The WGS 84 establishes specific ellipsoid parameters, which appear in **Table 3-1**, however, for practical purposes, they can be considered the same as those defined by GRS 80 (DMA, 1988 pp. 3-9). Of note is that GRS 80 does not have an associated Earth gravitation model whereas WGS 84 does.

WGS 84 is the reference system now employed by TxDOT and is especially important for collection of data using Global Positioning Systems.

Table 3-1: Reference Ellipsoid Parameters

Ellipsoid	semi-major axis (m)	flattening ratio	Gravitation Constant (GM) m^3s^{-2}	Angular Velocity (rad s^{-1})
Clarke 1866	6378206.4	1:294.9786982	-	-
GRS 80	6378137	1:298.257222101	-	-
WGS 72	6378135	1:298.26	-	-
WGS 84	6378137	1:298.257223563	3986001.5E8	7292115E-11

Abstracted from DMA (1988, pp. 7-12).

3.2.4 Vertical Positioning and Vertical Datum

The height above mean sea level (h) of a point on the Earth's surface is the difference between the orthometric height (H) and the geoid undulation (N):

$$h = H - N \tag{3-8}$$

The orthometric height is the distance between the geoid surface and the Earth's surface. Positive undulations are those in which the geoid appears above the reference ellipsoid surface.

Elevations are referred the geoid. For the US, the National Geodetic Vertical Datum of 1929 (NGVD 29), was established by the U.S. Coast and Geodetic Survey from about 75,000 km of U.S. level-line data and about 35,000 km of Canadian level-line data. Mean sea level was held fixed at 26 tide gauges that were spaced along the east and west coast of North America and along the Gulf of Mexico. This datum was originally named "Mean Sea Level Datum of 1929" and was changed to NGVD 29 in 1973 to eliminate reference to "sea level" in the title.

Since the 1929 adjustment, new leveling has been established and continued efforts have shown increasing discrepancies with NGVD 29. Some phenomena to which such disagreements are attributed include (1) vertical movement due to Earthquake activity, postglacial rebound, and ground subsidence, (2) disturbed or destroyed benchmarks due to highway maintenance, building, and other construction projects, and (3) more accurate instrumentation, procedures, and computations.

The North American Vertical Datum of 1988 is beginning to replace NGVD 29, however, the preponderance of data are referred to NGVD 29. In any event, it is essential to ensure that vertical datum differences between data sets are accommodated.

Effect of Elevation

The reference sphere or ellipsoid represents a mathematical approximation of the Earth at mean sea level. As one increases in altitude, the distance from the origin increases. For a fixed angular displacement, the distance represented on the surface of the sphere or ellipsoid is less than the actual distance at an altitude that is higher than mean sea level as indicated by **Figure 3-8**. Similarly, areas would appear smaller at mean sea level than altitudes higher than mean sea level. This may appear worrisome: land platting and construction of extensive features such as highways may warrant adjustment for average elevation. For example, at an elevation of 1000 m above mean sea level the error in arc length measurement of a 1° arc would be of the order of 17 m (about 0.02%). HDDS does not provide computational adjustments for elevation differences.

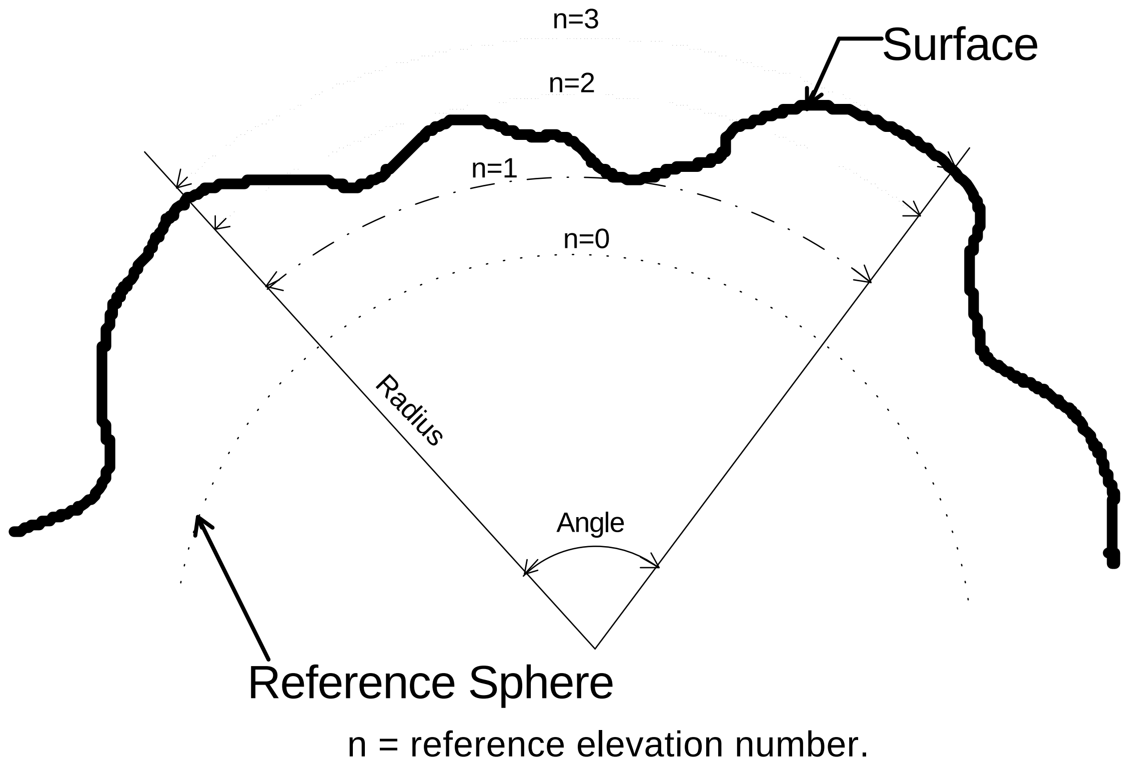

Figure 3-8: Effect of elevation on scale

3.2.5 Coordinate Systems and Map Projections

Traditionally, most visual representations of the Earth and its land masses have been two-dimensional. That is, maps are presented on paper or computer screen both of which are two-dimensional media. The previous sections discussed the three-dimensional features of the Earth, which is described as an oblate spheroid. Three-dimensional scaled representations of the whole Earth are available as globes but large-scale, 3-dimensional representations of specific areas of land are not practical for most uses. In order to represent the Earth or parts of it on a piece of paper, it is necessary to scale and project the desired area of the globe using mathematical or geometric transformations. There are many ways in which the Earth can be represented in two dimensions. It is not expected that the hydraulic engineer will wish to become an expert in map projections; however, a basic understanding of map projection concepts is necessary for any person wishing to make the transition into GIS. Therefore, this section presents some insight into the field of map projections insofar as the need is anticipated for most highway hydrology-related applications of GIS.

The most common system employed to define positions on the globe is the geographic coordinate system. This is not a projection: true positions are represented by longitude (λ) and latitude (ϕ) referenced to either a sphere or an ellipsoid. By definition, positions referenced to a sphere are geocentric, that is, angles are measured from the center of the reference sphere. For an ellipsoidal datum, the coordinates could be either geocentric or geodetic. For geodetic coordinates, angles of longitude are measured from the center of the ellipsoid in the Equatorial plane and angles of latitude (ϕ‘) are measured from a line that extends from the major axis to the point of interest and orthogonal to the surface of the reference ellipsoid as shown in **Figure 3-7**. Since geographic coordinates represent location by angular displacements, dimensions such as distance and area cannot be inferred directly. Spherical or ellipsoidal geometry may be applied to calculate such dimensions but this is not convenient for most mapping uses. Instead, other coordinate systems may be employed which involve projections.

It is impossible to represent the three-dimensional features of the Earth on a two-dimensional medium without either incurring significant discontinuities or some kind of distortion. One feature that is preserved in all standard projections is location. Various projection types have been devised to minimize specific distortions such as shape, area, direction, or distance. Unfortunately, the features of interest to a hydraulic engineer such as area, slope, direction and distance cannot all be preserved simultaneously.

Three basic projection surfaces exist: cylindrical, conic, and plane. **Figure 3-9** shows the simplest general forms of these projection surfaces which can be visualized by considering light rays radiating from either a point or linear source through points on the globe on to a projection surface. Many possibilities exist for each basic type. Projections that preserve direction are termed conformal (or orthomorphic) while those preserving area are termed equal area (or equivalent), and those preserving scale (or distance) a referred to as equidistant. Three of the most common projection methods used in the U.S. are Universal Transverse Mercator, Lambert Conformal Conic, and Albers Equal Area. These are introduced below but a more detailed review of standard projection types is provided by Snyder (1987).

Universal Transverse Mercator

It is difficult to discuss the Universal Transverse Mercator (UTM) projection without first discussing the Mercator and Transverse Mercator projections from which the UTM is derived. The Mercator projection is probably the most familiar name to the layperson. Traditional maps of the world often employ the Mercator projection. It is a cylindrical, conformal projection in which the axis of the cylinder is coincident with the polar axis and the surface is tangential to the Equator. The projection process can be visualized initially as shown in **Figure 3-9** for a typical cylindrical projection. The graticule would be represented by equally spaced vertical lines (meridians) and perpendicular straight lines of equal length (latitude). This results in the poles being out in infinity and the upper latitudes grossly exaggerated. To establish conformality, the spacing of lines of latitude are adjusted by the same ratio as the exaggeration ratio of the length of lines of latitude. Areas and lengths still become exaggerated away from the Equator, but direction and shape are preserved. Dimensions within a 30° band centered around the Equator can be considered true for most practical purposes.

