ENVIRONMENTAL GEOLOGY OF URBAN AND URBANIZING AREAS

A Case Study from the San Marcos Area, Texas

VOLUME 1

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A CASE STUDY FROM THE SAN MARCOS AREA, TEXAS

Volume 1

by

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DISSERTATION

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ENVIRONMENTAL GEOLOGY OF URBAN AND URBANIZING AREAS:

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APPROVED BY SUPERVISORY COMMITTEE:

Keith Young

Charles G Groat

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Preface to Digital Version

This dissertation, which was originally prepared in 1976, has been converted to digital form to take advantage of the many features of up-to-date word processing software. Overall, the content of the original text has been preserved, but many changes have been made in format and presentation for improved readability. Many of the figures and tables have been reduced and placed within the text rather than on separate pages. The figures with photos, which were in small black and white form in the original text, have been enlarged substantially and presented in color where possible. The dissertation is now available in both word processor and image (PDF) files. The ten oversize plates, which were contained in a back pocket of the original dissertation, have been scanned at full size and are available as PDF files. In addition, the plates have been prepared in segments that will readily print in 8.5 x 11 inch format.

Two of the plates comprising the geologic maps of the dissertation area have been replaced. They have been digitized, put into Geographic Information System (GIS) format, and developed in a single map entitled, "Geologic Map of the San Marcos North Quadrangle and Adjacent Portions of the Mountain City and San Marcos South Quadrangle, Hays, Caldwell, and Guadalupe Counties, Texas".

This digital version of the dissertation is in two volumes. Volume 1 contains the text, and Volume 2 contains the 8.5 x 11 inch versions of the plates as described above. The digital files of Volumes 1 and 2 are available on a flash drive that accompanies this digital version.

The land capability analysis methods presented in this dissertation, which constituted a central component of the research, were developed before emergence of modern geographic information system (GIS) capabilities. Modern GIS functions now permit comparable analysis to be accomplished in a highly automated and much less laborious manner than was possible when the dissertation was written. The dissertation methodology was subsequently refined from the perspective of "worth assessment" in a term paper[1] for a masters degree course at the LBJ School of Public Affairs. This paper and associated material are also on the flash drive.

Mark Helper, faculty member of the Department of Geological Sciences, is credited for converting the geologic maps into GIS form. Jeffrey Horowitz digitized the paper copies as the initial step. Gratitude is expressed to JoAnne Grimshaw, my spouse, for extensive assistance in preparing this digital version of the dissertation.

Thomas W. Grimshaw, Ph.D.
June 2013

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[1] Grimshaw, T.W., 2003, *Application of Multicriteria Decision Methodology to Land Capability Analysis: Additional Advances*. LBJ School of Public Affairs, Applied Quantitative Analysis I (Course), Semester Project Report, 41 p+.

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Original Preface

Beginning about the time of the awakening of environmental awareness in the United States during the early 1960s, geology has become increasingly recognized for the substantial contribution it can make toward the solution of problems stemming from man's interaction with the earth's physical environment. This increased recognition has led to the establishment and growth of an application of the science that is called environmental geology. This term, and the geologic application it signifies, are becoming well accepted in the geologic profession. This study attempts to formulate and demonstrate a methodology for conducting environmental geologic study of urban and urbanizing areas, where environmental problems are most acute.

I wish to thank Dr. Keith Young for serving as supervisor for this study and for his invaluable assistance with the field mapping part of the project. I wish also to thank the following individuals for serving on the supervising committee. Dr. L. J. Turk deserves credit for upgrading the overall quality of the study by his constructive criticisms and helpful suggestions. Dr. C. G. Groat provided valuable input by critiquing the study from the point of view gained by his environmental geologic work elsewhere in Texas. Dr. E. G. Wermund made significant contributions because of his familiarity with environmental geologic problems along the Balcones Escarpment. Peter Coltman, as a planner having considerable knowledge of geology, has helped greatly in the attempt of this study to convert geologic information into a form which is readily usable by nongeologists. In addition to these committee members one other individual, Mike Colchin, deserves commendation for serving as student editor for the dissertation.

Mr. Charles Batte, soil scientist for the Soil Conservation Service soil survey party in San Marcos, familiarized me not only with the soils in the study area, but also with the soil classification system now used by the SCS. In addition, he provided free access to unpublished soils maps of the area and filled many of the "holes" in the existing data. Dr. Glenn Longley, professor of Biology at Southwest Texas State University, contributed freely of his knowledge of environmental problems in the study area and provided much interesting discussion of the cavern system and the unusual fauna of the Edwards aquifer. Many landowners have my gratitude for allowing access to their ranches during the mapping phase of the project and for sharing their knowledge of various aspects of the area.

The Department of Geological Sciences assisted in this study not only by furnishing excellent physical facilities, but also by providing aerial photographs and a Jeep for carrying out the field mapping. I also give thanks to the Geology Foundation of the Department for a generous grant for summer field work in 1974 and for a fellowship from the Hogg-Sharp Scholarship Fund in the Spring semester, 1975.

Finally and foremost, I thank my wife, Susan, not only for her invaluable editorial efforts on the text, but also for her patience, support, and fortitude during the conduct of the study.

This dissertation was submitted to the supervisory committee in March, 1976.

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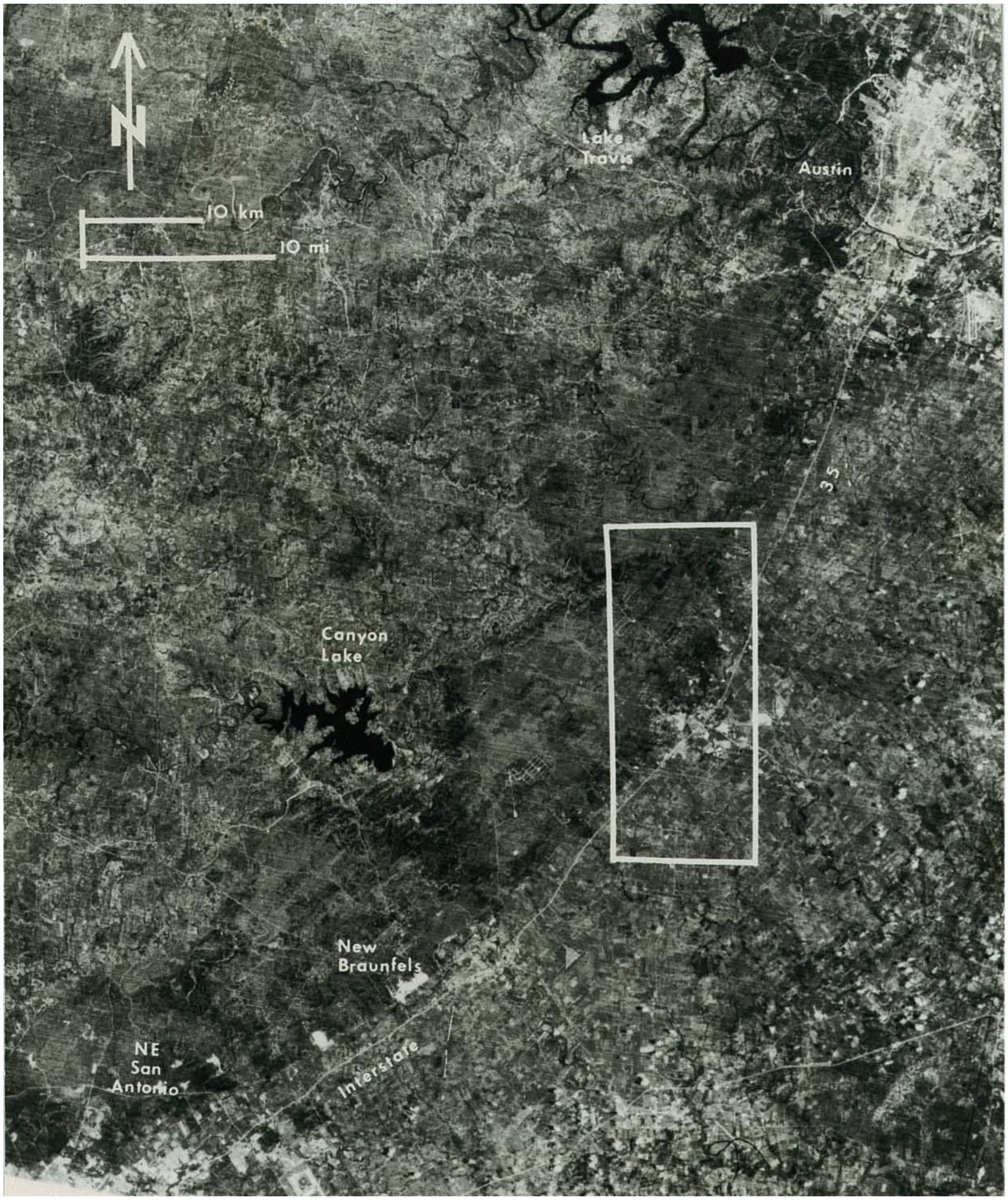
Frontispiece. The Balcones Escarpment between Austin and San Antonio

The city of San Marcos can be clearly seen just south of the center of the case study area (outlined in white). Note the offset in the scarp in the northern half of the area. This Landsat (ERTS) Band 5 image was made on July 21, 1973.



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Abstract

A major focus of environmental geologic work for the foreseeable future will be on the growing urban areas of the world. A systematic methodology for investigating the environmental geology of such areas can be developed by dividing the geologic environment into three major components (substrate, processes, and landform) and the urban system into four major components (situs, input, output, and transportation). These conceptual tools can then be used to develop a three-step procedure: 1) generation of the data source maps; 2) investigation of environmental geologic conflicts of existing urban systems; and 3) incorporation of geologic considerations in planning for future growth.

The data sources should be prepared in map form and should comprise two types of data, natural and cultural data. A conventional geologic map is the primary document used in the derivation of the five natural data source maps: 1) engineering geology; 2) soils; 3) resources; 4) processes; and 5) landform. The necessary cultural data source maps are a current land use and a land use control map.

In the investigation of environmental geologic problems of existing urbanization the urban system concept provides an excellent means of organizing the various facilities and activities of a city. If this scheme is used, the facilities can be systematically considered and their associated conflicts disclosed.

Environmental conflicts of future urbanization can be prevented by evaluating the ability of land to sustain the demands that will be imposed by projected urban facilities. The urbanization can then be fitted to the land by siting the facilities where the land can best meet their demands. The procedure for determining land suitability for an urban facility consists of three steps: 1) screening; 2) evaluation; and 3) verification. Areas that are totally unsuited for the facility are eliminated in the screening step. The remaining candidate areas are rated for their relative suitability in the evaluation step, which consists of an eight-step algorithm developed by adaptation of a formal decision-making technique. The results are confirmed in the verification step, and the final product, the suitability index map, should serve as the primary basis for determining where the facility will be located.

The San Marcos case study area comprises two 7-1/2 minute quadrangles in south-central Texas between Austin and San Antonio. The area is almost ideal for testing a methodology for environmental geologic investigation of growing urban areas. The methodology developed in this study was shown to be highly effective when applied to this area.

In its present state of development the methodology appears to be a conceptually sound and effective approach to optimizing the interaction between cities and their geologic environments. Future work should concentrate on adaptation of key sections for automation and on the application of the three-step procedure to a variety of different kinds of cities and geologic environments in order to refine and test it.

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9. Geologic Map of the Kyle Section (Replaced)
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GIS-Based Geologic Map (Replacement):
Geologic Map of the San Marcos North Quadrangle and Adjacent Portions of the Mountain City and San Marcos South Quadrangle, Hays, Caldwell, and Guadalupe Counties, Texas

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1 Chapter 1. Introduction

The term environmental geology was coined by Hackett in 1964 (Ivey, 1971, p. 3). Since then, the term has been variously defined by different authors (Hayes and Vineyard, 1969, p. 4; Flawn, 1970, p. xvii; Ivey, 1971, p. 3; Geyer and McGlade, 1972, p. 1; Turner and Coffman, 1973, p. 5; Fisher, 1974, p. 1). A concise and adequate definition for this study is as follows: "Environmental geology is the comprehensive use of geologic data, methods, and reasoning for optimizing the relation between man and the geologic aspects of his physical environment." This definition of the term has a strong ecological connotation. Ecology is defined simply as "the study of the relationships between organisms and their environments" (Gary, McAffee, and Wolf, 1972). Human ecology is therefore concerned with the relationship of man to his total environment, and environmental geology is that part of human ecology which deals specifically with the interaction of man with his geologic environment. Flawn (1970, p. xvii) early recognized this ecological basis of environmental geology in his definition of the term: "Environmental geology is a branch of ecology in that it deals with relationships between man and his geological habitat; …" The ecologic or interactive basis of environmental geology is a key element of this study.

The purpose of environmental geology is to avoid or reduce conflict of man's facilities or activities with the geologic setting in which they are located. In theory all subdisciplines of geology, including those involved with the procurement of mineral and fuel resources, could be thought of as comprising environmental geology. In practice much environmental geologic work includes a synthesis of such traditional geologic subdisciplines as engineering geology, hydrology, hydrogeology, and urban geology. This somewhat more restricted view of the scope of environmental geology has served to advance the use of geology in such activities as urban and regional land use planning, formulation of land use control measures, and site suitability studies.

It has become increasingly apparent that growing urban areas constitute a major focal point of environmental geologic study. The importance of cities was discussed by Flawn (1970, p. xvii): "A little reflection makes clear why the term urban geology is commonly used interchangeably with environmental geology. In urban areas the use of the earth is most intense and society has the most urgent earth problems." Legget, who believed geology to be so important to cities that he devoted an entire book to the topic, put it this way (1973, p. 3): "The purpose of this book is to show how essential is geology in the planning and development of cities … the use of geological information, and of geological methods to obtain new information about local subsurface conditions, should ... be an essential part of the physical planning of all cities."

The objective of this study is to present a systematic methodology for optimizing the interaction between man and his geologic environment in growing urban areas. Two aspects of this interaction, indicated by the terms urban and urbanizing in the title, will be considered. The urban aspect deals with urban facilities already in existence and involves primarily curative measures for environmental geologic problems of these facilities. The urbanizing aspect has to do with facilities not yet in existence. It deals with the role of geology in physical planning for cities, and therefore involves preventive measures for avoiding future environmental conflicts.

As used here, the term urban refers generally to concentrations of population not engaged in or supported directly by local agricultural pursuits. The scope of the methodology is confined to the immediate area of influence of the urban center being investigated. Distal effects of the city, such as environmental geologic problems of procurement of resources far removed from the city, are not considered. Also, environmental geological aspects of the study area that are not directly related to urbanization are not in general taken into consideration. For example, if a city were 4 located in an area where mining for metallic ore is also taking place, the use of this methodology would not account for the environmental geologic problems associated with that mining activity. Because most geologic problems of urban areas are caused by the improper use of land, the focus of this study will be on the environmental geologic implications of various urban land uses. Also, the main objective of this study is the mitigation and prevention of environmental conflicts of urban facilities and activities with their physical environment. Consequently, the avoidance of conflicts among various land uses stemming from their proximity to each other is not generally accounted for.

This study is organized into six chapters. Following this introductory chapter, Chapter 2 presents the methodology for conducting environmental geologic study of urban and urbanizing areas. In Chapter 3 the San Marcos case study area is described in general terms and the data sources are delineated for use in subsequent sections. Chapter 4 demonstrates the curative part of the methodology and uses the case study area as an example for the investigation of environmental geologic problems of urban facilities already in existence. Chapter 5 demonstrates the preventive part of the methodology by showing how environmental geology can be used in physical land use planning in the case study area. Chapter 6 rounds out the text with a short summary and conclusions, and the geologic report which serves as the backbone of the study appears in the Appendix. The plates referred to in the text are in a pocket at the end of the dissertation.

The San Marcos area was chosen as a case study chiefly because it is situated in the Interstate 35 growth corridor between Austin and San Antonio and because it is not yet fully urbanized. The suitability of the area as a case study is evaluated in Chapter 3.

2 Chapter 2. A Methodology for Environmental Geologic Investigation of Urban and Urbanizing Areas

A successful methodology for environmental geologic study of growing urban areas should meet three requirements: 1) It should be universally applicable; that is, it should be usable in as many urban areas as possible, regardless of their location or geologic setting; 2) It should be comprehensive; all of the significant environmental conflicts must be accounted for; and 3) It should be systematic, so that it can be readily comprehended and rigorously applied. In addition, the methodology must provide for both the curative and preventive aspects of the environmental geology of growing urban areas, as discussed in Chapter 1. The objective of this chapter is to develop in concept a methodology which meets these criteria.

Because of the fundamental ecological basis of environmental geology, the approach will be to emphasize the interaction of urban facilities with their environments. Both the impact of the environment on the facilities and the impact of the facilities on the environment will be considered. The primary emphasis will be on the geologic environment. Factors related to the atmospheric or biologic environment will be given little attention, and the cultural environment is considered only insofar as current land use and existing land use control measures are concerned. Social, political, and economic factors are not accounted for, but their relation to the geologic factors in physical land use planning is described.

The procedure of this chapter will be to: 1) analyze the components of urban areas and geologic environments, 2) describe the general nature of the interaction of urban areas with their geologic environments, 3) delineate the natural and cultural data sources to be used in subsequent steps, 4) present a method for systematically studying the environmental conflicts of existing urban systems, 5) describe a procedure for evaluating the capability of land to sustain the demands placed on it by various urban facilities, so that future environmental conflicts can be avoided, and 6) present a diagrammatic summary of the methodology.

2.1 Components of Geologic Environments and Urban Systems

Before a rigorous methodology for environmental geologic investigation of growing urban areas can be developed, a clear distinction should be made between a city and its geologic environment. Once this distinction is made, effective conceptual tools can be developed by analyzing the components of each. The objective of this section is to develop these tools by introducing organizational schemes for both urban systems and geologic environments.

2.1.1 Components of the Geologic Environment

A description of the geologic setting of a growing urban area should: 1) present the geological data in a way that reflects both how the geology influences urbanization and how it is influenced by urbanization, 2) concentrate on surface geologic phenomena, since much of the interaction of cities with their geologic settings occurs at the surface or in the shallow subsurface, and 3) be widely applicable. A scheme of organization that has these characteristics recognizes three broad categories – substrate, processes, and landform.

2.1.1.1 Substrate

The subsurface materials of a city fulfill three basic functions. First, they bear the weight or loads of buildings and other urban structures. Second, they are the medium that is excavated and used as fill as the land is modified for the city. Finally, the substrate serves as the source of locally derived low-value resources that are essential to the city's growth. The first two functions depend on the physical properties of the substrate, and the third depends on its resource potential. Because of these two vastly different aspects of the substrate, it is described below in two categories - physical properties and resource potential. As noted earlier, only the upper few meters of the substrate usually have significant implications for urbanization. Included in this zone are the soil horizons and the upper part of the bedrock. There are exceptions to this generalization, however, as exemplified by problems that are sometimes associated with utilization of ground water resources.

Physical Properties

The physical properties of the substrate determine how it will respond to the activities and stresses imposed by urbanization. Some important physical properties are shear strength and bearing capacity, consolidation characteristics under loading, swelling potential, corrosive potential, and porosity and permeability. These properties in turn depend upon more fundamental characteristics of the substrate, such as lithology and chemical composition, amount and chemical character of subsurface water, large and small scale structure, and amount and interconnection of void space. Physical properties are commonly different at depth in the bedrock than near the surface where bedrock has been altered by soil-forming processes. For this reason the physical properties are described in two parts – a deep substrate or engineering geology part and a shallow substrate or soils part.

Resources

Certain natural resources are very important in determining the suitability of an area for urbanization. These resources include the low-unit-value commodities, such as aggregates and water, which are essential to the maintenance and growth of a city. If they are not locally available in sufficient quantity, the cost of urbanization increases considerably, and if they are present, considerable environmental conflict frequently arises from their utilization. The indication of the resources on a map not only aids in their utilization, but also delineates areas where urbanization should be delayed until the resources have been utilized. Soil resources and locally derived food resources for the city are not accounted for in this study.

2.1.1.2 Processes

The geologic processes at work in an area also have much impact on urbanization. The processes of concern are geologic processes which occur at a rapid rate. Examples of important surface processes are fluvial, coastal, and mass movement processes. Subsurface processes of importance include earthquakes, fault movement, volcanism, regional tectonic subsidence, and subsidence associated with the withdrawal of ground water or petroleum. Other processes, such as karst processes and aquifer recharge, take place partly at the surface and partly in the subsurface. A map should be prepared to indicate where the significant processes are active.

2.1.1.3 Landform

As used in this study, the term landform refers to the shape of the earth's surface in the broadest sense rather than to geomorphic features. The landform of an area does not usually have as great an impact on urbanization as do the substrate and the processes. Also, landform is usually more subject to modification than are the substrate or the processes; excavation and filling operations are conducted in virtually all cities as they are built. Nevertheless, topography does affect the pattern of land development and contributes to the relative suitability of an area for urbanization. Not only does the landform determine the extent of cutting and filling required as urbanization proceeds, but it also dictates to a large extent the impact the urbanization will have on the environment. The landform can be described in many ways, but one of the most useful for indicating suitability for urbanization is to show the areal distribution of slope.

2.1.2 The Urban System

Just as the geologic environment can be divided into components that are useful for investigating the city-environment interaction, so can cities be classified based on their interaction with the geologic environment. A useful organizational scheme for this purpose views the city as a system having four components – urban situs, urban input, urban output, and transportation. The relationships among these components is shown diagrammatically in Figure 2-1. Each of the four components of the urban system is discussed briefly in this section, and the types of environmental problems to be considered in each are outlined. Because many urban environmental problems result from the use or misuse of urban land, the major land uses comprised by each category are also described.

2.1.2.1 Urban Situs

The urban situs component includes those aspects of the city-environment interaction which result from the physical location of the city. The problems considered in this component arise because the city is located at a particular site; these problems would be different or possibly would not exist at all if the city were located elsewhere. The problems include both the effect of the geologic environment on the city, such as the geologic hazards, and the effect of the city on the environment, such as uncontrolled waste materials released to the local environment. The concept of urban situs will be clarified considerably in later sections where the urban system scheme is actually applied.

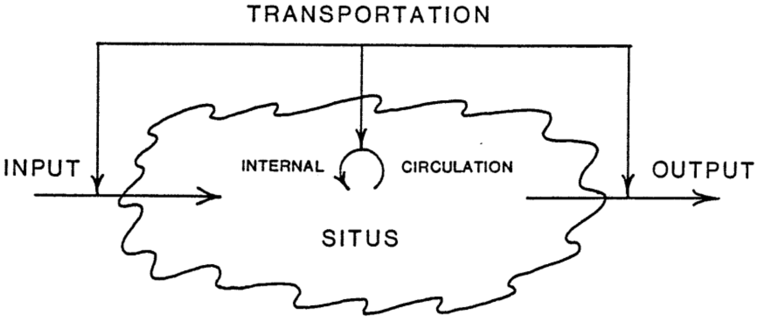


Figure 2-1. The Urban System

Because of the strong locational aspects of this component, urban land use plays a strong role in the problems considered. Many urban land use classifications have been formulated, but they all have basically the same categories with different groupings of these categories. Chapin (1965) presents a summary of a widely used systematic classification. Two simpler but useful classifications are given here:

A. Yeates and Garner, 1971, p. 234:
   1. Residential
   2. Industrial
   3. Commercial
   4. Roads and highways
   5. Public and semipublic
   6. Vacant

B. Detroit Metropolitan Area Regional Planning Commission, 1962:
   1. Residential
   2. Extractive and industrial manufacturing
   3. Manufacturing
   4. Transportation, communication, and utilities
   5. Commercial
   6. Personal, business, and professional services
   7. Public and quasi-public services
   8. Recreation
   9. Unused space

Some of the categories could be used directly, whereas others would require subdivision to more specific land uses. It would be futile in this study to attempt a comprehensive urban land use classification applicable to all cities. Instead, the classification should be tailored to suit the particular urban area under study.

2.1.2.2 Urban Input

Urban input consists of the energy and material commodities that are brought into the city for its maintenance and growth. A convenient classification of urban input consists of two categories - finished and unfinished commodities. The finished commodities are usually manufactured goods and are either transported into the city from some distance or are produced at industrial facilities in the city. Generally, they are not significant to the urban input category of this study, although they may be important to other categories such as urban output or transportation.

The unfinished commodities comprise the raw materials that are consumed or transformed within the city. These materials can be classed into two categories - goods produced locally and goods imported from some distance away. The imported unfinished goods are generally significant to this study only insofar as their transport into the area is concerned. The locally derived, unfinished commodities therefore have the greatest local environmental significance. These commodities are the low-unit-value, high-place-value resources (Bates, 1969, p. 7) that constitute the essential local basis for the growth and maintenance of a city. Examples of these resources are aggregates, such as crushed stone and sand and gravel, and water, including both ground water and surface water.

On first impression it may seem that the urban input category outlined here is essentially synonymous with the resources category introduced earlier for the geologic environment. However, there is a great difference in the application of these two. The resources category refers to the presence and location of the resources, whereas the urban input category is used as a vehicle for describing environmental problems associated with actual use of the resources.

Many types of resource extraction activities, such as gravel pits and stone quarries, require definite, sole commitment of land use, at least for the lifetime of the operation. Other activities, such as ground water pumpage, involve little or no exclusive commitment of land use.

2.1.2.3 Urban Output

The output which emanates from cities is of two basic types - finished goods and wastes. The finished goods comprise much of the economic value produced by the city and often provide the major economic reason for the city's existence, but they usually do not cause severe local environmental geologic problems. However, the wastes generated by a city comprise some of the most severe environmental conflicts associated with urban systems.

Urban wastes are amenable to many classifications. An important distinction to be made is between controlled and uncontrolled waste output. Uncontrolled waste output is released to the environment at or near the point of generation within the city. Examples are heat energy released to the atmosphere at industrial plants and solid waste discarded by residents as litter. Environmental degradation caused by this kind of waste is best considered in the urban situs category. Controlled waste output is that which is systematically collected, perhaps treated, and finally disposed of. This type of waste is the main topic of this section. Controlled waste output can be effectively classified as follows:

I. Solid wastes
    A. Individual and municipal wastes
        1. Individual dumps
        2. Collective dumps
        3. Sanitary landfills
    B. Industrial wastes
II. Liquid wastes
    A. Individual and municipal wastes
        1. Septic tank and drainfield systems
        2. Sewage treatment plants
    B. Industrial wastes
III. Gaseous wastes
IV. Energy (heat) wastes
    A. Air disposal
    B. Water disposal

Some of the categories of this classification require a commitment of land use at least for the duration of their operation, whereas others require no land use commitment at all. Solid waste disposal sites not only require land use commitment during operation, but also greatly restrict the use of the land after operations cease. Septic tank and drainfield systems, on the other hand, are designed specifically to be used in the subsurface while the surface is used for entirely different purposes. The gaseous and energy wastes often have few environmental geologic implications.

2.1.2.4 Transportation

Transportation is classed as a discrete component of the urban system because it ties a city together and links it to the surrounding area. Included in the transportation category are the common means of moving people, materials, and energy. Some of the components of urban input and output, excluded from those categories because they were significant only insofar as their transport is concerned, are indirectly considered in this category. Perhaps the most effective classification of the transportation component is according to the means of transport, as follows:

I. Automobiles and trucks
    A. City streets
    B. Roads and highways
II. Railroads
III. Mass transit systems
    A. Surface
    B. Subsurface
IV. Airports
V. Pipelines
VI. Power lines

Some of the environmental problems of the transportation facilities that are located within a city (internal circulation) are probably more effectively considered in the urban situs section than in this section.

2.1.3 Interaction of the Urban System with Its Geologic Environment

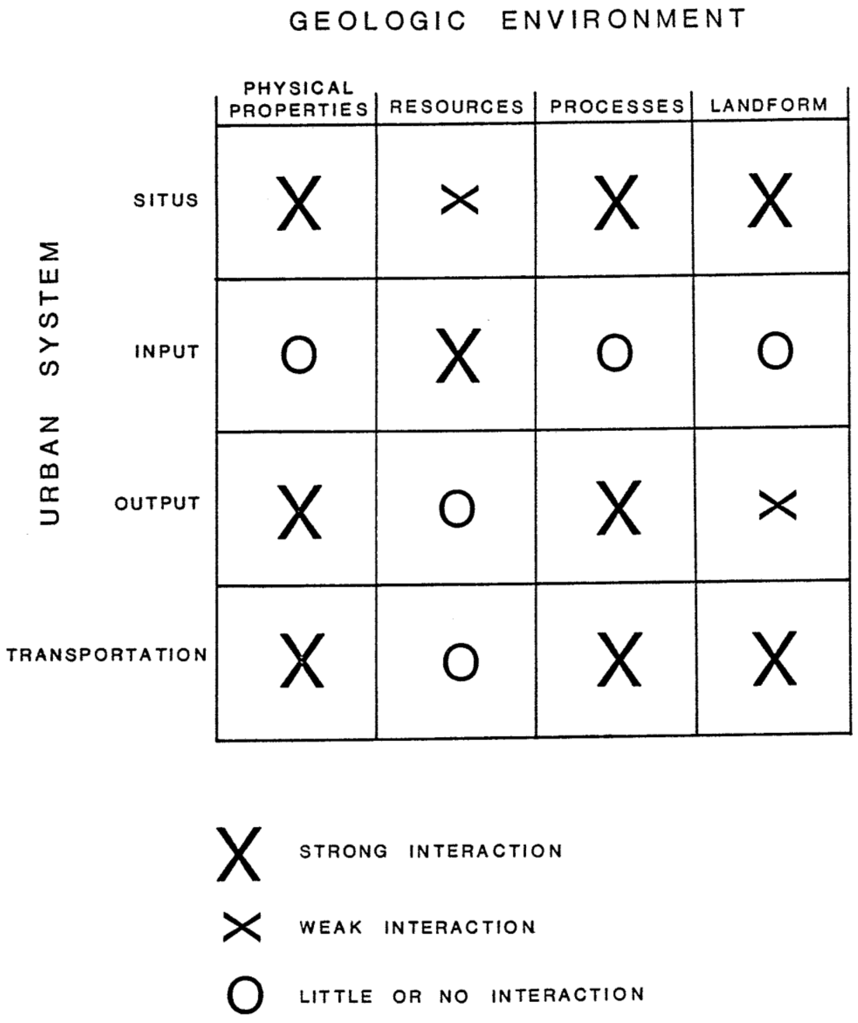
In summary, a clear distinction has been made between a city and its geologic environment. The urban system has been subdivided into four components which have different kinds of interaction with the geologic environment, and the geologic environment has likewise been subdivided, as shown in the following outline:

I. Substrate
    A. Physical properties
        1. Engineering Geology
        2. Soils
    B. Resources
II. Processes
III. Landform

The degree of interaction between the components of urban systems and their geologic environments can be illustrated by the conceptual interaction matrix in Figure 2-2. Although this interaction is shown in simplified form in the figure, it is in fact highly complex because each of the components of the urban system and the geologic environment are themselves highly complex. The crux of the problem of conducting environmental geologic investigation of urban and urbanizing areas thus lies in analyzing the conflicts arising from the interactions indicated in the matrix. An additional complicating factor is the two-fold nature of the problem noted in the introduction – the determination of conflicts between the geologic environment and urban facilities already in existence, and the prevention of future problems by incorporating environmental geologic considerations in physical land use planning for future urban systems. After the generation of the data source maps is described, the remainder of this chapter will approach each of these parts of the problem separately.

2.2 Generation of Data Sources

The first step in the methodology is to define the limits of the study area and generate the data sources that will be used in subsequent steps. The components described in the preceding section will be used to organize the data sources, and the data will be presented as a series of maps. Two broad classes of data – natural and cultural – are important in the environmental geologic investigation of growing urban areas, so the maps of this section will be presented in the context of this two-fold classification. A topographic map is probably the best base map for the data source maps.



GEOLOGIC ENVIRONMENT

URBAN SYSTEM	PHYSICAL PROPERTIES	RESOURCES	PROCESSES	LANDFORM
SITUS	X	×	X	X
INPUT	O	X	O	O
OUTPUT	X	O	X	×
TRANSPORTATION	X	O	X	X

X STRONG INTERACTION

× WEAK INTERACTION

O LITTLE OR NO INTERACTION

Figure 2-2. Interaction between Components of the Urban System and Components of the Geologic Environment

2.2.1 Definition of the Study Area

When a growing urban area is selected for environmental geologic study, the limits and extent of the area to be included in the investigation must be determined. The area to be covered depends on several factors: 1) the areal extent of existing urbanization; 2) the amount of area external to the urbanization but still under its strong influence, where land is used for resource procurement or waste disposal; 3) the rate or urban growth; 4) the primary projected directions of growth and any extant physical barriers, such as large water bodies; and 5) the length of time for which the planning period extends. Once the boundaries have been set, the scale of the data source maps can be determined. The scale should be as large as possible within the limits imposed by manageable map size, the resolution or quality of the data to be presented, and the economics of map reproduction.

2.2.2 Natural Data Sources

The natural data sources portray the geologic characteristics of the area. In the preparation of these maps the organizational scheme of the geologic environment is used, and a map is prepared for each of the lowest level categories. All map units of each category can usually be shown on a single map. However, if these units are numerous and overlapping, which is possible on the Resources and Processes maps, it may be desirable to use more than one map to avoid confusion. This procedure could, of course, be carried to the extreme so that a separate map could be prepared for each map unit. The Engineering Geology, Soils, and Landform maps will not have overlapping units and are therefore best shown as a single map.

2.2.2.1 Engineering Geology Map

The Engineering Geology map is intended to portray the engineering characteristics of the substrate below the soil zone. In this map geologic units are grouped together into physical property map units, and the location, extent, and distribution of each unit are depicted. The map is backed up by a table of the map units containing a qualitative description of each unit and, if data permit, the important engineering properties of the units. The physical properties of the substrate below the soil zone are a function of the bedrock, so the Engineering Geology map is a direct derivative of the conventional geologic map. The type of geologic map which should be prepared for derivation of the Engineering Geology map is discussed in a later section.

2.2.2.2 Soils Map

The physical properties of the bedrock are often greatly altered near the surface by soil-forming processes. The function of the Soils map is to express the areal distribution of the physical properties of the substrate above the bedrock. Probably the best type of soil unit to use is the soil series. The current soil classification used by the U. S. Department of Agriculture, Soil Conservation Service (Soil Survey Staff, 1960) is based on objective physical and chemical criteria (Buol, Hole, and McCracken, 1973, p. 198). Soil series recognized on the basis of this classification therefore adequately represent the physical properties of the shallow substrate. Most soil reports now published by the Soil Conservation Service include a tabulation of the physical and engineering properties of each soil series. A similar tabulation should accompany the soils map prepared for this study.

Soil series maps are best prepared by professional soil scientists who have a working knowledge of the somewhat difficult current soil classification. A considerable amount of work has been done on the application of soils data in land use planning for both urban and agricultural purposes. In some of this work soils data have been used somewhat unrealistically, such as for delineation of aquifer recharge areas. The use of soils information in this study is restricted to its more proper role of describing the distribution of the physical properties of the upper part of the substrate.

2.2.2.3 Resources Map

The Resources map shows the location, extent, and distribution of the low-unit-value, high-place-value resources that are essential to the growth and maintenance of an urban system. This map indicates both the availability of resources and the areas where urbanization should be delayed until the resources have been utilized. The resources shown are potential resources. Some of the resources indicated may not be economic to utilize because of market factors, and others may be unavailable because they are located on land whose value is too high for change to resource exploitation.

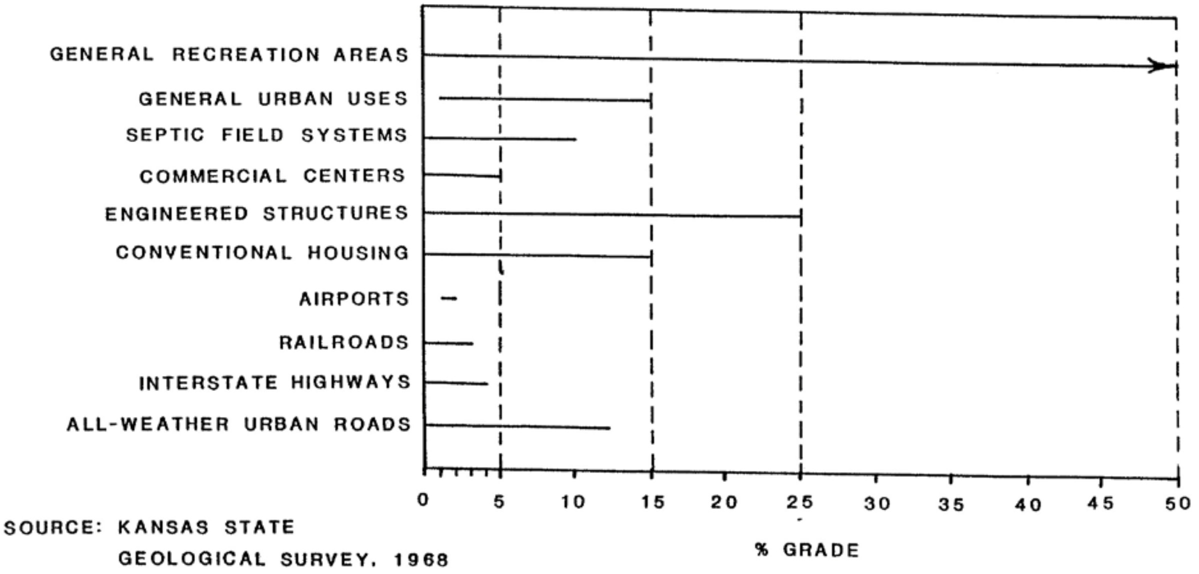
Resources are shown irrespective of any use that is made of them; resource utilization and the associated environmental implications are accounted for in a later section of the methodology. The resources are restricted to those which come from the substrate below the soil zone. Soil resources are primarily of agronomic value and are not considered here to be significant enough to local urbanization to warrant coverage. The resources indicated are further restricted to those that are related directly to local urban systems. Other geologic resources which are present but are not essential to urban growth and maintenance are not generally shown, even though they may be important to the economy of the city.

2.2.2.4 Processes Map

The Processes map shows the extent and distribution of the active geologic processes which have or are likely to have an impact on urbanization. The most important processes shown on this map are those which pose a geologic hazard to urban systems. Examples of the units depicted are flood-prone areas, unstable slope areas, and active faults. Some processes can be directly interpreted from the geologic map, whereas others, such as flood-prone areas, are determined only with considerable additional field work.

2.2.2.5 Landform Map

The purpose of the landform map is to depict the shape of the land surface in a way that best reflects how that shape will affect urbanization. As noted earlier, one of the most useful maps for this purpose is a slope map. Probably more than any other landform characteristic, slope determines the suitability of a site for various urban land uses and dictates the extent of landform change required to make the site more suitable for these uses. The units depicted on a slope map are areas having a certain range of slope values. The limits of the slope categories used as map units depend on the landform of the area being investigated and on the judgement of the investigator. The Kansas Geological Survey (1968, p. 11) presented a set of slope categories which are very useful for indicating relative suitability for various urban land uses (Figure 2-3). The slope map is derived directly from the topographic map of the study area.



SOURCE: KANSAS STATE GEOLOGICAL SURVEY, 1968

Figure 2-3. Optimum Ranges of Slopes for Various Urban Installations and Activities

2.2.2.6 Derivation of Natural Data Sources

The primary sources from which most of the natural data sources are derived are topographic and geologic maps. Topographic maps are available from the U.S. Geological Survey for most of the major urban areas in the United States. Geologic maps are not available for many urban areas, however, and where they are available, often they are not accurate enough or at a sufficiently large scale. Consequently, the preparation of a suitable geologic map is frequently necessary before environmental geologic investigation of an area can begin. The type of geologic map to be prepared for environmental geologic analysis depends largely on the kind of geology' in the area. A conventional ge9logic map which uses rock-stratigraphic units as defined in the Stratigraphic Code (American Commission on Stratigraphic Nomenclature, 1961) may be an excellent map, inasmuch as rock-stratigraphic units are defined on the basis of lithology and mappability. Since many of the properties shown on the natural data source maps, such as physical properties and resource potential, depend directly on lithology, a rock-stratigraphic geologic map would seem an ideal source for the data source maps. However, in some areas, such as where the existing rock-stratigraphic nomenclature does not adequately reflect the lithology of the rocks, other methods of geologic mapping are more effective. An example of improved geologic mapping for environmental purposes in areas underlain by sedimentary rocks is the depositional systems mapping which has been done in recent years by the University of Texas Bureau of Economic Geology (Fisher and others, 1972; Fisher and others, 1973). The primary objective in determining the type of geologic map to prepare for the methodology of this study is to produce a map which best shows the lithology, geometry, spatial arrangement, and areal distribution of distinctive, mappable bedrock units.