Instead of using the Equator as the line of tangency, the Transverse Mercator uses a meridian such that the axis of the cylinder is perpendicular to the polar axis and in the plane of the Equator. The meridians and parallels are represented by complex curves with the exception of the Equator, the central meridian, and each meridian 90° away from the central meridian. Scale is true only along the central meridian since the reference sphere or ellipsoid is tangential to the cylinder only along the central meridian. Areal enlargement increases away from the line of tangency.

The Universal Transverse Mercator projection (UTM) is a specific application and modification of the Transverse Mercator in which a reference ellipsoid is employed and specific parameters, such as central meridians, have been established. Also, instead of a tangential cylinder, a secant cylinder is used: a cylinder with a radius slightly smaller than the Equatorial radius so as to create a wedding ring-like band (zone) of the Earth outside the cylinder and parallel to the central meridian. Dimension errors are minimized within the band but become excessive elsewhere. Sixty zones cover the Earth between latitudes 84°N and 80° S mostly at a spacing of 6° longitude, a few exceptions exist but not over the USA. The zones are numbered from 1 to 60 beginning at the 180th meridian and proceeding east. A grid is established by dividing each zone with lines of latitude at a spacing of 8° for the USA, though variations exist at the higher (North and South) latitudes. For each zone, the resulting quadrangles are designated by single letters from South to North. All divisions occur at integer values of latitude and longitude. Each quadrangle is subdivided into 100,000 meter squares and are designated with double letters. The boundaries may be represented by partial cells.

Locations are defined in a two-dimensional Cartesian system established for each zone: the central meridian is established half way between the bounding meridians and, for civilian application in the Northern Hemisphere, the intersection of the Equator and the central meridian define the origin with an x coordinate of 500,000 meters and y coordinate of 0 meters.

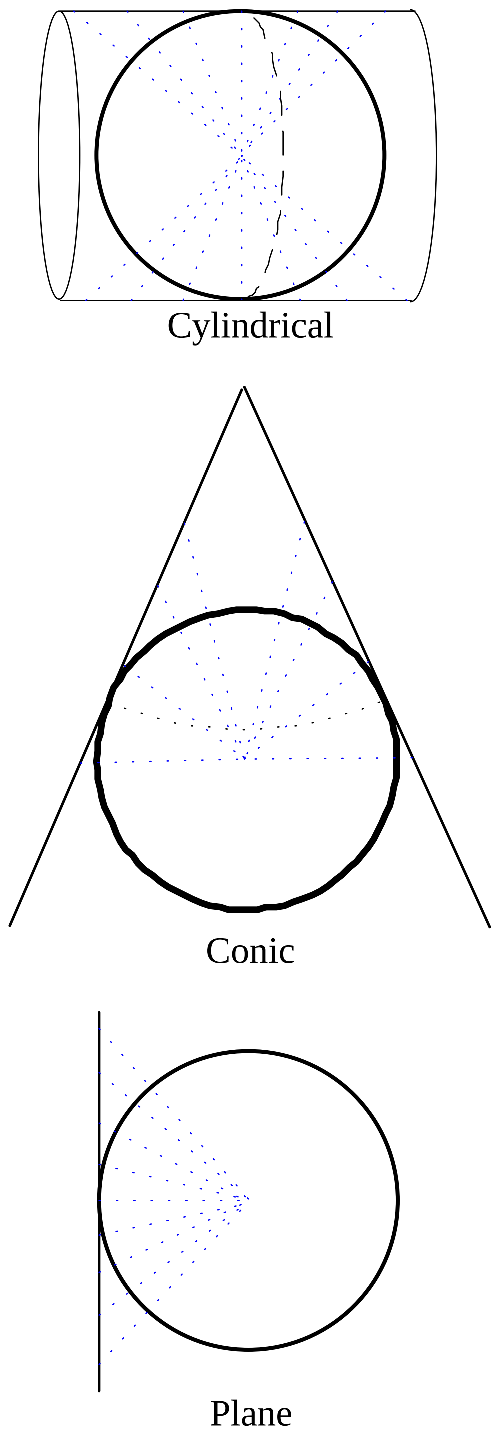

Figure 3-9: Projection surfaces

Lambert Conformal Conic

A tangential cone is represented in **Figure 3-9**. The Lambert Conformal conic projection is based on a secant cone in which a zone between two defined parallels (standard parallels) appears outside the cone. Parallels are represented by unequally spaced, concentric arcs, more closely spaced near the center of the map (between the standard parallels). Meridians are equally spaced radii perpendicular to the parallels. The pole near the apex of the cone is represented by a point.

With reference to **Figure 3-10**, it can be seen that scale in all directions within the standard parallels is compressed. Outside the standard parallels, scale is exaggerated. The scale is constant along any given parallel and true scale is represented only along standard parallels.

Albers Equal Area

Albers Equal Area is a conic projection in which a conceptual secant cone has an apex vertically above the pole, an axis which is coincident with the polar axis, and cuts through the globe at two latitudes (two standard parallels). Like the Lambert Conformal, the projection results in concentric arcs for parallels and equally spaced radii as meridians which are perpendicular to the parallels. Unlike the Lambert Conformal Conic, the parallels decrease in spacing away from the standard parallels. The pole towards the apex of the cone is represented by an arc which is concentric with the parallels. The other pole is not represented (out in infinity).

Scale is preserved only along the standard parallels. As with the Lambert Conformal Conic, scale along the parallels between the standard parallels is compressed. Outside the standard parallels, dimensions along parallels are exaggerated. The converse is true for dimensions along meridians. In fact, for the Albers Equal Area projection, the scale factor along the meridians is the reciprocal of the scale factor along parallels such as to maintain equal area. Only the standard parallels are free from angular distortion.

Since areas are represented true to scale (not necessarily true shape), the Albers Equal Area projection is suitable for drainage area determination. the Albers Equal Area is the projection of choice for HDDS. The HDDS projection parameters appear in **Table 3-2**. False eastings and northings refer to situations in which the coordinates are adjusted usually to avoid negative values of x and y respectively. These adjustments are convenient for hand computations but are not really needed for computer applications.

As long as a projection can be described mathematically, at least two potential options exist for minimizing errors associated with the Earth's curvature: the most common practice is to create a site-specific projection - one in which the projection type, origin, and standard parallels are established to minimize the distortions within the region of interest but which may incur gross errors outside the region. Many GIS packages allow such a capability. The main drawback is that the larger the region, the higher the order of error. Furthermore, if there is the need to merge data from several projects, each with its own projection, each data set would have to be transposed into a common projection prior to merging.

An alternative that previously would not have been practical, is the potential of computing scale factors necessary to adjust dimensions from those measured in a projection to those that would be represented on the surface of the ellipsoid. HDDS establishes one means by which this can be accomplished, the components of which are discussed in this section and in Section 4.2.2.

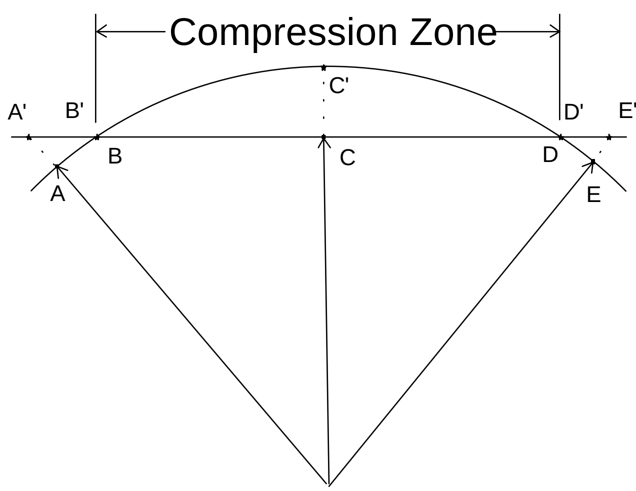

Figure 3-10: Distortion of scale in Lambert Conformal Conic projection

State Plane and Texas Statewide Mapping System

The Texas State Plane coordinate system employs the Lambert Conformal Conic projection. Five zones exist, each of which is a separate projection. While this system incurs smaller scaling errors than would ensue from use of only one statewide projection, there is no match between boundaries of zones.

The Texas State GIS Standards Committee established the Texas Statewide Mapping System to minimize scaling errors while allowing continuous representation of the whole state of Texas. **Table 3-2** includes projection parameters for the Texas State Plane Coordinate System and the Texas Statewide Mapping System. Though HDDS employs neither of these projections, they are important for consistent mapping of data. Any data created in HDDS may be transposed in Arc/Info by using the appropriate projection parameters.

Map Projection Scale Factors

The projections discussed above consist of transformations that can be described mathematically. As such, there exists the potential to measure distances and areas on the map and calculate scale factors by which these measurements can be adjusted to determine the equivalent dimensions on the surface of the sphere or ellipsoid.

HDDS employs the Albers Equal Area projection using GRS 1980 ellipsoid as the basis for all spatial data. The following details equations abstracted from Snyder (1987, pp. 15 - 102) and rearranged to allow calculation of longitudinal and latitudinal distance scale factors for a reference ellipsoid. By definition, no areal scale factors are required for an equal area projection.