2.2.3 Cultural Data Sources

The cultural data sources express man's current relation to the land, and the cultural factors depicted are the characteristics of the land resulting from the previous land uses and other land-related activities of man. Two aspects of man's relation to the land are of foremost importance to environmental geologic investigation - current land use and regulatory measures that have been instituted for future land use.

2.2.3.1 Current Land Use Map

The purpose of the Current Land Use map is to show how the land is being used by the owners and occupants of the land. These land uses may be categorized into two broad classes – urban-related and agricultural uses. The latter category generally denotes areas into which urbanization may expand in the future. Land in the urban-related use category can be further categorized according to the urban systems organizational scheme introduced above. Thus, four major classes of urban land use are recognized - urban situs, urban input, urban output, and transportation. Various land use categories can be delineated within each of these if necessary.

2.2.3.2 Land Use Control Map

The Land Use Control map delineates those parts of the areas of investigation in which some form of land use regulation is exercised. Such regulation includes measures, such as city zoning, which seek to make the uses of adjacent land areas compatible with each other. Also included are controls which attempt to reduce damages from geologic hazards, such as ordinances prohibiting development of flood-prone or landslide areas. In addition, some controls may have been instituted to provide a measure of protection for areas of resource value or particular environmental sensitivity, such as aquifer recharge zones and coastal lagoons and embayments.

The primary use of this map will be to depict areas which cannot be used for certain land uses under existing regulatory measures. The results of the environmental geologic analysis presented in this study could well be used, however, for recommending changes in these measures. New criteria for land use controls may emerge, and new areas may be found which should be included under existing controls. In addition, some areas may be found which are limited unnecessarily and can safely be removed from control. The Land Use Control map is the most ephemeral of the data source maps; the areas shown are easily changed by actions as simple as a vote of a city councilor a directive of a state agency.

2.2.3.3 Derivation of Cultural Data Sources

The Land Use Control map is derived by obtaining the data from the appropriate regulatory authorities, such as a city government or a state agency. The Current Land Use map is prepared from several sources. One of the most important of these is the topographic map which is used, if it is available, as the base map for all the data source maps. Many important current land use features, including roads, railroads, buildings, and water bodies can be found on a topographic map. Another important source of information is a land ownership map, which is often available from the local real estate taxing authority. The land ownership map indicates the degree of land subdivision; large areas of single ownership usually denotes agricultural use, whereas numerous small land parcels indicate a more urban usage. After the topographic and land ownership maps have been utilized, aerial photographs should be examined because they usually indicate land uses directly if they are recent enough. The final step in determining current land use is field verification. The results of the initial steps, which are conducted in the office, are checked, and the areas of uncertainty are clarified.

2.2.4 Summary and Discussion

In summary, the conceptual tools developed in the first part of the chapter were utilized in this section for organizing the natural and cultural data source maps which will be used in subsequent steps in the methodology. The maps presented are probably best thought of as the "minimum basic" data sources needed. Other nongeologic factors, such as a biologic assemblages map, could also be generated at this stage for later use. The Soils map, since it is only partly related to the geology, illustrates the potential for a more interdisciplinary scope of this section of the methodology. However, this study is restricted primarily to the geologic concerns of urbanization.

It will be noted that an environmental geologic map has not been presented as one of the data source maps. It would be possible, of course, to combine the data source maps to produce a composite map illustrating the most significant land characteristics. This composite map would constitute one type of environmental geologic map. However, this approach may require deletion of less important but nevertheless still significant factors. The data source maps presented here attempt to depict the physical characteristics separately and in as complete a form as possible. They will be used in the following sections for identifying existing urban environmental geologic problems and for evaluating land suitability for future urban uses.

2.3 Environmental Geologic Problems of Existing Urban Systems

Most urbanizing areas have an existing urban center which serves as the nucleus for urbanization of the surrounding outlying areas. The objective of this section is to utilize the conceptual tools and data sources developed earlier and to construct a systematic procedure for investigating the environmental geologic problems of existing urbanization. This section thus addresses the curative aspect of urban environmental geology described in the introductory chapter.

Either a geologic approach or an urban systems approach could be used in this section. If the geologic approach were used, the various components of the geologic environment could be analyzed individually and the interaction of each with the existing urbanization could be considered. If the urban systems approach were used, each component of the system could be investigated and the interaction of each with the geologic environment could be described. The urban systems approach is adopted here because it is more likely to be universally applicable. That is, different cities generally have more in common than do different geologic settings. This approach also ensures that no significant urban facilities will be omitted from consideration. Completeness of coverage of the geologic environment has already been provided for in the generation of the natural data sources.

The procedure of this section is to systematically consider each of the four major components of the urban system and delineate the environmental conflicts associated with the facilities and activities of each. Within each component either of two approaches can be used. If an interactive approach is used, the activities and facilities of the component are considered as a whole, and their interaction with the environment is analyzed. In the subcomponents approach the specific activities and facilities are considered individually and their environmental conflicts are examined. Both approaches will be used in succeeding sections.

Regardless of which approach is used, the procedure consists of a three-step process. First, the Current Land Use map, which shows the locations of the existing urban facilities, and the natural data source maps are studied to identify potential conflicts. Next, the facilities are visited in the field to confirm or refute the existence of the problems and to identify other problems not anticipated by map study. Finally, recommendations are made either for alleviation of the problems or for further study before corrective action is taken. The recommendations for eliminating or lessening the conflict may entail such steps as engineering modification of the site or, where unavoidable, actual changes in existing land uses. This procedure in effect identifies environmental problems stemming from the inability of the land at the locations of the urban facilities to sustain the demands of those facilities. The procedure in the final section of the methodology attempts to avoid these conflicts by siting future urban facilities on land which is most capable of sustaining their demands.

2.3.1 Urban Situs

As noted in the section where the urban situs concept was introduced, the environmental problems described in this category result from the location of a city in a particular geologic setting. Falling within the scope of this category are the urban facilities within the city and the associated urbanization in the surrounding outlying area. As was shown in the land use classification of cities, most urban areas comprise a large variety of land uses. Consequently, the subcomponents approach, in which each land use is considered individually, is not used. Instead, the interaction approach will be used, and the city will be considered as a whole. First, the impact of the environment on the city will be analyzed and then the impact of the city on the environment will be considered.

2.3.1.1 Impact of the Environment on the City

The greatest impact of the environment on a city is in the form of what are commonly viewed as geologic hazards. The hazards posed for a city vary widely across the entire spectrum of geologic conditions in which cities have been built. A few examples, including floods, landslides, and active faults, have already been mentioned. Most geologic hazards stem from geologic processes and will thus most likely be depicted on the Processes map. This map can therefore be used to delineate the various parts of the city that are likely to be subject to the different hazards. Field investigation will then document the extent and seriousness of these hazards.

2.3.1.2 Impact of the City on the Environment

Cities usually do little to enhance the overall quality of the natural environment. The impacts with which man is chiefly concerned are those which alter the environment in such a way that the environment in turn adversely affects man and his activities. Some typical examples, such as changes in the hydrology of the stream basin in which the city is located, pollution of surface water by uncontrolled wastes, and increased erosion and sedimentation, illustrate the kinds of impacts that should be considered. Clearly, the impact of a city on the geologic environment is primarily on the geologic processes and landform and to a lesser extent on the substrate. Field investigation of the existing urban facilities should identify the major impacts of the city on its geologic environment and document the seriousness of that impact.

2.3.2 Urban Input

The environmental conflicts analyzed in this category stem from utilization of the locally derived, low-unit-value resources. Because the types of activity involved in urban input are few, and because their environmental implications are usually quite different, the subcomponents approach is probably the most effective. The subcomponents of urban input are the different kinds of resources which are used for the growth and maintenance of a city, such as aggregates, water, and sometimes energy. Field investigation will usually disclose the environmental conflicts resulting from these activities or from post-operation land use or reclamation. The Resources map is not extensively used in this section. Its primary implication for urban input lies in the control that the indicated resources have exercised on the location of the input activities.

2.3.3 Urban Output

The environmental geologic problems included in this section stem from the disposal of wastes generated in the city. As in the previous category, the subcomponents approach is probably more effective than the interaction approach. The classification of urban wastes presented earlier in this chapter should be used, and the environmental problems associated with each category should be analyzed. The location of most of the various urban waste activities and disposal sites are shown on the Current Land Use map as a separate category. Potential problems at these sites can often be discerned by examination of the five natural data source maps. Field investigation is needed to confirm the presence or absence of these conflicts and to discover unanticipated conflicts. In general, these conflicts are primarily in one direction - impact of the site on the environment. The impact of the environment on most output facilities is minimal or of little significance.

2.3.4 Transportation

The environmental geologic problems associated with transportation facilities can probably be delineated equally well using either the interaction or the subcomponents approach. An effective organizational scheme for the categories of the transportation component was introduced earlier. Some of the categories, such as roads and railroads, are similar enough that they could be grouped together and analyzed using the interaction approach. On the other hand, the number of different components is commonly small enough that they can be efficiently analyzed individually. As was the case for the other components of the urban system, transportation facilities are shown as a separate category on the Current Land Use map. Environmental conflicts should be analyzed as before by comparing the Current Land Use map with the five natural data source maps and confirming the results by field investigation.

2.3.5 Summary and Discussion

The urban system organizational scheme has provided an effective means of systematically analyzing the environmental geologic conflicts of existing urban facilities and activities. If each of the four components of the urban system is considered in turn, most of the significant environmental geologic problems of a city can be effectively outlined.

The procedure was outlined step by step, but in practice some of the steps can be carried out concurrently. For example, site visitation to determine the presence and extent of environmental conflict is often done at the same time the geologic map or the data source maps are prepared. After the analysis is completed, recommendations should be made to solve or ameliorate the problems or at least to indicate where further study is needed before a solution can be recommended. As noted earlier, solutions to the indicated problems may involve engineering modifications at the sites of conflict or actual land use changes.

2.4 Environmental Geology in Physical Land Use Planning for Urban Growth

An important function of environmental geology is to prevent conflicts such as those disclosed in the preceding section from occurring in future urbanization. This function constitutes the preventive aspect of the environmental geology of urbanizing areas, and the objective is to optimize the interaction of the geologic environment and future urban activities and facilities. In this way the expensive and inefficient "patch-up" efforts to correct environmental conflicts can be avoided.

The approach of this section will be to evaluate the capability of the land to sustain the demands placed on it by the various facilities and activities of the urban system. Once this capability has been determined for the various urban land uses, it should be possible to fit future urbanization to the geologic environment. A successful technique of land capability evaluation must take several factors into consideration: 1) The various urban land uses must be considered separately, because different demands are placed on the land by different uses; 2) All of the demands of each land use should be considered, and the relative importance of the demands must be taken into account; 3) All of the significant characteristics of the land that determine its ability to meet those demands must be evaluated; and 4) The areal variation of these characteristics must be taken into consideration. The methodology of this section attempts to account for these factors by using the following five-step process:

1. Selection of the urban facility or land use for which the land suitability is to be evaluated
2. Construction of the blank suitability score grid
3. Screening procedure

4. Evaluation procedure
5. Verification procedure

This process must be repeated for each different facility or land use. The result of this process is a grid map for each projected urban use which shows in terms of a percent the relative suitability of the various parts of the study area for that use. This map of numerical values can then be used as the basic data source for optimally siting the various future urban facilities. The following paragraphs outline the five steps in detail and show how the results can be used in formulating a physical land use plan for the study area.

2.4.1 Selection of Land Use

The first step of the procedure is to select the urban use for which the land is to be analyzed. The urban systems organizational scheme provides an effective tool here for outlining the various urban land uses anticipated for a study area. The land use selected determines to a large extent the data source maps that will be used in succeeding steps. A data source map that is used extensively for one land use may be utilized very little or not at all for another land use. Also, the stage at which the data source maps are used will vary for different land uses. For example, a data source used only in the screening procedure for one land use may be used extensively in the evaluation procedure for another use.

2.4.2 Construction of the Blank Suitability Score Grid

After the urban land use has been selected, the next step is the construction of the blank suitability score grid. This uniformly sized grid will be used in subsequent steps to overlay the data source maps, and the individual grid squares will be the units used in evaluating land suitability.

A grid system has some inherent drawbacks for land evaluation. One of the main problems is the use of a rigid network of uniform grid cells to overlay data source maps that portray irregularly shaped map units. A corollary to this problem is that of boundaries; many of the grid squares will inevitably fall astride the boundaries between map units. The decision must then be made between which unit will be represented in the square. However, a superior and easily applied alternative to the grid system has not yet been devised (Ferris and Fabos, 1974). Grid squares will therefore be utilized here as the basic land elements in the following steps.

The major problem to be solved in this step is the determination of the coarseness of the grid. Two opposing factors have great impact on grid coarseness: 1) The finer the grid is, the more exact the final results will be. Smaller grid squares divide the area into smaller units, and the areal variation of the land characteristics can be more accurately expressed. Thus, a finer grid enhances the resolution of the final result. 2) The coarser the grid is, the less is the work in applying the procedure. Each grid square is considered many times in the procedure below. If the grid square dimensions are halved, the number of grid squares to be evaluated is quadrupled, thus making more difficult an already time-consuming process.

Three major factors must be considered in determining grid coarseness: 1) the size of the study area and the scale of the data source maps; 2) the size of the smallest map units on the data source maps; and 3) the size of land parcel required by the land use for which the land is being analyzed. The maximum grid square size allowable is generally determined by the size of the smallest data source map units and the size of the land parcel required by the land use. The minimum grid size depends on the size of the study area and the extent of use of automation in applying the procedure. The use of computers, as will be suggested below, may eventually provide the solution to most of the problems inherent to the grid overlay approach by permitting the use of very fine grids which can closely approximate actual field conditions.

2.4.3 Screening Procedure

The objective of the screening procedure is to eliminate areas that are totally unsuited for the land use under consideration. By removing these areas at this stage the needless effort of subjecting them to the rigorous evaluation of the next step is avoided. Examples of land characteristics which could cause some areas to be screened are zoning restrictions, current land use, susceptibility to floods, unstable slopes, and active faults. It could also be argued that some areas should b~ screened at this point because they have a potential for a better land use than that being analyzed for. This approach is not used here, however, because the relative suitabilities of all projected urban land uses are to be determined. The trade-offs and compromises necessary in actual land use determination should be made during the formulation of the physical land use plan as described in a later section.

The screening procedure is a six-step operation: 1) Decide which factors contribute to screening for the land use under consideration; 2) Arrange these factors in order according to the total area covered and the sizes of individual map units; 3) Beginning with the first factor, overlay the blank suitability score grid on the appropriate data source map and trace the boundaries of the screened areas; 4) Repeat step three for all the screening factors; 5) Combine the screened areas to depict the total "unacceptable'! area; and 6) Convert the results into the grid format by shading the grid squares in the unacceptable area. These shaded squares are assigned a value of zero for the Evaluation Procedure.

2.4.4 Evaluation Procedure

In the evaluation procedure the candidate areas left after the screening procedure are evaluated for their relative suitability for the urban land use under consideration. The procedure used for this suitability analysis is an assessment algorithm adapted from a decision-making technique developed by Miller (1970). This technique is a subjective, numerical method of making a decision where complex factors must be taken into account. One of the fundamental features of the procedure is the clear distinction that is made between the demands or requirements of the land use and the ability of the land, based on its physical characteristics, to meet those demands. This distinction makes it possible to outline the demands of a land use objectively and without regard to how well the area being investigated can meet the demands.

The adaptation of Miller's technique used here has involved some simplification. For example, as originally presented, the method was based on the assumption that most of the data needed to make a decision is available. The adaptation used here determines relative suitability of the land based on available data, which may not be complete. Also, the original version was developed for making a decision only once. As applied here, the same decision-making process is applied many times – once for each square of the grid. Despite these changes, the conceptual soundness of the method is left intact.

The procedure for land suitability analysis is outlined step by step in the following paragraphs. The devices used will be introduced and described and will be referred to thereafter with an abbreviation. A glossary of the terms introduced is given with the appropriate abbreviations near the end of this chapter.

2.4.4.1 Step 1. Conceptualize the Overall Objectives

In the first step the urban land use for which land is being analyzed is considered generally, and the broad categories of the demands which that use will place on the land are conceived. These categories are listed in random order as they come to mind. Examples of topics which might be included in this list are water quality protection, suitability of engineering characteristics of the substrate, and freedom from geologic hazards of a particular type. This list will be a starting point and will undoubtedly undergo many changes in subsequent steps.

2.4.4.2 Step 2. Construct the Demand Analysis Hierarchy

In this step the items on the list from Step 1 are subjected to a process of successive subdivision. Each item is divided into its conceptual components, and each component is further subdivided to a lower level. This process is continued until the lowest level criteria represent demands on the land for which a particular, specific property of the land can be measured to indicate how well the land can meet this demand. The result of this subdivision process is a treelike hierarchy (Figure 2-4), designated the Demand Analysis Hierarchy (DAH), whose trunk is the land use being analyzed for and whose largest branches are the overall objectives established in Step 1. The outermost branches at the other end of the hierarchy are the Lowest Level Demand Criteria (LLDCs).

The generation of the DAH is a dynamic, fertile process in that many changes are made as the subdivision proceeds. Some criteria may be included as parts of others, and new criteria may continually emerge. Criteria may also change positions of level within the hierarchy. If the DAH is generated in this manner, nearly all of the demands imposed on the land by the urban use under consideration should be determined. Many of these demands, however, are eliminated here from further consideration in subsequent steps. For example, the degree to which some of the demands are met is measured by characteristics which are uniform over the study area. For rating the relative suitability within an area, there is clearly no point in considering this kind of demand.

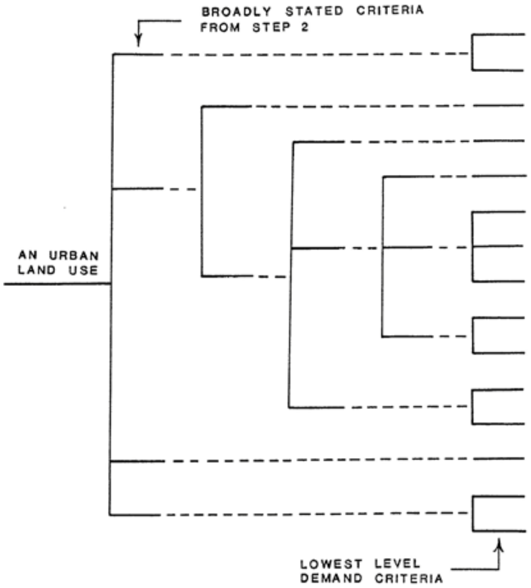


Figure 2-4. Diagram of a Demand Analysis Hierarchy

Also, demands which fall beyond the scope of this geologically oriented analysis are not considered. Another type of demand that is eliminated is that which depends on the location attributes of a site. That is, each site (grid square) is analyzed for its inherent physical characteristics only, and the location of the site with respect to other facilities or activities is not taken into account. Consideration of locational attributes is reserved for the formulation of the physical land use plan as outlined in a later section.

The criteria which are deleted from further consideration in subsequent steps in effect constitute "dead branches" of the DAH. In generating the DAH the best procedure is probably to formulate the hierarchy complete with dead branches and then to signify these branches with some type of symbol. A key to the symbols should then be presented to explain the rationale for branch elimination. The DAH is therefore generated in two stages - formulation of the complete DAH followed by elimination of the dead branches to obtain a condensed DAH.

For practical purposes, particularly if subsequent steps are carried out without the benefit of automation, the number of LLDCs which can be considered is limited to about thirty or forty. A larger number requires too much effort in managing the data. If the condensed DAH has greater than this number, then two alternatives are available. On the one hand the condensed DAH could be derived as described above and then, after the weighting process of Step 5, the low-weight LLDCs could be eliminated. This solution is not particularly satisfactory, but is relatively safe as long as no more than 10% of the weight is thus deleted. A second alternative would be to abandon formulation of the DAH for this land use and begin anew with two or more subcategories of the land use. For example, one might attempt to construct a DAH for a housing development only to find that the number of LLDCs generated is far too large. He might then begin again using specific aspects of the development, such as septic tank suitability or foundation suitability, as the land use demands.

In some hierarchies, there may be a repetition of branches in different parts of the hierarchy. If these branches "work" in the same direction, they will reinforce each other, and if they "oppose" each other, they will cancel each other out in proportion to their weights.

In summary the analysis of land use demands by the hierarchy method should be a highly effective approach. The method not only assures that no criteria will be omitted, but also shows how the criteria are related to each other. In addition, the demands are subdivided to a level where their degree of satisfaction can be determined by a clear, measurable physical characteristic of the land.

2.4.4.3 Step 3. Select the Physical Performance Measures

After the DAH has been completed and reduced to the condensed DAH, the Physical Performance Measures (PPMs) must be selected. For each LLDC a characteristic of the land is selected as the best measure of how well the land is able to meet the demand represented by that criterion. It is this characteristic which serves as the conceptual bridge between the demand criteria of the DAH and the actual physical properties of the land in the area under study. In theory, the PPMs are formulated only after the DAH has been completed. In practice, however, the measures that will ultimately be used must be kept in mind during subdivision of the DAH in order to know when the subdivision can stop. In other words the associated PPM helps to define what constitutes an LLDC.

The land characteristic chosen as a PPM for a particular LLDC depends primarily on the LLDC itself, but it is also determined in part by the nature and quality of the information on the data source maps. In an ideal case, where all the data on all land characteristics of an area is available in map form, a measure could be selected which would rate the land exactly for the LLDC . In practice, however, such complete data are never available, so an approximate measure must be used. Step 6 provides a means of measuring the relative effectiveness of PPMs for their associated LLDCs. Examples of typical LLDCs are shown in Table 2.1 with some possible associated PPMs.

2.4.4.4 Step 4. Formulate the Suitability Score Functions

After the PPMs have been chosen for the LLDCs, a device must be formulated for actually rating the land according to the PPMs. The mechanism designed to fill this need is the Suitability Score Function (SSF). An SSF provides the means for assigning a dimensionless numerical value to a land unit (grid square) which is a direct indication of the ability of the unit to meet the LLDC. As the name implies, an SSF is usually in the form of a mathematical function whose axes are set up in standard Cartesian coordinates. The units of the PPM are established along the x-axis, and a scale of score points from 0 to 100 is placed on the y-axis. The relation between the score points and the units of the PPM (that is, between the x-axis and y-axis values) is then expressed by sketching a curve of the appropriate shape in the x-y space. The delineation of this relationship is

LLDC	PPM
1. Excavation potential	1. Depth to bedrock
2. Shape of land surface	2. Slope
3. Ground water proximity	3. Depth to water table
4. Potential for infiltration	4. Substrate permeability
5. Potential for bearing a load	5. Substrate shear strength

Table 2-1.
Typical Lowest Level Demand Criteria and Associated Physical Performance Measures

the key element of this step of the evaluation procedure. The shape of the curve is determined on the basis of judgement and experience, and numerous factors must be considered in its determination. Probably the best procedure is to consult the literature and solicit the opinion of several professionals experienced in working with the land use under consideration. As will be shown in Step 7, the SSFs are applied to each grid square and a dimensionless score value is assigned to the square.

Several variations of the SSF as described above are possible. Most SSFs will probably use arithmetic scales on both axes, but in some functions semilog or log-log scales may be more desirable. When reliable quantitative descriptions are available for the PPM, numerical units should be used on the x-axis of the SSF, and the function will then usually be a smooth curve. Sometimes, however, only qualitative descriptions are available for the PPM, and the function should then be a step function with score values assigned to different verbal descriptions. Quantitative data can also be scored using discrete steps rather than a smooth curve by assigning particular score values to ranges of values on the abscissa. This capability of translating equally well both qualitative and quantitative data into score values is one of the major advantages of the SSF approach to land rating. Another important advantage is the translation of physical characteristics of many different types into easily compared dimensionless score value units. Examples of some different SSFs are illustrated in Figure 2-5.

Ideally, the units of the SSF abscissa should be determined only by the LLDC with which the SSF is associated. In practice, however, these units must to some extent depend also on the data available and the range of data in the area under study. There is little point, for example, in including within the range of the abscissa values that are not represented within the study area.

2.4.4.5 Step 5. Assign Weights to the Demand Analysis Hierarchy

After the SSFs have been formulated, it is necessary to return to the DAH to perform a weighting operation. The purpose of this step is to determine the relative importance of the land use demand criteria set forth in the DAH. The condensed DAH is used, and beginning at the highest level of the hierarchy tree, the relative importance is estimated in percent terms for each criterion at that level. This process is repeated within subcategories down the hierarchy tree until the level

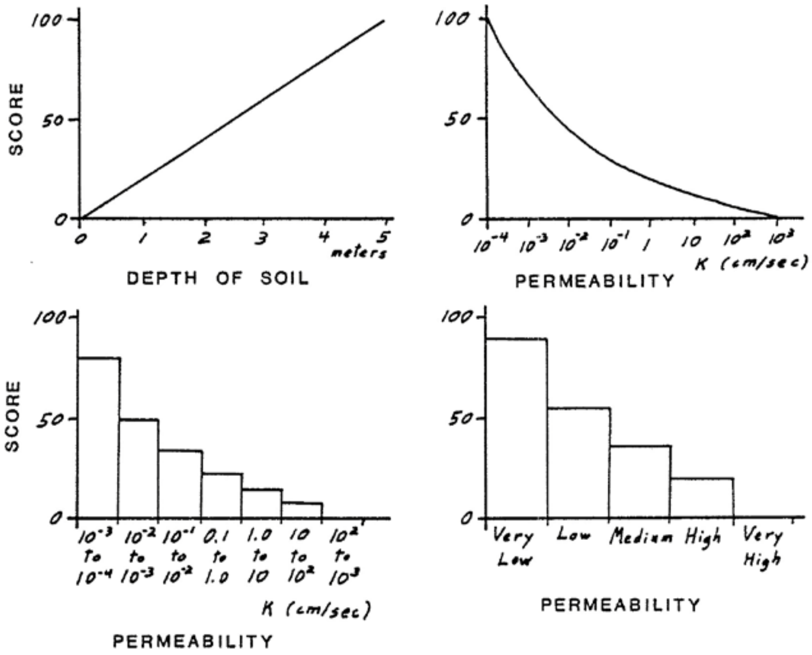


Figure 2-5. Examples of Suitability Score Functions

of the LLDCs is reached. The process is always performed within a subcategory and at a particular level on the basis of 100 (percent). When the procedure is completed for all branches of the DAH, the weights are distributed proportionately by multiplication down the various branches. That is, at each level, the weight allotted to that level is distributed among the criteria at that level by multiplying that weight by the percent assigned to each criterion. The final result of this process is the assignment of a weight to each LLDC. The sum of the weights of the LLDCs should, of course, equal 100. An example illustrating this procedure is shown in Figure 2-6. The first number of each branch is the percent assigned to reflect the importance of that branch relative to its peers. The second number (in parentheses) is the net weight of the branch obtained by multiplying the percent times the weight allotted to all branches at that level.

The percentages assigned to the various branches of the DAH are determined from judgement and experience as in the preceding step. Probably the best approach is again to search the literature and to obtain a consensus of opinion from experienced professionals.

2.4.4.6 Step 6. Adjust the Weights

It was noted in Step 3 that the PPMs assigned to the various LLDCs often do not, mostly because of incomplete data, exactly measure the ability of the land to meet the demand criterion. Therefore, an adjustment of the raw weights derived in the preceding step is necessary to allow for the varying degrees of effectiveness of the PPMs. The procedure for this adjustment is to consider each LLDC and its associated PPM and to make an estimate, in percent terms, of the effectiveness of the PPM. This percentage, called an adjusting factor, is then multiplied by the

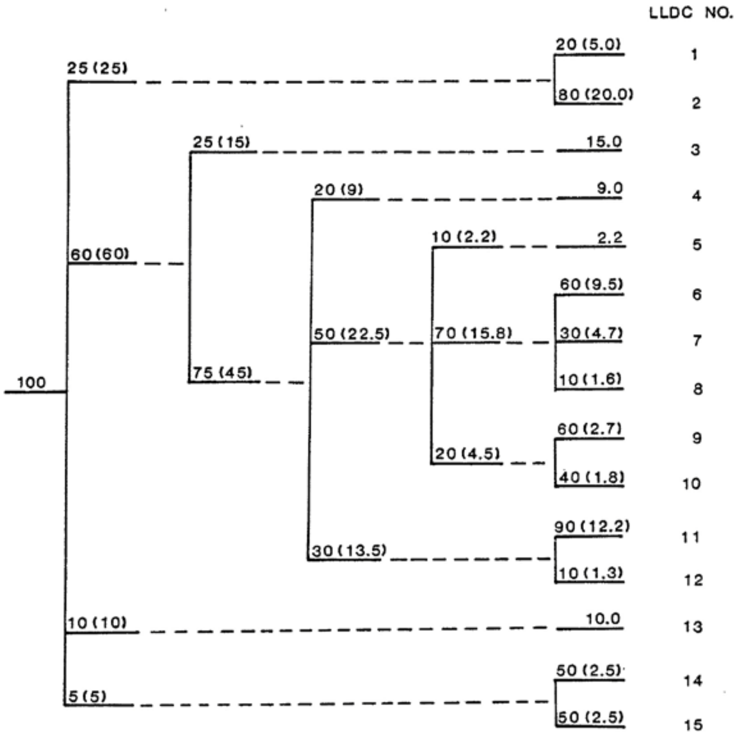


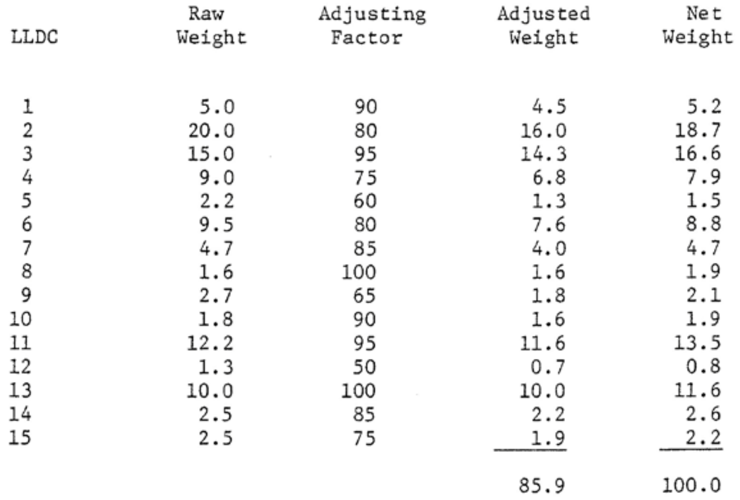
Figure 2-6. Example of the Weighting of the Demand Analysis Hierarchy

raw weight to yield an adjusted weight. The process is repeated for all LLDCs, and the adjusted weights are then recalculated to a basis of 100, resulting in a net weight for each LLDC. An example demonstrating this process for the hierarchy in Figure 2-6 is shown in Table 2-2.

The net effect of this step is to emphasize those LLDCs for which the data is best. However, it should be noted that, as shown in Table 2-2, although there is some transfer of weight, no gross changes in the weight distribution has occurred. Thus the original derivation of the raw weights in the preceding step has far greater effect on the final results than the weight adjustments of this step.

2.4.4.7 Step 7. Prepare the Suitability Score Grids

With the completion of Step 6, the preparatory work for land suitability assessment is finished and the actual assessment process can begin. Three tools that were developed earlier in this chapter are utilized: 1) the data source maps; 2) the blank suitability score grid; and 3) the score functions. The procedure for preparation of the Suitability Score Grids (SSGs) begins with the first LLDC in the DAH. The associated SSF is selected, and the previously screened blank suitability score grid is overlaid on the appropriate data source map. The data source map selected depends on the PPM and SSF of the LLDC under consideration. After the blank grid is



LLDC	Raw Weight	Adjusting Factor	Adjusted Weight	Net Weight
1	5.0	90	4.5	5.2
2	20.0	80	16.0	18.7
3	15.0	95	14.3	16.6
4	9.0	75	6.8	7.9
5	2.2	60	1.3	1.5
6	9.5	80	7.6	8.8
7	4.7	85	4.0	4.7
8	1.6	100	1.6	1.9
9	2.7	65	1.8	2.1
10	1.8	90	1.6	1.9
11	12.2	95	11.6	13.5
12	1.3	50	0.7	0.8
13	10.0	100	10.0	11.6
14	2.5	85	2.2	2.6
15	2.5	75	1.9	2.2
			85.9	100.0

Table 2-2. Example of Adjustment of Weights of Lowest Level Demand Criteria

overlaid in proper register, the scoring of the grid squares begins. Each square is examined and the map unit overlain by the square is noted. The SSF x-axis value associated with that map unit is noted and the corresponding score value (y-axis value) is derived from the SSF. This score value is then assigned to the grid square. The procedure is repeated for all the grid squares of the grid except those that were eliminated and assigned a value of zero in the screening procedure. The entire process is carried out for each LLDC, resulting in a number of SSGs equal to the number of LLDCs.

The most important part of this step is the determination of the SSF x-axis values corresponding with the map units of the various data source maps. As noted earlier, the maps used in this step are primarily the five natural data source maps. The scoring process is quite easy if the data corresponding to the abscissa parameters have been tabulated for the data source map units. These parameters can be either qualitative or, preferably, quantitative. If such a tabulation is not available, then one of three approaches can be used: 1) An estimate may be made for each grid square directly from the data source map, and the score value can then be assigned; 2) A separate map showing the distribution of the parameter in question can be prepared as a derivative from the data source map; or 3) A score map can be prepared as a type of derivative map. The difference among these approaches, however, is more apparent than real.

Some of the data source maps, particularly the Engineering Geology and Soils maps, portray map units having a large number of associated characteristics. It may therefore be expected that these maps will be used for the grid overlay several times during the preparation of the SSGs.

Occasionally, an LLDC will have an associated PPM and SSF for which none of the data source maps will provide a value for determining a score. In such cases, there are two alternatives. Either a supplemental data source map which will supply the required values can be prepared or, if this option is not feasible, the conservative approach can be adopted and a score of zero assigned for that LLDC to all grid squares. This option is equivalent to using an adjusting factor (Step 6) of zero, and has a direct impact on the validity of the results, as will be shown below.

In theory, as described above, one SSG is prepared for each LLDC. However, several LLDCs, some of which are identical and some of which have different names, will use the same PPH and therefore the same SSG. Duplicate SSGs could be prepared for each of these LLDCs, but an equivalent and easier approach is to add the weights of all these LLDCs. In this way, only one SSG need be prepared and the combined weights of the LLDCs used in the next step. When SSGs are prepared manually as they are in this study, the maximum number that can be reasonably considered is approximately twenty, depending on the number of grid squares used in the blank suitability score grid.

2.4.4.8 Step 8. Calculate the Suitability Index Map

The final step of the land suitability analysis procedure is the calculation of the Suitability Index Map (SIM). The data used in this step are the SSGs from Step 7 and the net weights derived in Step 6. The procedure for calculating the SIM is a two-step operation. First, the SSG for each LLDC is converted to a weighted SSG by multiplying the net weight of the LLDC by the score value of each grid element in the SSG. Second, the SIM is derived by summing the weighted SSGs in stack fashion. That is, the weighted SSGs are stacked one above the other and the values of corresponding grid elements are added together. The resulting sums are the final suitability scores or suitability indexes, and the grid of sums is designated the SIM. A diagram illustrating the two-step procedure is shown in Figure 2-7.

The SIM should, if all steps have been performed properly, indicate in percent terms the relative suitability of each grid element for the land under consideration. In theory, the SIM should indicate both the absolute suitability of the land and the relative suitabilities of different parts of the land in the area under study. However, some of the simplifications in preceding steps have limited the usefulness of the SIM in an absolute sense. Some of the factors which determine the absolute suitability of the land were deleted when the complete DAH was reduced to the condensed DAH. Also, when the SSGs were formulated, some score values were assumed to be zero where data were lacking for determining the actual score value. Although the value of the SIM was reduced in its usefulness in the absolute sense by these measures, its value for indicating the relative suitabilities of the different grid elements, based on the factors and the data taken into account, has not been affected and remains valid.

2.4.4.9 Automation of the Evaluation

The application of the evaluation procedure is clearly an arduous task requiring manipulation of large quantities of data. Many of the steps of the procedure can be greatly simplified or enhanced by use of a digital computer. The generation and weighting of the DAH could be greatly aided if programming were available which would make it possible to do the hierarchy subdivision at a computer console. This capability is especially attractive if many DAHs must be constructed, as

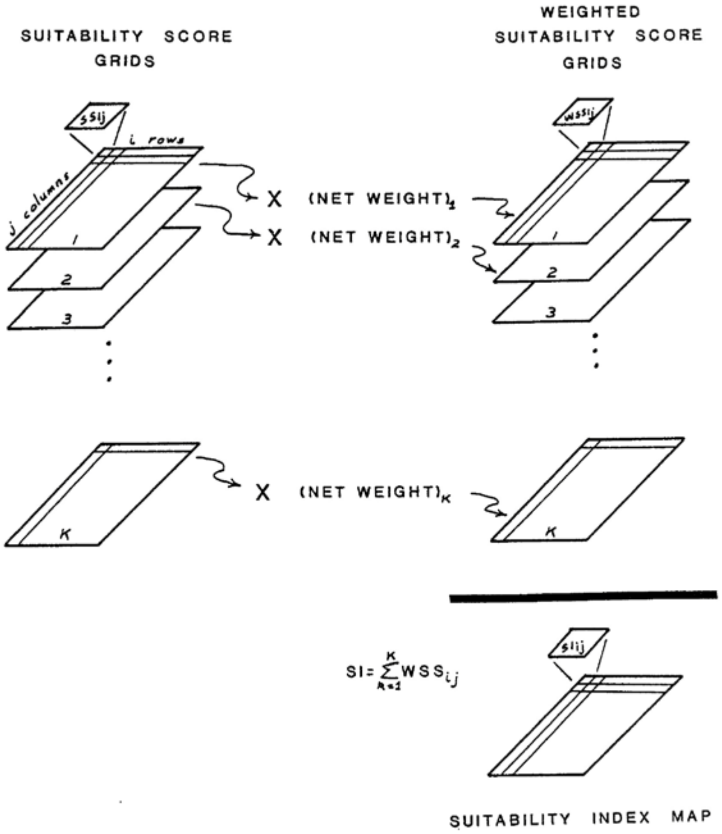


Figure 2-7. Calculation of the Suitability Index Map

is the case when land is evaluated for many different urban uses. The programming for hierarchy generation could also be written so that like branches of different hierarchies could be shared, thus allowing another savings of time.

One of the most promising uses of a digital computer lies in the construction of the SSGs. If the evaluation procedure is to become practical and widely applicable, a means must be found for aiding the arduous process of scoring the hundreds or thousands of grid squares in each SSG, and then repeating the process for several different SSGs. Automation of the process is particularly important when fine grids are used to closely approximate actual field conditions. Computers could be used to formulate the SSGs by the following steps: 1) The data source maps could be imaged in computer memory or on magnetic tape by using one of several geographic information systems now available (Ferris and Fabos, 1974); 2) The SSFs could also be stored in computer memory; 3) The blank suitability score grid could be represented in computer memory as a two-dimensional matrix; 4) For each matrix, the computer could be instructed which data source map is to be used and what x-axis value of the SSF is associated with each map unit on the data source map; and 5) The machine could then be made to "look at" each grid square (matrix element), note the data source map unit within the grid square, extract the appropriate score from the SSF, and assign that score to the matrix element.