First, the following constant parameters are defined with values based on the GRS 1980 reference ellipsoid (**Table 3-1**) and HDDS projection parameters (**Table 3-2**):

a = semi-major axis of ellipsoid = 6378137 m

e = eccentricity of ellipsoid = 0.081819221

ϕ_0 = latitude of origin of projection coordinate system = 23° = 0.4012 radians

ϕ_1 = first standard parallel = 29.5° = 0.5146 radians

ϕ_2 = second standard parallel = 45.5° = 0.7941 radians

λ_0 = longitude of central meridian = -96.0° = 1.6755 radians

n = cone constant as calculated using **Eq. (3-9)**. All angles are in radians.

$$n = \frac{(m_1{}^2 - m_2{}^2)}{(q_2 - q_1)} \quad \textbf{(3-9)}$$

where,

$$m_n = \frac{\cos\phi_n}{(1 - e^2 \sin^2 \phi_n)^{1/2}} \quad \textbf{(3-10)}$$

and,

$$q_n = (1-e^2)\left(\frac{\sin\phi_n}{1-e^2\sin^2\phi_n} - \frac{1}{2e}\ln\left[\frac{1-e\sin\phi_n}{1+e\sin\phi_n}\right]\right) \quad \textbf{(3-11)}$$

Using **Eq. (3-10)**, m_1 = 0.871062964 and m_2 = 0.702105833.

Using **Eq. (3-11)**, q_0 = 0.77670266, q_1 = 0.979314365 and q_2 = 1.4201783

Substituting for m_1, m_2, q_1, and q_2 in **Eq. (3-9)** gives n = 0.602902769.

The radius of latitude of the origin, ρ_0, is calculated from **Eq. (3-12)**:

$$\rho_0 = \frac{a(C-nq_0)^{1/2}}{n} \quad \textbf{(3-12)}$$

where,

$$C = m_1^2 + nq_1 \;=\; 1.34918203 \quad \textbf{(3-13)}$$

so that ρ_0 = 9928937.007

All of the above values are constant for the given reference ellipsoid and projection parameters. For any given location using the projection coordinates (x and y), the polar coordinates (ρ and θ) must be computed. All angles are in radians.

Equation (3-14) determines the radius at the latitude of a given point x, y:

$$\rho = \left[x^2 + (\rho_0 - y)^2\right]^{1/2} \quad \textbf{(3-14)}$$

and the angular displacement is given by **Eq. (3-15)** as

$$\theta = \arctan\left[\frac{x}{(\rho_0 - y)}\right] \quad \textbf{(3-15)}$$

The latitude, ϕ, of the point may be calculated from **Eq. (3-16)**

$$\phi = \beta + \left(\frac{e^2}{3} + \frac{31e^4}{180} + \frac{517e^6}{5040}\right)\sin 2\beta + \left(\frac{23e^4}{360} + \frac{251e^6}{3780}\right)\sin 4\beta + \frac{761e^6}{45360}\sin 6\beta$$

(3-16)

where,

$$\beta = \arcsin\left(\frac{q}{\left\{1-\left[\frac{(1-e^2)}{2e}\right]\ln\left[\frac{(1-e)}{(1+e)}\right]\right\}}\right) \quad \textbf{(3-17)}$$

and,

$$q = \frac{C - \frac{\rho^2 n^2}{a^2}}{n} \qquad \textbf{(3-18)}$$

Then the scale factors along a parallel (k) and a meridian (h) may be determined using **Eq. (3-19)** and **Eq. (3-20)** respectively.

$$h = \frac{\cos\phi}{\left(C - 2n\sin\phi\right)^{1/2}} \qquad \textbf{(3-19)}$$

$$k = 1 / h \qquad \textbf{(3-20)}$$

The scale factors h and k apply to distances measured along the meridian and parallel, respectively, only in the vicinity of the point for which the factors are calculated. The factors vary with location. Section 4.2.2 includes an outline of the development of a cell-based scheme by which the above equations may be used to determine point-to-point distances using **Equations (3-9)** to **(3-20)** inclusive.

Table 3-2: Projection Parameters

Parameter	HDDS	Texas State Plane	Texas Statewide
Horizontal Datum	NAD 83	NAD 27	NAD 83
Reference Ellipsoid	GRS 80	Clarke 1866	GRS 80
Projection Type	Albers Equal Area	Lambert Conformal Conic	Lambert Conformal Conic
Central Meridian	96° 00'W	-	100° W
1st standard parallel	29° 30'N	North - 34° 39'N N. Central - 32° 08'N Central - 30° 07'N S. Central - 28° 23'N South - 26° 10'N	27°25' N
2nd standard parallel	45° 30'N	North - 36° 11'N N. Central - 33° 58'N Central - 31° 53'N S. Central - 30° 17'N South - 27° 50'N	34°55' N
Longitude of Origin	96° 00'W	North - 101° 30'W N. Central - 97° 30'W Central - 100° 20'W S. Central - 99° 00'W South - 98° 30'W	100° W
Latitude of Origin	23° 00'N	North - 34° 00'N N. Central - 31° 40'N Central - 29° 40'N S. Central - 27° 50'N South - 25° 40'N	31° 10'N
False Northing	0	0	1,000,000 m
False Easting	0	0	1,000,000 m

3.3 HYDROLOGIC METHODS

During the design of highway drainage facilities, estimates of peak discharge and sometimes runoff hydrographs are essential. Discharge can be considered as hydraulic load as it directly affects the design size of a drainage structure. Generally, it is not economically feasible to design for the most extreme possible floods. Therefore, either a risk analysis approach is employed or standard practice may establish design frequencies. In either case, it is necessary to establish a relationship between discharge and frequency of occurrence.

This project addresses the data requirements and procedures for three commonly used methods for determining peak flow rates: rural regression equations, statistical analysis of stream gauge records, and the Soil Conservation Service (SCS) runoff curve number method. These are outlined in order to clarify the use of parameters that are determined in HDDS. In each of the methods, discharge versus frequency relationships may be established using six flow frequencies: 2 year, 5 year, 10 year, 25 year, 50 year, and 100 year.

3.3.1 Regional Regression Equations

Regional regression equation methods are widely accepted for establishing peak flow versus frequency relationships at ungauged sites or sites with insufficient data for a statistical flood frequency derivation. A study by the U.S. Geological Survey (Schroeder and Massey, 1977) resulted in regression equations for six hydrologic regions in Texas.

Figure 3-11 presents the designated hydrologic regions for Texas and **Table 3-3** presents the equations developed for each region. Regression equations were not developed for some areas in South Texas, the Trans-Pecos region due to a paucity of data, and the High Plains due to the presence of playa lakes.

Figure 3-11
Hydrologic regions in Texas for regional regression equations
Shaded areas are undefined.
Adapted from TxDOT (1985, pp. 2-12)

Table 3-3: Rural Regression Equations for Texas Hydrologic Regions

Region 1	Region 2	Region 3
$Q_2 = 89.9\ A^{0.629}\ S^{0.130}$	$Q_2 = 216\ A^{0.574}\ S^{0.125}$	$Q_2 = 175\ A^{0.540}$
$Q_5 = 117\ A^{0.685}\ S^{0.254}$	$Q_5 = 322\ A^{0.620}\ S^{0.184}$	$Q_5 = 363\ A^{0.580}$
$Q_{10} = 131\ A^{0.714}\ S^{0.317}$	$Q_{10} = 389\ A^{0.646}\ S^{0.214}$	$Q_{10} = 521\ A^{0.599}$
$Q_{25} = 144\ A^{0.747}\ S^{0.386}$	$Q_{25} = 485\ A^{0.668}\ S^{0.236}$	$Q_{25} = 759\ A^{0.616}$
$Q_{50} = 152\ A^{0.769}\ S^{0.431}$	$Q_{50} = 555\ A^{0.682}\ S^{0.250}$	$Q_{50} = 957\ A^{0.627}$
$Q_{100} = 157\ A^{0.788}\ S^{0.469}$	$Q_{100} = 628\ A^{0.694}\ S^{0.261}$	$Q_{100} = 1175\ A^{0.638}$
Region 4	**Region 5**	**Region 6**
$Q_2 = 13.3\ A^{0.676}\ S^{0.694}$	$Q_2 = 4.82\ A^{0.799}\ S^{0.966}$	$Q_2 = 49.8\ A^{0.602}\ (P\text{-}7)^{0.447}$
$Q_5 = 42.7\ A^{0.630}\ S^{0.641}$	$Q_5 = 36.4\ A^{0.776}\ S^{0.706}$	$Q_5 = 84.5\ A^{0.643}\ (P\text{-}7)^{0.533}$
$Q_{10} = 80.7\ A^{0.604}\ S^{0.596}$	$Q_{10} = 82.6\ A^{0.776}\ S^{0.622}$	$Q_{10} = 111\ A^{0.666}\ (P\text{-}7)^{0.573}$
$Q_{25} = 163\ A^{0.576}\ S^{0.535}$	$Q_{25} = 180\ A^{0.776}\ S^{0.554}$	$Q_{25} = 150\ A^{0.692}\ (P\text{-}7)^{0.608}$
$Q_{50} = 248\ A^{0.562}\ S^{0.497}$	$Q_{50} = 278\ A^{0.778}\ S^{0.522}$	$Q_{50} = 182\ A^{0.709}\ (P\text{-}7)^{0.630}$
$Q_{100} = 397\ A^{0.540}\ S^{0.442}$	$Q_{100} = 399\ A^{0.782}\ S^{0.497}$	$Q_{100} = 216\ A^{0.725}\ (P\text{-}7)^{0.647}$

Adapted from TxDOT (1985, pp. 2-11)

Variable definitions are as follows:

A = Watershed area in square miles.

S = Average watershed slope, in feet per mile, measured as the slope of the stream bed between points 10 per cent and 85 per cent of the distance along the main stream channel from the outfall to the basin divide

P = Mean annual precipitation in inches, if needed.

The equations apply neither to urban watersheds nor to streams that are regulated by physical controls such as water resource and flood control projects, irrigation systems, or major channel improvements. In Region 6, the equations do not apply to areas with an elevation more than 4,000 feet above mean sea level due to insufficient data. **Table 3-4** shows the range of watershed areas and slopes within which the regression equations are considered valid.

Table 3-4: Regression Equation Limitations

Flood frequency region	Drainage area (square miles)	Slope (feet/mile)
1	0.39 - 4,839	0.85 - 206.2
2	0.33 - 4,233	1.16 - 108.1
3	2.38 - 4,097	-
4	1.09 - 3,988	2.33 - 74.8
5	1.08 - 1,947	9.15 - 76.8
6	0.32 - 2,730	-

Texas Hydraulics System

The Texas Hydraulics System computer program (THYSYS, 1977) is a package of hydrologic and hydraulic analysis routines. One subsystem employs the regional regression equations as outlined above. For determination of flood frequency using the regression equations for Texas, an ASCII input data file is required which specifies the following:

- hydrologic method (regression equations),
- hydrologic region number,
- watershed area,
- average watershed slope (if applicable), and
- mean annual precipitation (if applicable).

Additional Regression Parameters

The aforementioned regression equations were published in 1977. Standard errors were estimated to be of the order of 50%. Now, longer records and more stream gauge sites are available for analysis. The Texas Department of Transportation is sponsoring a six-year study to develop new regression analysis procedures for Texas. Preliminary indications are that the following parameters are significant:

- watershed area*,
- average watershed slope*,
- average annual precipitation*,
- Watershed shape factor, defined as area divided by square of length of mainstream)*, and
- Drainage density, defined as area divided by square of total length of streams in the watershed.

These parameters are spatially varying in which case GIS is an appropriate means of deriving them. HDDS currently demonstrates derivation of the parameters indicated above by an asterisk.

3.3.2 Estimation of Peak Discharge from Stream Gauge Data

Stream gauges recording annual peak discharges have been established at 936 stations around Texas (Slade, personal communication, 1995). If the gauging record covers a sufficient period (typically, at least 8 years), it is possible to develop a peak-discharge versus frequency relationship by statistical analysis of the observed data.

For the equations to be valid, the urbanization character of the watershed must not change enough to affect the characteristics of peak flows within the total time of observed annual peaks and no significant flow regulation must exist. The record of observed data must be consistent in that no significant changes in the channel or basin should have taken place during the period of record. If any of these changes occur, the resulting peak-stream flow frequency relation could be flawed.

For peak-stream flow frequency analyses, the Interagency Advisory Committee on Water Data (Bulletin 17 B, 1982), formerly known as the U.S. Water Resources Council, recommends the Log-Pearson Type III statistical distribution procedure which uses a series of annual-peak discharges for the subject gauge station. This method employs the three most important statistical parameters: mean value, standard deviation, and coefficient of skew.

The mean value is calculated using **Eq. (3-21)**.

$$\overline{Q}_L = \frac{\sum x}{N} \qquad \textbf{(3-21)}$$

where,

x is the logarithm of the annual peak discharge, and

N is the number of annual peak measurements.

The standard deviation of the log values is determined using:

$$s_L = \sqrt{\frac{\sum x^2 - \left(\sum x\right)^2 / N}{N-1}} \qquad \textbf{(3-22)}$$

and the coefficient of skew is:

$$Cs = \frac{N^2 \sum x^3 - 3N \sum x \sum x^2 + 2\left(\sum x\right)^3}{N(N-1)(N-2)s^3} \qquad \textbf{(3-23)}$$

The flood magnitude versus frequency can then be calculated using:

$$\log Q = \overline{Q}_L + KS_L \qquad \textbf{(3-24)}$$

where K is a frequency factor dependent on coefficient of skew and return period. Bulletin 17 B (1982, pp. 3-1) presents tables of skew coefficients (K values). The discharge can be computed for a range of frequencies for which K coefficients exist.

The skew represents the form of curvature of the plotted curve as shown in **Figure 3-12**. For a negative skew, the flood-frequency curve is concave downward and for a positive skew, the curve is concave upward. If the skew is zero, the plotted relation forms a straight line, the logarithm of the distribution is defined as normally distributed, and the standard deviation becomes the slope of that straight line.

The erratic nature of flooding in the State of Texas can result in records in which some of the observed annual-peak discharge rates do not seem to belong to the population of the series. These may be extremely large or extremely small with respect to the rest of the series of observations. Such values may be "outliers" which possibly should be excluded from the set of data to be analyzed. Bulletin 17 B (1982, pp. 17) outlines statistical checks for outliers.

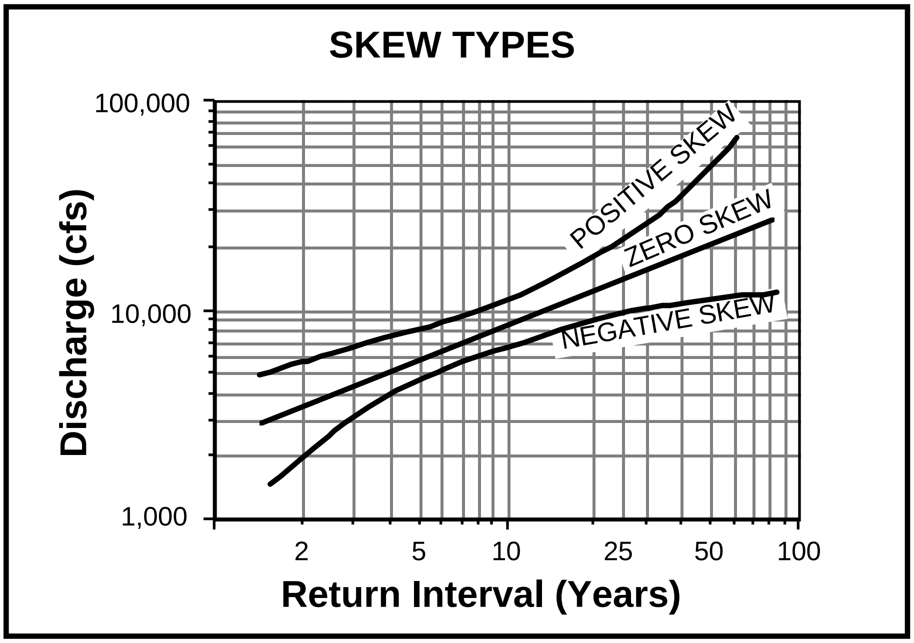

Figure 3-12: Typical discharge versus frequency curves
Adapted from Reagan and Smith (1993)

HDDS assists in application of this method by identifying which (if any) stream gauge records apply to streams within a delineated watershed.

3.3.3 Soil Conservation Service Runoff Curve Number Method (SCS)

The National Engineering Handbook (SCS, 1985) outlines peak discharge and runoff hydrograph determination by a rainfall-runoff method commonly referred to as the SCS Runoff Curve Number Method. This section discusses the most basic components of the method which may be used to determine peak discharges and runoff hydrographs from uncontrolled watersheds using a dimensionless unit hydrograph as shown in **Figure 3-13.**

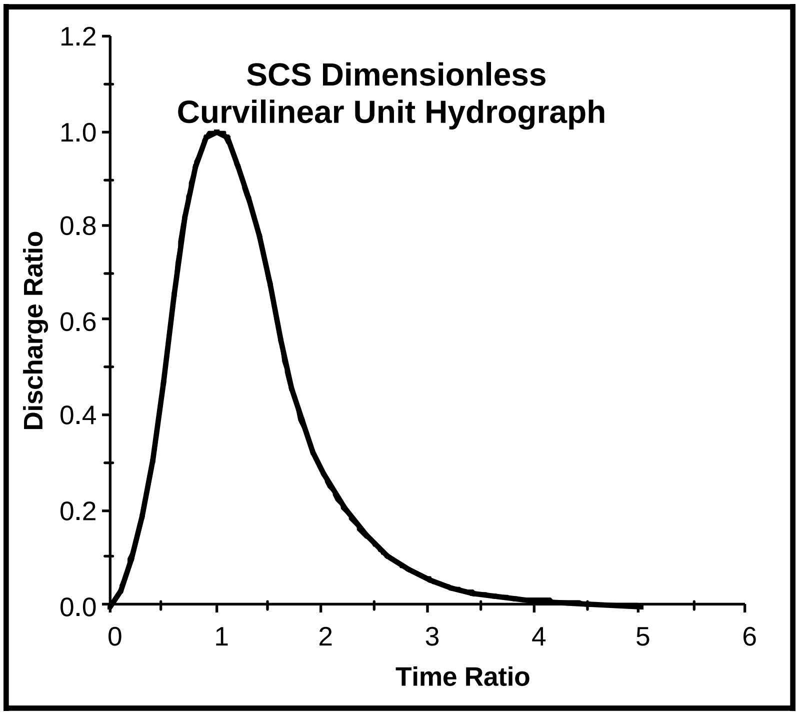

Figure 3-13: SCS dimensionless unit hydrograph
Adapted from SCS (1985, pp. 16.3)

The primary input variables are:

- drainage area size (A) in sq.mi.,
- time of concentration (T_c) in hours,
- weighted runoff curve number (RCN),
- rainfall distribution (SCS Type II or III for Texas), and
- total design rainfall (P) in inches.