These uses of the computer have great potential for future application, but much programming remains to be done before they are possible. Such extensive programming is not undertaken here. The objective of this section is to present and demonstrate a methodology, not to conduct a large exercise in computer programming. The computer is used here, however, for calculating the SIM as described in Step 8. High-speed computation capability is essential both for converting the SSGs to the weighted SSGs and for summing the weighted SSGs to obtain the SIM. A flow chart, computer program, and deck structure for the calculation of the SIM are shown in Figures 2.8 to 2.10. This program is written for an SSG having a maximum width of forty elements and a maximum length of fifty elements. If a greater width is needed, another run of the program is required for an adjacent grid. The length of the grid can be increased either by making another run of the program as before or by increasing the parameters of the DIMENSION statement of the program. This program is written for a uniform grid size both within each SSG and for all SSGs. It would be possible to develop a program which allows the use of different sizes of grid squares, but the effort of additional programming exceeds the effort saved by using the smaller number of grid squares made possible by a variable grid size.

Several other uses of the computer in this methodology can be pointed out, but will not be elaborated here. Contouring programs for converting point data to area data in map form are available, for example, and many different display techniques of output of land data have been developed. Interesting examples have been presented by Turner and Coffman (1973) and by Tillman, Upchurch, and Ryder (1975).

2.4.5 Verification Procedure

After the screening and evaluation procedures have been completed, the results must be verified. The verification procedure is conducted in two stages. The initial stage takes place before formulation of the physical land use plan and consists merely of checking the Suitability Index Map with the data source maps to eliminate obvious errors. The second stage is done after the physical land use plan is completed. It involves confirming the results of the Suitability Index Map by checking the sites chosen for the various planned urban land uses in the field. This field checking consists of a minimum of site visitation and may include considerable additional work, such as detailed local field mapping or collection of subsurface samples for engineering tests.

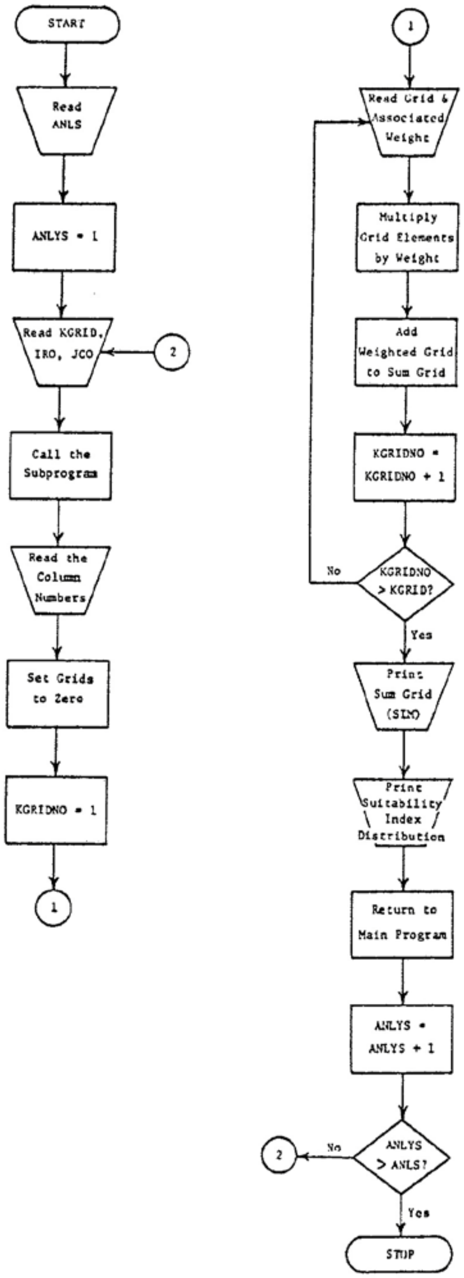
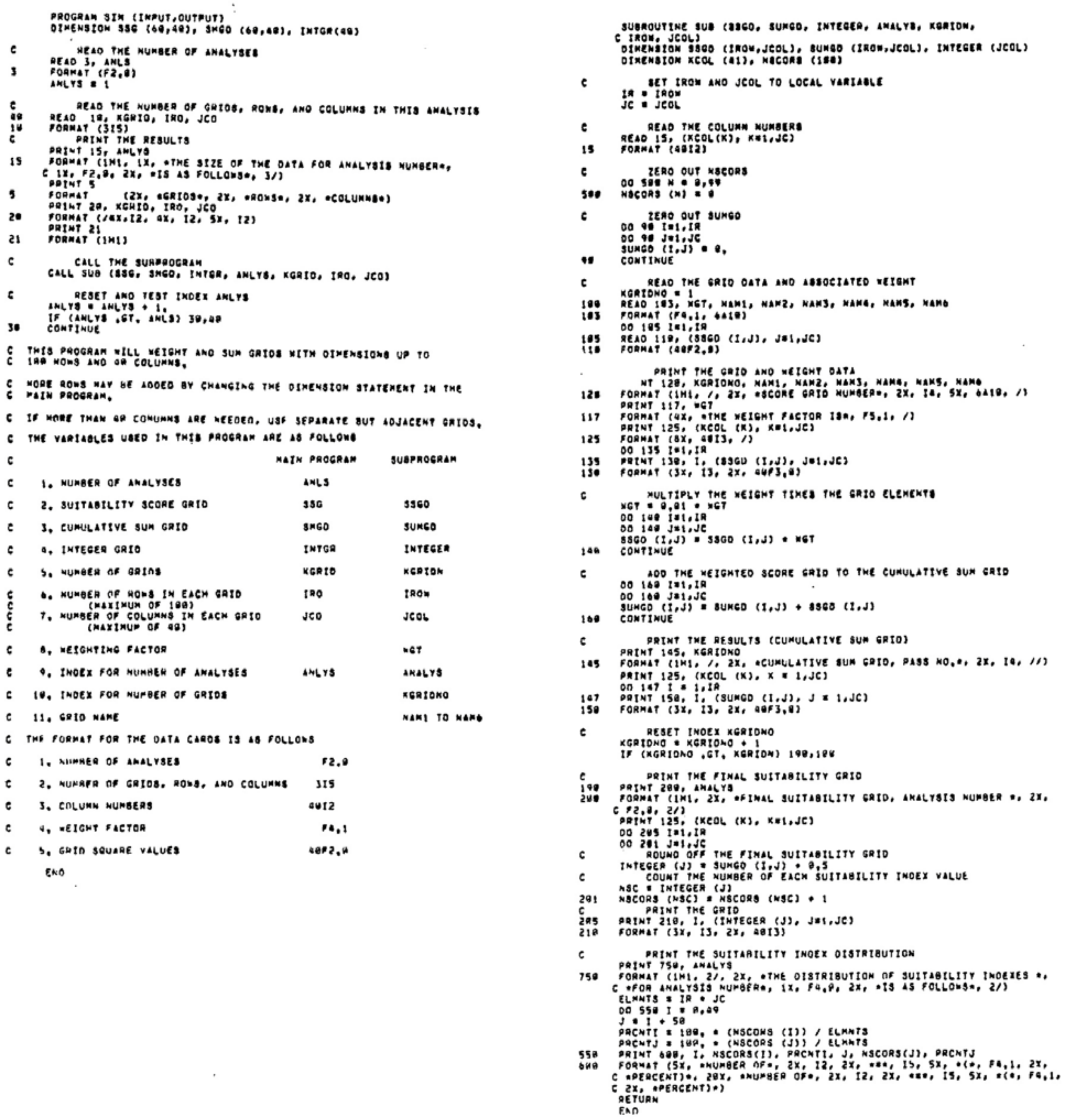


Figure 2-8. Flow Chart of Computer Program for Calculation of the Suitability Index Map



```
      PROGRAM SIM (INPUT,OUTPUT)
      DIMENSION SSG (60,40), SMGD (60,40), INTGR(40)

C          READ THE NUMBER OF ANALYSES
      READ 3, ANLS
3     FORMAT (F2.0)
      ANLYS = 1

C          READ THE NUMBER OF GRIDS, ROWS, AND COLUMNS IN THIS ANALYSIS
40    READ  10, KGRID, IRO, JCO
10    FORMAT (3I5)
C          PRINT THE RESULTS
      PRINT 15, ANLYS
15    FORMAT (1H1, 1X, *THE SIZE OF THE DATA FOR ANALYSIS NUMBER*,
     C 1X, F2.0, 2X, *IS AS FOLLOWS*, 3/)
      PRINT 5
5     FORMAT      (2X, *GRIDS*, 2X, *ROWS*, 2X, *COLUMNS*)
      PRINT 20, KGRID, IRO, JCO
20    FORMAT (/4X,I2, 4X, I2, 5X, I2)
      PRINT 21
21    FORMAT (1H1)

C          CALL THE SUBPROGRAM
      CALL SUB (SSG, SMGD, INTGR, ANLYS, KGRID, IRO, JCO)

C          RESET AND TEST INDEX ANLYS
      ANLYS = ANLYS + 1.
      IF (ANLYS .GT. ANLS) 30,40
30    CONTINUE

C  THIS PROGRAM WILL WEIGHT AND SUM GRIDS WITH DIMENSIONS UP TO
C  100 ROWS AND 40 COLUMNS.

C  MORE ROWS MAY BE ADDED BY CHANGING THE DIMENSION STATEMENT IN THE
C  MAIN PROGRAM.

C  IF MORE THAN 40 COLUMNS ARE NEEDED, USE SEPARATE BUT ADJACENT GRIDS.

C  THE VARIABLES USED IN THIS PROGRAM ARE AS FOLLOWS

C                                           MAIN PROGRAM     SUBPROGRAM

C    1. NUMBER OF ANALYSES                    ANLS

C    2. SUITABILITY SCORE GRID                SSG              SSGD

C    3. CUMULATIVE SUM GRID                   SMGD             SUMGD

C    4. INTEGER GRID                          INTGR            INTEGER

C    5. NUMBER OF GRIDS                       KGRID            KGRIDN

C    6. NUMBER OF ROWS IN EACH GRID           IRO              IROW
C            (MAXIMUM OF 100)
C    7. NUMBER OF COLUMNS IN EACH GRID        JCO              JCOL
C            (MAXIMUM OF 40)

C    8. WEIGHTING FACTOR                                       WGT

C    9. INDEX FOR NUMBER OF ANALYSES          ANLYS            ANALYS

C   10. INDEX FOR NUMBER OF GRIDS                              KGRIDNO

C   11. GRID NAME                                              NAM1 TO NAM6

C  THE FORMAT FOR THE DATA CARDS IS AS FOLLOWS

C    1. NUMBER OF ANALYSES                        F2.0

C    2. NUMBER OF GRIDS, ROWS, AND COLUMNS     3I5

C    3. COLUMN NUMBERS                          40I2

C    4. WEIGHT FACTOR                             F4.1

C    5. GRID SQUARE VALUES                      40F2.0

      END
```

```
      SUBROUTINE SUB (SSGD, SUMGD, INTEGER, ANALYS, KGRIDN,
     C IROW, JCOL)
      DIMENSION SSGD (IROW,JCOL), SUMGD (IROW,JCOL), INTEGER (JCOL)
      DIMENSION KCOL (41), NSCORS (100)

C          SET IROW AND JCOL TO LOCAL VARIABLE
      IR = IROW
      JC = JCOL

C          READ THE COLUMN NUMBERS
      READ 15, (KCOL(K), K=1,JC)
15    FORMAT (40I2)

C          ZERO OUT NSCORS
      DO 500 N = 0,99
500   NSCORS (N) = 0

C          ZERO OUT SUMGD
      DO 90 I=1,IR
      DO 90 J=1,JC
      SUMGD (I,J) = 0.
90    CONTINUE

C          READ THE GRID DATA AND ASSOCIATED WEIGHT
      KGRIDNO = 1
100   READ 103, WGT, NAM1, NAM2, NAM3, NAM4, NAM5, NAM6
103   FORMAT (F4.1, 6A10)
      DO 105 I=1,IR
105   READ 110, (SSGD (I,J), J=1,JC)
110   FORMAT (40F2.0)

           PRINT THE GRID AND WEIGHT DATA
        NT 120, KGRIDNO, NAM1, NAM2, NAM3, NAM4, NAM5, NAM6
120   FORMAT (1H1, /, 2X, *SCORE GRID NUMBER*, 2X, I4, 5X, 6A10, /)
      PRINT 117, WGT
117   FORMAT (4X, *THE WEIGHT FACTOR IS*, F5.1, /)
      PRINT 125, (KCOL (K), K=1,JC)
125   FORMAT (8X, 40I3, /)
      DO 135 I=1,IR
135   PRINT 130, I, (SSGD (I,J), J=1,JC)
130   FORMAT (3X, I3, 2X, 40F3.0)

C          MULTIPLY THE WEIGHT TIMES THE GRID ELEMENTS
      WGT = 0.01 * WGT
      DO 140 I=1,IR
      DO 140 J=1,JC
      SSGD (I,J) = SSGD (I,J) * WGT
140   CONTINUE

C          ADD THE WEIGHTED SCORE GRID TO THE CUMULATIVE SUM GRID
      DO 160 I=1,IR
      DO 160 J=1,JC
      SUMGD (I,J) = SUMGD (I,J) + SSGD (I,J)
160   CONTINUE

C          PRINT THE RESULTS (CUMULATIVE SUM GRID)
      PRINT 145, KGRIDNO
145   FORMAT (1H1, /, 2X, *CUMULATIVE SUM GRID, PASS NO.*, 2X, I4, //)
      PRINT 125, (KCOL (K), X = 1,JC)
      DO 147 I = 1,IR
147   PRINT 150, I, (SUMGD (I,J), J = 1,JC)
150   FORMAT (3X, I3, 2X, 40F3.0)

C          RESET INDEX KGRIDNO
      KGRIDNO = KGRIDNO + 1
      IF (KGRIDNO .GT. KGRIDN) 190,100

C          PRINT THE FINAL SUITABILITY GRID
190   PRINT 200, ANALYS
200   FORMAT (1H1, 2X, *FINAL SUITABILITY GRID, ANALYSIS NUMBER *, 2X,
     C F2.0, 2/)
      PRINT 125, (KCOL (K), K=1,JC)
      DO 205 I=1,IR
      DO 201 J=1,JC
C          ROUND OFF THE FINAL SUITABILITY GRID
      INTEGER (J) = SUMGD (I,J) + 0.5
C          COUNT THE NUMBER OF EACH SUITABILITY INDEX VALUE
      NSC = INTEGER (J)
201   NSCORS (NSC) = NSCORS (NSC) + 1
C          PRINT THE GRID
205   PRINT 210, I, (INTEGER (J), J=1,JC)
210   FORMAT (3X, I3, 2X, 40I3)

C          PRINT THE SUITABILITY INDEX DISTRIBUTION
      PRINT 750, ANALYS
750   FORMAT (1H1, 2/, 2X, *THE DISTRIBUTION OF SUITABILITY INDEXES *,
     C *FOR ANALYSIS NUMBER*, 1X, F4.0, 2X, *IS AS FOLLOWS*, 2/)
      ELMNTS = IR * JC
      DO 550 I = 0,49
      J = I + 50
      PRCNTI = 100. * (NSCORS (I)) / ELMNTS
      PRCNTJ = 100. * (NSCORS (J)) / ELMNTS
550   PRINT 600, I, NSCORS(I), PRCNTI, J, NSCORS(J), PRCNTJ
600   FORMAT (5X, *NUMBER OF*, 2X, I2, 2X, *=*, I5, 5X, *(*, F4.1, 2X,
     C *PERCENT)*, 20X, *NUMBER OF*, 2X, I2, 2X, *=*, I5, 5X, *(*, F4.1,
     C 2X, *PERCENT)*)
      RETURN
      END
```

Figure 2-9. Computer Program for Calculation of the Suitability Index Map

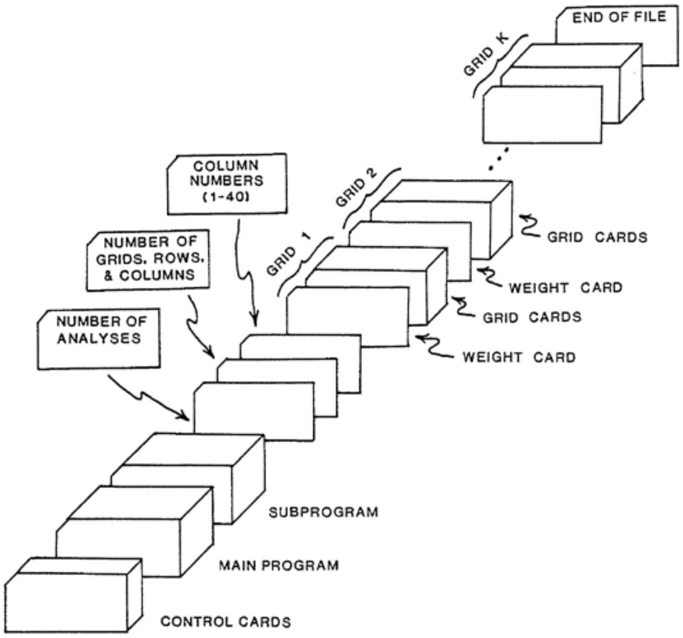


Figure 2-10. Deck Structure for Computer Program

2.4.6 Formulation of a Physical Land Use Plan

As noted earlier, the land suitability assessment procedure must be applied to each projected urban facility and activity, and the urban systems scheme provides a convenient and effective means of organizing these urban land uses. The Suitability Index Maps do not in themselves constitute a physical land use plan, but rather are a form of input to the formulation of such a plan. Land use planning is probably best conducted by trained professional planners who are equipped to consider other factors, such as social, economic, and political conditions, in addition to the physical suitability of the land when making final land use determinations. Nevertheless, the relative physical land suitability, as indicated by the Suitability Index Maps, should form the primary basis of land use decision-making. Areas characterized by grid squares having high Suitability Index values should be given highest priority for a given land use, and areas with Suitability Index values of zero (screened areas) should be avoided entirely. The nonphysical factors should control the location of an urban land use only within the context of areas having a high range of Suitability Index values.

One of the major achievements of the assessment procedure presented here lies in the fact that the planner or other land use decision-maker is supplied the information he needs about land suitability in an easily understood form. In theory, little or no knowledge is required about how the Suitability Index values are determined, and little or no technical knowledge about the factors considered is needed. In practice, however, more intelligent decision-making is possible if the planner has some appreciation for the data considered and the process of its analysis. Nevertheless, the procedure developed here bridges the communication gap between the planner and the geologist who provides him with the data he needs on land characteristics.

2.4.7 Discussion

Some aspects of the suitability assessment need further elaboration and discussion. Clearly, the primary emphasis of the methodology is on land use; the assessment procedure works best for urban facilities and activities requiring some commitment of land. Also, the suitability assessment is conducted according to the present state of the land. Engineering improvements of the land in addition to those which would be done for a facility regardless of where it is located are not taken into account. If some type of special land modifications were to be allowed for, then a second run of the assessment procedure would have to be made with the Suitability Score Grids appropriately changed. The primary thrust of the assessment is to control the immediate effects of a particular land use. Many secondary effects or implications of a land use are not accounted for.

As presented here, the procedure is used for land suitability assessment over a large area. It is equally applicable, however, for evaluating a single site having uniform properties over its entire area. In such cases the procedure is used in an absolute rather than a relative sense, so a complete DAH would have to be used and the data would need to be improved in order to avoid using score values of zero where data are lacking and to bring the weight adjusting factors of Step 6 close to 100. Because just one site is being evaluated, it should be economically feasible to obtain the detailed data needed. This approach could, in fact, be used as an intermediate step in the verification procedure. That is, in the formulation of the physical land use plan, when the sites for various future urban facilities are being chosen, the Suitability Index Map grid squares having the highest 2%, 5%, or 10% of Suitability Index values could be subjected to a "second cycle" of the assessment procedure. These grid cells could be selected for additional work to obtain more detailed and more exact data, and the procedure could be reapplied to the much smaller number of units. In this second cycle use of the improved data base and complete DAH would yield greatly improved results. The relative suitabilities of these sites would in effect be sharpened to indicate absolute suitability.

The overall effectiveness of the procedure depends on several factors. Foremost among these are the skill and experience of the personnel preparing for the evaluation, and the amount of time and care taken in the conduct of the evaluation. The construction and weighting of the Demand Analysis Hierarchy, the selection of Physical Performance Measures, and the formulation of the Suitability Score Functions should be done with the best expertise available. Once the score values of the various data source map units are determined, the preparation of the Suitability Score Grids is largely mechanical but should nevertheless be done with care. The quality of the data sources and the fineness of the score grid used also have a great effect on the results as discussed earlier. At its best, the procedure should indicate both the absolute and the relative suitability of the study area for various urban uses. At worst, the method at least forces an evaluator to layout and organize the criteria he is using to evaluate land.

Several possibilities for the extension and improvement of the procedure in the future can be readily discerned. In the first few applications of the procedure for different land uses all the steps must be repeated each time an analysis is conducted. Eventually it should be possible, however, to converge upon universal Demand Analysis Hierarchies which could then be condensed and modified for adaptation to specific areas. It should also be possible to test the correctness of the weights and score functions once the procedure is fully automated. Several analyses could be run with different weights and score functions to analyze the sensitivity of the results to these changes. However, care must be taken not to lose the objectivity built into the procedure. Changing and testing weights and scores should not degenerate to a juggling process to make certain "desired" areas appear most suitable.

As applied here the scope of the procedure is limited to certain geologic and cultural features of the study area. As noted earlier, this scope could easily be expanded to include many other land characteristics, such as vegetation assemblages, provided the appropriate data source maps were also prepared.

In summary, the procedure outlined in this section provides the framework for a method of rigorous assessment of land suitability for various urban uses. A better approach to the problem of land suitability assessment may be to construct a mathematical model of the interacting city and geologic environment under study. Using this model, projected urban uses could be hypothetically located at various places and the model run to test the environmental implications. However, models having the required degree of sophistication have not yet been developed. Perhaps the procedure outlined in this section will provide an interim solution to the problem of planning city growth to be compatible with the geologic environment.

2.4.8 Definitions

Demand Analysis Hierarchy (DAH) - The treelike structure resulting from the logical analytical subdivision of the requirements of an urban land use into their simplest elements, the Lowest Level Demand Criteria.

Lowest Level Demand Criterion (LLDC) - The simplest element of the DAH. Its relative degree of satisfaction can usually be measured (using an SSF) by a mappable physical characteristic of the area under investigation.

Physical Performance Measure (PPM) - A physical parameter associated with an LLDC which is intended to measure to what extent or how well the LLDC is satisfied by the land being evaluated.

Each PPM has an associated SSF which is used for the actual evaluation of the land.
Suitability Score Function (SSF) - The device used to translate a physical characteristic of a site (such as a grid square) into a value that reflects the relative degree which the site satisfies an LLDC. A different SSF is usually required for each LLDC and associated PPM.

Suitability Score Grid (SSG) - A grid resulting from overlaying a data source map with a blank grid and applying the SSF to each grid square. Each square is assigned a suitability score.

Suitability Index Map (SIM) - The grid resulting from summation of all the weighted SSGs for all the LLDCs of the DAH. Each grid square contains a number, the Suitability Index, which should reflect the relative suitability of that square for the land use under consideration.

2.5 Summary of Methodology

The methodology for conducting environmental geologic study of urban and urbanizing areas can be summarized in three major steps: 1) Delineation of the data source maps; 2) Analysis of environmental geologic problems of existing urban systems; and 3) Determination of the environmental geologic suitability of land for various future urban uses. These steps can be effectively illustrated by means of a procedural flow chart (Figure 2-11). The chart begins at the left with the definition of the limits of the study area. Next, the natural and cultural data source maps are generated and set aside for use in subsequent steps. The procedure then splits into two branches - a curative branch for the environmental geology of existing urbanization and a preventive branch for incorporating environmental geologic considerations in planning for future urbanization. The curative branch is relatively simple and straightforward. The urban systems organizational scheme is used, and the data source maps are input to the analysis of existing more complicated. The urban systems organizational scheme is again used, but in this case the land suitability for future urban land uses is evaluated. The procedure outlined for land suitability assessment is carried out for each land use, and the resulting Suitability Index Maps are used as the basic framework for formulating a physical land use plan.

This methodology was developed after literature review and as the result of experience gained from environmental geologic study of one case study area. Vast improvements can no doubt be made, but it is hoped that the procedure can contribute to more systematic and effective use of geology in improving the relation of cities to their geologic environments.

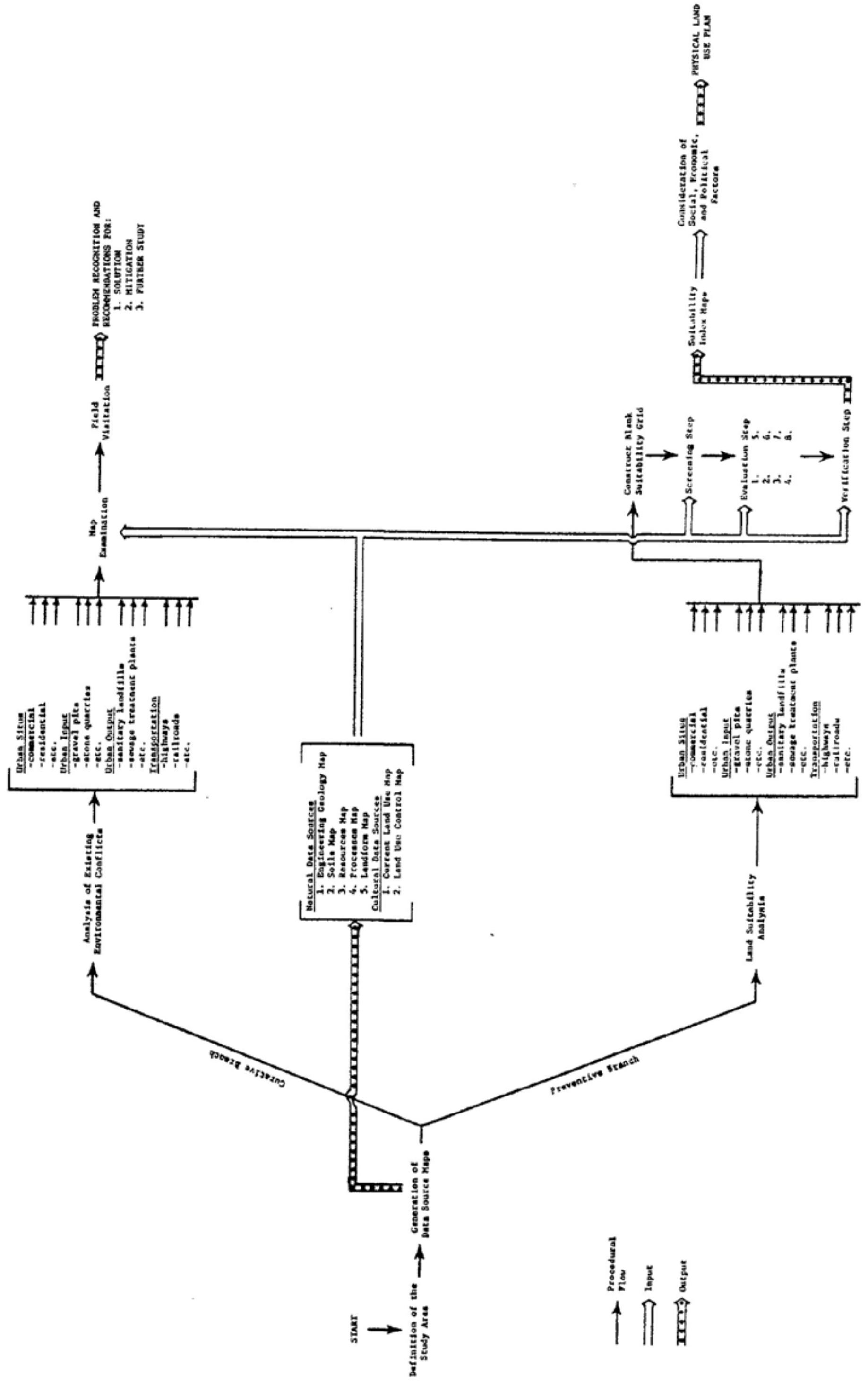


Figure 2-11. Procedural Flow Chart for Systematic Environmental Geologic Investigation of Urban and Urbanizing Areas Factor

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3 Chapter 3. Description of the San Marcos Case Study Area and Delineation of Natural and Cultural Data Sources

The first steps in applying the methodology of Chapter 2 to a case study area are to describe the area in general, including its boundaries, and to present the natural and cultural data sources which will be used in subsequent steps of the methodology. The San Marcos area was selected primarily for its merits as a case study for environmental geologic investigation of growing urban areas. The objectives of the study are strictly academic, and no direct recommendations are made for changes in present land uses or for land use control measures. However, geology has been important in determining past land use patterns in the area and will remain important in controlling land suitability for future uses as well. The influence of geology has been subtle and indirect in the past largely because the detailed geology has been poorly understood. This study should contribute to a greater understanding of the geology and its relation to urbanization in the area so that residents can take steps to improve this relationship.

3.1 Description of the Study Area

3.1.1 Location and Boundaries

The San Marcos area is in south-central Texas about 50 kilometers southwest of the capital city of Austin (Frontispiece, Figure 3-1). The area comprises two 7-1/2 minute quadrangles that are situated across the Balcones Escarpment and are in the Interstate 35 growth corridor. About 90% of the area is in Hays County, and the remainder is in adjoining Guadalupe and Caldwell Counties.

The area does not coincide with 7-1/2 minute topographic quadrangles of the U.S. Geological Survey, but is shifted northward by one-third quadrangle. The northern half, designated the Kyle section, includes the southern one-third of the Mountain City quadrangle and the northern two-thirds of the San Marcos North quadrangle. The southern half is designated the San Marcos section and encompasses the southern one-third of the San Marcos North quadrangle and the northern two-thirds of the San Marcos South quadrangle. This northward shift was made in order to include all of the city of San Marcos, which is split in half by the boundary between the San Marcos North and San Marcos South quadrangles, on a single map sheet and to include all of the reach of the Blanco River where it crosses the most intense part of the Balcones fault zone. The northern and southern boundaries of the entire area are latitudes 30 0 02'30"N and 29°47'30"N respectively, and the eastern and western boundaries are 97°52'30"W and 98°W. The area includes about 334 square kilometers (129 square miles).

The area as a whole is named the San Marcos area for the city of San Marcos, the major geographic feature and the primary influence on present and future urbanization in the area. Because the boundaries were chosen within the framework of U.S. Geological Survey topographic maps, a few of the urban facilities considered in the text are not within the map area. However, these facilities are located close enough to the area that site visitation was sufficient to get the data needed for the study.

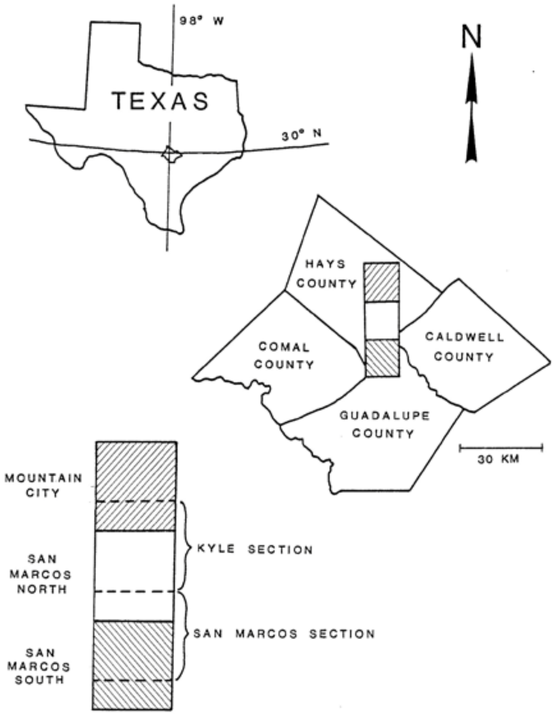


Figure 3-1. Location of the San Marcos Case Study Area

3.1.2 Physical Geography

The San Marcos area is on the boundary between the Edwards Plateau and the Gulf Coastal Plain, two of the major physiographic provinces of the southwestern United States. An overview of the major geographic features and the climate, soils, and vegetation in this zone of transition is given in the following paragraphs.

3.1.2.1 Major Geographic Features

The physical geography of the San Marcos area is dominated by the Balcones Escarpment (Figure 3-2a), which separates the dissected eastern margin of the Edwards Plateau on the west from the interior-most belt of the Gulf Coastal Plain on the east. The term Balcones, Spanish for balconies, was first applied by Spanish explorers who envisioned the hills as balconies from which one can look down upon the prairies to the east. The escarpment is well expressed in the San Marcos section, where it traverses the area northeastward through the city of San Marcos, but is much less well defined in the Kyle section where it extends northward approximately through the town of Kyle. The dissected Edwards Plateau west of the escarpment is known locally as the Texas Hill Country. This area has generally steep relief, thin soils, and limestone bedrock (Figure 3-2b). East of the escarpment the Blackland Prairie comprises the innermost belt of the Gulf Coastal Plain. This area is characterized by low, rounded hills (Figure 3-2c), thick, black soils, and clay substrate.

Figure 3-2. Balcones Escarpment and Contrasting Landforms on Each Side of the Scarp

a. Westward view of the escarpment near the Blanco River in Universal Transverse Mercator (UTM) grid square 3311-605

Figure 3-2. Balcones Escarpment and Contrasting Landforms on Each Side of the Scarp

b. Rugged, forested hill country terrain west of the escarpment where the best agricultural use is ranchland. The view is northward across the Blanco River gorge in about UTM 3320-599.

Figure 3-2. Balcones Escarpment and Contrasting Landforms on Each Side of the Scarp

c. Rounded, gently rolling Blackland Prairie east of the escarpment. Most of this land is used as cropland or pastureland.

Drainage in the area is eastward and southeastward off the escarpment. The major streams are the Blanco and the San Marcos Rivers. The Blanco enters the area near the northwest corner and flows northeastward and then southeastward to its confluence with the San Marcos River in the eastern part of the San Marcos section. The San Marcos River heads at Spring Lake, an artificial reservoir over San Marcos Springs within the city of San Marcos, and flows eastward out of the study area.

The population centers are the city of San Marcos and the town of Kyle, both of which are described in some detail below. Interstate 35, a regional trunk highway, forms the backbone of a well-integrated road network that provides easy access to all parts of the area.

3.1.2.2 Climate

The climate of the San Marcos area is humid subtropical with hot summers (Environmental Science Services Administration, 1968). The mean annual temperature is 19.9 0 C (68 0 F), and the mean annual total precipitation is 86 centimeters. Tropical maritime air masses predominate throughout the spring, summer, and fall, and the wind is then mostly from the south and southeast. In the winter modified polar air masses take over, providing a continental type of climate and predominately northwest winds. Prolonged periods of cold weather are rare. Most cold temperatures are associated with periodic incursions of cold fronts, known locally as "northers,” which usually last between 36 and 72 hours.

A meteorological phenomenon of particular importance to the San Marcos area is the orographic lifting effect of the Balcones Escarpment. Inland-moving maritime air masses must rise from 200 to about 400 meters as they cross the escarpment, and the resulting adiabatic cooling often causes these air masses to release large quantities of precipitation along the scarp. This effect is particularly pronounced when the moisture-laden air of tropical storms (sometimes in the form of spent hurricanes) crosses the escarpment (Baker and others, 1974, p. 11).

3.1.2.3 Soils

The soils of the San Marcos area are mostly residual and thus strongly reflect the lithology of the bedrock parent material. The Balcones Escarpment demarks a sharp discontinuity of soil types. West of the scarp the soils are thin, poor, rocky mollisols and are mapped as the Tarrant - Brackett - Speck Association on the state soils map (Godfrey, McKee, and Oakes, 1973). East of the escarpment the soils are generally thick, rich, black vertisols and mollisols and are mapped as the Houston Black - Heiden - Austin Association.

The primary reasons for the profound change in soil types across the escarpment are the differences in slope and bedrock material on either side. East of the scarp the slopes are gentle, and soil-forming processes are more than able to keep pace with soil erosion. The substrate parent materials are the relatively soft Upper Cretaceous clay-shale units which are readily amenable to pedogenic processes. West of the escarpment, where the topography is rugged and slopes are steep, soil erosion generally keeps pace with or exceeds the rate of soil formation, and the soils are quite thin. In addition, the hard limestone parent material is generally much more resistant to pedogenic processes. Some of the soils in this area are relict terra rosa soils from an earlier, wetter climatic period and are now in process of adjusting to the present drier climatic regime. The Speck soil series is the primary example of these degrading terra rosa soils.

3.1.2.4 Vegetation

The Balcones Escarpment, besides being a boundary between vastly different soil types, also marks a sharp discontinuity in plant assemblages. Blair (1950) recognized the Balconian Biotic Province and Texan Biotic Province west and east of the escarpment respectively. Gould (1962) defined the Edwards Plateau Vegetation Region and the Blackland Prairie Vegetation Region, respectively, on the west and east sides of the scarp. The vegetation on either side of the escarpment was well summarized by Longley (1975, p. 86 and 107):

> The plant community . . . on the Edwards plateau is predominantly an Oak-Juniper association well suited for use as rangeland. Dense growths of oaks commonly occur on limestone outcrops. Juniper (is on) marly slopes, and Elm and Hackberry interspersed with Oak are common along stream bottoms … The region below the escarpment but removed from the river bottoms is Blackland Prairie, which is classed as a true prairie with Little Bluestem as the climax dominant.

Because the area is located in this transition between different vegetation zones, it is not unusual to find plants that are normally of dissimilar habitats in close proximity to each other. Most of the natural vegetation of the Blackland Prairie has been removed and supplanted by cropland agriculture, but west of the escarpment, where rangeland agriculture predominates, much of the natural oak juniper forest still stands. Commonly, however, the forest has been considerably modified by removal of the junipers and understory in order to increase the growth of grass for grazing.

Cuyler (1931) was the first to note the usefulness of vegetation for mapping the Cretaceous rocks of central Texas. The relatively close correlation between certain species and certain stratigraphic units is indirect, and the link between the two is the soil. The soil, as noted earlier, strongly reflects the geologic bedrock, and the soil in turn controls the distribution of the vegetation. Several generalizations can be made about the relation between stratigraphic units and vegetation. Mesquite is usually found on clayey formations, such as the Del Rio Clay and the Eagle Ford Formation west of the Balcones Escarpment (Figure 3-3) and the Upper Cretaceous clay formations east of the escarpment. However, mesquite also sometimes grows on the limestones of the Edwards Group where the relict clayey terra rosa soils are sufficiently thick. Junipers grow most profusely on marly slopes of the Georgetown Formation and on the chalky limestones of the Austin Group. Live oaks flourish best on the hard, fractured limestone units, such as the Edwards Group, the Buda Formation, and the limestone units of the Austin Group. The prickly pear cactus is strikingly abundant on the Edwards Group limestones. One association which is difficult to explain is that of the ball moss with the Eagle Ford Formation. This plant, as an epiphyte, does not derive its nutrients from the soil and does not live as a parasite on the host tree, yet it grows in such profusion in trees on the Eagle Ford that the trees are often killed for lack of room for their leaves to grow.

Figure 3-3. Profuse Growth of Mesquite on the Del Rio Clay

This isolated patch of mesquite is surrounded by oak-juniper assemblage, visible in the background, that is typical of the dominantly limestone terrane west of the Balcones Escarpment. The mesquites are growing on a small fault block of Del Rio. The view is generally northeastward in the Valley View housing development (UIM 3313-600). The scale, which is two meters high, is used in several photos hereafter.

San Marcos Springs and the associated Spring Lake and San Marcos River provide a unique habitat in this region for both flora and fauna (Longley, 1975). Because of the high flow volume, high quality, and uniform temperature of the water from these springs, several unusual species are flourishing, including at least one unique species, the Texas wild rice (Zizania texana).

3.1.3 History

The San Marcos area has had a rich history. Three distinct historical periods - the Aboriginal, the Spanish-Mexican, and the Modern periods - are readily recognizable.