HDDS is designed to develop these parameters with the exception of rainfall distribution type.

Rainfall-Runoff Equation

Equation (3-25) represents a relationship between accumulated rainfall and accumulated runoff. This was derived by the SCS from experimental plots for numerous soils and vegetative cover conditions. Data for land treatment measures, such as contouring and terracing, from experimental watersheds were included.

$$R = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \textbf{(3-25)}$$

where: R = accumulated direct runoff, inches

P = accumulated rainfall (potential maximum runoff), inches

I_a = initial abstraction including surface storage, interception, and infiltration prior to runoff, inches

S = potential maximum retention, inches

The potential maximum retention (S) may be computed as

$$S = \frac{1000}{RCN} - 10 \qquad \textbf{(3-26)}$$

which is valid if S < (P-R).

Where RCN is the runoff curve number described below.

Equation (3-25) was developed mainly for small watersheds from recorded storm data that included total rainfall amount in a calendar day, but not its distribution with respect to time. Therefore, this method is appropriate for estimating direct runoff from 24-hour or 1-day storm rainfall.

Generally, I_a may be estimated as:

$$I_a = 0.2S \cdot \qquad \textbf{(3-27)}$$

which, when substituted in **Eq. (3-25)** gives:

$$R = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad \textbf{(3-28)}$$

Accumulated Rainfall (P)

For most highway drainage design purposes, the accumulated rainfall may be abstracted from Technical Paper 40 (NWS, 1961) for a 24 hour duration storm for the relevant frequency. The 24 hour 2, 5, 10, 25, 50, and 100 year frequency for Texas counties are presented in the **Table 3-5**.

Rainfall Distribution

The SCS (TR 55, 1986) presents two design dimensionless rainfall distribution types that are valid for Texas; Type II and Type III which are shown in **Figure 3-14**. The differences between Type II and Type III are minimal and as such, no effort has been expended here to differentiate the two in HDDS.

Soil Groups

Soil properties influence the relationship between rainfall and runoff by affecting the rate of infiltration. The SCS (1985) has divides soils into four hydrologic soil groups based on infiltration rates, groups A, B, C, and D which are described as follows.

Group A Soils having a low runoff potential due to high infiltration rates even when saturated (0.30 - 0.45 in/hr). These soils consist primarily of deep sands, deep loess and aggregated silts.

Group B Soils having a moderately low runoff potential due to moderate infiltration rates when saturated (0.15 - 0.30 in/hr). These soils consist primarily of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures (shallow loess, sandy loam).

Group C Soils having a moderately high runoff potential due to slow infiltration rates (0.05 - 0.15 in/hr if saturated). These soils consist primarily of soils in which a layer near the surface impedes the downward movement of water or soils with moderately fine to fine texture (clay loams, shallow sandy loams, soils low in organic content, and soils usually high in clay).

Group D Soils having a high runoff potential due to very slow infiltration rates (less than 0.05 in/hr if saturated). These soils consist primarily of clays with:

- high swelling potential
- soils with permanently high water tables
- soils with a claypan or clay layer at or near the surface
- shallow soils over nearly impervious parent material (soils that swell significantly when wet, heavy plastic clays, and certain saline soils).

Runoff Curve Number (RCN)

Rainfall infiltration losses primarily are dependent on soil characteristics and land use (surface cover). The SCS method uses a combination of soil conditions and land use to assign runoff factors known as runoff curve numbers. These represent the runoff potential of an area when the soil is not frozen. The higher the RCN, the higher the runoff potential. **Tables 3-6 through 3-9** provide an extensive list of suggested runoff curve numbers. The assigned land use codes are discussed in Section 4.2 and have been established as part of this thesis. The RCN values assume medium antecedent moisture conditions. Chow et al. (1988, pp. 149) provide equations to adjust the RCN for wet and dry antecedent moisture conditions. **Equation (3-29)** adjusts values for expected dry soil conditions (antecedent moisture condition I). **Equation (3-30)** should be used to accommodate wet soils (antecedent moisture condition III). **Table 3-10** assists the determination of which moisture condition applies.

$$RCN(I) = \frac{4.2RCN(II)}{10 - 0.058RCN(II)} \qquad \textbf{(3-29)}$$

$$RCN(III) = \frac{23RCN(II)}{10 + 0.13RCN(II)} \qquad \textbf{(3-30)}$$

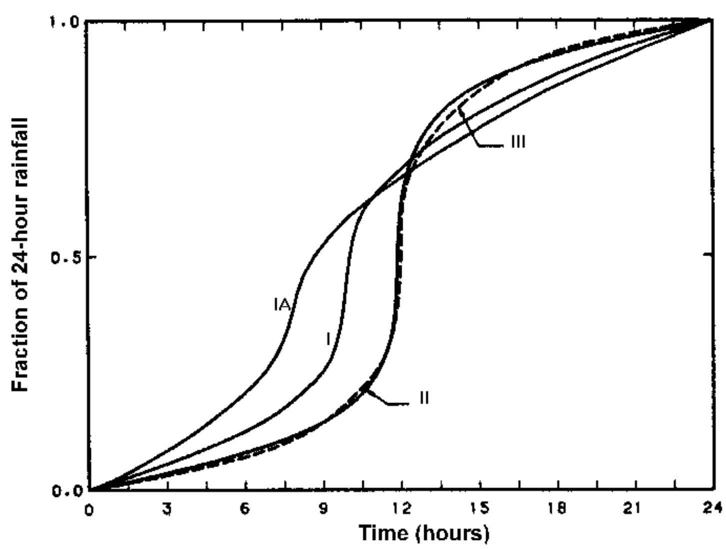

Figure 3-14: Soil Conservation Service 24-hour rainfall distributions
Adapted from TR55 (1986, pp. B-1)

Time of Concentration

The time of concentration (T_C) is the time required for water to travel from the most hydraulically distant point in a watershed to its outlet. In general, the time of concentration is equal to the distance of runoff along the watercourse divided by the average velocity of runoff: however, surface flow velocities vary considerably with topography, surface cover, and cross-section characteristics. Therefore, it is advisable to divide the watercourse into segments of overland and channel flows and determine flow velocities for each segment. The time of travel for each segment can be computed as the quotient of length and velocity. The sum of times of travel along each segment in series yields the total travel time.

An inordinate number of paths may be possible for the time of concentration. It is necessary to identify the path of runoff within the watershed which will define the longest travel time. Manual methods require trial and error estimates. The designer might choose what appears to be the longest distance from the watershed boundary to the outfall, but the topography and surface roughness could be such that the longest time results from a different travel path. HDDS has been designed to determine the time of concentration
based on the longest travel time. This is detailed in Section 4.2.

The Texas Department of Transportation (TxDOT, 1985) recommends use of **Figure 3-15** for estimating velocity of runoff for overland flow and shallow swale flow. Since the subject watershed component may not have exactly the definition as shown on the chart, it may be necessary to interpolate between lines with identification similar to the subject watershed characteristics.

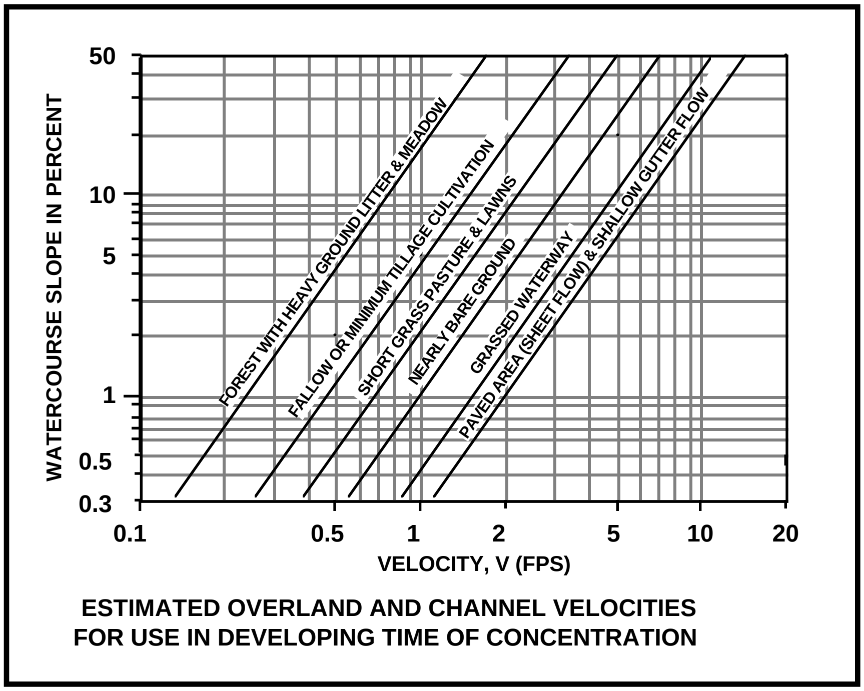

Figure 3-15: Velocities for estimating time of concentration
Adapted from NEH (1985, pp. 15-8)

Generally, the travel time along concentrated flow reaches such as streams should be estimated using channel analysis techniques. Oftentimes, Manning's Equation, **Eq. (3-31)**, is used assuming bank full flow. Currently, HDDS does not incorporate development of channel analysis parameters, however, flow velocities can be specified from which times can be calculated. See Section 4.2.

$$V = \frac{1.49AR^{2/3}S^{1/2}}{n} \tag{3-31}$$

where,

V = average flow velocity (fps),

A = channel section area (ft^2),

R = hydraulic radius = area/wetted perimeter (ft),

S = water surface slope which is approximated by channel bed slope (ft/ft), and

n = Manning's roughness coefficient.