American Indians lived in central Texas for a long time before Europeans arrived. Archeological evidence indicates the region was occupied more or less continuously for 12,000 years or more, but the aboriginal picture in Hays County is reasonably clear only after 6000 B.C. (Roberson, 1972, p. 31). Four cultural stages - the Paleo-American Stage, the Archaic Stage (Edwards Plateau Aspect), the Neo-American Stage (Central Texas Aspect), and the Historic Stage - have been recognized in the region (Suhm and others, 1954). About thirty archeological sites have been discovered within the limits of the study area by the Texas Archeological Survey. Most of these were recognized during a survey for the Upper San Marcos watershed (Patterson, 1974). One dart point from the Paleo-American Stage has been found, and the remainder of the archeological materials have been assigned to the Edwards Plateau Aspect. A burnt rock midden site of the Edwards Plateau Aspect, located about 8 kilometers north of the study area, was recently excavated and studied by Wier (1967).

The first European to visit the San Marcos vicinity was the shipwrecked Spaniard Cabeza de Vaca, who apparently crossed the Balcones Escarpment about 1535 as he was attempting to make his way back to Spanish settlements in Mexico. Members of the Alonso de Leon expedition passed through the area in 1689 and applied the name San Marcos to the "first considerable river" east of the Guadalupe (Webb, 1952, p. 559), and this name was subsequently applied to the present San Marcos River. The hill above San Marcos Springs was occupied for a short period in 1755 and 1756 by the "San Xavier missions," which included the missions San Francisco Xavier, San Ildefonso, and the Candelaria (Dobie, 1948, p. 13). Another attempt at settlement by the Spanish was made in 1808, when several families were brought in to establish a community on El Camino Real as a means of strengthening the Spanish presence in the region. This original village of San Marcos, called villa de San Marcos de Neve, was located at the crossing of El Camino Real over the San Marcos River. When first established, the village comprised about eighty-one inhabitants (Dobie, 1948, p. 14). However, a serious flood occurred during the first year, and the population declined progressively, primarily because of the pressure of repeated Indian raids (Dobie, 1932, p. 18). The site was eventually abandoned in 1812 (Figure 3-4), and the Spanish presence in the area was negligible thereafter.

The Modern period began in the San Marcos area about the time Texas achieved statehood in 1846. The first English-speaking settler moved from Bastrop in that year to a location near the confluence of the Blanco and San Marcos rivers. At the time Hays County was created by the Texas Legislature. In 1848, the county population was reported to be 387. The county was

Figure 3-4. Historic Marker Showing the Location of the Spanish Settlement of San Marcos de Neve

This marker is located near the crossing of El Camino Real over the San Marcos River. The reasons for the failure of the settlement are described on the marker.

named for a noted Texas Ranger, Captain “Jack” Hays. The city of San Marcos was laid out by three entrepreneurs hoping to make a real estate profit, and the town was eventually incorporated in 1874 (San Marcos Record, 1936, p. 1). The construction of the International and Great Northern Railroad (now a part of the Missouri Pacific Line) from Austin to San Antonio in 1880 effected several changes in the settlement patterns in the area. The town of Kyle was founded at a rail station in 1881 by a group of real estate promoters in cooperation with the railroad company. The new community attracted people from the surrounding area, and eventually caused the abandonment of the nearby settlement of Mountain City (Barkley, 1970, p. 140) and another small community further west on Onion Creek (Roberson, 1972).

3.1.4 Population and Government

Since the Hays County area was first settled, the population has grown steadily but somewhat erratically. In recent years Hays County has been the fastest growing of the four counties in the Interstate 35 corridor between Austin and San Antonio. Hays County experienced a growth rate of 39% in the 1960-1970 decade, compared to growth rates of 22%, 17%, and 23% respectively for the adjoining Comal, Guadalupe, and Caldwell Counties. Much of the Hays County growth has been concentrated in the vicinity of San Marcos within the limits of the study area.

3.1.4.1 Population Statistics

The historical and projected populations of Hays County and San Marcos are shown in Figure 3-5. Beginning with the first census in 1870, San Marcos has grown continuously with the exception of one decade. This growth was especially rapid (214%) in the period from 1940 to 1970. The population increased by 48% in the 1960s and is presently approximately 25,000.

The total population of Hays County has generally reflected the growth of San Marcos. The picture is different, however, when the county exclusive of San Marcos is considered separately, as shown by the lower dashed line in Figure 3-5. There, the population peaked at just under 12,000 at the turn of the century and has declined almost continuously since. Although obscured by such factors as the extension of the corporate limits of the city and the disproportionate growth of Southwest Texas State University, which presently accounts for 30-40% of San Marcos's population, a definite shift of the population from rural Hays County to urban San Marcos is indicated. This trend is also apparent from the upper dashed line which indicates the proportion of the Hays County population living in San Marcos. This percentage shows an increase from about 20% at the turn of the century to about 70% at present. A recent slight reversal of this trend is probably the result of urbanization outside San Marcos, such as establishment and growth of housing developments, rather than a remigration back to rural agricultural areas.

Population projections for the area indicate both continued growth and a continued trend toward increasing population concentration in urban areas. San Marcos' population projections from two sources are shown in Figure 3-5. These sources are in close agreement, except that the more recent study indicates a population figure somewhat higher than the earlier projection. Both projections indicate a growth of 100%, to just under 40,000, for San Marcos in the period 1970-1990. Total Hays County population is projected to increase by 89% to over 50,000 by 1990. Hays County outside San Marcos will also continue to increase in population, but its percentage of the total will decrease to below 25% by 1990.

3.1.4.2 Governmental Entities

The principal governmental organizations in the study area are Hays County, the city of San Marcos, and the town of Kyle. Hays County is governed by a Commissioners Court, which is not a court in the usual sense, but is an administrative and policy-making body (League of Women Voters, 1973, p. 3). The county seat is in the county courthouse located in the center of downtown San Marcos. The city of San Marcos has a Council-Manager form of government, and the town of Kyle is governed by elected aldermen.

Other governmental authorities of particular significance to the study area are the Capital Area Planning Council (CAPCO), the Edwards Underground Water District, and the Upper San Marcos Reclamation and Flood Control District. CAPCO is the regional council of governments

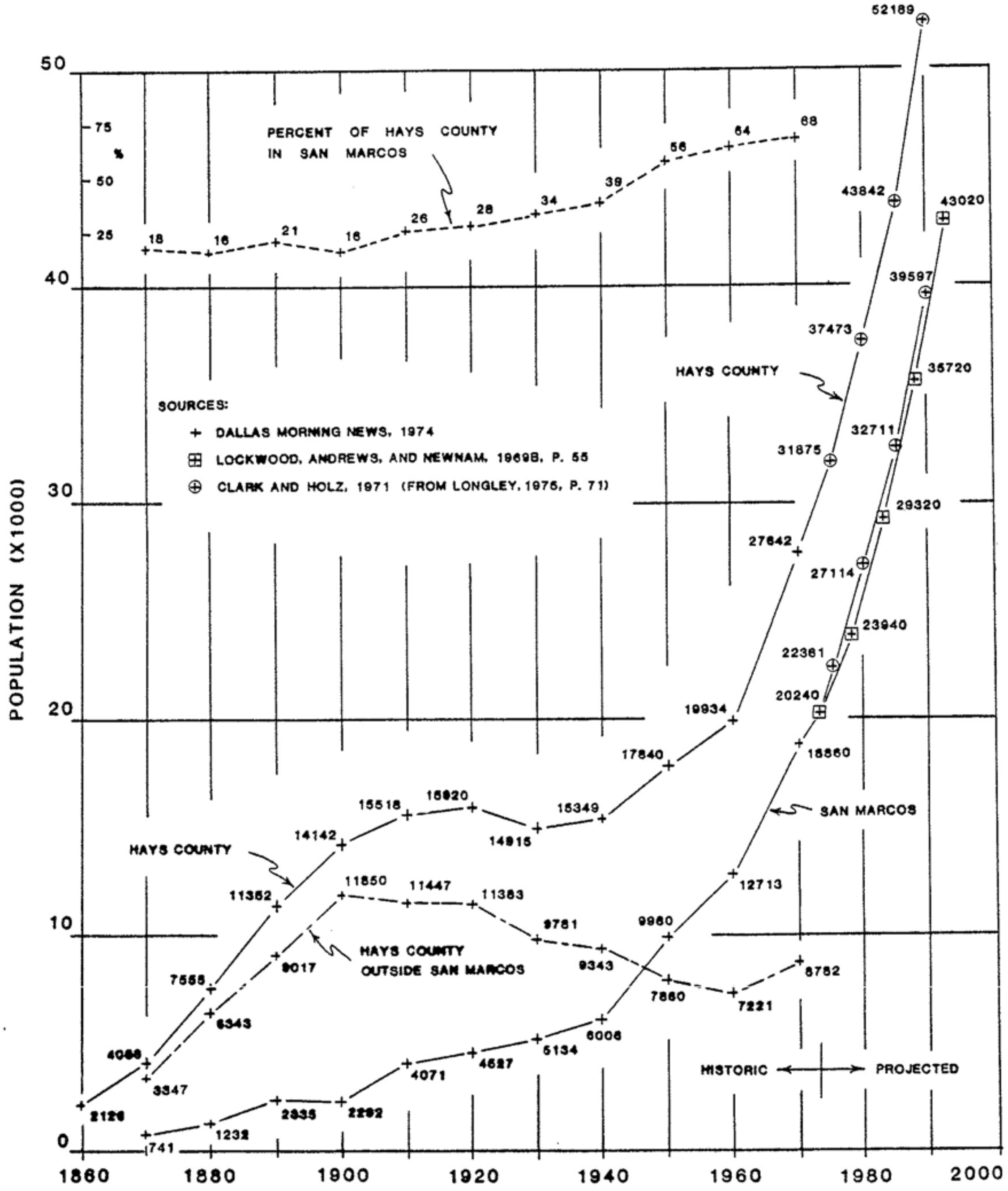


Figure 3-5. San Marcos and Hays County Population Statistics

responsible for long range planning for a ten county area, including Hays County, in central Texas. One of its prime responsibilities is the regional coordination of federally funded urban facilities such as water and sewage treatment plants. Participation in CAPCO by member governments is voluntary, and the agency has no enforcement authority except the power to deny federal funding of specific projects. The Edwards Underground Water District was created by the Texas Legislature in 1959 to protect the Edwards aquifer from depletion. This organization has a real estate taxing authority and has funded several studies of the aquifer. The primary mission of the Upper San Marcos Reclamation and Flood Control District is to bring the flood problem in San Marcos under control.

3.1.5 Economy

Urbanization in the San Marcos area is closely related to the area's economy. In general, the economic health of the area is good, primarily because of the rapid population growth. Also, the economic base has broadened significantly in recent years, thus reducing the vulnerability resulting from reliance on only a few economic sectors (Longley, 1975, p. 71).

The economy of an area can be described on the basis of any one or a combination of several aspects, including production, personal income, and employment. The best available report on the economy of San Marcos and Hays County (Savage, Morgan, and Yeargan, 1971) is based on employment data. In that report the economy of the area is divided into seventeen sectors and each sector is compared to the same sector for the national economy. The results of the study are presented as concentration coefficients, which express as a ratio the proportion of the work force employed in each sector relative to the proportion of the national work force employed in that same sector. The analysis shows that seven of the seventeen sectors form the economic base of the area. Listed in order of importance, these are:

1. Colleges and universities
2. Federal government
3. Manufacturing
4. Agriculture
5. Amusements and lodging
6. Elementary and secondary schools
7. Construction and mining

3.1.5.1 Colleges and Universities

Owing to the presence in San Marcos of Southwest Texas State University, the colleges and universities sector of the economy is by far the most important in the area. The concentration coefficient is 6.11, which indicates that this sector is over six times more important to the local economy than it is to the national economy. Enrollment has almost tripled in the last decade, from 4,461 in 1964 to 12,894 in 1974.

3.1.5.2 Federal Government

The second most important economic sector is provided by the Federal government, with a concentration coefficient of 3.98. Most of this contribution is from the Gary Job Corps Center, which is located a few miles east of San Marcos. This facility, the largest of its kind in the country, is a voluntary national training center for economically disadvantaged young men from around the country who are out of school and out of work. About 3,000 men are usually in residence, but this number has been reduced in recent years because of budgetary cutbacks.

3.1.5.3 Manufacturing, Agriculture, and Amusements and Lodging

The next three economic sectors - manufacturing, agriculture, and amusements and lodging - are about equal in importance, with concentration coefficients very close to 2.70. Sixteen firms in or near the study area employ eight or more people each, and the following five companies have fifty or more employees each:

1. Kerr-Ban Furniture Manufacturing Co. (wooden furniture)
2. Wide-Lite Corporation (lighting fixtures)
3. Thermon Manufacturing Co. (heating and cooling equipment)
4. Bollman Industries of Texas (scoured wool)
5. Longhorn Machine Works (steel forgings)

The San Marcos Chamber of Commerce continues to try to increase the manufacturing sector by attracting additional small manufacturing firms.

Although agriculture used to be the foremost sector of the area's economy, it has been losing ground recently because of urbanization. Considerable quantities of land formerly devoted to agriculture have been urbanized or are being held vacant in anticipation of urbanization (Clark and Holz, 1971, p. 21). The population shift from rural to urban areas demonstrated by population statistics is supported by data on the size and number of farms in Hays County. Between 1940 and 1964, the average farm size increased from 323 to 619 acres and the number of farms decreased from 1,233 to 591 (Clark and Holz, 1971). It seems clear that as some of the population leaves the rural areas, the abandoned farms are bought up by the remaining residents who thus increase the size of their farms.

Two major tourist attractions, Aquarena Springs and Wonder World, are chiefly responsible for the importance of amusements and lodging in San Marcos's economy. Both of these attractions prosper chiefly because of the proximity of Interstate 35, which is the transportation artery not only between Dallas and San Antonio, but also for much of the interior United States to Mexico. Aquarena Springs is a concession operated on Spring Lake whose main attraction is a glass-bottom boat ride in which the flow of San Marcos Springs can be seen on the lake bottom. About 500,000 tourists visit the concession annually. Wonder World, with one of the larger caves of the Edwards Group as its major attraction, is visited by about 100,000 people annually.

3.1.5.4 Elementary and Secondary Schools

The concentration coefficient of the elementary and secondary schools sector is 1.7, no doubt because two private schools are located in San Marcos. The San Marcos Baptist Academy is a college preparatory school having 1,000 students and forty faculty. The Brown Schools offer care and training for mentally and emotionally handicapped children. Two of the five units of the schools are in San Marcos and the remaining three are in Austin.

3.1.5.5 Construction and Mining

The construction and mining sector has a concentration coefficient of 1.45 and is therefore only slightly above the national average. The primary cause of this importance is probably the construction which has been undertaken in recent years at Southwest Texas State University to keep pace with the rising enrollment.

3.1.5.6 Summary

The economy of the San Marcos area is quite healthy, owing chiefly to an expanding population. The original agricultural economy has steadily become more stable through diversification. The economic base of the area is now centered on Southwest Texas State University. The Gary Job Corps Center, manufacturing, agriculture, and amusements and lodgings playa lesser but nevertheless important role.

3.1.6 Historical Influence of Geology on Land Use

Geology had a strong impact on the original settlement patterns in the San Marcos area and since then has exercised strong control on agricultural land use patterns. The original settlement patterns were controlled in large part by the presence of the Balcones Escarpment and by the large springs located at various points along the foot of the escarpment. Wilie (1940) was one of the first to describe the importance of the escarpment and its associated springs on land use patterns. Bybee (1952) expanded and published ideas similar to those of Wilie. The original, short-lived settlement of San Marcos de Neve, as noted earlier, was a short distance east of the escarpment on the San Marcos River at the crossing of the Spanish road El Camino Real. This site was undoubtedly chosen because of the abundant water supply to the river. The Anglo-American village of San Marcos was established 40 years later near San Marcos Springs and the associated river chiefly because of their potential for supplying both water and power.

The escarpment itself has also exercised considerable control on the original pattern of settlement. Because the escarpment constituted a considerable barrier to early means of transportation, most early routes were forced into a north-south direction along the foot of the scarp. This pattern was established during the Spanish occupation, continued through the American settlement, and is still strongly expressed today. Many westward-migrating pioneers who had found travel across East Texas relatively easy were more inclined to settle on the Blackland Prairie east of the scarp rather than hazard further travel across the difficult terrain of the hill country. The routes of the major highways - first U.S. 81 and now Interstate 35 - were chosen to follow the long established path at the foot of the escarpment, and the projected area of major growth in central Texas is along this line.

The escarpment had a pronounced effect on agricultural land use patterns because of the great discontinuity in soil fertility across the scarp mentioned earlier in this chapter. Westward-bound settlers found that the escarpment marked the western limit of soils suitable for cultivation for cropland, and hence tended to settle to the east on the rich Black1and Prairie. Because of the change in agricultural suitability westward across the escarpment from cropland to ranchland, the scarp eventually came to form the boundary between the Deep South and the Old West. Within the study area the distribution of abundant ground water supplies and rich agricultural soils has given rise to an ironic agricultural situation. West of the escarpment, where the Edwards aquifer provides an abundant source of water, the soils are too thin and poor for crops. East of the scarp, where the soils are rich and highly suitable for irrigable crops, the Edwards and other potential aquifers produce only saline, sulfurous water. R. T. Hill first proposed using water from the San Marcos Springs and River for irrigating the Blackland Prairie (Hill and Vaughn, 1898, p. 308), but no serious attempt has ever been made to institute his suggestion.

3.1.7 Suitability of the San Marcos Area as a Case Study

The San Marcos area is ideally suited as a case study for the methodology being presented in this study. Four major aspects of the area contribute to this suitability: 1) the presence of a variety of existing urban systems; 2) the strong likelihood of continued and accelerating urbanization; 3) the excellent opportunity which still exists for planning for future urbanization; and 4) the strong and dynamic role of geology in determining land suitability.

Three kinds of urbanization - the city of San Marcos, the smaller town of Kyle, and the outlying housing developments and mobile home parks - are present in the area. Because these three are experiencing a variety of environmental conflicts, they present an excellent spectrum for demonstrating the methodology.

Inasmuch as continued and accelerating growth are almost a certainty in the study area, the area also provides an excellent opportunity for incorporating environmental geologic considerations into planning for future urbanization. The projected population increases during the next 15 to 20 years were indicated earlier for Hays County (89%) and San Marcos (100%) (Figure 3-5). Several characteristics of the area contribute to this high growth rate. First, the area possesses most of the amenities of good living, including a mild climate, clean air, aesthetic hill country surroundings, and a generally more relaxed pace of life than is to be found in metropolitan areas. Second, the basic resources essential for urban growth, particularly water and aggregates, are abundant. Third, there is no effective natural barrier to growth in any direction, although some of the characteristics of the land do limit its capability for certain urban uses. Fourth, the area is advantageously located in the Interstate 35 growth corridor and within reasonable commuting distance to Austin and San Antonio. Demographers predict two megapoli in Texas - one on the Gulf Coast and the other stretching from Dallas to San Antonio (Flawn, 1965, p. 6), and San Marcos lies directly in the path of the latter.

Despite the existence of a considerable amount of urbanization, most of the land in the area is still in agricultural use. Consequently, there is still excellent opportunity for intelligent physical planning for the urbanization that is certain to come. An essential part of that planning consists of environmental geologic considerations.

3.2 Natural Data Sources

Five natural data source maps and two cultural data source maps are presented as Plates I to 7. The study area is depicted as two maps on these plates, with the northern or Kyle section on the left and the southern or San Marcos section on the right. All the maps were prepared at a scale of 1:24,000, but have been reduced for final presentation to a scale of 1:48,000.

A natural data source map was prepared for each of the lowest categories in the classification of the geologic environment. Plates 1 to 5 therefore include an Engineering Geology, a Soils, a Resources, a Processes, and a Landform map. Much of the data shown on these maps was derived directly from a conventional geologic map of the area. The geologic map, which was prepared in the initial phases of this study, presents rock-stratigraphic units as defined in the Stratigraphic Code (American Commission on Stratigraphic Nomenclature, 1961). The map appears in two parts (Plates 9 and 10), and a condensed geologic report of the area is given in the Appendix.

3.2.1 Engineering Geology Map

The Engineering Geology map (Plate 1) depicts the location and distribution of the bedrock units having contrasting physical properties. This map is derived directly from the geologic map of the area by grouping together rock-stratigraphic units having similar lithic and engineering characteristics. Fortunately, the rock-stratigraphic units in the area are relatively uniform in composition and physical properties both through their stratigraphic thicknesses and laterally over the extent of the study area, so that no subdivision of geologic map units was necessary. The grouping procedure led to the definition of four units on the Engineering Geology map: hard limestones, mixed hard and soft limestones, clay, and alluvium.

Determination of the rock-stratigraphic units to be included in the four map units was relatively straightforward. The hard limestones unit (LH) includes the limestone, dolomite, and dolomitic limestone strata of the two formations - the Kainer and the Person - of the Edwards Group as well as the limestone and marly limestone of the Buda Formation. The mixed limestones unit (LM) includes several rock-stratigraphic units which are composed of either marls or interbedded hard and soft limestone strata. The rock-stratigraphic units composing the clay unit (C) are mostly calcareous smectitic mudstones, clays, and clay-shales. One of the formations of the clay unit, the Eagle Ford, consists of calcareous siltstone and sandstone flags through about 25% (about 1.2 meters) of its thickness. The alluvium unit (A) includes the floodplain and terrace deposits of the intermittent and perennial streams in the area.

The four map units of the Engineering Geology map are tabulated in Table 3-1. For each unit, a brief lithologic description is given, the stratigraphic units included are listed, and approximate

Map Unit	Lithologic Description	Stratigraphic Units Included	Unit Weight (lb/ft^3)	Moisture (% by volume)	Triaxial Compress. (T/ft^2)	Unconfined Compress. (T/ft^2)	Plasticity Index	Adsorpt. Swell (%)	Adsorpt. Pressure (lb/ft^2)
LH hard limestones	Hard carbonates, including both limestone and dolomite; may contain chert nodules and solution porosity	Kka Kainer Kpe Person Kbu Buda	140 (est.)	N/A	unk.	50-200	N/A	N/A	N/A
LM mixed limestones	Mixed hard and soft limestones, marls, and dolomites; individual beds or fault blocks range from very hard to very soft	Kgr Glen Rose Kgt Georgetown Kau Austin	80-130	N/A	unk.	10-300	N/A	N/A	N/A
C clays	Clay, mostly smectite, usually calcareous, approaching a marl in places; may contain a 5-foot thickness of flaggy limestones	Kdr Del Rio Kef Eagle Ford Ksp Sprinkle Kpg Pecan Gap Kbe Bergstrom Kco Corsicana	80-130	10-50	0.1-8.0	0.9-25.0	10-70	0.1-9.0	800-6600
A alluvium	Alluvium, generally unconsolidated silty limestone gravel with lesser quantities of sand; locally with caliche-cemented conglomerate cap	Qht High terrace Qal Alluvium and low terrace	80-110	3-70	0.1-5.0	0.1-7.0	4-60	0-5	2-6000

Compiled from:
Rodda, Garner, and Dawe, 1970
Garner, 1974
Garner, 1975

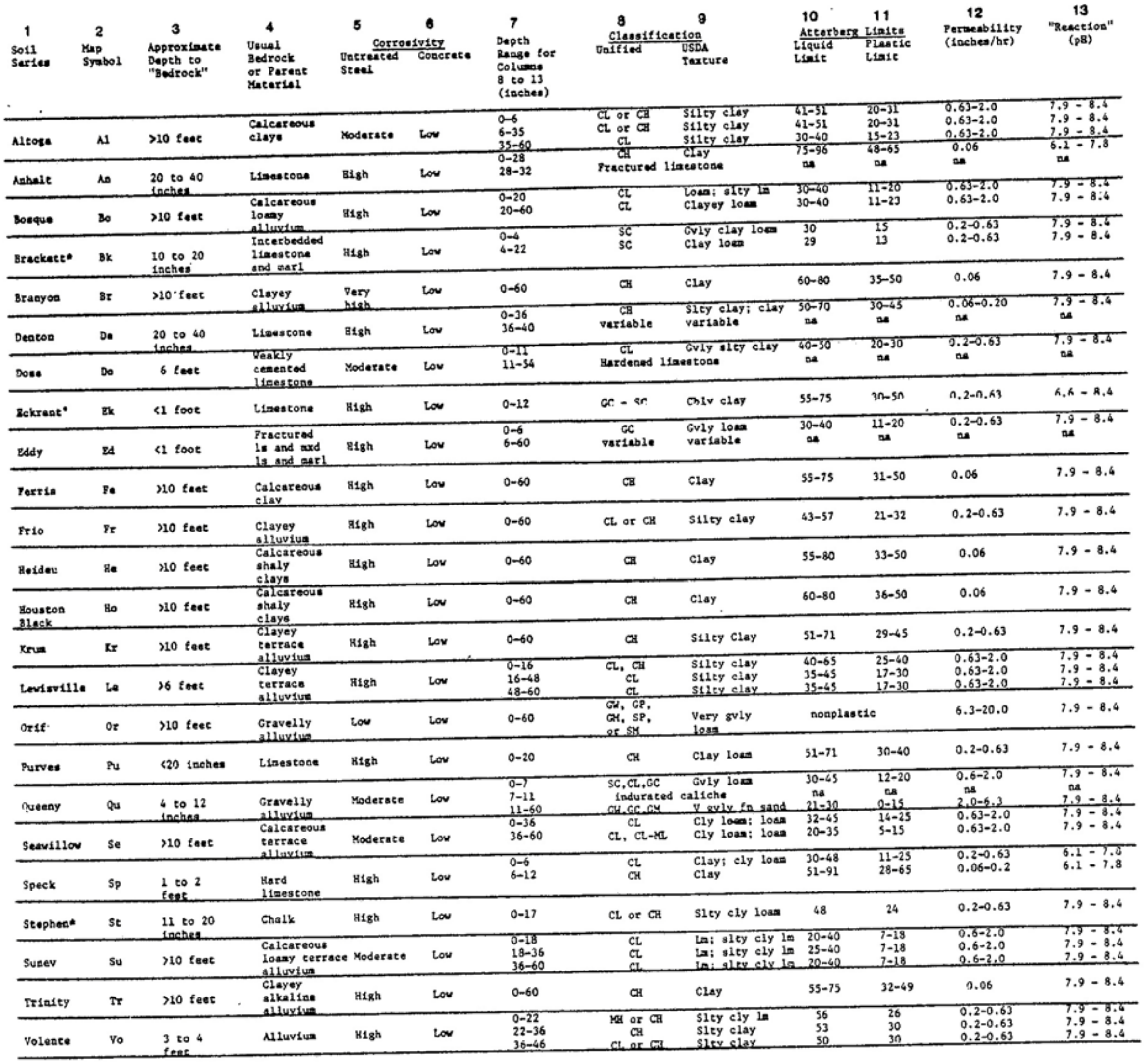
Table 3-1. Engineering Characteristics of the Engineering Geology Map Units values of the more important engineering characteristics are presented. The values listed for the engineering characteristics are taken from previous work on rock-stratigraphic units about 50 kilometers to the northeast of the study area in the vicinity of Austin. However, because of the strong lateral uniformity of the rock-stratigraphic units in the central Texas region, the values are believed to be fairly representative for the study area. Much work remains to be done to determine these properties more exactly for the study area, but such additional work is beyond the scope of this study.

The distribution of the Engineering Geology map units over the study area is largely controlled by the Balcones fault zone. The Kyle section is underlain mostly by hard limestones in its western half and by mixed limestones in its eastern half. A complex zone of irregularly shaped patches of all four units separates these two halves. A broad terrace of alluvium covers part of the mixed limestones, and the southeastern corner of the area is underlain by clay. The San Marcos section is divided into two distinct parts at the Balcones Escarpment. Southeast of this boundary the area is underlain by alluvium in the north and by clay in the south. Northwest of the boundary the substrate consists mostly of hard limestones with irregular patches of clay. A strip of mixed limestones parallels the escarpment in the western half of the San Marcos section.

3.2.2 Soils Map

The Soils map for the study area (Plate 2) depicts the areal distribution of the physical properties of the shallow substrate. This map was prepared from data provided by personnel of the USDA Soil Conservation Service. Part of the area, indicated by the mapping credits on Plate 2, was mapped and published as a planning tool for the immediate vicinity of the city of San Marcos (Lowther, 1972). The data for the remainder of the area is based on unpublished mapping on aerial photos provided by the Soil Conservation Service Soil Survey Party in San Marcos. Soils mapping is in progress for Hays and Carnal Counties, and a combined county soils report should be available by 1980. Part of the study area has not yet been mapped, and the mapping in the remainder of the area not included in the published report is derived in part from work for the current project and in part from earlier work which was done on a farm-by-farm basis and by several different soil scientists. Also, the soil series have not been correlated with other series in the region and are therefore subject to change. Despite those limitations the data presented in Plate 2 are the best currently available. Plate 2 should be replaced by the HaysCarnal County soil report as soon as the report becomes available.

The map units on the Soils map are soil series because, as noted in Chapter 2, the series is now defined on the basis of objectively determined physical and chemical properties of the soils. The twenty-four soil series in the area are shown in Table 3-2 along with most of their important engineering properties. These data are taken chiefly from Lowther (1972). The data for series not recognized in Lowther's report are taken from the county soils report for Travis County (Werchan, Lowther, and Ramsay, 1974), which is located immediately to the north of the study area.



1 Soil Series	2 Map Symbol	3 Approximate Depth to "Bedrock"	4 Usual Bedrock or Parent Material	5 Corrosivity Untreated Steel	6 Corrosivity Concrete	7 Depth Range for Columns 8 to 13 (inches)	8 Classification Unified	9 Classification USDA Texture	10 Atterberg Limits Liquid Limit	11 Atterberg Limits Plastic Limit	12 Permeability (inches/hr)	13 "Reaction" (pH)
Altoga	Al	>10 feet	Calcareous clays	Moderate	Low	0-6 6-35 35-60	CL or CH CL or CH CL	Silty clay Silty clay Silty clay	41-51 41-51 30-40	20-31 20-31 15-23	0.63-2.0 0.63-2.0 0.63-2.0	7.9 - 8.4 7.9 - 8.4 7.9 - 8.4
Anhalt	An	20 to 40 inches	Limestone	High	Low	0-28 28-32	CH Fractured limestone	Clay	75-96 na	48-65 na	0.06 na	6.1 - 7.8 na
Bosque	Bo	>10 feet	Calcareous loamy alluvium	High	Low	0-20 20-60	CL CL	Loam; slty lm Clayey loam	30-40 30-40	11-20 11-23	0.63-2.0 0.63-2.0	7.9 - 8.4 7.9 - 8.4
Brackett*	Bk	10 to 20 inches	Interbedded limestone and marl	High	Low	0-4 4-22	SC SC	Gvly clay loam Clay loam	30 29	15 13	0.2-0.63 0.2-0.63	7.9 - 8.4 7.9 - 8.4
Branyon	Br	>10 feet	Clayey alluvium	Very high	Low	0-60	CH	Clay	60-80	35-50	0.06	7.9 - 8.4
Denton	De	20 to 40 inches	Limestone	High	Low	0-36 36-40	CH variable	Slty clay; clay variable	50-70 na	30-45 na	0.06-0.20 na	7.9 - 8.4 na
Doss	Do	6 feet	Weakly cemented limestone	Moderate	Low	0-11 11-54	CL Hardened limestone	Gvly slty clay	40-50 na	20-30 na	0.2-0.63 na	7.9 - 8.4 na
Eckrant'	Ek	<1 foot	Limestone	High	Low	0-12	GC - SC	Cbly clay	55-75	30-50	0.2-0.63	6.6 - 8.4
Eddy	Ed	<1 foot	Fractured ls and mxd ls and marl	High	Low	0-6 6-60	GC variable	Gvly loam variable	30-40 na	11-20 na	0.2-0.63 na	7.9 - 8.4 na
Ferris	Fe	>10 feet	Calcareous clay	High	Low	0-60	CH	Clay	55-75	31-50	0.06	7.9 - 8.4
Frio	Fr	>10 feet	Clayey alluvium	High	Low	0-60	CL or CH	Silty clay	43-57	21-32	0.2-0.63	7.9 - 8.4
Heideu	He	>10 feet	Calcareous shaly clays	High	Low	0-60	CH	Clay	55-80	33-50	0.06	7.9 - 8.4
Houston Black	Ho	>10 feet	Calcareous shaly clays	High	Low	0-60	CH	Clay	60-80	36-50	0.06	7.9 - 8.4
Krum	Kr	>10 feet	Clayey terrace alluvium	High	Low	0-60	CH	Silty Clay	51-71	29-45	0.2-0.63	7.9 - 8.4
Lewisville	Le	>6 feet	Clayey terrace alluvium	High	Low	0-16 16-48 48-60	CL, CH CL CL	Silty clay Silty clay Silty clay	40-65 35-45 35-45	25-40 17-30 17-30	0.63-2.0 0.63-2.0 0.63-2.0	7.9 - 8.4 7.9 - 8.4 7.9 - 8.4
Orif	Or	>10 feet	Gravelly alluvium	Low	Low	0-60	GW, GP, GM, SP, or SM	Very gvly loam	nonplastic		6.3-20.0	7.9 - 8.4
Purves	Pu	<20 inches	Limestone	High	Low	0-20	CH	Clay loam	51-71	30-40	0.2-0.63	7.9 - 8.4
Queeny	Qu	4 to 12 inches	Gravelly alluvium	Moderate	Low	0-7 7-11 11-60	SC,CL,GC indurated caliche GM,GC,GM	Gvly loam V gvly fn sand	30-45 na 21-30	12-20 na 0-15	0.6-2.0 na 2.0-6.3	7.9 - 8.4 na 7.9 - 8.4
Seawillow	Se	>10 feet	Calcareous terrace alluvium	Moderate	Low	0-36 36-60	CL CL, CL-ML	Cly loam; loam Cly loam; loam	32-45 20-35	14-25 5-15	0.63-2.0 0.63-2.0	7.9 - 8.4 7.9 - 8.4
Speck	Sp	1 to 2 feet	Hard limestone	High	Low	0-6 6-12	CL CH	Clay; cly loam Clay	30-48 51-91	11-25 28-65	0.2-0.63 0.06-0.2	6.1 - 7.8 6.1 - 7.8
Stephen*	St	11 to 20 inches	Chalk	High	Low	0-17	CL or CH	Slty cly loam	48	24	0.2-0.63	7.9 - 8.4
Sunev	Su	>10 feet	Calcareous loamy terrace alluvium	Moderate	Low	0-18 18-36 36-60	CL CL CL	Lm; slty cly lm Lm; slty cly lm Lm; slty cly lm	20-40 25-40 20-40	7-18 7-18 7-18	0.6-2.0 0.6-2.0 0.6-2.0	7.9 - 8.4 7.9 - 8.4 7.9 - 8.4
Trinity	Tr	>10 feet	Clayey alkaline alluvium	High	Low	0-60	CH	Clay	55-75	32-49	0.06	7.9 - 8.4
Volente	Vo	3 to 4 feet	Alluvium	High	Low	0-22 22-36 36-46	MH or CH CH CL or CH	Slty cly lm Slty clay Slty clay	56 53 50	26 30 30	0.2-0.63 0.2-0.63 0.2-0.63	7.9 - 8.4 7.9 - 8.4 7.9 - 8.4

Data are from Lowther, 1972 unless otherwise noted
*Data from Werchan and others, 1974
'Formerly called Tarrant

Table 3-2. Tabulation of Soil Series and Associated Engineering Properties

Most of the soils in the study area are residual and therefore strongly reflect the lithology of the underlying geologic parent rock. The Balcones Escarpment marks a sharp discontinuity in soil type which is expressed on the state soils map as a change from the Houston Black - Heiden - Austin Association in the east to the Tarrant - Brackett - Speck Association in the west. The distribution of soil series in the area strongly reflects this regional pattern. Where slopes are steep and the soils are underlain by the hard limestones of the Edwards Group in the northern and western parts of the study area, the soils are primarily the Eckrant and Speck Series. Southeast of the Balcones Escarpment and south of the San Marcos River, thick black vertisols comprising chiefly the Houston Black and Heiden series have developed on the Upper Cretaceous clays. In the east-central part of the area and extending a considerable distance upstream on either side of the Blanco River, several series, including the Branyon, Bosque, and Lewisville series, have developed on the alluvial deposits of the broad floodplain and terrace of the Blanco and San Marcos Rivers. In the central part of the area along the Balcones Escarpment, the complex faulting of the Balcones fault zone, with the resulting irregular, patchy occurrences of geologic substrate, have given rise to a complex distribution of soil series.

3.2.3 Resources Map

In the San Marcos area the most important resources for urbanization are the plentiful supplies of water and aggregates. The location, extent, and distribution of the various categories of these resources are shown on the Resources map (Plate 3). In general the resources indicated on this map should be considered as potential resources whose existence and value at a particular location would have to be confirmed by detailed study at the site in question.

The map units shown on the Resources map are derived from several sources. The areas of potential aggregates resources are taken directly from the geologic map, and the availability of surface water is indicated on U. S. Geological Survey topographic maps. Areas where significant quantities of ground water are available were determined by study of the geologic map and by consultation of published and unpublished hydrogeologic studies of the Edwards aquifer.

The water and aggregates resources are generally described irrespective of their actual utilization; the use of resources for urban input and the resulting environmental conflicts are reserved for coverage in Chapter 4. Only the resources of direct significance to urban maintenance and growth are discussed despite the presence of several potential resources which could in the future have great economic importance to the cities. These potential resources include petroleum, limestone as a source of lime or cement, and a small deposit of sulfur. In general these resources are not in danger of being eliminated from utilization by the growth of urbanization over the resource deposits.

3.2.3.1 Water Resources

Both surface water and ground water resources are indicated on the Resources map. Surface water resources are readily available for urban use from the almost-perennial Blanco River and the perennial San Marcos River. Other surface water bodies in the area, such as artificial reservoirs, are too small to be considered for urban uses and are not considered. Although little urban use is presently being made of surface water, the channels of the Blanco and San Marcos Rivers are indicated on the Resources map as potential surface water resources for urbanization.

An abundant supply of high quality ground water is probably the most significant natural resource for urbanization in the San Marcos area. Nearly all of this water comes from the prolific Edwards limestone aquifer. With its annual water budget of about 500,000 acre-feet, the Edwards is one of the most important aquifers in the southwestern U.S. Because of its importance to the economy and well-being of south-central Texas, the Edwards has been studied and described at considerable length (see, for example, Klemt and others, 1975, Abbott, 1975; Abbott, 1973; Alexander and others, 1964; DeCook, 1963; and DeCook, 1960). The study area lies over the northeastern tip of the well-recognized major portion of the aquifer. San Marcos Springs, which has an average discharge of about 265 cubic meters per hour (155 cubic feet per second) flows from the Edwards.

The areas where potable ground water can be obtained by drilling wells into the Edwards are indicated in three zones on the Resources map. The wide dashed lines indicating the boundaries between the three zones are highly generalized and are intended primarily to show that the aquifer is quite variable in productivity. Much additional work remains to be done on this intensely faulted, highly nonuniform and anisotropic aquifer before its hydrogeologic characteristics, including the areal distribution of its productivity, are known in detail. The zones on the Resources map should not be construed as more than broad guidelines to be used until more detailed and accurate maps of the aquifer properties are available. The boundary indicated as Gl on Plate 3 is the so-called "bad-water line" which marks the limit of the aquifer in the San Marcos area. Southeast of this line Edwards water is not potable because it is charged with H2S and has a dissolved solids content of more than 1,000 mg/l. This line is taken from maps in the U.S. Geological Survey Water Resources Division office in San Antonio. The boundary indicated as G2 is the regional transmissivity contour of 1 million gallons per foot per day as delineated by Klemt and others (1975, Figure 9). The zone between line Gl and line G2 is the most prolific part of the aquifer, where wells producing over 230 cubic meters per hour (1,000 gallons per minute) can be drilled in most places. The line indicated as G3 is based primarily on general observations of the productivity of existing wells. Wells drilled in the zone from the G3 line to the G2 line typically will produce between 23 and 230 cubic meters per hour (100 and 1,000 gallons per minute). Northwest of the G3 line wells will generally produce less than 23 cubic meters per hour (100 gallons per minute). Near the Blanco River trench the Edwards is essentially dry because recharge is drained out by springs in the trench walls. In that area even small domestic wells for residences in the Highlands development must be drilled into the Glen Rose Formation.

Some water is also pumped from minor aquifers in the Glen Rose Formation, the Austin Group, the Taylor Group, and the Quaternary alluvial deposits, but these are greatly overshadowed in importance by the Edwards aquifer. These minor aquifers are not indicated on the Resources map for three reasons: 1) Their distribution is too irregular and too unpredictable to indicate with confidence on a map, 2) They are usually not productive enough to support population densities associated with urbanization, and 3) The water is often too highly mineralized for satisfactory domestic use.

3.2.3.2 Aggregates Resources

The San Marcos area possesses abundant aggregates resources. Considerable parts of the area are underlain by limestone that is suitable for crushed stone or by alluvium which can provide sand and gravel. These resources are indicated by three map units on the Resources map and are significant from two standpoints. First, they indicate where the potential resources may be found and utilized, and second, they indicate where urbanization should be delayed until after the resource has been mined, thus allowing multiple sequential use (Flawn, 1970, p. 91).

The areas underlain by substrate potentially suitable for crushed stone lie generally west of the Balcones Escarpment, and essentially coincide with the hard limestone and mixed hard and soft limestones (LH and LM) of the Engineering Geology map. Because of the widespread occurrence of these units, and because their thicknesses usually exceed the depth limit of economic quarrying, this resource is virtually inexhaustible.

The sand and gravel resources in the area are largely alluvial floodplain and terrace deposits of the Blanco and San Marcos Rivers (Figure 3-6). These potential resources are shown on the Resources map as two units. The lower terrace and floodplain deposits are mapped separately from the upper terrace deposits because the lower deposits are more widespread and abundant and are of higher quality for use as aggregates. The lower deposits are generally uncemented and in places exceed nine meters in thickness, whereas the upper terrace deposits are usually capped by well-cemented caliche conglomerate and are generally less than five meters thick. Except for the difference in degree of cementation, both types of deposits yield a high-quality aggregate; the clasts are composed mostly of limestone with a small admixture of dolomite and chert.

Figure 3-6. Blanco River Alluvium

This deposit, composed of about 6 meters of limestone gravel overlain by about 3 meters of sand, silt, and clay, is the best source of sand and gravel in the area. This site is in UTM 3313-605. The view is eastward across the Blanco from a wet-operation gravel pit now in operation.

3.2.3.3 Energy Resources

The local availability of water power has been of great historical importance to urbanization of the San Marcos area. Water power could still be taken from both the Blanco and the San Marcos

River, but it is not presently considered a significant resource, so it is not indicated on the Resources map. Energy input to the area is now derived from distant sources.

3.2.4 Processes Map

The geologic processes of significance to urbanization are fluvial, karst, mass-movement, and shrink-swell processes (Plate 4). Other much slower but geologically important processes, such as erosion of the limestone uplands west of the Balcones Escarpment, are not mapped because they have little impact on urbanization. Tectonic processes that cause seismic activity are not active in the study area; the Balcones fault zone has not been active in historic time, and the central Texas region is in zone Zero of the seismic risk map of the United States (Oliver and others, 1969).

3.2.4.1 Fluvial Processes

The most significant fluvial process in the area is flooding. The flood-prone areas are derived in part from maps and air photos showing the "l00-year" floodplain as delineated by the U.S. Army Corps of Engineers (1971) and the U.S. Geological Survey (1973). Other flood-prone areas were approximated by: 1) interpolation of flood elevations and flood depths between the mapped areas; 2) use of geologic evidence, particularly the recent alluvial deposits; and 3) comparison of drainage basins in the area with basins in nearby quadrangles in which the l00-year floodplains have been mapped by the U. S. Geological Survey. Comparison basins were chosen that were similar with respect to size, topography, and geology to the basins in the study area.

Plate 4 shows that most of the flood-prone area is in the San Marcos section and includes the broad, relatively flat area around the eastern half of the city of San Marcos. This large area extends eastward to the eastern edge of the study area and upstream on either side of the Blanco River to the vicinity of Kyle. The remainder of the flood-prone area includes a narrow zone further upstream along the Blanco River and numerous narrow strips along the intermittent streams. These strips are generally shown upstream to the point where the floodplain width is less than about 100 meters.

3.2.4.2 Karst Processes

Aquifer recharge and sinkhole collapse are the significant karst processes in the study area. Aquifer recharge is included here as a karst process because the aquifer involved is the Edwards limestone aquifer. Most of the recharge occurs in streambeds (Figure 3-7), but some water also enters by direct infiltration through fractures and sinkholes. The areas of this recharge are important to urbanization from two standpoints. First, because the Edwards is a limestone aquifer having solutional porosity, it probably has poor potential for renovation of polluted recharge water and is therefore believed to be very susceptible to degradation of ground water quality by urban runoff. Second, the availability of an abundant supply of potable water from the Edwards

Figure 3-7. Recharge Point for the Edwards Aquifer

Note the cave and the smaller scale "burrow" porosity. The burrow porosity results from the solution of burrow fill formed by infauna during the deposition of the limestone. The 5-foot pole indicates the scale. The location is in the channel of Purgatory Creek in UTM 3305-598.

aquifer is essential to future urbanization in the area. Therefore, the residents of the area have a large stake in protecting the water quality of the aquifer. Recent studies of the tritium content of water from San Marcos Springs (Pearson, Rettman, and Wyerman, 1975) indicate that a significant part of the Edwards water in this area is derived from local recharge.

The Edwards recharge zone in the study area is shown in two parts on the Processes map - a primary and a secondary zone. The primary recharge zone coincides with the outcrop of the Edwards Group on the geologic map. The secondary recharge zone includes two types of areas: 1) outcrop areas of the Georgetown Formation and of alluvial deposits overlying the Edwards Group, and 2) areas which lie outside the primary zone but which lie in the drainage basins whose streams cross either the primary zone or the secondary zone as defined in 1). In general, the primary recharge zone includes the western half of the Kyle section and the northwestern corner of the San Marcos section of the study area. The secondary zone takes in a wide band which lies proximal to and east of the primary zone.

Sinkholes are common in the Edwards Group limestones (Figure 3-8), but they are not particularly noted for a tendency to collapse. However, the presence of post-Edwards strata in some sinkholes (Figure 3-8c) shows that collapse can occur, and at least one historic example of sinkhole collapse in central Texas has been documented (Hunt, 1973, p. 233). For these reasons the sinkholes in the study area are shown on the Processes map as sites of potential collapse.

Figure 3-8. Sinkholes in the Edwards Group

a. Aerial view of a sinkhole used as a stock tank. The black specks, which are cattle, indicate the scale. This sinkhole is in UTM 3322-597 and the view is to the north.

Figure 3-8. Sinkholes in the Edwards Group

b. Ground view of another typical sinkhole. This sink is also used as a stock tank when it contains water. Note the pond remnant in the left center of the photo. The sink is in UTM 3312-597 and the view is eastward.

Figure 3-8. Sinkholes in the Edwards Group

c. Collapsed sinkhole in the Edwards Group. This sinkhole cross section is exposed in a quarry wall in UTM 3309-603. The easily eroded Del Rio Clay, visible in the center of the photo, has collapsed into the Edwards limestones and overlying Georgetown marl. This view is to the northwest.

These sinkholes occur within the outcrop area of the Edwards Group limestones in the western half of the Kyle section and in the northwest corner of the San Marcos section of the study area. They are found mostly in flat upland areas where stream dissection has not destroyed them, and they are particularly abundant in the northwest corner of the Kyle section on a karstic plain.

3.2.4.3 Mass Movement Processes

Several areas around San Marcos have unstable slopes where clay substrate and steep slopes occur together, such as along cut banks of streams (Figure 3-9). The unstable slope unit on the Processes map includes only those areas which are experiencing active movement; areas which are underlain by clay substrate are not included unless movement is taking place under natural conditions. Slopes that are not actively moving but which may become unstable if they are oversteepened for cuts during construction can be delineated by using the Engineering Geology map and the Landform map (described below) together. Clay units indicated on the Engineering Geology map may be regarded as potentially unstable if they coincide with slopes greater than 15%. Most of the areas of active mass movement are east of the Balcones Escarpment.

Figure 3-9. Unstable Slope in the Pecan Gap Formation of the Taylor Group

This slope has been over steepened naturally along a cut bank of the San Marcos River in UTM 3303-605. This northwestward view shows tilted juniper trees and hummocky topography typical of slump terrane. A new house is under construction just off the left side of the photo.

3.2.4.4 Shrink-Swell Processes

The term shrink-swell is used here for the cyclic change in volume of expansive clay substrate under varying moisture conditions. The seasonal shrinking and swelling of the clay causes a self-churning action of the soils. In undisturbed natural conditions the churning action creates micro-relief (gilgai) on the surface, but this feature has been mostly destroyed in the study area by cultivation. The great soil group term for these soils is vertisol in the modern soil classification system (Buol, Hole, and McCracken, 1973, chapter 16). On the Processes map the unit used to delineate areas where this process is active is termed high shrink-swell. This unit can cause severe structural damages to foundations unless special construction techniques are used. The areas where the shrink-swell process is active include most of the clay substrate terrane east of the Balcones Escarpment.

3.2.5 Landform Map

The landform of the San Marcos area affords both opportunities and limitations for urbanization. One of the major opportunities is the availability of excellent scenic vistas along the Balcones Escarpment (Figure 3-10). Major limitations are also presented to the construction of various types of urban facilities. As noted in Chapter 2, a slope map is probably the best means of

Figure 3-10. House Built on the Balcones Escarpment

This house was located to take advantage of the excellent eastward view over the Blackland Prairie. The home is in San Marcos in UTM 3307-603.

portraying the landform insofar as its implications for urbanization are concerned. Four categories of slope, shown below, are depicted on the Landform map (Plate 5) for this study:

Category	Slope
1	<2%
2	2-5%
3	5-15%
4	>15%

These categories are adopted primarily from the Kansas Geological Survey (1968, p. 11) because they are, based on the slope requirements of several major urban land uses (Figure 2-3).

The slope map on Plate 5 was derived from the U. S. Geological Survey 7-1/2 minute topographic maps having a contour interval of 10 feet. This slope map clearly shows the profound influence of the Balcones Escarpment on the landform of the area. The section east of the escarpment has mostly slopes in the range of 0 to 5%, whereas the section west of the scarp is dominated by slopes over 5%.

3.3 Cultural Data Sources

3.3.1 Current Land Use Map

The Current Land Use map (Plate 6) shows the locations and distribution of present urban and agricultural uses. This map was compiled from several sources. The U.S. Geological Survey 7-1/2 minute topographic quadrangles served as the base map and showed the locations of most major features, such as the cities, highways, buildings, and cemeteries. The San Marcos North and San Marcos South quadrangles are dated 1964, and the Mountain City quadrangle is dated 1968, but all three were photo-revised in 1973. Two sets of aerial photographs were another prime source of land use data, particularly for agricultural uses. One set was flown in 1965 for a scale of 1:20,000 and the other was flown in 1973 for a scale of 1:48,000. Land ownership maps, which were obtained from the Hays County tax assessor's office, were also very valuable. The land use information from these sources was compiled in the office and then confirmed by field observation.

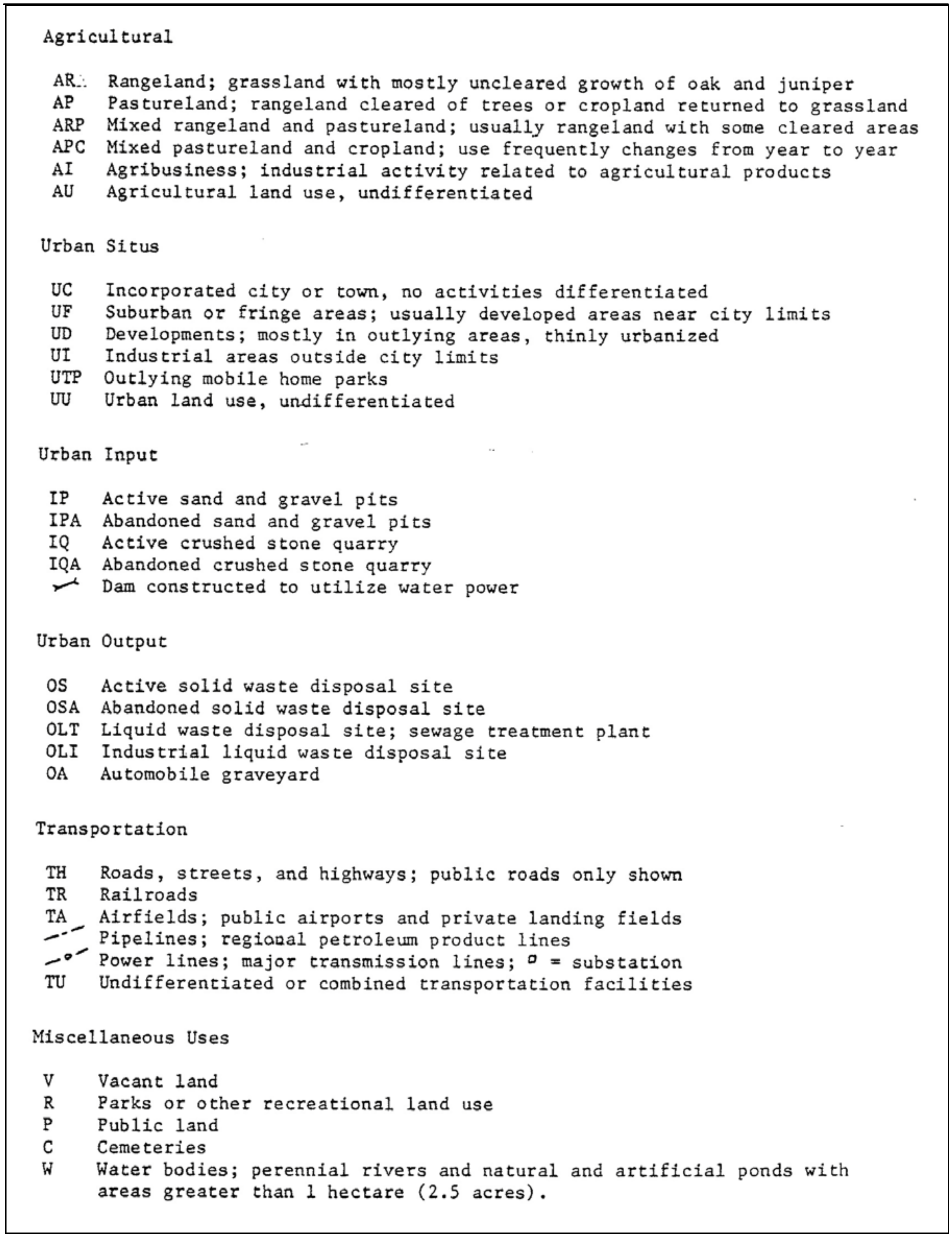
The land use categories shown on the Current Land Use map are shown in Table 3-3. Six major categories are used - one for agricultural uses, one for each of the four major urban system components, and one for miscellaneous uses. A total of thirty-three subcategories are recognized.

The distribution of land use is strongly controlled by the long-established agricultural use and by the locations of urban centers. Table 3-4 shows the major land use categories and the area occupied by each as well as the percentage of the total study area occupied by each category. The major land use is clearly still agricultural, since this category takes in over 80% of the area. Mixed rangeland and pastureland are dominant west of the Balcones Escarpment and mixed cropland and pastureland dominate east of the scarp. The land use becomes generally more urban toward the city of San Marcos and, to a lesser extent, toward Kyle. Outlying developments now occupy a considerable portion of the former agricultural land west of the escarpment.

3.3.2 Land Use Control Map

Land use control measures that have been instituted for some parts of the study area will have profound influence on the future uses of the land affected. The Land Use Control map (Plate 7) depicts four kinds of areas where governmental regulations control land use. These are: 1) the Edwards aquifer recharge zone; 2) the city limits of San Marcos; 3) the extraterritorial jurisdiction (ETJ) of San Marcos; and 4) the city limits of Kyle.

The land use control measure having the greatest impact on the study area is Texas Water Quality Board Order Number 75-0128-20, which was adopted in January, 1975. This order recognizes a recharge zone of the Edwards aquifer and sets forth certain land use controls within that zone. The specific controls may be found by referring to a copy of the order, which can be obtained from the Board. The area covered by the order is shown on 7-1/3 minute topographic maps that are on file at the Board, and the parts of the study area affected are shown on Plate 7. When this area was delineated by the Board, it was intended to coincide with the outcrop area of the Edwards Group limestones, so it should be a replica of the primary recharge zone depicted on the Processes map (Plate 4) of this study. A comparison of Plates 4 and 7 shows that the areas match generally, but there are some discrepancies. The area outlined by the Water Quality Board is based on earlier, less detailed geologic data than the maps prepared for this study.



Agricultural

AR	Rangeland; grassland with mostly uncleared growth of oak and juniper
AP	Pastureland; rangeland cleared of trees or cropland returned to grassland
ARP	Mixed rangeland and pastureland; usually rangeland with some cleared areas
APC	Mixed pastureland and cropland; use frequently changes from year to year
AI	Agribusiness; industrial activity related to agricultural products
AU	Agricultural land use, undifferentiated

Urban Situs

UC	Incorporated city or town, no activities differentiated
UF	Suburban or fringe areas; usually developed areas near city limits
UD	Developments; mostly in outlying areas, thinly urbanized
UI	Industrial areas outside city limits
UTP	Outlying mobile home parks
UU	Urban land use, undifferentiated

Urban Input

IP	Active sand and gravel pits
IPA	Abandoned sand and gravel pits
IQ	Active crushed stone quarry
IQA	Abandoned crushed stone quarry
―<	Dam constructed to utilize water power

Urban Output

OS	Active solid waste disposal site
OSA	Abandoned solid waste disposal site
OLT	Liquid waste disposal site; sewage treatment plant
OLI	Industrial liquid waste disposal site
OA	Automobile graveyard

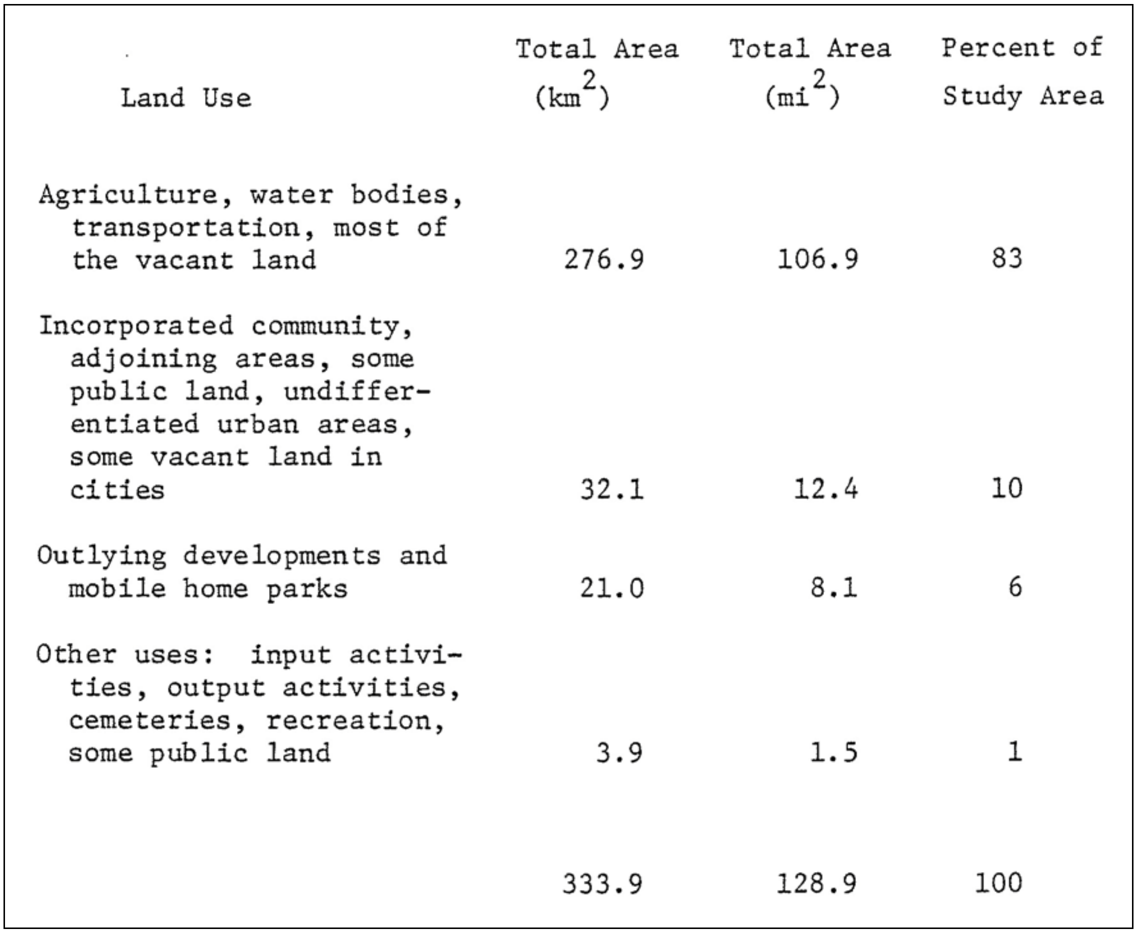
Transportation

TH	Roads, streets, and highways; public roads only shown
TR	Railroads
TA	Airfields; public airports and private landing fields
–·–	Pipelines; regional petroleum product lines
–∘–	Power lines; major transmission lines; ▫ = substation
TU	Undifferentiated or combined transportation facilities

Miscellaneous Uses

V	Vacant land
R	Parks or other recreational land use
P	Public land
C	Cemeteries
W	Water bodies; perennial rivers and natural and artificial ponds with areas greater than 1 hectare (2.5 acres).

Table 3-3. Categories of Current Land Use



Land Use	Total Area (km^2)	Total Area (mi^2)	Percent of Study Area
Agriculture, water bodies, transportation, most of the vacant land	276.9	106.9	83
Incorporated community, adjoining areas, some public land, undifferentiated urban areas, some vacant land in cities	32.1	12.4	10
Outlying developments and mobile home parks	21.0	8.1	6
Other uses: input activities, output activities, cemeteries, recreation, some public land	3.9	1.5	1
	333.9	128.9	100

Table 3-4. Approximate Areas Devoted to the Major Land

The city of San Marcos exercises zoning control over the area falling within its city limits. These limits, which are shown on the Land Use Control map, were adopted effective January 1, 1975 and are current as of this writing (February, 1976). A zone map of the affected area can be obtained from the city government, and the controls exercised over the various zones can be determined from city ordinances. The extraterritorial jurisdiction (ETJ) extends for one mile beyond the city limits and is approximately indicated on the Land Use Control map. The city has formal control only over land subdivision in this area, but some informal control is also exercised in the form of requests and recommendations. A similar type of informal control is exercised by the town of Kyle over land which falls within its city limits. The Kyle city limits shown on the Land Use Control map were adopted in 1968 and are current as of this writing.

4 Chapter 4. Environmental Geology of Existing Urban Systems In the San Marcos Area

With the background information and the natural and cultural data source maps developed in Chapter 3, it is now possible to apply the curative part of the methodology outlined in Chapter 2 to the San Marcos case study area. The procedure of this chapter will be first to describe the urbanization in the area and then to investigate the environmental geologic problems of this urbanization using the urban systems organizational scheme.

4.1 Urban Systems in the San Marcos Area

Table 3-4 shows that about 16% of the land surface in the San Marcos area is now devoted to urban-related uses. Three categories of urbanization are recognized: 1) the city of San Marcos; 2) the town of Kyle; and 3) the outlying housing developments and mobile home parks.

4.1.1 The City of San Marcos

The city of San Marcos is in the southern half of the study area at a pronounced break in topography along the Balcones Escarpment (Figure 4-1). The city presently has a population of about 25,000. The corporate limits include about 22.7 square kilometers (S.S square miles), but the Current Land Use map shows that urbanization in the city and surrounding area covers 30.4 square kilometers (11.7 square miles). With the exception of heavy industry the city possesses the activities and facilities common to most urban systems. Urban situs, urban input, urban output, and transportation are all relatively well represented. The city has a well-defined central business district, many residential areas, and a growing light industrial section. A large section of the city adjoining the central business district on the north is occupied by the campus of Southwest Texas State University (Figure 4-la). The city has had both a public water supply system and a public sewage collection and treatment system for many years.

The distribution of the urban activities of the city is strongly influenced by the Balcones Escarpment. The light industrial areas and most of the commercial areas are located either at the foot of the escarpment or further to the east (Figure 4-lc), whereas the more aesthetic surroundings of the hill country in the western part of the town are used mostly for residential areas. During the strong growth period 1963-1968, 69% of the residential construction was in the western part of the city and 31% was in the eastern part (Lockwood, Andrews, and Newnam, 1969c, p. 53).

4.1.2 The Town of Kyle

Kyle is in the northeastern corner of the study area at a point on the Balcones Escarpment where the topographic expression of the scarp is relatively weak (Figure 4-2a). The population of Kyle is approximately 1,500, and the corporate limits include about 2.6 square kilometers (1.0 square miles). However, the Current Land Use map shows that only about 1.4 square kilometers (0.5 square miles) have actually been urbanized. Most of the town's area is devoted to residential use,

Figure 4-1. City of San Marcos

a. Northward and downward view of the central part of the city. The central business district surrounds the Hays County Courthouse in the center of the photo, and the campus of Southwest Texas State University adjoins the CBD on the northeast. Several residential areas surround the city center, and Spring Lake and the San Marcos River can be seen in the lower right portion of the photo.

Figure 4-1. City of San Marcos

b. Southwest aerial oblique view. The Balcones Escarpment is clearly visible on the left side of the photo. The central part of the city is on the escarpment on the right side of the photo, and the thinly urbanized portion of the city east of the scarp can be seen in the foreground. An arm of Spring Lake appears on the right side of the photo.

Figure 4-1. City of San Marcos

c. Light industrial area in the southern part of the city along Interstate 35. This industrial park is gradually being occupied by small manufacturing firms

Figure 4-2. Town of Kyle

a. Northeast aerial oblique view of the town. Interstate 35 can be seen on the eastern edge of the town in the upper part of the photo.

but there is a small central business district (Figure 4-2b). Many of the residents of Kyle are employed elsewhere, particularly in Austin and San Marcos, so the town is at least partly a bedroom community. One manufacturing firm engaged in the production of steel forgings is located north of town. The town has had a municipal water system for several years and in the past decade has also built a public sewage collection and treatment system.

Almost all of Kyle is situated on the mixed hard and soft limestones of the Austin Group. This stable substrate, combined with the flat topography, small town size, and primarily residential land use, have resulted in relatively minor environmental problems.

4.1.3 Outlying Housing Developments and Mobile Home Parks

Of the 16% of the study area devoted to urbanization, 6%, or 21 square kilometers (8.1 square miles), is devoted to housing developments and mobile home parks. No population data are available for this type of urbanization, but at the present rate of growth, the population is undoubtedly increasing almost monthly. A few mobile home parks, one of which is shown in Figure 4-3, have been established in the proximity of San Marcos to meet housing demands in excess of housing availability in the city. Many of the units in these parks are occupied by students of Southwest Texas State University.

Six housing developments outside of existing communities have also been started in the area. Virtually all land use in these developments is residential. Most of the housing developments are

Figure 4-2. Town of Kyle

b. Westward view of the small central business district.

Figure 4-3. Mobile Home Park.

This facility, Woodland Hills mobile home park, has been expanded to nearly twice the size shown here. The park is located about 3.2 kilometers south of Kyle in UTM grid 3314-607. This aerial oblique view is to the north.

built by subdivision of the aesthetic hill country ranchland west of the Balcones Escarpment. When such a subdivision is built, commonly a road network is first constructed to provide access (Figure 4-4), and then lots are sold individually in sizes ranging from 0.4 to 4 hectares (1 to 10 acres). Many of these lots are purchased by people living outside the study area, particularly in Houston, Austin, and San Antonio, for vacation homes and for real estate investment. In all but one of the subdivisions each landowner must install his own water supply and sewage disposal system, usually with a well and septic tank. These requirements, coupled with the location of most of the developments in environmentally sensitive areas, have resulted in considerable environmental geologic conflict.

4.2 Environmental Geologic Problems of Existing Urban Systems

Because of long exposure the residents of the San Marcos area have grown somewhat accustomed to urban problems related to the geologic environment. Most of these problems are associated with the city of San Marcos because it is the largest urban center, it has the greatest variety of urban land uses, and it is located where a diversity of land characteristics give rise to a variety of environmental problems. Neither the town of Kyle nor the outlying housing developments exhibit the intensity or variety of environmental conflicts found in and around San Marcos.

Figure 4-4. Outlying Housing Development

a. Entrance to the Valley View development, showing the availability of lots and an advertisement of features. A house built on one of the lots can be seen in the background. The development is located west of the Balcones Escarpment in UTM 3312-601.

Figure 4-4. Outlying Housing Development

b. Southward aerial oblique view of Valley View. Note that few houses have yet been built in the development. The entrance shown in the preceding picture is in the upper center of this photo.

The procedure of this section will be to consider each of the four components of the urban system in turn and examine the environmental conflicts of the various facilities and activities of each category. The interaction approach will be used for the urban situs category, and the locations of features described in the text are indicated by use of the Universal and the subcomponents approach will be used in the input, output, and transportation categories. The Current Land Use map (Plate 6) shows the locations of many of the existing urban facilities, Transverse Mercator (UTM) grid system. This grid is taken from the U. S. Geological Survey topographic maps and is depicted on the Current Land Use map. The five physical data source maps illustrate the geologic settings of the various facilities, but most of the observations of this section resulted from field visitation of the facilities.

Many of the problems described in this analysis are indicated rather than confirmed problems, and much of the information presented is qualitative and descriptive. Most of the problems would require additional work to evaluate their seriousness and determine the steps needed to solve them. This additional effort is beyond the scope of this study because the objective here is to demonstrate an organizational methodology for delineating and describing potential environmental geologic problems. Additional work necessary for their validation and mitigation should be undertaken either by those who are causing the problem or those who are affected by the problem.

4.2.1 Urban Situs

Urban situs comprises two facets of the interaction of urban systems with the geologic environment - impact of the environment on the cities and impact of the cities on the environment.

4.2.1.1 Impact of the Geologic Environment on Urbanization

The San Marcos area is rather remarkable for the severity of both insidious and catastrophic hazards that are posed for urbanization. The most important of these are the problem of flooding and problems caused by outcrops of clay substrate in some parts of the area.

Flood Hazard

Owing to its location over the Balcones Escarpment, the area of study is in one of the most flood-prone areas in the U.S. (Baker, 1975), and flooding is without doubt its most serious environmental geologic problem. The escarpment produces an orographic lifting effect on inland-moving maritime air masses (see Chapter 3) and influences cold fronts that push their way southeastward across the state. These fronts are sometimes stalled in the vicinity of the scarp or vacillate back and forth across it, thus causing major thunderstorms.

Both the local, relatively small intermittent streams and the Blanco River, whose drainage basin includes about 1,100 square kilometers (430 square miles) in the eastern edge of the Edwards Plateau, flood frequently. The Processes map (Plate 4) indicates the flood-prone areas by depicting the IIl00-year floodplain.1I Most flood damages are caused by the Blanco and San Marcos rivers and Sink Springs, Purgatory, and Willow Springs creeks.

Although the topography at Kyle is relatively flat, some rather serious flooding occurred in November, 1974, and the town applied for eligibility for federal flood insurance in January, 1975 (San Marcos Record, 1975). Most of the housing developments in the area have not been greatly affected by flooding in the past, although parts of some of them are in flood-prone areas. At least one example of road damage caused by flooding in a subdivision was observed, but overall flood damage to subdivisions has been relatively minor because most of the subdivided areas have not yet been fully urbanized.

Historically, the city of San Marcos and the immediate vicinity have suffered the most serious flood damage, and they comprise the area most seriously threatened by future floods. The original Spanish settlement of San Marcos de Neve was abandoned primarily because of a flood, and the present city has been flooded several times since its establishment. The most serious floods occurred in 1913, 1921, 1929, 1952, and 1970 (U.S. Army Corps of Engineers, 1971, p. 4), and "nuisance" floods commonly occur two or three times each year (Hays County Citizen, June 12, 1975). The highest magnitude flood recorded occurred in September, 1921, but the May, 1970 flood was the most damaging because of increased urbanization of the floodplain (U.S. Army Corps of Engineers, 1971, p. 6). In the 1970 flood two lives were lost, and damage was estimated at over $3 million (Longley, 1975, p. 139). A comparison of the flood-prone areas shown on Plate 4 with the urbanization in those same areas as indicated on the Current Land Use map shows that most of San Marcos east of the Balcones Escarpment is subject to flooding. Figure 4-5a shows the floodwaters of the 1970 flood as they appeared just downstream from Spring Lake after the flood had abated considerably, and Figure 4-5b shows a housing development in San Marcos that was in process of being occupied when the flood occurred (San Marcos Record, 1970, p. 6).

San Marcos is subject to flooding both by local intermittent streams and by the more regional Blanco River. Blanco River floods reach San Marcos at least in part by "blackflow" up the San Marcos River from the confluence of the two rivers. Although the intermittent streams have much smaller watersheds, they flow directly through the city and occasionally experience very high discharges. The 1970 flood was caused primarily by overflow of Sink Springs, Purgatory, and Willow Springs creeks. These streams also show evidence of high discharge both by the presence of trees that are damaged at considerable heights (Figure 4-6) and by large, meter-long limestone boulders that are in the stream channels. These boulders are clearly transported only when discharges are very high.

Floodplain management and flood prevention measures are both used to alleviate the flood hazard. In the floodplain management method a floodwater elevation map prepared for the 1970 flood (U.S. Department of Agriculture, Soil Conservation Service, 1971) is used, and landowners are required to construct structures in the flood area a minimum of one foot above the 1970 flood elevation. Flood prevention measures consist of the construction of several dams. Floods caused

Figure 4-5. The 1970 San Marcos Flood

a. Floodwaters at and below Spring Lake Darn. The overtopped dam can be seen in the upper left corner of the photo, and the large buildings are the Clear Springs Apartments. The arrow pointing to the building on the right shows the high water mark at about the top of the lower floor. This aerial oblique was taken in a northeasterly direction. (Courtesy of San Marcos Record)

Figure 4-5. The 1970 San Marcos Flood

b. Flooded housing development in eastern San Marcos. This development is in UTM 3307-604, and the aerial oblique view is eastward. (Courtesy of San Marcos Record)

Figure 4-6. Flood-Damaged Trees Below Spring Lake Dam

Note the height at which branches have been broken off by floodwaters. The view is eastward, and the scale is 2 meters high. This scale is also used in several photos hereafter.

by precipitation in the upper part of the Blanco River basin will presumably be brought under control by construction of the Cloptin Crossing Dam about 19 river kilometers upstream near the community of Wimberley (U.S. Army Corps of Engineers, 1964). This dam will not, however, prevent floods resulting from intense precipitation events between the dam and San Marcos (Victor Baker, personal communication).

Two types of flood prevention methods have been proposed for the intermittent streams in the area - the bypass method and the up-basin retention method. The bypass method, proposed by the U.S. Army Corps of Engineers (1971), consists of several measures, including channelizing long segments of the streams and excavating a channel from Sink Springs Creek at a point just upstream from Spring Lake eastward to the Blanco River. This method was rejected by the city in favor of an up-basin retention method proposed by the Soil Conservation Service Watershed Planning Unit for the Upper San Marcos Reclamation and Flood Control District. The primary feature of this method is the construction of seven dams on Sink Springs, Purgatory, and Willow Springs creeks and their tributaries not only for retaining floodwater, but also for recharge of the Edwards aquifer. This plan has been accepted by the city, and the acquisition of land easements for the dams and reservoirs is expected to begin in the near future. The project is expected to eliminate between 90 and 95% of the flood damages to urban property in San Marcos (Longley, 1975, p. 185).

In general, the proposed measures for flood prevention in the San Marcos area should be adequate for controlling smaller magnitude floods. However, additional steps should probably be taken to more clearly delineate the areas subject to the low frequency, extremely high-magnitude floods characteristic of the Balcones Escarpment. Not only should future development be curtailed in such areas, but steps should probably be undertaken to make some changes in current land use. The "100-year floodplain" as demarcated by the U. S. Army Corps of Engineers and the U.S. Geological Survey probably is not adequate for delineation of areas affected by these very high magnitude floods (Baker, 1975, p. 13).

Clay Substrate Problems

"Poor soil conditions," as they are called locally, have long been a troublesome problem in the San Marcos area. One of the four, Hays County courthouses that have been built in San Marcos, for example, was abandoned and destroyed in the l800s after only 10 years of use because of "earth shiftings" at the courthouse site (from Texas Historical Commission historic marker). The primary causes of these problems are the clay units depicted on the Engineering Geology map (Plate 1). These clays cause a variety of problems because of their low shear strength, their tendency to consolidate under a load, and their susceptibility to cyclic volume changes (shrinking and swelling) with seasonal variations in soil moisture.

The occurrence and distribution of the clay substrate units, as shown on Plate 1, is different on either side of the Balcones Escarpment. The entire area east of the scarp is underlain by Upper Cretaceous clay units except where these units are mantled with alluvium. The composition of stratigraphically equivalent units further north in Travis County was found to be dominantly calcareous Ca-montmorillonite having poor engineering properties (Funk, 1975; Tipple, 1975). Unpublished work by the author indicates that the results of the Travis County work can be reasonably extrapolated this far south. West of the Balcones Escarpment the clay substrate units occur in an irregular, patchy distribution in a dominantly hard and mixed limestone terrane. Two stratigraphic units - the Del Rio Clay and the Eagle Ford Formation - comprise the clay substrate in this area. The Del Rio at depth, where it is unweathered, is composed of kaolinite, illite, and a small admixture of mixed layer illite-montmorillonite and is apparently stable. In the weathered zone, however, the illite and mixed-layer clay are converted to montmorillonite, and the engineering properties are correspondingly degraded. About 25% of the 7.5-meter thickness of the Eagle Ford Formation is not clay, but consists of thin calcareous siltstone and limestone flags. The remainder of the formation is a bentonitic smectite clay having poor engineering properties.

Despite the much wider occurrence of clay units east of the escarpment, most of the problems associated with clay substrate occur at or just west of the escarpment. This anomalous situation is explained by the location of most of the present urbanization near the escarpment and by the fact that the presence of clay units and their poor properties east of the scarp are well recognized by most of the inhabitants. West of the escarpment, however, most of the substrate is hard or mixed limestone, and the complicated Balcones faulting leaves the residents at a loss to predict where they will encounter the erratic clay units.

The city of San Marcos is the urban area most seriously affected by unstable clay substrate. Kyle is underlain by relatively stable mixed hard and soft limestones. Most of the outlying housing developments are in the hard limestone terrane west of the escarpment, and the few developments that encompass substantial areas underlain by clay substrate are not yet sufficiently urbanized to be greatly affected. Although some parts of the eastern half of San Marcos are underlain by clay, the impact is somewhat subdued because land uses that are compatible with the clay substrate are usually chosen. Thus, most of the conflicts are in the western part of San Marcos, where the city is located on the Balcones Escarpment. There the Del Rio Clay forms a nearly complete circle around the flanks of the large hill that underlies most of this part of the city, and the Eagle Ford Formation caps this hill. Most of the city at the foot of the escarpment is also underlain by clay. A variety of problems has been caused by these clay substrate units. Shrinking and swelling has caused widespread buckling of sidewalks and road destruction which constitutes a continuous and expensive maintenance problem. Minor structural damage of the type illustrated in Figure 4-7 is also quite common. This example is believed to have been caused by shrinking and swelling in combination with consolidation of the clay substrate.

Unstable slopes comprise the most serious and hazardous problems caused by the clay substrate. These problems occur almost entirely in Del Rio Clay outcrops in steep slopes in the western part of San Marcos. Failure of these slopes is either by creep (Figure 4-8) or, more commonly, by a slump or related type of shear failure. Figure 4-9 shows a classic slump caused by over-steepening of a slope during construction of the extension of Sessom Street. A cut made for a nearby apartment complex is shown in Figure 4-10 before and after a slump-like failure. Also shown is the retaining wall which was later installed by the developer at an unanticipated cost of more than $10,000. Like the in situ clay, spoil material from excavations in the Del Rio can also be unstable when placed in overly steep slopes as shown in Figure 4-11.