Peak Flow and Runoff Hydrograph Determination

Much like other rainfall runoff methods, it is necessary to perform the following:

- determine cumulative rainfall,
- determine cumulative and incremental excess rainfall,
- establish a unit hydrograph for the specific watershed, and
- determine runoff hydrograph by convolution of excess rainfall and unit hydrograph.

The following briefly outlines how this may be accomplished for the SCS method:

1. Derive a cumulative rainfall table by multiplying each ordinate of the standard rainfall distribution (**Figure 3-14**) by the total design rainfall (P) as determined from **Table 3-5**.
2. Determine the duration of unit excess rainfall (runoff), D, using **Eq. (3-32)**. For convenience, D may be rounded such that the duration of precipitation is a whole number times D.

   $$D = 0.133T_c \qquad \textbf{(3-32)}$$

   where T_c = time of concentration (hours).
3. Calculate the peak discharge (q_p)for the unit hydrograph using **Eq. (3-33)**.

   $$q_p = \frac{484AQ}{T_p} \qquad \textbf{(3-33)}$$

   where,

   A = drainage area (sq. mi.),

   T_p = time to peak of the unit hydrograph (U.H.) = 0.67 T_c (for rural watersheds)

   Q = volume of runoff per unit area during time interval (= 1 in for the U.H.)
4. Develop the unit hydrograph ordinates using the dimensionless hydrograph from **Figure 3-14**. For each time step, $D \times \frac{t}{T_p}$, $q = q_p \times \frac{q}{Q}$.

   A plot of all the ordinates represents the runoff resulting from 1.0 inch of rainfall excess occurring during a time of D hours.
5. Using the cumulative rainfall table from Step 1, calculate the accumulated runoff and incremental runoff using a time increment of D, the estimated RCN, **Eq. (3-26),** and **Eq. (3-28)**. If, for any time interval, P - 0.2 S = 0, then R = 0.

6. Compute the hydrographs resulting from each increment of runoff by multiplying the ordinates of the unit hydrograph by the increment of runoff. This will result in as many hydrographs as there are increments of runoff, each of which should be displaced by the duration time from the previous hydrograph. At each time step, summate the runoff values to yield the composite runoff hydrograph.

The aforementioned process describes appropriate steps for the simplest analysis in which no consideration is given to the effect of spatial distribution of rainfall and individual runoff hydrographs resulting from tributaries within the watershed. By dividing the watershed into subareas and employing channel routing techniques, the SCS runoff curve number method may be employed to better accommodate differences in subarea characteristics. HDDS aids the process by delineating subareas, estimating subarea times of concentration and flow path, and weighting design rainfall and runoff curve numbers by subarea.

Computer programs such as TR 20 (1986) and THYSYS (TxDOT, 1977) are available to perform the hydrologic computations. HDDS is designed to develop the data required as input for such programs as discussed in **Section 4.2**.

Table 3-5: Design 24-Hour Rainfall in Inches for Texas Counties

CNTY_NAME	24hr Design Rainfall (inches) by Frequency (F years)					
	F2_24	F5_24	F10_24	F25_24	F50_24	F100_24
Anderson	4.40	6.00	7.00	8.40	9.50	10.50
Andrews	2.60	3.50	4.30	5.00	5.60	6.50
Angelina	4.80	6.50	7.70	9.20	10.50	11.50
Aransas	4.50	6.30	7.50	9.00	10.30	11.80
Archer	3.65	4.90	5.70	6.80	7.70	8.70
Armstrong	2.80	3.80	4.60	5.30	5.90	6.70
Atascosa	4.00	5.50	6.70	7.80	8.80	10.00
Austin	4.65	6.35	7.75	9.10	10.40	11.80
Bailey	2.60	3.40	4.20	4.70	5.80	6.20
Bandera	3.80	5.20	6.20	7.40	8.30	9.40
Bastrop	4.20	5.70	6.80	8.00	9.00	10.10
Baylor	3.55	4.80	5.40	6.60	7.50	8.40
Bee	4.25	6.00	7.10	8.50	9.50	11.00
Bell	4.10	5.50	6.70	7.80	8.80	9.90
Bexar	3.80	5.30	6.50	7.80	8.70	9.90
Blanco	3.80	5.30	6.50	7.60	8.60	9.70
Borden	2.90	4.10	4.75	5.70	6.40	7.20
Bosque	4.00	5.40	6.50	7.50	8.50	9.50
Bowie	4.40	5.75	6.85	7.85	8.80	9.85
Brazoria	5.10	7.00	8.50	10.00	11.50	13.00
Brazos	4.50	6.13	7.30	8.75	9.75	11.00
Brewster	2.60	3.40	4.30	5.00	5.70	6.50
Briscoe	2.90	3.95	4.70	5.45	6.10	6.80
Brooks	4.25	6.00	7.10	8.40	9.50	11.00
Brown	3.70	5.10	6.10	7.10	8.10	9.10
Burleson	4.45	6.10	7.25	8.75	9.65	10.95
Burnet	3.80	5.30	6.30	7.50	8.50	9.50
Caldwell	4.10	5.60	6.70	7.90	8.90	10.00
Calhoun	4.60	6.40	7.80	9.30	10.50	12.00
Callahan	3.60	4.90	5.70	6.80	7.80	8.80
Cameron	4.60	6.30	7.40	9.00	10.00	11.50
Camp	4.40	5.80	6.85	7.95	8.90	9.90
Carson	2.80	3.70	4.50	5.20	5.80	6.60
Cass	4.45	5.80	6.85	7.90	8.90	9.90
Castro	2.65	3.60	4.30	4.90	5.50	6.30
Chambers	5.50	7.30	8.80	10.10	11.70	13.10
Cherokee	4.50	6.10	7.20	8.50	9.50	10.30
Childress	3.20	4.30	5.00	5.90	6.90	7.50
Clay	3.70	5.10	5.80	7.00	7.90	8.90
Cochran	2.55	3.40	4.20	4.75	5.30	6.20
Coke	3.30	4.50	5.30	6.40	7.20	8.20
Coleman	3.60	5.00	5.80	6.90	7.80	8.90
Collin	4.00	5.40	6.40	7.60	8.60	9.60
Collingsworth	3.10	4.20	4.90	5.80	6.70	7.30
Colorado	4.60	6.30	7.60	9.00	10.20	11.60
Comal	3.80	5.30	6.30	7.50	8.50	9.50
Comanche	3.80	5.20	6.20	7.20	8.20	9.20
Concho	3.60	4.80	5.70	6.80	7.70	8.80
Cooke	3.80	5.20	6.20	7.30	8.20	9.30
Coryell	4.00	5.40	6.40	7.60	8.60	9.65
Cottle	3.20	4.40	5.10	6.00	7.00	7.70
Crane	2.60	3.60	4.40	5.00	5.80	6.50

CNTY_NAME	F2_24	F5_24	F10_24	F25_24	F50_24	F100_24
Crockett	3.00	4.30	5.10	6.10	6.90	7.80
Crosby	2.90	3.80	4.75	5.55	6.35	7.00
Culberson	2.00	2.70	3.40	4.10	4.50	5.10
Dallam	2.40	3.20	3.90	4.50	5.20	5.80
Dallas	4.00	5.40	6.50	7.60	8.60	9.60
Dawson	2.80	3.90	4.70	5.30	6.00	6.80
Deaf Smith	2.60	3.50	4.20	4.80	5.40	6.20
Delta	4.15	5.60	6.80	7.80	8.80	9.80
Denton	3.90	5.30	6.30	7.40	8.40	9.40
De Witt	4.30	6.00	7.20	8.50	9.60	11.00
Dickens	3.10	4.25	5.00	5.90	6.75	7.45
Dimmit	3.70	5.20	6.20	7.40	8.30	9.50
Donley	2.90	4.00	4.80	5.60	6.30	6.90
Duval	4.10	5.75	6.90	8.10	9.10	10.50
Eastland	3.70	5.10	6.00	7.00	8.00	9.00
Ector	2.60	3.60	4.40	5.00	5.80	6.50
Edwards	3.50	4.80	5.70	6.80	7.80	8.80
El Paso	1.50	2.30	2.80	3.20	3.60	3.80
Ellis	4.10	5.40	6.60	7.70	8.70	9.80
Erath	3.80	5.20	6.30	7.30	8.30	9.30
Falls	4.20	5.70	6.80	8.00	9.00	10.10
Fannin	4.05	5.45	6.50	7.60	8.60	9.60
Fayette	4.50	6.10	7.30	8.60	9.70	11.00
Fisher	3.25	4.50	5.25	6.30	7.10	8.10
Floyd	2.90	4.00	4.75	5.50	6.25	6.90
Foard	3.40	4.60	5.20	6.20	7.20	8.10
Fort Bend	4.90	6.70	8.20	9.55	11.00	12.45
Franklin	4.25	5.70	6.85	7.85	8.90	9.90
Freestone	4.33	5.90	6.90	8.20	9.25	10.30
Frio	3.80	5.30	6.30	7.60	8.50	10.00
Gaines	2.60	3.50	4.25	4.90	5.60	6.40
Galveston	5.30	7.20	8.60	10.10	11.60	13.10
Garza	2.90	4.10	4.80	5.70	6.50	7.10
Gillespie	3.80	5.20	6.20	7.40	8.30	9.40
Glasscock	2.90	4.10	4.80	5.75	6.50	7.30
Goliad	4.30	6.10	7.20	8.50	9.70	11.10
Gonzales	4.20	5.90	7.00	8.40	9.50	10.70
Gray	2.90	3.90	4.70	5.50	6.20	6.70
Grayson	3.90	5.40	6.40	7.40	8.40	9.40
Gregg	4.50	5.95	7.00	8.10	9.20	10.20
Grimes	4.62	6.30	7.55	9.00	10.00	11.50
Guadalupe	4.10	5.60	6.70	7.90	8.90	10.00
Hale	2.75	3.75	4.55	5.25	5.85	6.70
Hall	3.00	4.20	4.80	5.75	6.50	7.20
Hamilton	3.90	5.30	6.40	7.40	8.50	9.50
Hansford	2.70	3.60	4.30	5.00	5.70	6.30
Hardeman	3.30	4.50	5.20	6.20	7.20	8.10
Hardin	5.25	7.20	8.45	10.00	11.10	12.65
Harris	5.00	6.80	8.30	9.60	11.00	12.50
Harrison	4.55	6.00	7.00	8.20	9.20	10.20
Hartley	2.50	3.30	4.00	4.70	5.20	6.00
Haskell	3.50	4.70	5.40	6.40	7.40	8.30
Hays	4.00	5.40	6.50	7.70	8.70	9.80
Hemphill	2.90	4.00	4.80	5.50	6.30	6.90
Henderson	4.30	5.80	6.90	8.00	9.10	9.90