The engineering behavior of the Del Rio Clay is strongly affected by weathering as noted earlier. The preceding examples of failure occurred in the Del Rio where it is exposed at the surface and is therefore deeply weathered. Where the clay is protected from weathering by the overlying Buda limestones, it may be quite stable. The very steep slope in the Del Rio shown in Figure 4-12, for example, has been standing for over 25 years, and except for minor surficial sloughing, gives no indication of instability.

4.2.1.2 Impact of Urbanization on the Geologic Environment

Within the San Marcos area the most important impact of urbanization on the geologic environment is probably the reduction of surface water quality caused by runoff from the urbanized areas. Other less significant impacts are changes in stream basin hydrology and problems of increased erosion and sedimentation.

Figure 4-7. Structural Damage Attributed to Clay Substrate

a. Cracks in the side of a brick church in UTM 3305-601. These cracks are almost certainly caused by heaving clay substrate.

In general, the impact of urbanization on surface water quality is negative and results, for example, in increased bacterial, dissolved solids, and turbidity content and in decreased dissolved oxygen content of the water. The water quality characteristics of urban runoff in the San Marcos area have not been studied, but a few generalizations can be stated. Because the land use in the housing developments is primarily residential and because the developments are not yet fully urbanized, the quality of their runoff is probably not greatly different from its original predevelopment character. San Marcos and Kyle are more densely populated than the developments and have a better representation of urban land uses, so they should be expected to produce a relatively typical urban runoff. The impact of urbanization on surface water quality in the San Marcos area is significant not so much because of a particularly large volume or special toxicity of the urban runoff, but rather because of the extraordinary sensitivity of some parts of

Figure 4-7. Structural Damage Attributed to Clay Substrate

b. Foundation damage in same building caused by pressures from swelling clay. Note that the foundation has pushed out slightly beyond the wall.

the area to poor surface water quality. Two features of the area - the Edwards aquifer and the biologically unique Spring Lake and San Marcos River - account for this sensitivity. The high flow volume, constant temperatures, and high water quality of the San Marcos Springs have resulted in the development of both lentic and lotic ecosystems that are unique at least in the state, if not in the country. Many of the unusual and even unique species thrive in the reservoirs and watercourse of the San Marcos River because of the good quality of water and may therefore be highly susceptible to pollution. Consequently, the watershed of the San Marcos River, at least to the confluence of the Blanco River, should probably be considered highly sensitive to urban runoff. The sensitivity of the Edwards aquifer recharge zone to polluted water was described in Chapter 3.

Figure 4-8. Failure of a Retaining Wall

This failure is caused by downslope creep of the Del Rio Clay. Also note the tilted power pole. This view is southwestward along Burleson Street in UTM 3305-601.

Figure 4-9. Sessom Street Slump

a. The slump as it appeared shortly after failure.

Figure 4-9. Sessom Street Slump

b. The slump as it appeared one week later. This slump in the Del Rio Clay was caused by oversteepening of a slope for a roadcut. Both views are to the south across Sessom Street in UTM 3307-602

Figure 4-10. Slope Failure in the Del Rio Clay at an Apartment Complex

a. Freshly cut, over-steepened slope before failure. The cut was made to create a pad, shown in the foregound, for the new apartment building.

Figure 4-10. Slope Failure in the Del Rio Clay at an Apartment Complex

b. The same slope two days later after a rainstorm and subsequent failure.

Figure 4-10. Slope Failure in the Del Rio Clay at an Apartment Complex

c. Retaining wall which was put in to remedy the problem. All views are southeastward. The site is in UTM 3307-602.

Figure 4-11. Slope Failure in Del Rio Clay Spoil Material

The spoils from the excavation in Figure 4.10 were pushed out on the hillside to create this parking lot. Note the steep slope on the right side of the photo. The view is southeastward.

Figure 4-12. An Oversteepened but Apparently Stable Slope in the Del Rio Clay

a. Southwest frontal view showing the contact with the overlying Buda Formation. The folding is the result of fault drag associated with the nearby San Marcos Springs fault.

Figure 4-12. An Oversteepened but Apparently Stable Slope in the Del Rio Clay

b. Northwest side view showing the steepness of the slope. This outcrop is on Ed J. L. Green Drive near Spring Lake (UTM 3307-602).

The town of Kyle poses little or no threat to either of the two sensitive areas. The drainage of the town is not into the San Marcos River watershed and does not cross the Edwards recharge zone. Several of the outlying housing developments are located in either or both the San Marcos River watershed and the Edwards recharge zone, but as noted above their impact on runoff is probably not yet significant. These developments may pose a threat to the Edwards aquifer, however, because of the widespread use of septic tanks as described below in the urban output section.

Urban runoff from the city of San Marcos may present a serious threat to the San Marcos River and, to a lesser extent, the Edwards recharge zone. Virtually all of the city lies in the river's watershed at and around the river's source at Spring Lake. The resulting implications for the unusual fauna and flora of the lake and river are being studied by personnel at Southwest Texas State University (Glenn Longley, personal communication, 1975). Much of the western part of San Marcos lies in the primary or secondary recharge zone of the Edwards aquifer, as can be seen by comparing the Current Land Use map with the Processes map. The potential damage to the aquifer caused by recharge of polluted urban runoff in the vicinity of the city is all the more serious considering the intense use of water from the aquifer by the city for its municipal water supply. More complete study of the potential pollution of the Edwards aquifer by urban runoff is clearly indicated.

Besides affecting the quality of runoff of the stream basins in the study area, urbanization may also affect the hydrology of the stream basins. Leopold (1968) summarized the effects of urbanization on stream hydrology. This impact of urbanization on streams in the San Marcos area has not been fully analyzed, but a few generalizations can again be made. The outlying housing developments are generally too small and too vacant to have had appreciable impact on the hydrology of the basins in which they are located, and Kyle is also probably too small to have effected great changes in the hydrology of local streams. Probably only the city of San Marcos is large enough to have caused changes in the local stream basins. However, the natural hydrology of streams west of the Balcones Escarpment (Baker, 1975, p. 3) is such that urbanization may not have great impact. Thus, that part of San Marcos located east of the escarpment is the most likely to have experienced changes in stream basin characteristics. Two meander loops in this part of the city have in fact been cut off artificially, and efforts to "channelize" the local streams continue.

Increased erosion and sedimentation caused by urbanization are evident in the San Marcos area but do not appear to be a major problem at present. In the city of San Marcos excessive erosion may occur on the slopes of Del Rio Clay if they are cleared of vegetation and not reseeded in a short time (Figure 4-13). Also, local examples of stream rejuvenation and downcutting apparently caused by urbanization (Figure 4-14) can be seen. At least one example of increased sedimentation caused by urbanization is present. A small tributary that rises within the city limits

Figure 4-13. Rill Erosion of an Exposed Clay Slope

a. Fresh slope exposed in a roadcut for Sessom Street in UTM 3307-602.

Figure 4-13. Rill Erosion of an Exposed Clay Slope

b. The same slope about 18 months later, showing the deep rills that have formed. The first view is to the southwest and the second view is southward.

Figure 4-14. Channel Scour Attributed to Urbanization

The downcutting of this stream is probably the result of increased runoff caused by a housing development constructed in the drainage basin. The development, part of which can be seen in the background, is in UTM 3307-600. The exposed bedrock in the channel is the Buda Formation. The view is to the southeast.

of San Marcos has built a gravel deposit out into the San Marcos River just below Spring Lake dam (Figure 4-15) and has caused some concern for the river's biota (Glenn Longley, personal communication, 1975). It is possible that this increased sedimentation occurred during construction of an apartment complex upstream on the tributary.

In summary, it may be concluded that the urbanization in the study area does not in itself present any special hazards to the geologic environment, but the geology in the area make it unusually sensitive to the effects of urbanization. Further study is clearly needed to document the problems discussed and to determine the- steps needed to solve or mitigate them.

4.2.2 Urban Input

The San Marcos area is rich in the basic resources that must be derived locally and are essential for urban maintenance and growth. Three types of urban input - aggregates, water, and energy - have the greatest environmental geologic significance in the San Marcos area.

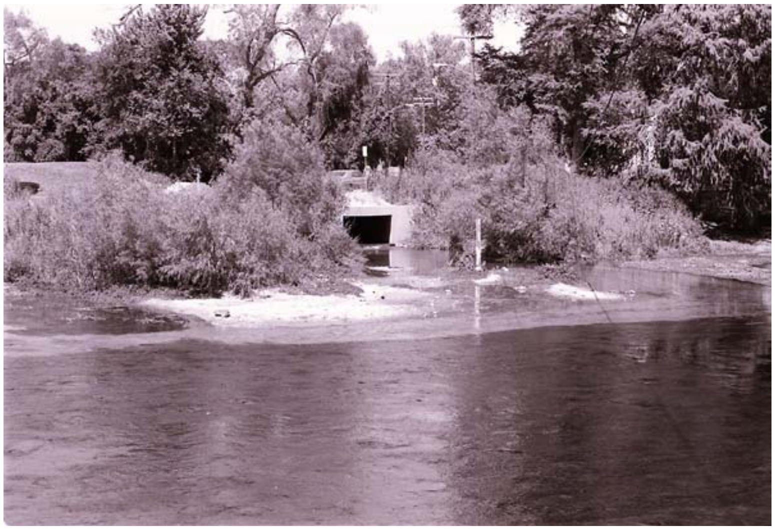


Figure 4-15. Sedimentation in the San Marcos River

This gravel deposit, which is located just below Spring Lake Dam, was built out into the river by a small stream that enters the river through the large culvert. The entire length of the stream is within the city limits of San Marcos. This view is westward.

4.2.2.1 Aggregates Input

Two kinds of aggregates - crushed limestone and sand and gravel - are mined in the San Marcos area for urban related uses. Most of the environmental geologic conflict associated with the utilization of aggregates is expressed in one direction only - the impact of the operations on the environment. Aside from determining their locations, the geologic environment has little impact on the operations chiefly because of the relatively small permanent capital investment that is subject to geologic hazards.

Crushed Stone

The Resources map (Plate 3) shows that potential crushed limestone resources are to be found over most of the area west of the Balcones Escarpment, and the locations of the quarries as shown on the Current Land Use map (Plate 6) strongly reflect this availability. Crushed limestone is taken from quarries in the Edwards Group, the Georgetown, Buda and Eagle Ford Formations, and the Austin Group. Most of these quarries were opened during the construction of Interstate 35 and were abandoned when the highway was completed.

The primary environmental problem of the quarries lies in their reclamation, or rather, their lack of reclamation. Some of the quarries are still operated intermittently, and their owners are reluctant to close them down completely for reclamation. Also, the quarries are relatively difficult to reclaim. Because of the hardness of the limestone, the high walls that are left when operations cease can be reduced only with difficulty and at considerable expense. In addition, the original soils on the limestones at the quarry sites are mostly very thin, thus making revegetation of the sites very difficult. The chief reason for the lack of reclamation, however, is economic. The land values in the area are generally not great enough to economically justify the costs of reclamation, and no state legislation or tax incentives have yet been instituted to require or encourage reclamation efforts. For these reasons few of the quarries have been reclaimed, and they remain for the most part as large scars on the countryside (Figure 4-16). Fortunately, with two or three exceptions, the abandoned quarries are not misused as waste disposal sites. Waste disposal in quarries in the Edwards Group would likely be particularly damaging because of the potential pollution of the Edwards aquifer.

Sand and Gravel

Sand and gravel are presently the most important form of aggregates input into urban systems in the San Marcos area. As shown on the Resources map (Plate 3), the available sand and gravel deposits are floodplain and terrace gravels of the Blanco and San Marcos Rivers. Most of the gravel pits of consequence are shown on the Current Land Use map. Two types of gravel pit operations - wet operations and dry operations - are present in the area. The wet operations are the larger of the two types. Two of these are in production on the Blanco River (Figure 4-17), and a third, abandoned pit is also present.

Unlike the wet-operation pits, the dry-operation pits are not restricted in their locations to the immediate proximity of a water source and are therefore found throughout the area where gravel is available. The wet-operation pits are restricted to the floodplain gravels along the Blanco, but the dry-operation pits are in both the floodplain and the higher terrace gravels. Most of the dry-operation pits are either abandoned or are operated only intermittently (Figure 4-18).

Figure 4-16. Unreclaimed Crushed Limestone Quarries

a. Abandoned quarry in the upper Buda and lower Eagle Ford Formations. This quarry is located about 2.8 kilometers southwest of Kyle· in UTH 3317-605. The aerial oblique view is southward.

Figure 4-16. Unreclaimed Crushed Limestone Quarries

b. Ground view of the quarry shown in a. The line is drawn at the contact of the Buda and Eagle Ford Formations. Note the calichification of the lower clay unit on the hillside. The view is northward.

Figure 4-17. Wet-operation Sand and Gravel Pits

a. Active pit located on the Blanco River about 5.3 kilometers southwest of Kyle in UTM 3313-605. Five-mile Dam is only about 1 kilometer downstream. The single arrow indicates the pond which is used as a silt trap. The double arrow indicates the direction of river flow. This aerial oblique view is to the north.

Figure 4-17. Wet-operation Sand and Gravel Pits

b. Active pit (inside meander loop) and abandoned pit (foreground). These pits are also on the Blanco River about 4 kilometers southeast of downtown San Marcos in UTM 3303-605 and 3304-605. The single arrow indicates the location of the pipeline. The double arrow indicates the direction of river flow. Note the abandoned equipment in the pit in the foreground. The aerial oblique view is northward.

Figure 4-18. Dry-operation Gravel Pit

Aggregates taken from this pit are not washed and screened before use. The pit, which is operated only intermittently, is in alluvium of the Blanco River in UTM 3307-606. The view is northward.

Environmental geologic problems of three different types are associated with sand and gravel operations in the study area: 1) the problem of "urbanizing over" the gravel deposits before they are utilized; 2) the problem of stream and reservoir siltation by the wet-operation pits; and 3) the problem of post-operation use and reclamation of the pits. Within the limits of the study area,

considerable areas of sand and gravel deposits have been eliminated from utilization because they have been covered by urbanization. A comparison of the Resources map with the Current Land Use map shows that most of eastern San Marcos is located over potential sand and gravel resources. The result of this urbanization is to upgrade the land values in that area so that land use for sand and gravel operations is now economically unfeasible. In addition, the noise and ugliness of these operations makes it politically unlikely that they could be located this close to the city. Further loss of these valuable resources that are located closest to the city where transport costs are the lowest should be prevented in the future by instituting multiple sequential land use.

The wet-operation pits in the area pose a potential situation hazard to the Blanco River. The fines that are left after the sand and gravel are washed and screened must be disposed of in some manner and, until recent years, the practice has been simply to allow these tailings to flow into the river. The wet-operation pits are located just upstream from dams on the Blanco, so the chief problem is one of local siltation of reservoirs rather than pollution of surface water by increased turbidity. Considerable siltation of the reservoir behind Alvord Dam no doubt occurred when the now-abandoned wet-operation pit at UTM 3303.5-605.3 was in production, but the extent of filling of the reservoir has not been documented. Siltation of the reservoir would still be taking place because of the wet-operation pit across the river from the abandoned pit were it not for the discharge pipe (Figure 4-19a) that has been installed across the river. This pipe transports the tailings from the present operation across the river for deposition in the abandoned pit, which is thus being used as a silt trap (Figure 4-l9b).

Probably the most serious siltation problem in the area is caused by the wet-operation pit at UTM 3313.3-605.8 (Figure 4-l7a). This facility is just upstream from Five-mile Dam and the associated Dudley Johnson County Park, one of the more popular recreation spots in the area. Considerable siltation of the reservoir from the dam has been reported by park users and a small island has formed in the reservoir just upstream from the dam. An embankment has been constructed in the channel of the Blanco to trap silt from the operation, but this measure is only a Short-term expedient because the embankment will undoubtedly be destroyed during the next large flood of the Blanco and the silt will be released to the river.

The flushing action on the silted reservoirs by Blanco River floods has not been evaluated. If flood waters flush much of the silt the filling of the reservo.irs is only a short term problem, but water quality implications for the river because of increased turbidity may then arise further downstream. Clearly, more work remains to be done before the impact of the silt produced by the wet-operation pits can be evaluated for the river generally and for the reservoirs specifically.

The post-operation use and reclamation of the gravel pits is one of the primary environmental geologic concerns of sand and gravel utilization. As was the case for the crushed stone quarries, little or no reclamation is done solely for the sake of reclamation. However, a variety of post-operation uses are made of the pits. Unfortunately, with the exception of the use of an abandoned wet-operation pit for a silt trap as described earlier, the best post-operation uses at present consist of no use at all. The primary reason for the lack of proper reclamation measures is again economic. The lack of sufficiently high land values, tax incentives, or mandatory requirements make reclamation economically unfeasible. Post-operation use of the dry-operation gravel pits consists primarily of merely filling them with whatever materials are most easily obtained, including urban solid waste. At one site (Figure 4-20) near San Marcos, a mobile home park has been built around an abandoned pit which is now full of water. Although this pond could potentially be developed into a duck pond or other aesthetic feature of the park, it is instead merely being filled with relatively inert construction and building demolition wastes. At a nearby site which has no associated trailer park, another pit is being filled (Figure 4-21). Although only inert materials are supposedly allowed at the site, in fact almost all types of urban wastes are deposited, and the pit has degenerated to a virtual dump.

Figure 4-19. Use of an Abandoned Gravel Pit as a Silt Trap

a. Pipeline across the Blanco River for transporting silt-laden water from the current operation on the far side of the river to the abandoned pit. The location of this pipeline was shown in Figure 4-l7b. This view is to the north.

Figure 4-19. Use of an Abandoned Gravel Pit as a Silt Trap

b. Discharge point of the silt-laden water in the abandoned pit. The view is to the south.

Figure 4-20. Abandoned Gravel Pit Now Used as a Mobile Home Park

The pit is slowly being filled with relatively inert waste material, such as fill dirt and construction and demolition wastes. The pit is in UTM 3307-605, and the view is northeastward.

Figure 4-21. Abandoned Gravel Pit Being Reclaimed by Filling With Solid Waste

The view is southeastward. The site is in UTM 3307-605.

4.2.2.2 Water Input

Water use in the San Marcos area is restricted to ground water because of the abundance, widespread availability, and high purity of water from the Edwards aquifer. Both San Marcos and Kyle have municipal water supply systems which take water from the Edwards aquifer (Figure 4-22) and subject it only to chlorination (Figure 4-23) before distributing it in the city water mains. One of the housing developments has a collective water supply system operated by a private company (Figure 4-24), but the residences in the other developments have individual wells and water supply systems (Figure 4-25). Most industries in the area use municipal water supplies, but a wool-scouring plant pumps its own water from the Edwards at Sink Springs (Figure 4-26) for use in some of its plant operations.

Little environmental conflict is associated with ground water usage as long as wells are properly constructed. Well completion practices now used by water well drillers, combined with county regulations on well construction, ensure that at least the newer wells are environmentally secure. The Edwards aquifer is in some danger of being polluted by urbanization, but this danger is not related to water use for urban systems. Depletion of the aquifer is also a possibility, but this problem can be attacked only by regional aquifer management, and not by local action alone.

4.2.2.3 Energy Input

Energy input into urban systems in the San Marcos area is of several types, including electricity and liquid and gas petroleum products. These are all imported from sources outside the area, and their primary local environmental significance lies in the facilities that are used to bring them in, such as highways, pipelines, and power lines.

One of the primary attractions of the site at San Marcos Springs for building a city was the ready availability of water power, which was one of the most widely used forms of energy at the time of Anglo-American settlement. Five dams were built on the San Marcos River to make use of this energy source, and most of these dams are still in place. The dams and their associated reservoirs are now used primarily for recreation. They were originally constructed for utilization of water power for urban related activities, however, so their environmental geologic problems will be discussed in this section. Two of the dams were used for generation of electricity, and the remaining three transformed the water power into mechanical energy for running mills of different types.

Spring Lake Dam, the uppermost of the dams, impounds Spring Lake (Figure 4-27) which inundates most of the San Marcos Springs's discharge points. This dam was originally built in 1895 to power a water wheel for a mill, but was later converted to electric power generation. Power from this generator was used to supply electricity to San Marcos as late as 1932 (Dobie, 1932, p. 3), and much of the structure of the plant is still in place (Figure 4-28).

Figure 4-22. Municipal Water Wells

a. San Marcos municipal well near Comanche Street in UTM 3306-601. This well is one of two at this site. Three additional wells are located near Spring Lake of Ed J. L. Green Drive.

Figure 4-22. Municipal Water Wells

b. Kyle municipal well near the intersection of Moore and Meyer Streets in UTM 3317-607. This well is one of two used by the town.

Figure 4-23. Water Treatment System for the City of San Marcos

The bottle contains chlorine gas. The chlorine metering device can be seen in the upper right corner of the photo. This system is at the pump station on Ed J. L. Green Drive.

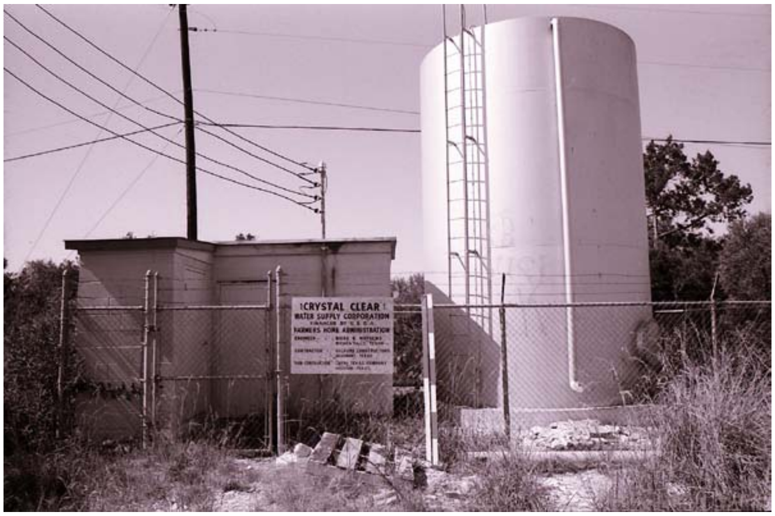


Figure 4-24. Pumphouse and Water Tank for a Water Well Operated by a Private Company

This facility, which supplies water to one of the outlying housing developments, is one of several operated by the company. The view is to the south, and the site is located in UTM 3302-598.

Figure 4-25. Typical Water Well Installed in the Outlying Developments

These wells are usually used by one to three residences. Well diameters are about 15 centimeters, and down-hole submersible pumps are used to pump water into the pressure tank. This installation is in the northwestern part of the area in UTM 3318-598.

Figure 4-26. Pumphouse at Sink Springs

The arrow indicates the intake pipe. The water withdrawn is used in operations of a nearby wool-scouring plant. The water surface in the sink is at the static level of the Edwards aquifer. This view is generally westward, and the site is at UTM 3307.3-604.0.

Figure 4-27. Spring Lake and Spring Lake Dam

a. Spring Lake. The discharge points of San Marcos Springs are inundated by the west arm of the lake (shown on the right in this photo). The Aquarena Springs concession is on the peninsula between the two arms. Spring Lake Dam is at the upper edge of the photo. The view is to the southwest.

Figure 4-27. Spring Lake and Spring Lake Dam

b. Western segment of Spring Lake Dam. Although the upper surface is covered with concrete, the dam proper is constructed of rock and earth. This view is northeastward.

Figure 4-28. Structure Remaining from a Power Generating Plant on Spring Lake Dam

a. Upper part of the facility, showing the concrete structure and part of the mechanical gear. The view is generally westward.

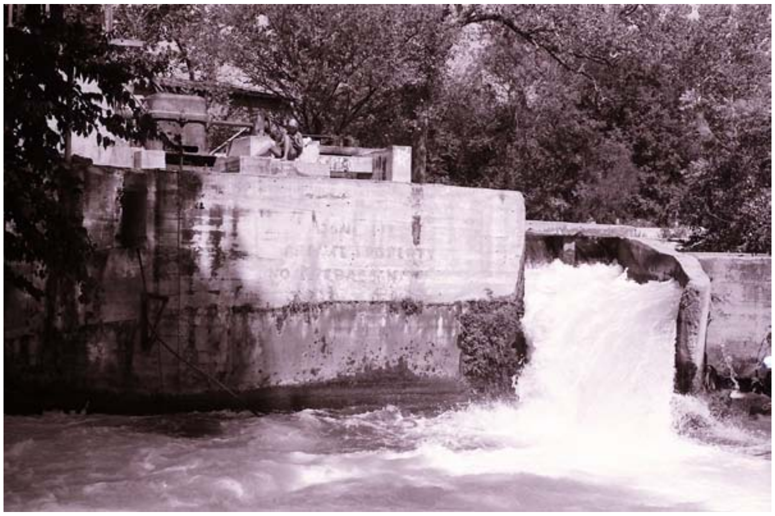


Figure 4-28. Structure Remaining from a Power Generating Plant on Spring Lake Dam

b. Lower part of the facility, showing the discharge of San Marcos Springs. The sunbather indicates the scale. The view is northeastward.

The second dam downstream is Rogers Dam (Figure 4-29), which was built to provide mechanical power for a nearby mill that is now abandoned. The reservoir behind the dam is presently used as part of a city park. The next two dams are Upper and Lower Cape dams. Both are in a state of near total disrepair and do not impound significant reservoirs. The upper dam does, however, divert a significant part of the flow of the San Marcos River into a canal (Figure 4-30). This canal in turn feeds a mill race for a large cotton gin that was abandoned within the last 20 years.

The furthest downstream dam on the San Marcos River is Alvord Dam, which was built early in this century for electric power generation (Figure 4-31) and was operated as recently as about 1960 by the Lower Colorado River Authority. Although the dam is in need of some repair, it appears to be structurally intact. No apparent use is presently being made of the dam or the reservoir.

Since these dams are no longer fulfilling the function for which they were originally built, it would at first appear that only their impact on the environment should be of concern. However, the reservoirs of some of the dams have assumed a new importance for recreation, so the impact of the environment on them must also be considered. The primary impact of the geologic environment is the flood hazard posed to the dams, Probably because it is the furthest upstream dam, Spring Lake Dam appears to receive the most damage from the periodic floods of Sink Springs Creek. The dam was almost completely destroyed by flooding at least once since it was built, and considerable repair is required after almost every sizeable flow of the creek. Alvord Dam, which is below the confluence of the Blanco River, has in the past also been subjected to considerable flood damage. The present dam is in fact a replacement for a dam which was destroyed by a flood in the 1920s, probably the 1921 flood.

All of the dams in the area are quite small and, with the exception of Alvord Dam, are built of rock, earth, or a combination of rock and earth, so there has apparently been little problem with foundation failures. Alvord Dam, despite the fact that it is constructed of concrete and is built at least in part in clay substrate, appears to be structurally intact.

The impacts of the dams on the geologic environment are somewhat difficult to assess because they have been in place for so long that little data on pre-dam conditions is available. The same generalization may also be made for their impact on the unusual biologic assemblages of the river. The reservoirs of each dam downstream from Spring Lake extend upstream almost to the tail waters of the next dam (U.S. Army Corps of Engineers, 1971, p. 23), so the original flow pattern of the river has been greatly altered. The mixed fast-water and slow-water flow has given rise to a combination of both lotic and lentic ecosystems, as noted earlier. The primary environmental geologic effect of the dams is the impact of Spring Lake on San Marcos Springs.

Figure 4-29. Rogers Dam and Associated Works

a. Aerial view of dam and reservoir. Rio Vista city park is on the right bank of the river (left side of this photo). The arrow indicates the canal which directs part of the river flow into a mill race. The dam is in UTM 3305-603, and this view is northwestward.

Figure 4-29. Rogers Dam and Associated Works

b. Mill race and abandoned mill at Rogers Dam. Some of the old mill works are still in place and can be seen in the lower part of the mill. The view is to the southeast.

Figure 4-30. Upper Cape Dam and Associated Canal

The normal course of the river is from right to left and under the trees in the upper left part of the photo. Cape Dam can be seen where the white cascade of water overtops the dam in the left center of the photo. Water flow is partially diverted into the canal extending from the dam to the left edge of the photo. This aerial oblique view is generally southward. The dam is in UTM 3304-603.

Figure 4-31. Alvord Dam and Associated Works

a. Distal view showing the dam and powerhouse. The dam is in UTN 3303-604, and this view is southwestward.

Figure 4-31. Alvord Dam and Associated Works

b. Downward view of the dam from the powerhouse. Note that the dam is constructed of concrete. All the flow of the San Marcos River is over the top of the dam.

Figure 4-31. Alvord Dam and Associated Works

c. Remains of the power generator left in the powerhouse when the plant was abandoned. Both the armature and the field coils have been removed, presumably for salvage of the copper.

Some of the springs' discharge points have been inundated by up to 13 meters of water, and the resulting head on the springs may be decreasing the spring flow. An early attempt to increase the water power at Spring Lake by increasing the height of the dam reportedly was abandoned because the springs ceased flowing altogether. Unfortunately, no pre-dam spring flow data are available to assess the effect of the lake on the springs.

4.2.3 Urban Output

Urban waste products are the form of urban output having the greatest environmental geologic significance. In this section the urban waste classification presented in Chapter 2 will be used and the environmental implications of the various waste categories in the San Marcos area will be discussed. The environmental effects of the wastes are almost entirely in one direction - impact of the wastes on the environment. Two major categories of wastes - solid and liquid wastes - are recognized because they have generally quite different environmental implications. Little environmental geologic effect results from energy and gaseous wastes produced in the area.

4.2.3.1 Solid Wastes

Virtually all of the solid waste output of urban systems in the San Marcos area is either waste produced by individual residences or municipal waste that is typical of small cities. The industrial wastes produced are not distinctive, and no hazardous wastes are recognized or disposed of by special methods. Three methods of solid waste disposal are used in the study area - individual dumps, collective dumps, and sanitary landfills.

Individual Dumps

The dumping of solid wastes at or near the place where they are generated no doubt began during the early days of settlement in the area, when transportation was difficult and local disposal was necessary and expedient. Unfortunately, this practice continues to the present at some locations (Figure 4-32). The environmental degradation caused by these dumps could be quite serious. Not only are they aesthetically unpleasing, but they may also be lowering the quality of the water of the stream basins in which they are located. If these drainage basins are in the Edwards aquifer recharge zone, as most of them west of the Balcones Escarpment are, then the surface water quality threat may also become a problem of ground water quality.

Ranchers owning land in the cavernous limestone terrane of the Edwards Group west of the escarpment have frequently used caves as solid waste disposal sites (Figure 4-33). This practice could result in degradation of water quality in the Edwards, but definitive data are lacking. Fortunately, the use of caves as disposal sites has been largely discontinued, but those caves that have been filled have not been cleaned out.

Figure 4-32. Individual Dump

The site is on the property of the persons who are using the dump. The view is generally southeastward. The site is in UTM 3315-599.

Figure 4-33. Use of a Cave for Solid Waste Disposal

The cave, which is behind and beneath the visible trash, has apparently been filled to the level of the land surface with waste materials. This site is in UTM 3323-598 and the view is to the east.

East of the Balcones Escarpment solid waste is often dumped into ravines in an attempt to control erosion (Figure 4-34). Poor agricultural practices in the past, such as planting row crops (mostly cotton) with the rows oriented in the down-slope direction, have resulted in severe soil erosion problems in the clayey soils and substrate. Although these practices have been mostly eliminated by soil conservation measures, the excessive erosion which was set in motion in earlier years is very difficult to bring under control. Solid waste dumping is a common but highly questionable means used to stop the gullying, both from the standpoint of effectiveness and environmental protection. The primary environmental effect of these dump sites in the eastern and southeastern part of the study area is their possible degradation of surface water quality.

Figure 4-34. Use of an Individual Dump to Retard Erosion

The arroyo has been filled with trash for a length of about 100 meters. This site is in UTM 3301-604. The view is northeastward.

The practice of disposing of solid wastes in individual, widely dispersed sites should be discontinued, and in areas of particular environmental sensitivity such as the Edwards aquifer recharge zone, steps may also be needed to clean up existing sites and remove the wastes for more environmentally secure disposal. However, further study is needed before these expensive measures are undertaken.

In addition to the common dumps, which are composed mostly of household trash and wastes of agricultural activities, two other types of dump sites are present in the area. A now-abandoned industrial dump is located north of San Marcos on a hill above the Blanco River (Figure 4-35). This site was used by a wool-scouring plant for dumping what appears to be relatively inert materials. For this reason, and because the dump has apparently been abandoned for some time, the environmental effects of this site are probably not serious. The second type of site is the junked automobile graveyard (Figure 4-36). Two or three of these are present in the area, and no

Figure 4-35. Abandoned Industrial Solid Waste Disposal Site

The dump is near the top of the hill. The site is in UTM 3312-605 and the view is to the west.

Figure 4-36. Junked Automobile Graveyard

This site is at the edge of San Marcos in UTM 3308-605. The view is northeastward.

significant attempt to reclaim the scrap iron is apparently being made. These sites are not aesthetically pleasing, but their environmental impact probably is not particularly serious. No data are available to document possible contribution of heavy metal cations, especially iron, to surface water.

Collective Dumps

Until recent years the urban systems in the San Marcos area have used collective dumps for solid waste disposal. At least three of these dumps are present in the area, but two are no longer used and the third is about to be abandoned.

The oldest collective dump is in UTM grid square 3310-604. It was apparently active around the turn of the century, but it has not been used for many years. The dump is apparently almost completely decomposed and stabilized, although it may still be releasing iron and possibly other heavy metal cations. The chief environmental significance of the site lies in the demonstration of the ability of the hill country west of the escarpment to recover naturally from environmental degradation. The site is almost completely grown over with the natural vegetation of mostly junipers with a few live oaks. All that remains to visibly document the existence of the dump are isolated concentrations of glass and rusted cans. The presence of the dump would not be suspected without careful examination of the site. Perhaps the remaining glass and tin can should be recovered and disposed of properly, but no other action at the site is apparently called for.

The city of San Marcos operated an open-burning dump north of the city near Lime Kiln Road (Figure 4-37) for many years before abandoning it in about 1969. It appears that during operation, the solid waste was dumped near the top of a hill, burned in the open air, and then pushed over the side of the hill with a bulldozer. The resulting configuration of the dump, in which the mass of the dump rests on the side of a hill, gives rise to a hydrogeologic situation that is apparently ideal for producing leachate. Leachate can in fact be observed emanating from the toe of the dump (Figure 4-37c). This leachate may pose a water quality threat to the local drainage and the Edwards aquifer, since the site lies in the secondary recharge zone of the aquifer. Drainage from the site flows into Sink Springs Creek in a reach that almost certainly contributes significant aquifer recharge when the creek is flowing. Several aspects of this dump, however, prevent it from being a much greater environmental liability than it is. The substrate at the site are the Del Rio Clay and overlying Buda Formation, so that clay of the Del Rio effectively prevents direct ingress of the dump's fluids into the aquifer. After the dump was closed, limited efforts were made to cover its upper surface with clay from downslope of the dump, so access of surface runoff has been in part curtailed. The open burning of the dump material no doubt reduced its organic content, so the potential for mobilization of heavy metal cations has been reduced somewhat. Also, since it is over five years old, the dump may now be stabilizing, and the rate of leachate production is probably declining. Nevertheless, further steps may be needed to reclaim the dump site and further reduce its environmental degradation. If additional study shows that this degradation is serious, the dump should be reduced in profile,

Figure 4-37. Abandoned San Marcos City Dump.

a. Aerial oblique view showing the dump mass (outlined by dashed lines). Note the mesquite growth on top of the dump. The land disturbance caused by removal of earth for cover material for the top of the fill can be seen in the foreground below the face of the dump. The dump is in UTM 3310-602. This view is generally westward.

Figure 4-37. Abandoned San Marcos City Dump

b. Ground view showing the exposed face of the dump. The view is to the west.

Figure 4-37. Abandoned San Marcos City Dump

c. Leachate flowing from the toe of the dump. The dark tone (arrow) indicates grass which is green and thriving because of the moisture provided by the leachate. Elsewhere (double arrow) the grass has apparently been killed by the pollutants, leaving bare earth spots.

provided with at least 0.6 meters of impermeable cover material, and possibly landscaped for a park or other suitable land use. In addition, a trench may have to be provided at the toe of the dump for collecting the leachate produced in the future. This leachate could then be removed from the site for proper treatment, perhaps at a sewage treatment plant.

Residents of Kyle have for many years used a dump located on private property about 2 kilometers southwest of town (Figure 4-38). At this site trash of all types is dumped at the foot of large windrows, allowed to burn in the open air, and periodically pushed or scooped up onto the windrow near which it is located. Clearly, little attempt has been made to protect the environment at the site, and the solids, liquids, and gases emanating from the dump are not controlled in any way. Also, no provision has been made for environmental health factors, so that rats and flies constitute a possible health hazard in the vicinity. Air pollution in the form of both odors and smoke has been a chronic problem for nearby residents, and windblown trash from the dump (Figure 4-38c) is scattered over adjoining property. Precipitation which falls at the site is free to infiltrate the dump and flow into a nearby tributary of the Blanco River. Perhaps the primary environmental hazard of the dump is the potential reduction of surface water quality both in the small tributary and the Blanco River. Little threat is posed to ground water quality because the dump is not located on the recharge zone of any aquifer of significance, nor does the drainage cross the recharge zone of the Edwards aquifer. Fortunately, the dump is in process of

Figure 4-38. Kyle City Dump

a. Aerial oblique view showing the closed outer windrows and the two inner windrows of trash. The site is in UTM 3317-606 and this view is to the south.

Figure 4-38. Kyle City Dump

b. Ground view showing the size of the windrows. The view is generally northward.

Figure 4-38. Kyle City Dump

c. Windblown trash from the Kyle dump. The fence in the foreground marks the supposed limit of the dump site. The view is to the southeast.

being closed, and Kyle will henceforth use a sanitary landfill that will be located at an as yet undetermined location east of the Balcones Escarpment. However, several corrective measures may be required to prevent the dump from continuing to pose an environmental threat after it is closed. Site reclamation steps that may be indicated by further study are similar to those at the San Marcos dump, and would consist of leveling the windrows, covering the dump materials with an adequate thickness of impermeable cover material, and excavating a trench on the downslope side to trap leachate for removal and treatment.

Sanitary Landfill

Increasing regulation of methods of solid waste disposal in Texas, notably by the Texas Department of Health Resources and the Texas Water Quality Board, has caused a shift from the open dump to the sanitary landfill method of solid waste disposal in the study area. As noted earlier, the city of San Marcos ceased operation of its open dump and opened a sanitary landfill in 1969, and the town of Kyle will also soon begin operating a sanitary landfill. Both sanitary landfill sites are outside the limits of the study area, but the San Marcos landfill is close enough to the eastern edge that some consideration can be given to it here. This landfill is located on municipal property at the north end of the municipal airport near Gary Job Corps Center. The trench and progressive slope method is used at the site (Figure 4-39), and a cover of at least 15 centimeters is supposed to be placed on the working face at the end of each day. The upper surface of the landfill is also provided with a cover having a minimum thickness of 0.6 meters.

Figure 4-39. San Marcos Municipal Sanitary Landfill

This landfill uses the trench-and-progressive-slope method of operation. The site is located just east of the study area on the north end of Gary Job Corps Center and the municipal airport.

a. Operations begin with the excavation of a trench about 10 meters deep. This view is southwestward.

Figure 4-39. San Marcos Municipal Sanitary Landfill

b. The trench is then filled with solid waste by using a progressive slope. A bulldozer (not shown) is used to push the trash up the face and partially compact it at the same time. This view is to the south.

Figure 4-39. San Marcos Municipal Sanitary Landfill

c. The trench is filled to near ground level, and the waste is covered with spoils from the original excavation. This view is southwestward.

This landfill is a vast improvement over the open dump that it replaces, but it does pose a possible hazard to a potential local aquifer. The trenches for the landfill are excavated in alluvial silt, sand, and gravel of the Blanco River, and this deposit has in places served as a minor aquifer of local importance. The substrate below the alluvium consists of the impermeable clays of the Taylor Group, so the potential problem is confined to the alluvium itself. Leachate from the landfill may be polluting the potential alluvial aquifer, but many factors would have to be evaluated in order to determine the existence and magnitude of the hazard. The present and future use of this minor aquifer would have to be estimated and the hydrogeology of the aquifer would have to be determined. It would also be necessary to estimate the rate of leachate production of the landfill and the leachate renovation capacity of the alluvium.

Aside from this potential ground water pollution problem, the landfill is apparently environmentally secure, and it represents the most progressive solid waste disposal method used in the area. Unfortunately, the site is limited in its capacity, and a new site will have to be sought in the near future.

4.2.3.2 Liquid Wastes

Most of the liquid wastes generated in the San Marcos area are domestic and municipal sewage wastes, but some industrial wastes are also produced. Domestic wastes are disposed of through septic tanks and municipal sewage treatment plants. Two industries dispose of some of their wastes in lagoons.

Septic Tank Disposal

The simplest method of sewage treatment and disposal used in the area is the septic tank and drainfield method. Virtually all of the residences outside the municipal service areas of San Marcos and Kyle use this method, and even inside these communities, some homes are still not "on line" and are using septic tanks. The most intense use of septic tanks is in the outlying housing developments, where the density of residences is becoming relatively high and no collective treatment facilities are available. Each homeowner is responsible for providing his own sewage disposal system, and the common practice is to put in a precast or cast-in-place septic tank and a relatively short drainfield downslope from the residence.

Except for the areas underlain by alluvium, the study area is generally unsuited for proper septic tank operation. The reasons for this unsuitability are different on either side of the Balcones Escarpment. East of the scarp, where clay substrate and clayey soils predominate, the high shrink-swell potential may create problems in keeping the drainfield pipes connected and intact. In addition, the substrate permeability is generally too low to allow proper seepage of the effluent from the drainfield. Consequently, drainfields often fail and ponding of the effluent may occur. However, if the drainfield can be made to function properly, perhaps by increasing its area, the clay substrate makes an otherwise ideal septic tank milieu. No aquifer of significance is endangered, and the thick soils and the clay mineralogy of the substrate should provide excellent renovation of the drainfield effluent.

West of the Balcones Escarpment the effect of septic tanks on the environment may be pronounced and significant. Not only do the substrate conditions inhibit proper operation of the septic tanks and drainfields, but the area may be especially susceptible to environmental damage from septic tank effluent. The very thin soils and mostly hard limestone substrate make emplacement of septic tanks and drainfields difficult in the first place (Figure 4-40), and once they are in place, often they cannot function properly. Because of the thinness of the soil and the emplacement of the drainfield in porous limestone bedrock, the effluent may not be subjected to proper renovation by soil filtration and the action of soil bacteria. The direct infiltration of untreated effluent into the limestone bedrock may pose hazards to ground water resources both locally and regionally. Walz (1974) found that septic tank effluent discharged into limestones of the Glen Rose Formation, which are similar in composition to the hard limestones in the San Marcos area, is only partially renovated in the limestone. The bacterial content was found to decrease considerably in only a few meters, but the dissolved solids were not similarly removed. Although the dissolved solids were precipitated in the zone of aeration during dry periods, they were remobilized during rains when the aeration zone becomes nearly saturated.

The regional ground water pollution hazard by septic tanks is extant over the primary and secondary recharge zones of the Edwards aquifer as delineated on the Processes map (Plate 4). The potential implications of direct infiltration of raw or only partly renovated effluent into this limestone aquifer are clear. The presence of a few septic tanks would probably have little regional effect on the water quality of the Edwards aquifer, but if all future residences in all the developments in the area use septic tanks, their cumulative effect could severely damage the aquifer.

The potential local ground water pollution hazard is exemplified by the situation depicted in Figure 4-40, where the water well of a residence in a development is located only about 100 meters from the septic tank drainfield. The well and septic tank are both in the cavernous Edwards Group limestones and are therefore almost certainly hydraulically connected. Although the septic tank is located downslope from the well, the shape of the local potentiometric surface could easily be such that ground water flow is in the unslope direction. If so, the proximity of the septic tank to the well, combined with the minimal renovation of the septic tank effluent in either the soil zone or the limestone bedrock, mean that the well may be polluted in the near future.

Much work remains before the impact of septic tank and drainfield systems on local and regional pollution of the Edwards aquifer can be evaluated. If further study indicates they are warranted, sewage collection and treatment systems should be installed in the developments before the housing density increases appreciably. About the only parts of the study area amenable to the use of septic tanks are the areas underlain by the alluvium and terrace gravels of the Blanco River. Neither the limestone terrane west of the escarpment nor the clay terrane east of the scarp provide proper conditions for good septic tank operation.

Sewage Treatment Plant Disposal

The city of San Marcos has had a municipal sewage treatment system for many years, and Kyle has built a system within the last decade. In addition, the Gary Job Corps Center also has a sewage treatment plant for treatment of its liquid wastes. The bulk of the sewage produced by the urban systems and treated at these plants consists of domestic sewage similar to that which goes into the septic tanks. However, other types of wastes, such as industrial liquid wastes and much of the storm runoff from the cities, is also treated at the plants. Four treatment plants are locatedin or close to the study area. San Marcos operates two plants (Figure 4-41) - an older trickling filter plant whose effluent is discharged into the Blanco River and a newer contact stabilization plant whose effluent is discharged into the San Marcos River upstream from the confluence of the Blanco. The older plant is now obsolete and will be taken out of operation before 1980, and its load will be assumed by expansion of the newer plant. Kyle operates an aeration lagoon plant (Figure 4-4lb), and the Gary Job Corps Center is using a recently renovated trickling filter plant. Both of these plants are located somewhat to the east of the study area, and their effluents are discharged into nearby intermittent streams.

These sewage treatment plants represent a generally more secure method of treating and disposing of liquid waste than the septic tank and drainfield method. The primary environmental problem caused by these operations is the possible lowering of the water quality of the streams into which their effluent is discharged. This problem may be especially acute for the contact stabilization plant, which discharges into the extraordinarily pure and biologically sensitive San

Figure 4-40. Typical Septic Tank and Drainfield System Used in Outlying Housing Developments

a. Aerial oblique view showing the residence and associated septic tank (left arrow) and drainfield. The right arrow indicates the location of the well. The site is in UTM 3318-598 and this view is southeastward.

Figure 4-40. Typical Septic Tank and Drainfield System Used in Outlying Housing Developments

b. Ground view showing the drainfield and septic tank (arrow) in place in the thin soil and hard limestone bedrock.

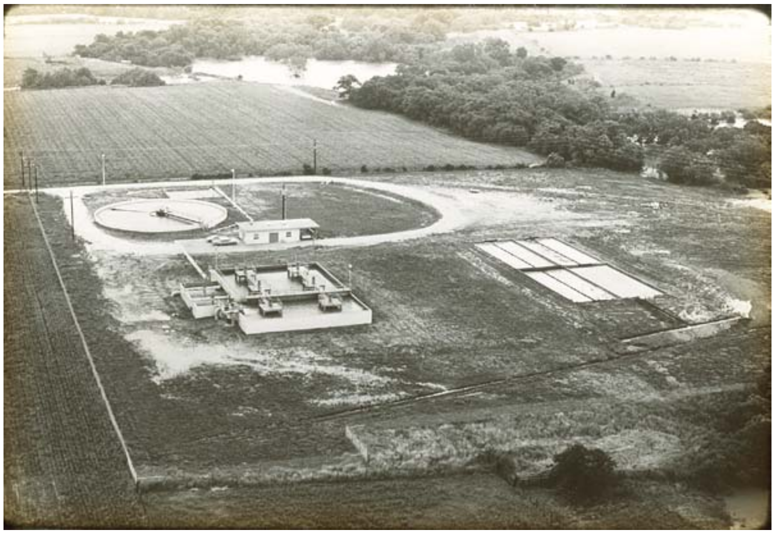


Figure 4-41. Sewage Treatment Plants in the San Marcos Area

a. Aerial oblique view of the newer, plant for the city of San Marcos. The plant is in UTM 3304-603. This view is generally southeastward. Courtesy of the San Marcos Record)

Figure 4-41. Sewage Treatment Plants in the San Marcos Area

b. Part of the aeration lagoon treatment plant of the town of Kyle. This northeast view shows the aeration drums and a corner of the oval-shaped lagoon. The plant is located east of Kyle just outside the limits of the study area.

Marcos River (Glenn Longley, personal communication, 1975). The problem may be expected to worsen when the plant is expanded in the near future to accommodate the additional load of the older plant. Fortunately, all four plants in the area are located east of the Balcones Escarpment and well away from the recharge zone of the Edwards aquifer, where sewage treatment plant effluent would pose a potential threat to the aquifer.

The primary impact of the environment on the sewage treatment plants is the hazard presented to the San Marcos plants by floods of the Blanco and San Marcos Rivers. Both plants are located in the flood-prone area shown on the Processes map (Plate 4), and the photo of the contact stabilization plant in Figure 4-4la was taken shortly after the plant was inundated by the 1970 flood. Water was still standing in low areas around the plant when the photo was taken, and flood waters near the San Marcos River can be seen on the right side of the photo.

Liquid Industrial Wastes

There are several small industries in the San Marcos area. Two of these industries are producing liquid wastes which are not treated at the municipal sewage treatment plants. Both industries, one of which is a slaughterhouse and the other a wool-scouring plant, are using open lagoons for disposal of at least some of their wastes. Liquid waste from the wool-scouring plant is hauled by tank truck from the plant to lagoons located in Blanco River alluvium (Figure 4-42). Geologic conditions at this site indicate that the lagoons may be posing a water quality threat to the Blanco River. The alluvium in which the lagoons are excavated overlies relatively impermeable limestone and chalk of the Austin Group and is composed of coarse, permeable limestone gravel (Figure 4-42b). Leakage of the fluid from the lagoons into the permeable alluvium may be moving laterally along the contact with the limestone bedrock and discharging into the Blanco. The points where the fluid may be discharging into the river cannot be observed, however, because the contact is below the water surface of the river.

As indicated on the Processes map (Plate 4) the lagoons are at the margin of the flood-prone area of the Blanco River. The lagoons could empty into the Blanco during times of flood either by overtopping of the embankments of the lagoons by very high stage floods or possibly by erosion of the embankments by lower floods. The effect of the contents of the lagoons on the water quality of the river would, however, be diminished in these instances by dilution of the waste with the much larger flood flow volume.

The lagoons used by the slaughterhouse are at UTM 3308.3-599.8. Their impact on the geologic environment is somewhat more difficult to evaluate. The water quality of nearby streams does not appear to be threatened, and the ponds have apparently been excavated in the impermeable Del Rio Clay. However, faulting in the Balcones fault zone is extremely intense in this area, and the presence of nearby outcrops of the Edwards Group limestones indicates that seepage from the lagoons could be entering the aquifer. If parts of the lagoons are excavated in the Edwards,

Figure 4-42. Industrial Liquid Waste Disposal Lagoons

a. Aerial oblique view showing the lagoons' location near the edge of the Blanco River terrace. These lagoons are used by a wool-scouring plant. Mixed limestones of the Austin Group crop out in the forested area on the left side of the photos and the Blanco River traverses the upper part of the photo. Figure 4-42b was taken across the river toward the logoons (upper middle location in the above photo). This view is to the northwest. The site is in UTM 3312-605 and 606.

Figure 4-42. Industrial Liquid Waste Disposal Lagoons

b. Coarse limestone gravel alluvium of the Blanco River. The lagoons are located about 150 meters from this site. The view is southward.

seepage into the aquifer could be direct, or if a nearby fault separates the Del Rio from the Edwards, then seepage could be crossing the fault and entering the aquifer. Much more detailed local study, including drilling boreholes and testing of water quality, are clearly needed both at this site and at the wools-scouring plant lagoons to determine their environmental impact.

4.2.4 Transportation

Transportation is classed as a principle category of the urban system because, as noted in Chapter 2, transportation facilities tie the other components together and connect the system to the surrounding region. In addition, the environmental conflicts of transportation facilities are generally different from those of other components of the urban system. In this section each transportation subcomponent will each be considered in turn. Five different types of transportation are distinguishable in the San Marcos area - roads, railroads, airports, pipelines, and power lines.

4.2.4.1 Roads

An excellent network of roads, streets, and highways has been built both within the urban systems in the San Marcos area and as connecting links with the surrounding region. The major highways include Interstate 35 and eight paved state highways. Numerous lesser county roads, city streets, and unimproved private roads serve to complete a road system which provides excellent access to all parts of the area. These roads are experiencing considerable conflict with the geologic environment, and additional conflicts may be expected as new roads are built to provide for increasing urbanization. These conflicts occur both during construction and after construction is completed. The environmental conflicts stemming from the construction and the presence of roads are different on either side of the Balcones Escarpment.

West of the escarpment environmental problems stem from the substrate and from recharge and flood processes. The predominance of hard limestone substrate and thin soil make road construction quite difficult, particularly where appreciable roadcuts are required. Few major roadcuts have yet been made in the area, but if long range plans for a west bypass around San Marcos (Lockwood, Andrews, and Newnam, 1969b, p. 99) are implemented, considerable blasting expense for roadcuts should be anticipated. Large numbers of roads have been built west of the escarpment in recent years for the outlying developments (Figure 4-43). The impact of these roads has not been assessed, but may be considerable, particularly in the primary and secondary recharge zones of the Edwards aquifer. Most of the roads are built by clearing the oak and juniper vegetation, doing whatever grading is possible in the thin soil and hard limestone substrate, spreading a thin subbase of locally derived marl, and applying a very thin pavement or "seal coat." Volatiles from this asphalt pavement may be picked up by surface water which enters the aquifer and may therefore pose a hazard to the recharge zone. In at least one instance a road has been constructed across one of the numerous sinkholes in the area (Figure 4-44). Although sinkholes in the Edwards Group limestones of central Texas are not particularly noted for a tendency to collapse, at least one case of recent sinkhole collapse has been documented

Figure 4-43. Road Network Under Construction for Outlying Housing Development

The northwest aerial oblique view is of the Highlands development (UTM 3316-598 and 599).

Figure 4-44. Road Constructed across Edge of Sinkhole

This segment of Hilliard Road, which provides sole access to two major housing developments, was built to shorten and straighten the heavily traveled road. Note the standing water on either side of the road. This site is UTI1 3311-600 and the view is to the northwest.

(Hunt, 1973), and a slight danger does exist. A greater danger is probably that posed to the Edwards aquifer by this road and its associated wastes over this point of recharge. Another minor problem of roads constructed for developments west of the Balcones Escarpment is that of occasional flooding of small, intermittent streams and the resulting washing out of pavement material as shown in Figure 4-45.

Figure 4-45. Road with Pavement Washed Out by Flooding

The graveled area on the left side of the road shows where pavement has been removed. This location is in the Valley View subdivision (UTM 3313-600). The view is northeastward.

East of the Balcones Escarpment, the environmental problems of roads are also serious, but the nature of the problems is very different. The chief cause of these problems is the clay substrate which, as shown by the Engineering Geology map (Plate 1), underlies most of the area east of the scarp. Similar problems are also found in the irregular, patchy occurrences of clay substrate west of the scarp. Most of the conflicts arise not during road construction, but after they have been in place for some time. In those rare instances where significant roadcuts are required east of the escarpment, their excavation is relatively easy. However, the long-term stability of a roadcut was described earlier in the urban situs section. A more common and more chronic problem is that of pavement destruction caused by shrinking and swelling of the expansive clays (Figure 4-46). This problem occurs if an adequate thickness of subbase is provided under the pavement, and it results in continuous and expensive maintenance problems in some road segments. Road destruction by heaving clay substrate is a serious problem for nearly all paved roads east of the escarpment except those over alluvial substrate around the San Marcos and Blanco rivers. However, Interstate 35 does not yet appear to be suffering greatly from the effects of clay substrate. No doubt a thick subbase was provided for this arterial highway, and road maintenance by the state highway department is excellent.

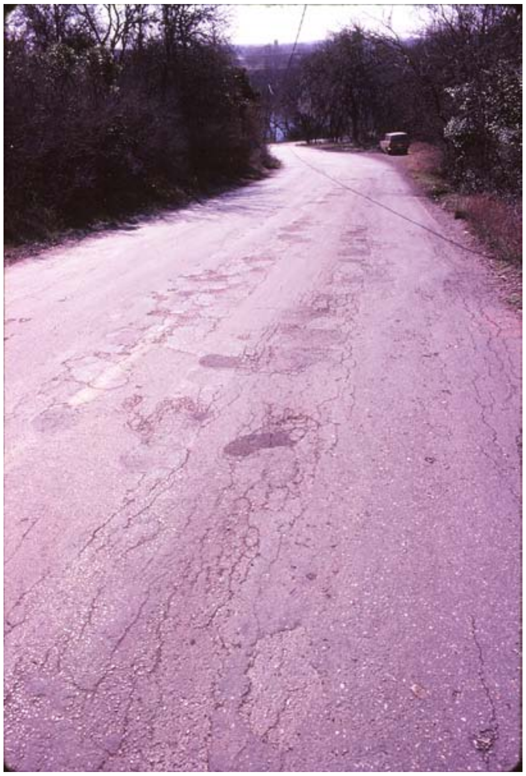


Figure 4-46. Road Destruction over Expansive Clay Substrate

Road cracking and destruction caused by inadequate subbase over expansive clay substrate. This road is on the Del Rio Clay and was not provided with adequate subbase. The location is on Alta Vista Drive near Spring Lake (UTM 3307-602). The rock hammer indicates scale. The view is to the south.

One of the major problems of roads on both sides of the escarpment is that of blockage at "low-water bridges" during increased stream discharges (Figure 4-47). At least ten bridges in the study area are of this type, and seven of these are on public roads. Most are over the perennial Blanco and San Marcos rivers. Many of these bridges are designed only for the base flow of the rivers, the problem is only a nuisance, because alternative routes without an impassable bridge can

Figure 4-47. Railroad Bridge and Low-Water Highway Bridge Across the Blanco River

The railroad bridge is above most of the floods of the river, but the highway bridge becomes impassable during river discharges that are only slightly above base flow level. This photo is at the crossing of the Missouri Pacific Railroad across the Blanco (UTI13312-606). The view is generally northward.

usually be found. However, all of the area serviced by Lime Kiln Road, including three major housing developments, becomes totally inaccessible by ordinary vehicles when Sink Creek is flowing appreciably and the Blanco River is above base flow stage. Lime Kiln Road is cut off at two points just north of San Marcos when Sink Creek flows, and the only alternative route to this area is cut off at a low-water bridge when the Blanco River is up. What is ordinarily only a nuisance problem can then become acute, because emergency service, such as that provided by ambulances and fire engines, becomes unavailable to the residents of the area affected. Clearly, the low-water bridges in the area should be replaced as urbanization proceeds, and bridges for the critical points on Lime Kiln Road should take first priority in this bridge improvement program.

4.2.4.2 Railroads

Two railroad companies - the Missouri Pacific and the Missouri, Kansas, and Texas (M-K-T) - have tracks that pass through the San Marcos area. The Missouri Pacific tracks enter the area from the northeast through Kyle, and the M-K-T tracks enter from the east near Gary Job Corps Center. The two sets of tracks converge in San Marcos, where they are connected by a spur, and parallel each other at the foot of the Balcones Escarpment southwestward from San Marcos and out of the study area.

At present, environmental geologic conflicts stemming from these tracks are apparently minimal, except for the impact of floods on some of the bridges (Figure 4-48). Many of the bridges are high enough to be unaffected by floods (Figure 4-47), however, and even the effect on bridges that are inundated is temporary, lasting generally only as long as the duration of the flood. Permanent damage to inundated bridges by the force of the floodwaters is often circumvented by parking loaded freight cars on the bridges during times of flood (Figure 4-49). The clay substrate under much of the length of the railroads in the area does not seem to have had any adverse effect on the tracks, probably because adequate subbase was provided during grading operations when the tracks were built. The embankments built for the tracks have also raised the tracks above the level of most minor floods in the area.

4.2.4.3 Airports

Two airports - the San Marcos municipal airport and Robert Lowman field - provide air service for the San Marcos area. The municipal airport, the larger of the two facilities, is located just east of the study area at the Gary Job Corps Center. It has four excellent runways, three of which are 1,675 meters long and one of which is 1,920 meters long (Figure 4-50). The field was built during World War II as a pilot-training facility and was eventually given to the city for use as a municipal airport, but no regularly scheduled flight service is offered. The smaller Robert Lowman field, which is located south of San Marcos along the east side of Interstate 35, has two the type of surface used on the runways, a loosely asphalt-cemented fine gravel, is apparently not narrow runways that are 790 meters in length and one runway which is 1,035 meters in length. This facility is used exclusively by small aircraft.

The locations of these fields were strongly influenced by topography and geology. Both are located east of the Balcones Escarpment where the topography is sufficiently flat and where the substrate is soft enough to be easily graded. The municipal airport was built on the flat Blanco River terrace, and Lowman field is on clay substrate. The environmental conflict of the airports is apparently minimal. They do not have appreciable impact on the geologic environment, and the only potential impact of the environment on the fields lies in the possible effects of swelling clay substrate. The municipal airport is on alluvial substrate and is therefore apparently not affected. Despite its location on clay substrate, Lowman field is also not being damaged because greatly affected by the heaving clay.

4.2.4.4 Pipelines

Two types of pipelines have been emplaced in the San Marcos area - local lines that fulfill the needs of the urban systems specifically and regional lines which transport petroleum products into and through the area. The local lines include the water mains, sewer lines, and natural gas lines which provide service to the three types of urbanization in the area. The regional lines mostly transport petroleum products through the area, but one or two gas lines bring natural gas into the area for local consumption.

Figure 4-48. Railroad Bridge over the San Marcos River During the 1970 Flood

Note the trash lying on the bridge, which indicates that the bridge was completely inundated during the flood peak. The aerial oblique view is southward in UTM 3305-603. (Courtesy of the San Marcos Record)

Figure 4-49. Protection of Railroad Bridges from Flood Forces by Loading Them with Freight Cars

The bridges in the foreground and background are across Purgatory Creek. This aerial oblique view is eastward in UTM 3305-602. (Courtesy of the San Marcos Record)

Figure 4-50. San Marcos Municipal Airport

The Gary Job Corps Center is in the background. This aerial oblique view is southeastward.

The environmental conflicts of the two types of pipelines are quite similar. West of the escarpment, the thin soils and hard limestone bedrock make emplacement of pipelines quite difficult (Figure 4-51), but once the lines are in place, they are relatively secure. East of the escarpment, where the mostly clay and alluvium substrate is easy to excavate, pipelines can beput in quite easily. However, the expansive soils and the clay substrate may cause frequent pipeline breakage and high resultant maintenance costs. The regional pipelines are designed to withstand the stresses caused by shrinking and swelling, but smaller, more local water and sewer the clay substrate east of the scarp.

The primary impact or potential impact of the pipelines on the geologic environment is the potential contamination of the substrate caused by breaks and leaks in the pipelines. The severity of this problem varies, of course, with the type of fluid being transmitted by the pipeline. Fortunately, in the clay substrate east of the escarpment where pipeline breakage is the most likely, the substrate is relatively impermeable and contamination would therefore be confined to a small area. Pipeline leakage is less likely west of the scarp, but is potentially much more serious if it does occur because much of the length of the pipelines is in the recharge zone of the Edwards aquifer.

Another effect of the pipelines is primarily aesthetic. When regional pipelines are put in, the vegetation is removed along the length of the line, and little attempt is made to restore the trees and shrubs after the line is in. In fact, vegetation is periodically recleared so that the pipeline can be inspected for leaks or other problems by using small aircraft. The result of this practice is a

Figure 4-51. Pipeline Emplaced in Hard Limestone Bedrock

Note the thin soil and the blocks of limestone that were broken out of the bedrock during excavation of the trench. The photo was taken at the crossing of McCarty Lane over the pipeline in UTM 3303-597. The view is northeastward.

linear scar across the countryside which might be considered aesthetically unpleasing but which probably does not represent significant environmental damage. This effect is most noticeable in the forested hill country west of the escarpment; east of the scarp, the cropland is little affected by vegetation clearing, and it recovers quickly from the effects of pipeline emplacement.

4.2.4.5 Power Lines

Both local power lines and regional high tension power lines are present in the San Marcos area. The impact of the geologic environment on these lines is somewhat like that of the pipelines. West of the Balcones Escarpment, the hard limestone substrate makes emplacement of power poles rather difficult (Figure 4-52), but once in place, the poles are secure. The softer clay and alluvial substrate east of the scarp makes pole emplacement quite easy, but heaving and mass movement can cause the poles to lean excessively in some areas, thus necessitating frequent resetting or replacement. The smaller local power lines are usually put in adjacent to roads, but the major high tension lines are erected in straight-line segments across the countryside. As was the case for the pipelines, the vegetation is usually cleared during construction of these power lines (Figure 4-53) and is kept clear to allow easy access for maintenance.

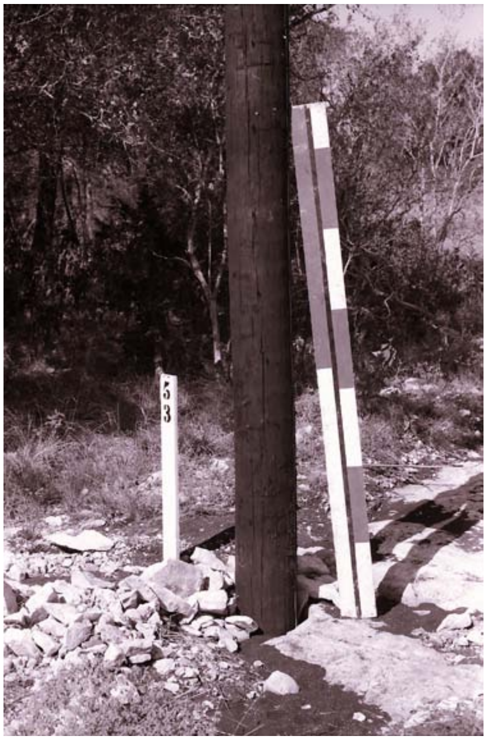


Figure 4-52. Power Pole in Limestone Substrate

The thin soil and hard limestone make emplacement of these poles very difficult. This site is UTM 3304-597.

Figure 4-53. High Tension Power Line

Note the wide swath of trees removed during construction. The photo was taken southeastward in UTM 3304-597.

4.2.5 Summary

In summary the San Marcos area has served as an excellent case study area for demonstrating the curative part of the methodology of Chapter 2. The coverage of the environmental conflicts of existing urban systems in the area has of necessity been quite broad and generalized. Many more questions about potential environmental geologic problems have been asked than have been answered; virtually all of the problems addressed would require further investigation before final recommendations could be made for their solution or mitigation. The objective here has been to demonstrate a procedure for systematically and comprehensively asking the right environmental geologic questions and to indicate the direction for future study to answer these questions.

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5 Chapter 5. Environmental Geology in Physical Land Use Planning for Urban Growth in the San Marcos Area

In the preceding chapter the curative part of the methodology of this study was demonstrated by using the San Marcos area as an example to show how environmental conflicts of existing urban systems can be systematically identified and solved. The objective of this chapter is to demonstrate the preventive part of the methodology by again using the San Marcos area as an example. The procedure will be to: 1) Describe briefly the nature of the urban growth that is expected in the area; 2) Use a specific land use, a sanitary landfill, as an example for determining land suitability, and 3) Show how the procedure can be repeated for other urban land uses. The ultimate objective of the repeated application of the procedure would be the formulation of a physical land use plan for future urbanization in the area. However, this chapter shows only the application of the method presented in Chapter 2 and how it could be utilized to produce such a plan.

5.1 Urban Growth in the San Marcos Area

Increasing urbanization is almost a certainty in the San Marcos area for the foreseeable future. Most of this growth will no doubt proceed by filling in and building out of the three kinds of urban systems in the area - the city of San Marcos, the town of Kyle, and the outlying housing developments and mobile home parks.

Of these three the city of San Marcos may be expected to display the fastest rate of growth. This growth rate has been clearly established in the past 3 to 4 decades and is projected to continue at least for 2 to 3 decades more. During the 1940 to 1970 period the population increased over 200%, and the growth between 1960 and 1970 was almost 50%. The present (1976) estimated population is about 25,000. A growth rate of about 100% is projected for the next 20 years, so the size of the city will probably be between 40 and 50 thousand by the year 2000.

Kyle will probably grow at a considerably slower rate than San Marcos. Since the town has only a very small economic base, population increases will be primarily by the influx of people who commute to jobs in nearby San Marcos and Austin. Some growth of Kyle has occurred in the past decade primarily on the west and southwest sides of town, and the majority of future growth should continue in those directions.

Most of the established housing developments are still mostly vacant (Figure 4-5), so much of their growth will no doubt be by a filling-in process. In addition, subdivision of new tracts of land can be expected as the existing developments are filled and as land demands continue. At the time of this writing (February, 1976) roads are being constructed for a new development immediately west of the study area near the road between San Marcos and Wimberley.

The growth of mobile home parks should be quite limited, and will probably be by expansion of existing parks. The park shown in Figure 4-4, for example, has almost doubled in size by expansion to the south since the photo was taken.

5.2 Land Suitability Analysis for a Sanitary Landfill

A sanitary landfill has been selected as an example for demonstrating the land suitability analysis procedure. A sanitary landfill is used for several reasons: 1) The problem of solid waste disposal is common to virtually all forms of urbanization, and sanitary landfilling is presently the most economic and environmentally acceptable method of municipal solid waste disposal available (National Center for Resource Recovery, Inc., 1974, p. 1); 2) Solid waste disposal is one of the chief environmental concerns of most cities in the United States, as indicated by the number of regulatory measures that have been instituted in recent years; 3) A considerable body of literature on sanitary landfills, their environmental problems, and their demands on the land is available for consultation in setting up and applying the methodology; 4) A sanitary landfill is a relatively specific urban land use category for applying the methodology; and 5) The communities in the study area are or soon will be seeking additional landfill sites. Kyle is in process of locating a replacement disposal site for the dump it has been using for years. The available space at the San Marcos sanitary landfill will be exhausted in a few years, and the operation will have to be moved to a new site.

5.2.1 Objectives and Restrictions

The objective of this analysis is to determine the locations of sites where emplacement of a sanitary landfill would cause the least negative interaction with the geologic environment. However, the effect of the environment on landfills is usually negligible; unlike most other urban land uses, landfills do not involve large capital investments that may be lost because of geologic hazards. The primary focus of the evaluation will therefore be on the protection of the environment from the detrimental effects of a landfill. The type of landfill to be considered is a municipal solid waste landfill, and the approach for protecting the environment from its effects will be to try to contain and isolate the fill material (Flawn, Turk, and Leach, 1970, p. 2). The types of materials usually found in municipal landfills have been classed into eleven categories by the American Public Works Association (1970, p. 13) as follows:

1. Garbage
2. Rubbish
3. Ashes
4. Street refuse
5. Dead animals
6. Abandoned vehicles
7. Industrial wastes
8. Demolition wastes
9. Construction wastes
10. Special wastes
11. Sewage treatment residue

A cursory view of wastes at the San Marcos sanitary landfill indicates that all categories are represented in the study area. Exotic or particularly hazardous wastes, which would require special disposal methods, are not produced in the area and will not be accounted for in the analysis. The type of operation assumed is a sanitary landfill in the strict sense of the term. The proper operation of a sanitary landfill has been set forth by the American Society of Civil Engineers (1959), the Public Health Service (1961), the American Public Works Association (1970), and the National Center for Resource Recovery, Inc. (1974). The primary operational requirements assumed for this study are the daily covering of the refuse face with about 15 centimeters of cover material and the final covering of each "lift" or "cell" with a minimum of about 0.6 meters of compacted earth. Specifically, the trench- and progressive-slope method of landfill operation is assumed because this method is presently being successfully used by San Marcos (Lockwood, Andrews, and Newnam, 1969a) and because the topographic and geologic conditions are most amenable to this method. As corollaries to this assumption, it is further stipulated that the maximum depth of excavation for the trench will be about 10 meters and that the cover material will be the spoil from the trench excavation.

A few additional stipulations must be made on the scope relative to the land characteristics of the area. First, those characteristics which are uniform over the study area will be mostly eliminated from consideration. Second, the locations of the various sites relative to most surrounding features, including adjacent sites, will not be taken into account. That is, each site is evaluated according to its inherent physical characteristics rather than its location. The location of a site relative to other features should be reserved for consideration in the final formulation of a physical land use plan. Finally, each site is evaluated on the basis of its natural or "as-is" condition; that is, as it exists naturally or as it has been altered by previous use. No allowance is made in this initial evaluation for significant engineering improvement of a site, except those which would be made as a matter of course regardless of where the landfill is located. If certain improvements are possible or anticipated, then a second run of the evaluation could be made to account for them.

5.2.2 Construction of the Blank Score Grid

The blank suitability score grid that will be used is constructed at a scale of 1:24,000, which is the original scale of the data source maps. The grid is based on the Universal Transverse Mercator system because it is readily available on the topographic base maps and because it is based on the metric system, which allows easy subdivision of the grid into any desired grid square size (grid coarseness). After consideration of such factors as the sizes of the smallest map units on the data source maps, and the limited use of automation in succeeding steps, a grid square size of 1 hectare (approximately 2.5 acres) has been selected. This grid results in a manageable number of grid elements, yet allows an adequate approximation of field conditions for the purpose of this study.

5.2.3 Screening Procedure

The screening procedure is carried out in three steps: 1) Description of the factors that make some parts of the area totally unsuited for a sanitary landfill; 2) Delineation of the unsuitable areas by tracing them on the score grid from the appropriate data source maps; and 3) Shading in of the grid squares over the unsuitable areas. These shaded grid elements are then assigned a value of zero (the significance of this value is described below), and they retain this value in subsequent steps. Where a grid square lies over a boundary between screened and unscreened areas, the square is usually eliminated only if more than half of it falls within the affected area. Before the affected areas are traced on the blank score grid, the area is divided into eighteen sectors at the 2-1/2 minute lines on the topographic base map (Figure 5-1). Each sector is then screened separately in order to enhance the accuracy of registration of the score grid over the data source maps. Considerable time can be saved by screening cumulatively; that is, by screening the factors that affect the most total area or the largest blocks of area first. In this way much effort can be saved in outlining a large number of small screened units in areas where large blocks are eliminated by a subsequent factor.

A total of eight factors, listed below in the approximate order of decreasing amounts of area affected, are critical enough to eliminate areas from consideration:

1. Edwards aquifer recharge zone as defined in the Texas Water Quality Board Order No. 75-0128-20
2. City limits of San Marcos and Kyle
3. Areas of "higher" current land use (land is too valuable to use as a landfill)
4. Primary and secondary Edwards aquifer recharge zone as outlined in this study
5. Major flood-prone areas
6. Areas of potential slope instability or sinkhole collapse
7. Areas with less than 3 meters of unconsolidated substrate
8. Areas of Category 4 slope (over 15%)

The areas affected by the first two factors are shown on the Land Use Control map (Plate 7), and these include most of the western half of the Kyle section and much of the northern half of the San Marcos section. The areas eliminated because of higher land use are depicted on the Current Land Use map. The specific uses screened included all urbanized areas, the sites of most of the current urban input and output activities, all of the transportation facilities, and all water bodies, parks, and cemeteries. The areas affected by the fourth factor, the Edwards aquifer recharge zones as outlined in this study, take in all of the area covered by the Edwards recharge zone of the Texas Water Quality Board (Factor 1) and considerable additional area as well. The flood-prone areas screened (Factor 5) include only the large floodplain east of San Marcos and along the Blanco River south of Kyle. The narrow floodprone areas along the small tributaries are not screened because flooding there can be relatively easily controlled by routine landfill operations. The areas of potential sinkhole collapse in the sixth factor were all eliminated during screening for the first factor. The areas of unstable slopes are taken from the Processes map. For elimination of areas of shallow unconsolidated substrate (Factor 7) the Soils map is used to screen soil series whose depth to hard bedrock was less than 3 meters. The results are then checked by overlaying the Engineering Geology map. Screened areas are reinstated if they are underlain by the clay (C) or alluvium (A) units because these units are usually unconsolidated to depths greater than 3 meters. The Landform map is used for screening areas having a slope of more than 15% (Factor 8).

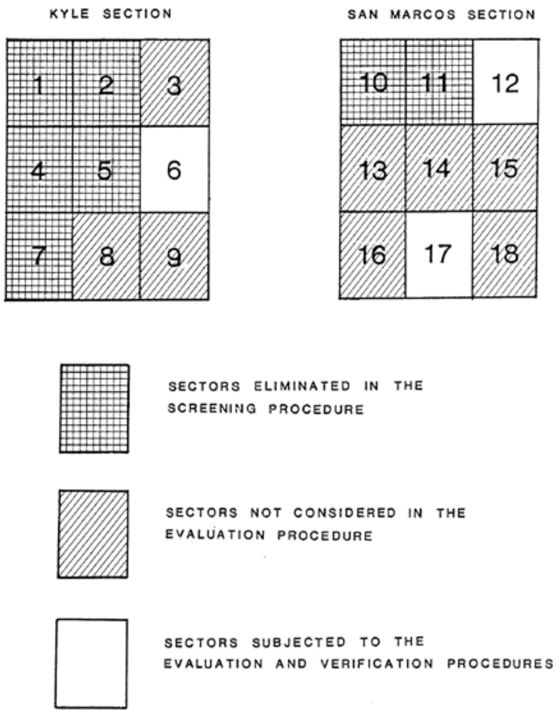


Figure 5-1. The 2½-minute Sectors of the San Marcos Area

As a result of the screening procedure, more than half of the study area is eliminated from further consideration in succeeding steps. Seven of the eighteen 2-1/2 minute sectors are eliminated totally (Figure 5-1), and large parts of several others are also screened. As might be expected, most of the remaining candidate areas are in the southern half of the San Marcos section, where the slopes are gentle, the substrate is impermeable clay, and few catastrophic processes are active.

5.2.4 Evaluation Procedure

The remaining candidate areas from the preceding step must now be evaluated for their ability to meet the demands of a sanitary landfill. Some parts of the methodology outlined in Chapter 2 will be repeated in the interest of clarity, and in places considerable amplification of the methodology will be needed as the abstract evaluation procedure is applied to the concrete example of a sanitary landfill. Of the eleven 2-1/2 minute sectors containing candidate areas, three have been chosen as representative of geologic and topographic conditions in the area and will be subjected to the evaluation procedure (Figure 5-1). Sector 6 has variable topography and is underlain by low-permeability, nonaquifer mixed limestones having soils of varying thickness. Sector 12 is relatively flat and has a mostly alluvial substrate with generally thick soils. Sector 17 has gentle, rolling topography and is underlain by clays that have thick soils. The evaluation of the other eight sectors must await the development of more complete automation of the methodology.