CNTY_NAME	F2_24	F5_24	F10_24	F25_24	F50_24	F100_24
Hidalgo	4.30	6.10	7.20	8.50	9.60	11.10
Hill	4.00	5.40	6.60	7.80	8.80	9.80
Hockley	2.65	3.60	4.40	5.00	5.65	6.45
Hood	3.90	5.20	6.40	7.40	8.40	9.40
Hopkins	4.20	5.65	6.85	7.85	8.85	9.90
Houston	4.60	6.25	7.50	8.80	9.95	11.20
Howard	2.90	4.10	4.80	5.70	6.50	7.30
Hudspeth	1.70	2.50	3.00	3.50	4.00	4.40
Hunt	4.10	5.50	6.60	7.80	8.70	9.70
Hutchinson	2.70	3.70	4.40	5.10	5.70	6.50
Irion	3.20	4.40	5.20	6.30	7.00	8.00
Jack	3.75	5.20	6.00	7.10	8.00	9.10
Jackson	4.60	6.40	7.80	9.20	10.50	12.00
Jasper	5.00	7.00	8.25	9.60	10.60	12.50
Jeff Davis	2.10	2.90	3.60	4.20	4.80	5.50
Jefferson	5.50	7.50	8.80	10.20	11.80	13.10
Jim Hogg	4.10	5.75	6.80	8.10	9.10	10.50
Jim Wells	3.90	5.90	7.10	8.30	9.50	10.90
Johnson	4.00	5.30	6.40	7.50	8.50	9.50
Jones	3.50	4.60	5.40	6.50	7.30	8.30
Karnes	4.20	5.80	7.00	8.30	9.30	10.70
Kaufman	4.20	5.60	6.70	7.80	8.80	9.80
Kendall	3.80	5.30	6.40	7.60	8.50	9.50
Kenedy	4.40	6.25	7.30	8.70	10.00	11.30
Kent	3.20	4.25	5.05	6.00	6.80	7.55
Kerr	3.80	5.20	6.20	7.30	8.30	9.30
Kimble	3.70	4.90	5.90	7.10	8.00	9.10
King	3.00	4.50	5.10	6.10	7.10	8.00
Kinney	3.50	4.80	5.70	7.00	8.00	9.00
Kleberg	4.30	6.20	7.30	8.60	9.90	11.30
Knox	3.40	4.60	5.30	6.40	7.30	8.20
La Salle	3.85	5.40	6.50	7.70	8.60	9.90
Lamar	4.20	5.55	6.80	7.80	8.75	9.75
Lamb	2.65	3.60	4.40	4.90	5.55	6.40
Lampasas	3.80	5.30	6.30	7.50	8.50	9.50
Lavaca	4.50	6.30	7.50	8.80	10.00	11.20
Lee	4.40	5.95	7.10	8.45	9.50	10.70
Leon	4.40	6.05	7.20	8.50	9.55	10.75
Liberty	5.25	7.00	8.50	9.90	11.10	12.60
Limestone	4.30	5.70	6.80	8.00	9.10	10.10
Lipscomb	2.90	3.90	4.60	5.40	6.10	6.80
Live Oak	4.20	5.75	7.00	8.20	9.10	10.60
Llano	3.90	5.20	6.30	7.50	8.40	9.50
Loving	2.30	3.00	3.80	4.40	4.90	5.60
Lubbock	2.80	3.80	4.60	5.30	6.00	6.80
Lynn	2.80	3.85	4.70	5.30	6.00	6.80
Madison	4.60	6.20	7.50	8.80	9.80	11.10
Marion	4.50	5.90	6.95	8.00	8.90	10.00
Martin	2.80	3.90	4.70	5.30	6.10	6.80
Mason	3.80	5.10	6.10	7.20	8.20	9.30
Matagorda	4.90	6.80	8.30	9.60	11.20	12.50
Maverick	3.50	5.00	5.80	7.00	8.00	9.00
McCulloch	3.70	5.00	5.90	7.10	8.00	9.10
McLennan	4.10	5.50	6.60	7.80	8.80	9.80
McMullen	4.00	5.55	6.70	8.00	9.00	10.30

CNTY_NAME	F2_24	F5_24	F10_24	F25_24	F50_24	F100_24
Medina	3.80	5.30	6.20	7.50	8.50	9.50
Menard	3.80	4.90	5.80	6.90	7.80	8.90
Midland	2.80	3.90	4.70	5.30	6.20	6.80
Milam	4.20	5.70	6.80	8.00	9.00	10.10
Mills	3.80	5.20	6.30	7.30	8.30	9.30
Mitchell	3.10	4.25	5.10	6.10	6.70	7.80
Montague	3.80	5.10	6.00	7.20	8.00	9.10
Montgomery	4.85	6.60	8.10	9.30	10.60	12.20
Moore	2.60	3.60	4.30	4.90	5.50	6.30
Morris	4.40	5.75	6.85	7.90	9.00	9.90
Motley	3.05	4.20	4.90	5.80	6.60	7.25
Nacogdoches	4.70	6.20	7.50	8.80	10.00	11.00
Navarro	4.20	5.60	6.80	7.90	9.00	9.80
Newton	5.10	7.00	8.25	9.60	10.60	12.50
Nolan	3.25	4.50	5.25	6.30	7.10	8.10
Nueces	4.30	6.10	7.30	8.60	10.00	11.30
Ochiltree	2.80	3.70	4.50	5.20	5.90	6.50
Oldham	2.60	3.30	4.10	4.70	5.30	6.10
Orange	5.50	7.40	8.80	10.10	11.60	13.00
Palo Pinto	3.80	5.10	6.20	7.20	8.20	9.20
Panola	4.60	6.20	7.20	8.50	9.50	10.60
Parker	3.90	5.20	6.30	7.30	8.30	9.30
Parmer	2.60	3.40	4.20	4.75	5.20	6.20
Pecos	2.70	3.70	4.50	5.20	6.00	6.80
Polk	4.85	6.60	8.00	9.40	10.50	12.00
Potter	2.70	3.60	4.40	5.00	5.60	6.40
Presidio	2.10	2.90	3.70	4.20	4.80	5.50
Rains	4.20	5.70	6.85	7.85	8.90	9.95
Randall	2.70	3.70	4.40	5.10	5.70	6.50
Reagan	3.00	4.10	4.90	5.90	6.70	7.50
Real	3.60	5.00	5.80	7.10	8.00	9.00
Red River	4.30	5.65	6.80	7.85	8.80	9.80
Reeves	2.30	3.10	3.90	4.50	5.00	5.70
Refugio	4.50	6.20	7.50	9.00	10.10	11.50
Roberts	2.80	3.80	4.60	5.30	6.00	6.70
Robertson	4.40	5.90	7.00	8.40	9.40	10.60
Rockwall	4.10	5.40	6.60	7.70	8.70	9.70
Runnels	3.60	4.80	5.60	6.70	7.50	8.60
Rusk	4.55	6.10	7.25	8.50	9.50	10.20
Sabine	4.87	6.60	7.90	9.10	9.75	11.50
San Augustine	4.80	6.50	7.75	9.05	10.00	11.50
San Jacinto	4.85	6.50	8.05	9.40	10.50	11.50
San Patricio	4.30	6.20	7.30	8.60	10.00	11.30
San Saba	3.80	5.20	6.20	7.30	8.30	9.40
Schleicher	3.40	4.60	5.50	6.50	7.40	8.40
Scurry	3.10	4.25	5.10	6.00	6.70	7.60
Shackelford	3.60	4.80	5.60	6.70	7.70	8.70
Shelby	4.75	6.30	7.60	8.70	9.95	11.00
Sherman	2.60	3.50	4.20	4.80	5.40	6.10
Smith	4.45	5.90	7.00	8.15	9.20	10.20
Somervell	3.90	5.30	6.40	7.40	8.40	9.40
Starr	4.10	5.50	6.90	8.20	9.30	10.60
Stephens	3.70	5.00	6.00	7.00	8.00	9.00
Sterling	3.10	4.25	5.10	6.10	6.80	7.80
Stonewall	3.00	4.50	5.20	6.30	7.10	8.10

CNTY_NAME	F2_24	F5_24	F10_24	F25_24	F50_24	F100_24
Sutton	3.40	4.70	5.50	6.60	7.50	8.50
Swisher	2.75	3.75	4.50	5.20	5.80	6.60
Tarrant	3.90	5.30	6.40	7.40	8.40	9.50
Taylor	3.50	4.60	5.50	6.50	7.50	8.40
Terrell	2.90	3.90	4.80	5.60	6.50	7.30
Terry	2.65	3.65	4.40	5.00	5.70	6.50
Throckmorton	3.60	4.80	5.60	6.60	7.60	8.50
Titus	4.30	5.75	6.85	7.90	8.90	9.90
Tom Green	3.40	4.60	5.50	6.50	7.30	8.40
Travis	4.10	5.60	6.70	7.90	8.90	10.00
Trinity	4.75	6.45	7.75	9.10	10.20	11.50
Tyler	4.80	6.50	7.75	9.50	10.55	12.10
Upshur	4.40	5.80	6.90	8.00	9.00	10.00
Upton	2.80	3.90	4.70	5.50	6.30	7.00
Uvalde	3.70	5.00	6.00	7.20	8.20	9.20
Val Verde	3.20	4.40	5.30	6.50	7.00	8.50
Van Zandt	4.20	5.80	6.80	7.90	9.00	9.90
Victoria	4.50	6.20	7.50	9.00	10.10	11.50
Walker	4.70	6.40	7.80	9.10	10.20	11.60
Waller	4.75	6.45	8.00	9.25	10.50	12.00
Ward	2.40	3.30	4.20	4.70	5.30	6.10
Washington	4.60	6.25	7.50	8.95	10.00	11.45
Webb	3.80	5.30	6.50	7.60	8.60	10.00
Wharton	4.80	6.50	8.00	9.40	10.70	12.00
Wheeler	3.00	4.10	4.80	5.70	6.50	7.10
Wichita	3.65	4.80	5.60	6.70	7.60	8.60
Wilbarger	3.55	4.70	5.40	6.50	7.40	8.30
Willacy	4.50	6.25	7.30	8.80	10.00	11.40
Williamson	4.10	5.60	6.70	7.90	8.90	10.00
Wilson	4.10	5.60	6.80	8.00	9.00	10.40
Winkler	2.40	3.30	4.20	4.70	5.30	6.10
Wise	3.80	5.20	6.20	7.30	8.20	9.30
Wood	4.25	5.75	6.90	7.90	8.95	10.00
Yoakum	2.55	3.40	4.20	4.75	5.40	6.20
Young	3.70	5.00	5.80	6.90	7.80	8.80
Zapata	3.90	5.50	6.70	7.80	8.90	10.20
Zavala	3.70	5.20	6.00	7.30	8.20	9.50

Table 3-6: Runoff Curve Numbers for Urban Areas

Cover Description			Curve numbers(RCN) for hydrologic soil groups			
Assigned lucode(s)	Cover type and hydrologic condition	Average % impervious area	A	B	C	D
18 & 181	Open space (lawns, parks, golf courses, cemeteries, etc.) Poor condition (grass cover <50%)		68	79	86	89
182	Fair condition (grass cover 50% to 75%)		49	69	79	84
183	Good condition (grass cover > 75%)		39	61	74	80
141	Impervious areas: Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
14 & 142	Streets and roads: Paved; curbs and storm drains (excluding right-of-way)		98	98	98	98
143	Paved; open ditches (including right-of-way)		83	89	92	93
144	Gravel (including right-of-way)		76	85	89	91
145	Dirt (including right-of-way)		72	82	87	89
171	Western desert urban areas: Natural desert landscaping (pervious areas only)		63	77	85	88
172	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:					
12	Commercial and business	85	89	92	94	95
13	Industrial	72	81	88	91	93
	Residential districts by average lot size:					
11 & 111	1/8 acre or less (town houses)	65	77	85	90	92
112	1/4 acre	38	61	75	83	87
113	1/3 acre	30	57	72	81	86
114	1/2 acre	25	54	70	80	85
115	1 acre	20	51	68	79	84
116	2 acres	12	46	65	77	82
	Developing urban areas					
173	Newly graded areas (pervious areas only, no vegetation)		77	86	91	94

Table 3-7: Runoff Curve Numbers for Cultivated Agricultural Land

Cover description				Curve numbers for hydrologic soil group			
Assigned lucode	Cover type	Treatment	Hydrologic condition	A	B	C	D
21 & 2111	Fallow	Bare soil	-	77	86	91	94
2112		Crop residue	Poor	76	85	90	93
2113		cover (CR)	Good	74	83	88	90
2114	Row	Straight row (SR)	Poor	72	81	88	91
2115	Crops		Good	67	78	85	89
2116		SR + CR	Poor	71	80	87	90
2117			Good	64	75	82	85
2118		Contoured (C)	Poor	70	79	84	88
2119			Good	65	75	82	86
2120		C + CR	Poor	69	78	83	87
2121			Good	64	74	81	85
2122		Contoured &	Poor	66	74	80	82
2123		terraced (C & T)	Good	62	71	78	81
2124		C&T + CR	Poor	65	73	79	81
2125			Good	61	70	77	80
2126		Small grain SR	Poor	65	76	84	88
2128			Good	63	75	83	87
2129		SR + CR	Poor	64	75	83	86
2130			Good	60	72	80	84
2131		C	Poor	63	74	82	85
2132			Good	61	73	81	84
2133		C + CR	Poor	62	73	81	84
2134			Good	60	72	80	83
2135		C&T	Poor	61	72	79	82
2136			Good	59	70	78	81
2137		C&T + CR	Poor	60	71	78	81
2138			Good	58	69	77	80
220		Close-seeded SR	Poor	66	77	85	89
222		or broadcast	Good	58	72	81	85
244		Legumes or C	Poor	64	75	83	85
245		Rotation	Good	55	69	78	83
246		Meadow C&T	Poor	63	73	80	83
247			Good	51	67	76	80

Table 3-8: Runoff Curve Numbers for Other Agricultural Lands

Cover description			Curve numbers for hydrologic soil group			
Assigned lucode	Cover type	Hydrologic condition	A	B	C	D
24 & 241	Pasture, grassland, or range-	Poor	68	79	86	89
242	continuous forage for grazing	Fair	49	69	79	84
243		Good	39	61	74	80
248	Meadow--continuous grass, protected from grazing and generally mowed for hay	--	30	58	71	78
33 & 331	Brush--brush-weed-grass	Poor	48	67	77	83
332	mixture, with	Fair	35	56	70	77
333	brush the major element	Good	30	48	65	73
43 & 431	Woods--grass combination	Poor	57	73	82	86
432	(orchard or	Fair	43	65	76	82
433	tree farm)	Good	32	58	72	79
434	Woods	Poor	45	66	77	83
435		Fair	36	60	73	79
436		Good	30	55	70	77
23	Farmsteads--buildings, lanes, driveways, and surrounding lots	--	59	74	82	86

Table 3-9: Runoff Curve Numbers for Arid and Semiarid Rangelands

Assigned lucode	Cover type	Hydrologic condition	A	B	C	D
31 & 311	Herbaceous--mixture of grass,	Poor		80	87	93
312	weeds, and low-growing brush,	Fair		71	81	89
313	with brush the minor element	Good		62	74	85
41 & 411	Oak-aspen--mountain brush	Poor		66	74	79
412	mixture of oak brush, aspen,	Fair		48	57	63
413	mountain mahogany, bitter brush, maple, and other brush	Good		30	41	48
42 & 421	Pinyon-juniper--pinyon, juniper,	Poor		75	85	89
422	or both; grass understory	Fair		58	73	80
423		Good		41	61	71
32 & 321	Sagebrush with grass understory	Poor		67	80	85
322		Fair		51	63	70
323		Good		35	47	55
324	Desert shrub--major plants	Poor	63	77	85	88
325	include saltbush, greasewood,	Fair	55	72	81	86
326	creosote-bush, blackbrush, bursage, palo verde, mesquite, and cactus	Good	49	68	79	84

Data for Tables 3-6 to 3-9 were abstracted from TR-55 (1986) considering average runoff conditions and initial abstraction, $I_a = 0.2S$. Detailed notes are provided on their use in the aforementioned reference. Assigned land use codes (lucodes) are discussed in Section 4.2.

Table 3-10: Rainfall Groups For Antecedent Soil Moisture Conditions During Growing And Dormant Seasons

Antecedent Condition	Conditions Description	Growing Season Five-Day Antecedent Rainfall	Dormant Season Five-Day Antecedent Rainfall
Dry Condition I	An optimum condition of watershed soils, where soils are dry but not to the wilting point, and when satisfactory plowing or cultivation takes place	Less than 1.4 inches	Less than 0.5 inches
Average Condition II	The average case for annual floods	1.4 to 2.1 inches	0.5 to 1.1 inches
Wet Condition III	When a heavy rainfall, or light rainfall and low temperatures, have occurred during the five days previous to a given storm	Over 2.1 inches	Over 1.1 inches