5.2.4.1 Step 1. Conceptualization of the Overall Objectives

The first step is to construct a list of generally stated factors that should be considered in the evaluation of a site for its suitability for a sanitary landfill. Six factors have been selected for consideration:

1. Volumetric capacity
2. Transportation
3. Environmental conflict
4. Substrate engineering characteristics
5. Land value
6. Aesthetics

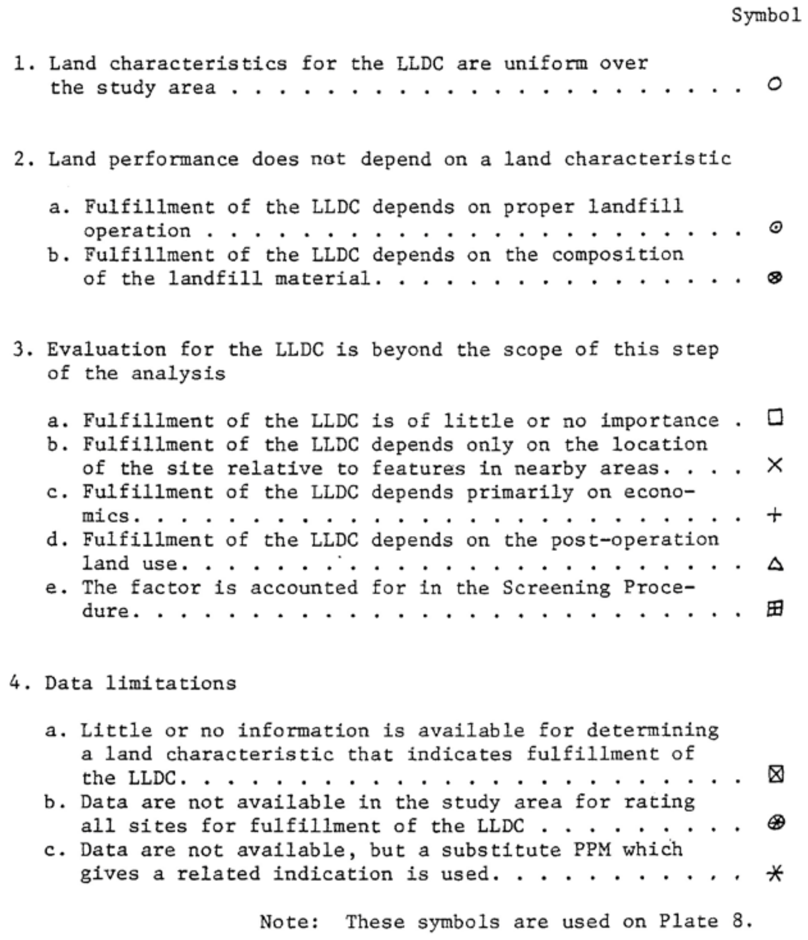
5.2.4.2 Step 2. Construction of the Demand Analysis Hierarchy

The Demand Analysis Hierarchy (DAH) is constructed by progressively subdividing each item on the master list of Step 1. Each criterion at the various levels of the hierarchy is stated generally as a completion of a question addressed to the land, such as "What is your .?" or "What is your potential for? " Several sources are available for consulting as the DAH is constructed for a sanitary landfill. Some of the most useful of these are as follows:

1. American Society of Civil Engineers, 1959
2. Cartwright and Sherman, 1968
3. Office of Science and Technology, 1969
4. California Department of Water Resources, 1969
5. Clark, 1972
6. Flawn, Turk, and Leach, 1970
7. Institute for Solid Wastes, 1970
8. Texas Department of Health, 1974
9. Hughes, Landon, and Farvolden, 1971

Although the subdivision process is begun with the six factors on the master list, several passes are made up and down the hierarchy. The resulting DAH (Plate 8) has over sixty Lowest Level Demand Criteria (LLDCs). Many of these LLDCs can be eliminated, however. The criteria for elimination of certain of the hierarchy branches are listed in Table 5-1 with a symbol for each, and the eliminated criteria of Plate 8 are signified with the appropriate symbol. Most of the criteria in Table 5-1 stem from the restrictions outlined in the introductory section of this chapter.

After the dead branches are identified, a condensed DAH can be constructed (Figure 5-2) and used in succeeding steps. The numbers and the PPMs on the figure are explained in later steps. The condensed DAH has a total of twenty-five LLDCs, but some of these are repetitions. The number of different LLDCs is seventeen, which is a manageable number for the evaluation as used here with only a very limited use of a computer. One of the six factors of the master list, transportation, was eliminated entirely during the condensing of the DAH because it involved primarily locational attributes of the various sites.



	Symbol
1. Land characteristics for the LLDC are uniform over the study area	○
2. Land performance does not depend on a land characteristic	
a. Fulfillment of the LLDC depends on proper landfill operation	⊙
b. Fulfillment of the LLDC depends on the composition of the landfill material	⊗
3. Evaluation for the LLDC is beyond the scope of this step of the analysis	
a. Fulfillment of the LLDC is of little or no importance	□
b. Fulfillment of the LLDC depends only on the location of the site relative to features in nearby areas	×
c. Fulfillment of the LLDC depends primarily on economics	+
d. Fulfillment of the LLDC depends on the post-operation land use	△
e. The factor is accounted for in the Screening Procedure	⊞
4. Data limitations	
a. Little or no information is available for determining a land characteristic that indicates fulfillment of the LLDC	☒
b. Data are not available in the study area for rating all sites for fulfillment of the LLDC	⊛
c. Data are not available, but a substitute PPM which gives a related indication is used	⚹

Note: These symbols are used on Plate 8.

Table 5-1. Criteria for Dead Branches of the Demand Analysis Hierarchy

5.2.4.3 Step 3. Selection of the Physical Performance Measures

For the twenty-five LLDCs of the condensed DAH, sixteen different Physical Performance Measures (PPMs) have been selected to rate the land. The same PPMs are used for repeated LLDCs, and two of the LLDCs that are different in name are also able to use the same PPM. The PPMs selected are shown with their associated LLDCs in Figure 5-2. These PPMs are chosen primarily on the basis of the LLDCs, but also in part based on the type and quality of the data available on the data source maps. The relative effectiveness of each PPM for its associated LLDC is considered below in Step 6.

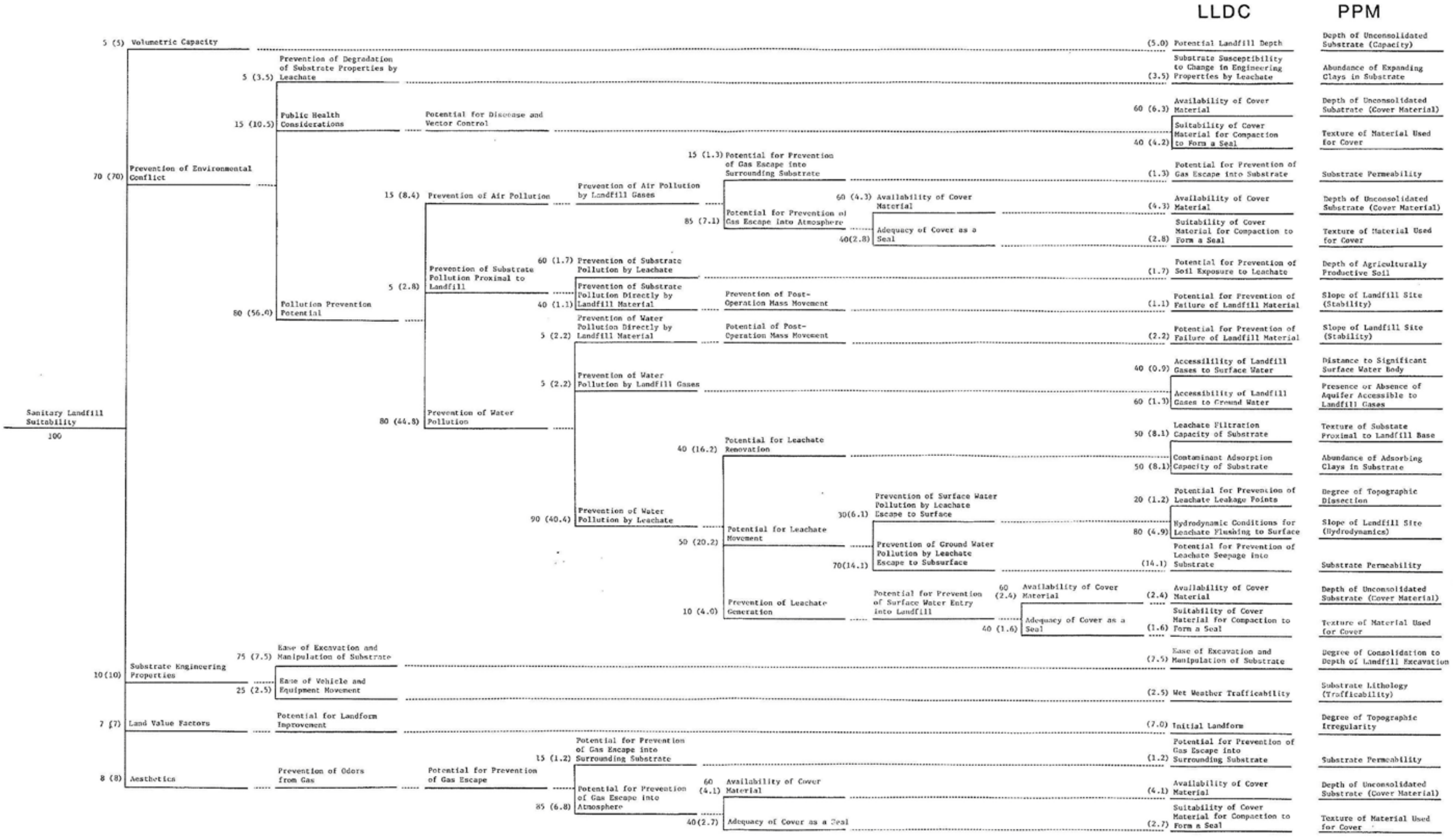


Figure 5-2. Condensed Demand Analysis Hierarchy for a Sanitary Landfill

5.2.4.4 Step 4. Formulation of the Suitability Score Functions

For each PPM a Suitability Score Function (SSF) must be constructed for use in assigning score values to the land. The SSF serves to convert the units used to describe the land characteristics of the PPM, such as length, substrate texture, or permeability, into a dimensionless number, the score. This number indicates in percent form the relative ability of the land to meet the associated LLDC. The sixteen different SSFs used for a sanitary landfill are shown in Figure 5-3. Most of these are close approximations of mathematical functions, but some have been tailored for special needs which cannot be filled by normal functions. All of them have been set up to be used easily with the data source maps.

5.2.4.5 Step 5. Assignment of Weights to the Demand Analysis Hierarchy

In this step the relative importance of the various LLDCs is determined by performing a weighting process on the condensed DAH. The procedure begins at the highest level (the left side) of the DAH in Figure 5-2 and proceeds to successively lower levels. In the first stage the five categories at the highest level are rated in percent terms according to their relative importance. The same exercise is performed at each level in the hierarchy, always on the basis of 100; that is, all the categories at a given level within a branch of the DAH are rated relative to each other in percent terms. The results are shown without parentheses throughout the DAH in Figure 5-2.

In the second stage the original 100 points at the highest level are distributed down the hierarchy by a series of successive multiplications of the percentages from the first stage. The final result of this process is the assignment of a raw weight to each of the LLDCs. The weights of the branches of the sanitary landfill DAH are shown in Figure 5-2 as numbers with parentheses. The sum of these numbers at the LLDC level is, of course, equal to 100.

5.2.4.6 Step 6. Adjustment of the Weights

The PPMs selected for the various LLDCs are highly variable in their effectiveness. That is, the PPMs, which are selected in part on the basis of the type and quality of the information on the data source maps, may do a perfect job of rating the land according to their associated LLDCs, or they may be highly imperfect. An adjustment of the raw weights of the LLDCs is therefore needed to account for these differences in the effectiveness of the PPMs. The procedure for this step is to consider each LLDC - PPM pair and make an estimate in percent terms of how well the PPM fills the function. This percent, termed the adjusting factor, is multiplied by the raw weight of the LLDC. The procedure is repeated for all the LLDCs, resulting in a tabulation of adjusted weights. These adjusted weights are then recalibrated to a sum of 100, which results in a list of net weights for the LLDCs. A tabulation of the raw weights (from Figure 5-2), adjusting factors, adjusted weights, and net weights for the LLDCs of the sanitary landfill DAH is given in Table 5-2. The net effect of this step is to shift the weights somewhat in favor of LLDCs for which the best data is available. However, it may be noted in Table 5-2 that although some shifting of the weights has occurred, the pattern of weight distribution established in Step 5 is not greatly changed.

1. Depth of Unconsolidated Substrate (Capacity)
2. Abundance of Expanding Clays in Substrate
3. Depth of Unconsolidated Substrate (Cover Material)
4. Texture of Material Used for Cover
5. Substrate Permeability
6. Depth of Agriculturally Productive Soil
7. Slope of Landfill Site (Stability)
8. Distance to Significant Water Body
9. Presence or Absence of Aquifer Accessible to Landfill Gases
10. Texture of Substrate Proximal to Landfill Base
11. Abundance of Adsorbing Clays in Substrate
12. Degree of Topographic Dissection
13. Slope of Landfill Site (Hydrodynamics)
14. Degree of Consolidation to Depth of Landfill Excavation
15. Substrate Lithology (Trafficability)
16. Degree of Topographic Irregularity

Figure 5-3. Suitability Score Functions for a Sanitary Landfill

a. Key: The names are the Physical Performance Measures from Figure 5-2.

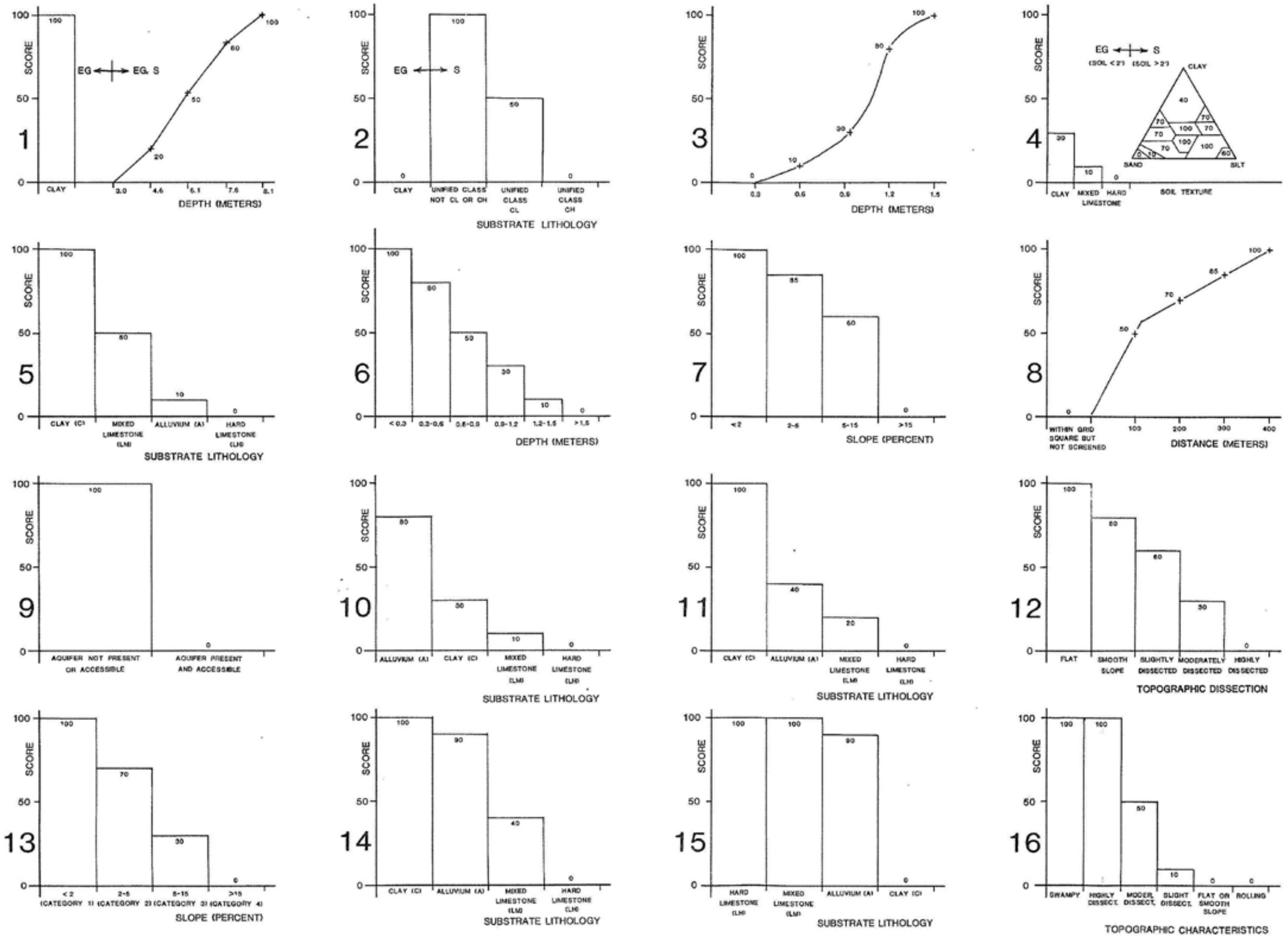
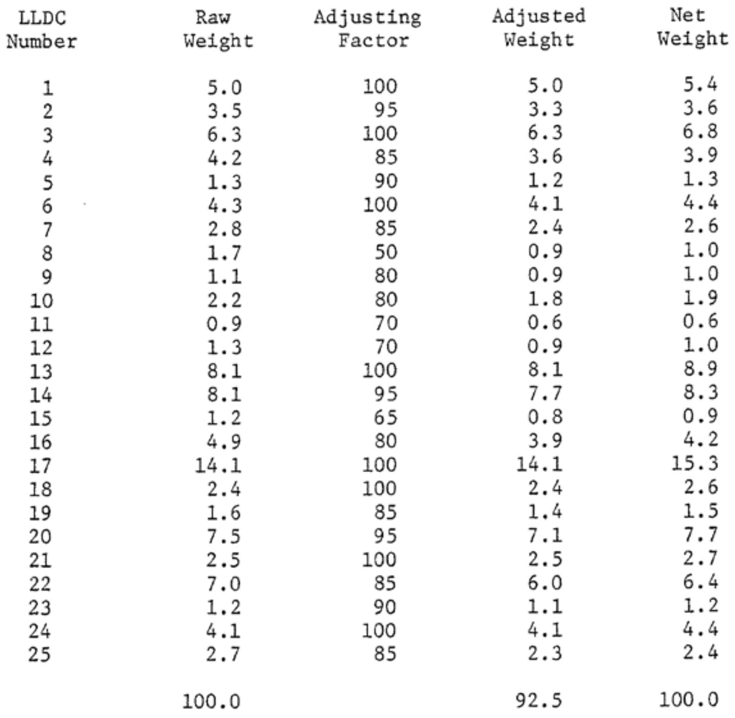


Figure 5-3. Suitability Score Functions for a Sanitary Landfill
b. Function Diaghrams



LLDC Number	Raw Weight	Adjusting Factor	Adjusted Weight	Net Weight
1	5.0	100	5.0	5.4
2	3.5	95	3.3	3.6
3	6.3	100	6.3	6.8
4	4.2	85	3.6	3.9
5	1.3	90	1.2	1.3
6	4.3	100	4.1	4.4
7	2.8	85	2.4	2.6
8	1.7	50	0.9	1.0
9	1.1	80	0.9	1.0
10	2.2	80	1.8	1.9
11	0.9	70	0.6	0.6
12	1.3	70	0.9	1.0
13	8.1	100	8.1	8.9
14	8.1	95	7.7	8.3
15	1.2	65	0.8	0.9
16	4.9	80	3.9	4.2
17	14.1	100	14.1	15.3
18	2.4	100	2.4	2.6
19	1.6	85	1.4	1.5
20	7.5	95	7.1	7.7
21	2.5	100	2.5	2.7
22	7.0	85	6.0	6.4
23	1.2	90	1.1	1.2
24	4.1	100	4.1	4.4
25	2.7	85	2.3	2.4
	100.0		92.5	100.0

Table 5-2. Adjustment of the Weights of the Lowest Level Demand Criteria

5.2.4.7 Step 7. Preparation of the Suitability Score Grids

With the completion of Step 6 preparation for the land suitability assessment for a sanitary landfill is finished and the actual assessment begins in this step. The procedure begins by considering the first LLDC and its associated PPM. The appropriate data source map is selected, and its map units are examined in conjunction with the SSF associated with the PPM. A score value is then assigned to each map unit by first noting the SSF abscissa value represented by that map unit and then reading the score value for that abscissa value. This score value is assigned to the map unit and the process is repeated until the data source map is in effect converted into a score map. The screened Suitability Score Grid (SSG) from the screening step is overlaid on this score map, and a score value is assigned to each grid square based on the score of the map unit overlain by the grid square. The screened grid squares all retain the score value of zero that was assigned to them earlier in the screening step. The scoring procedure is repeated for each PPM because a separate SSG is required for each of the sixteen different PPMs. A list of the PPMs used in the land suitability analysis for a sanitary landfill is given in Table 5-3 with the data source map or maps used for each. All of the sixteen SSGs produced in this step cannot be shown here because of reproduction costs, but Figure 5-4 illustrates a typical example. The maximum score that any grid element can receive is 100, but the highest score assigned is 99 because only two-digit numbers can be used in the computer program in the next step. However, this introduced error has negligible effect on the final results.

	Physical Performance Measure	Data Source Maps
1.	Depth of Unconsolidated Substrate (Capacity)	Engineering Geology Soils
2.	Abundance of Expanding Clays in Substrate	Engineering Geology Soils
3.	Depth of Unconsolidated Substrate (Cover Material)	Engineering Geology Soils
4.	Texture of Material Used for Cover	Engineering Geology Soils
5.	Substrate Permeability	Engineering Geology
6.	Depth of Agriculturally Productive Soil	Soils
7.	Slope of Landfill Site (Stability)	Landform
8.	Distance to Significant Water Body	Current Land Use
9.	Presence or Absence of Aquifer Accessible to Landfill Gases	Processes Resources
10.	Texture of Substrate Proximal to Landfill Base	Engineering Geology
11.	Abundance of Adsorbing Clays in Substrate	Engineering Geology
12.	Degree of Topographic Dissection	Landform Topographic
13.	Slope of Landfill Site (Hydrodynamics)	Landform
14.	Degree of Consolidation to Depth of Landfill Excavation	Engineering Geology
15.	Substrate Lithology (Trafficability)	Engineering Geology
16.	Degree of Topographic Irregularity	Landform Topographic

Table 5-3. Data Source Maps Used in the Preparation of the Suitability Score Grids

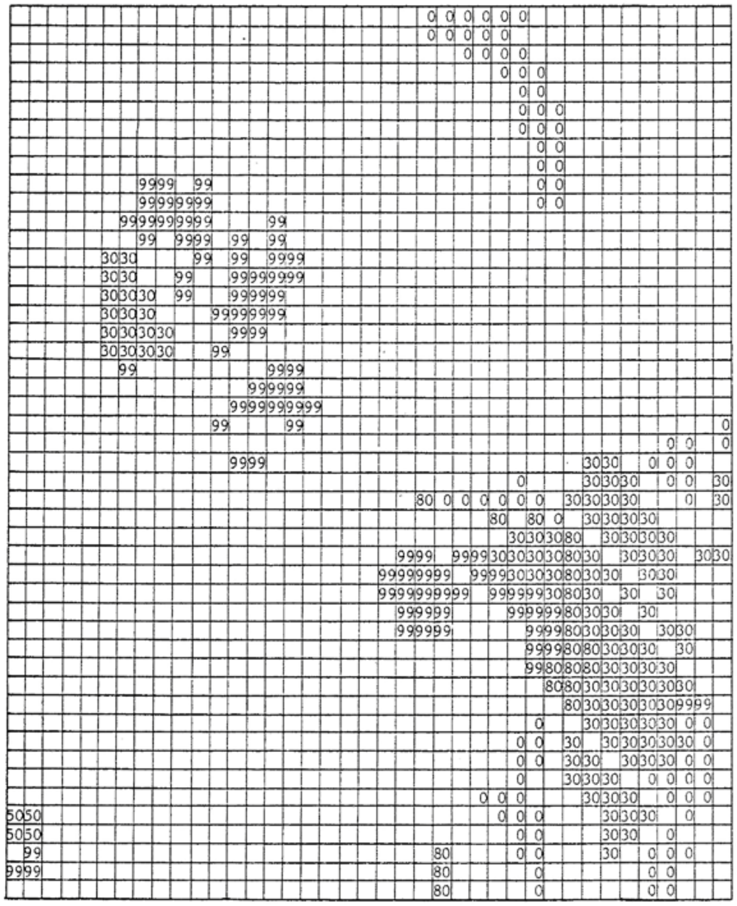


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Figure 5-4. Typical Suitability Score Grid for a Sanitary Landfill

This score grid is from Sector 6, and the Physical performance Measure is the Depth of Agriculturally Productive Soil. The blank grid cells are in the screened portion of the sector. The score values in the candidate grid cells are from Suitability Score Function no. 6 (Figure 5-3). Note that 99s are used in grid cells receiving a score of 100. The data source map used in the preparation of this score grid is the Soils map (plate 2).

5.2.4.8 Step 8. Calculation of the Suitability Index Map

The final step in land suitability assessment is the calculation of the Suitability Index Map (SIM) from the SSGs produced in the preceding step. The first stage of this calculation is to multiply all the grid elements of each SSG by the weight of the associated LLDC. This process is repeated for all the SSGs, and the resulting weighted SSGs are then summed in stack fashion in the second stage to give the SIM. Because of the large number of data elements involved in this process (up to 47,000 for each 2-1/2 minute sector), the computer program introduced in Chapter 2 (Figures 2-9 to 2-11) can be used effectively to perform the numerous elementary calculations. In the application of this program, one simplifying step can be taken. Instead of repeating some of the sixteen SSGs where necessary if all twenty-five LLDCs are considered separately, the weights of LLDCs having the same SSGs can be added. In this way only sixteen SSGs rather than twenty-five LLDCs need be weighted and summed, which reduces the number of data elements to about 32,000 per 2-1/2 minute sector. The final SIMs for the three sectors analyzed are shown in Figures 5-5 to 5-7. The shapes of the SIMs have been distorted by the computer output, but the grid square values can easily be transferred to a properly proportioned grid overlay.

5.2.4.9 Discussion of Results

Ideally, the suitability index values shown on the SIMs should indicate in an absolute sense the suitability (in percent terms) of each grid square for emplacement of a sanitary landfill. However, because many of the LLDCs were eliminated when the DAH was condensed to a manageable size, the suitability index values should be used only in a relative sense. That is, the SI values indicate the suitability of the grid squares relative to each other, but they do not indicate the total suitability of the square for a landfill. The absolute suitability of the squares is indicated only with respect to the 25 LLDCs accounted for in the condensed DAH, not for the entire DAH. The screened grid squares have SI values of zero which were assigned in the screening procedure.

Table 5-4 shows a comparison of the SI values of the three sectors analyzed. In this section each of the sectors is described, and the location and distribution of the most suitable parts of each sector will be outlined. The three sectors will then be compared to each other to show which type of geologic and topographic characteristics represented by each sector is most amenable to use for sanitary landfilling. A major factor is the minimum area required for a landfill. The smallest practical size of a landfill is about 12 hectares (30 acres), so high-suitability grid squares cannot be used unless they occur in blocks of this size or larger.

Sector 6 (Figure 5-5) is in the northeast part of the study area. It has highly variable topography and is underlain mostly by low permeability nonaquifer mixed limestones. The southeast quarter of this sector is underlain by clay and ancient terrace gravels. Soil thicknesses vary greatly over the differing bedrock and topographic conditions. The nonuniform character of the sector, which is reflected in the good spread of SI values (from 30 to 75), allows the evaluation method to make a good distinction between the different parts of the sector. In general, the sector is not

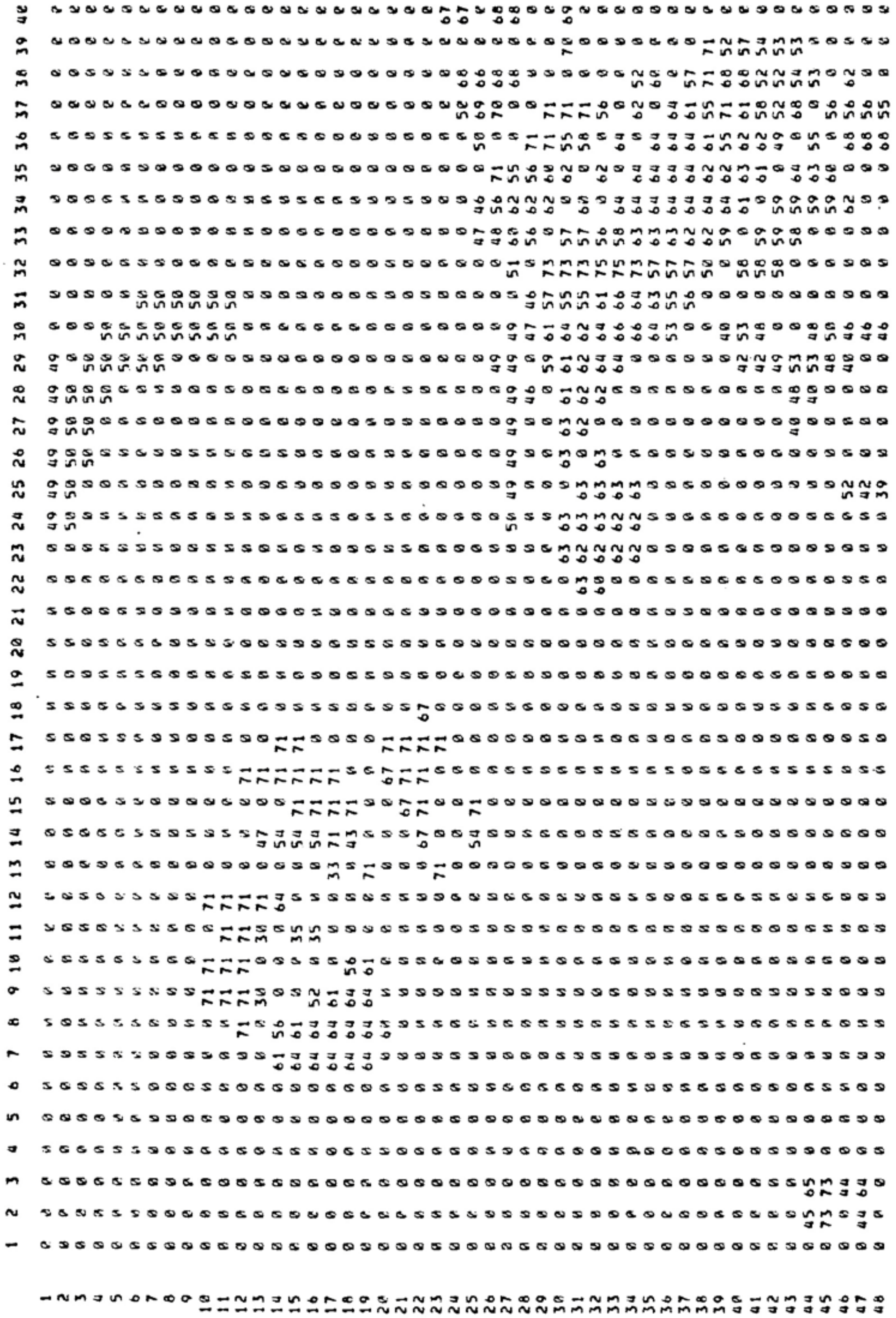

Figure 5-5. Suitability Index Map for Sector 6

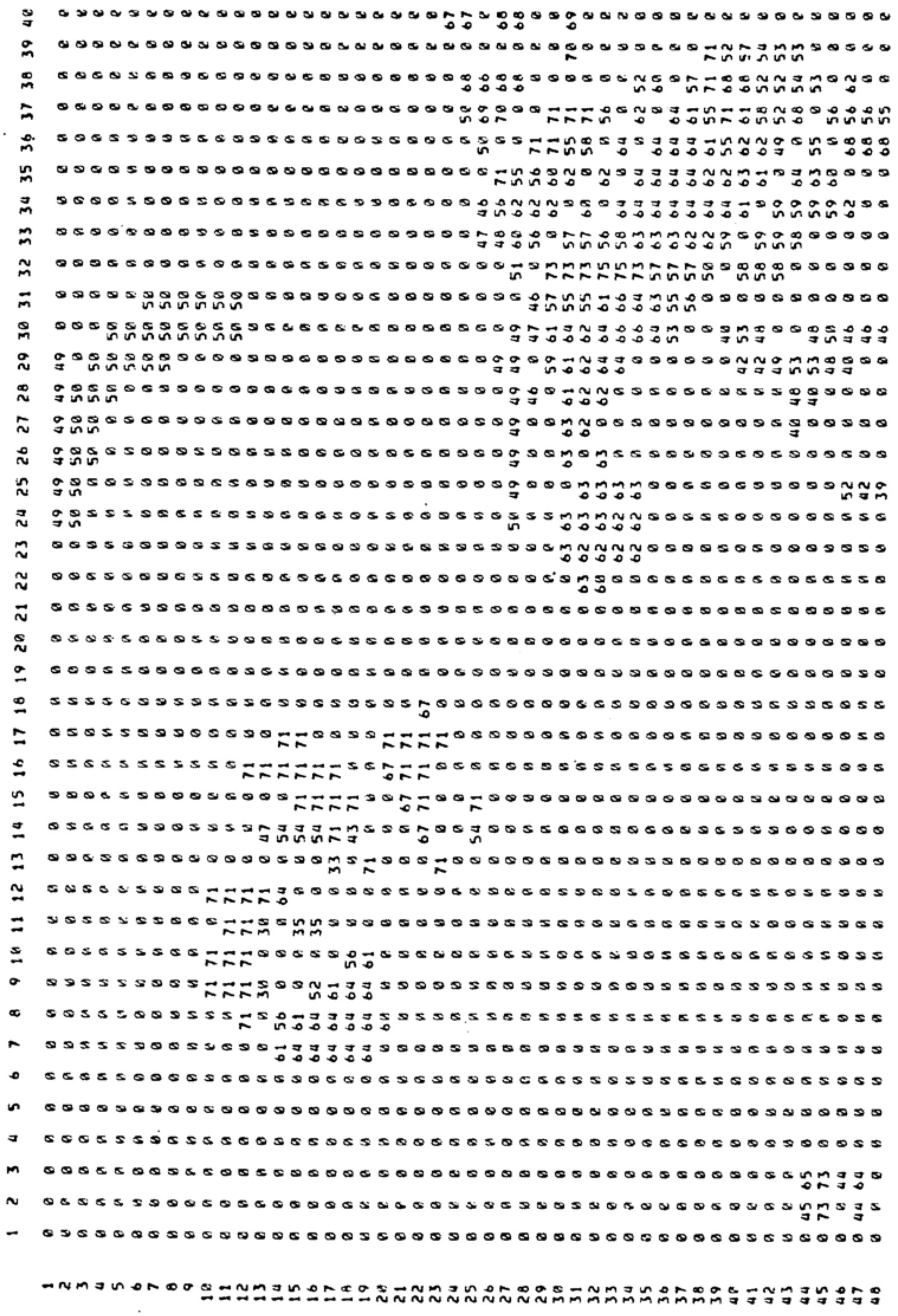

Figure 5-6. Suitability Index Map for Sector 12

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
1	72	72	72	72	72	72	0	70	70	70	70	70	70	70	70	72	0	72	0	0	0	72	72	72	72	0	0	0	0	0	67	68	70	70	70	70	70	70	70	70
2	72	72	72	72	70	0	70	70	70	70	70	70	70	70	70	0	72	72	72	0	0	0	72	0	0	0	70	70	70	0	0	72	72	72	72	72	72	70	70	70
3	70	70	70	70	0	70	70	70	70	70	70	70	70	70	70	0	72	72	72	0	0	0	0	0	72	72	72	70	70	68	0	0	70	70	70	72	72	70	70	70
4	70	70	70	0	70	70	70	70	70	70	70	70	70	70	70	0	70	70	71	0	0	0	72	72	72	72	72	0	68	68	72	0	0	70	70	70	70	70	72	70
5	70	70	0	70	70	70	70	70	70	70	70	70	70	69	68	0	70	0	0	0	0	0	0	0	0	72	0	0	68	68	72	72	0	70	70	70	70	70	70	67
6	70	0	70	70	70	70	70	70	70	70	70	70	70	69	68	0	0	0	70	71	0	0	0	0	0	0	0	0	70	70	72	72	70	0	70	70	70	70	70	67
7	0	0	70	70	70	70	70	70	70	70	70	70	0	0	0	0	70	70	70	70	0	0	0	0	0	0	0	0	70	70	72	71	70	0	0	70	70	70	70	70
8	0	70	70	70	70	70	70	70	70	70	70	0	0	70	68	0	71	69	70	70	70	0	0	0	0	0	0	0	0	70	70	70	70	70	0	0	70	70	70	70
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13	72	72	72	72	72	0	72	72	72	70	70	70	70	70	70	0	70	70	70	70	70	70	70	0	0	0	0	0	0	0	0	0	0	0	0	70	68	68	70	70
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21	70	70	71	72	72	72	72	72	72	72	72	70	70	70	0	70	70	70	70	70	70	72	72	72	72	72	72	72	72	72	72	72	70	70	70	70	70	70	70	70
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42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	70	70	70	70	70	70	0	0	72	70	70	72	79	79	70	70	70	70	70
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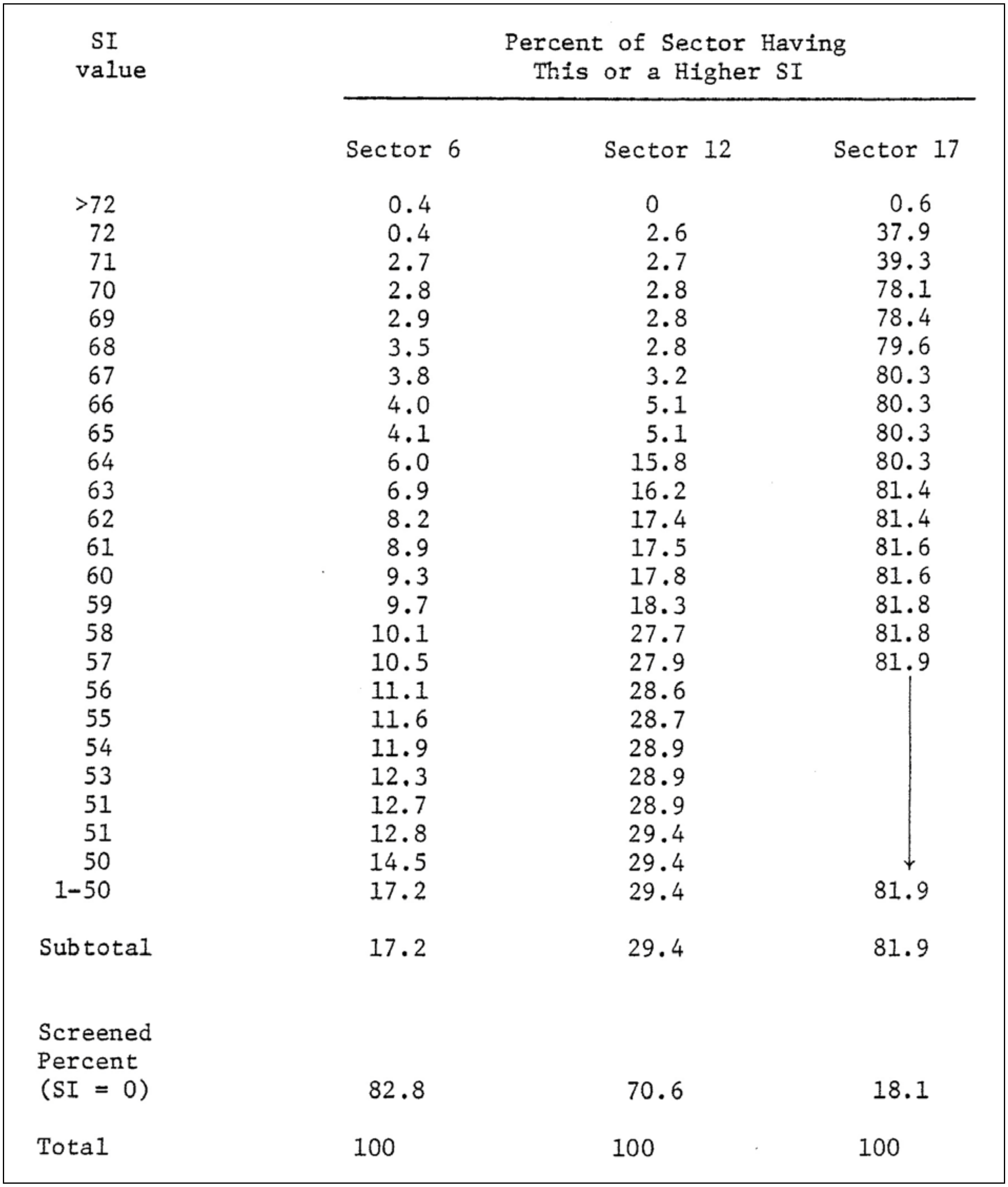
46	72	72	72	70	70	70	70	70	70	72	72	72	0	72	72	72	72	72	72	70	70	70	70	70	70	72	72	72	70	70	72	70	70	70	70	70	70	70	72	72
47	70	72	71	70	70	70	70	70	72	72	72	72	0	72	72	72	72	72	72	70	70	70	70	70	70	72	71	70	70	70	70	70	70	70	70	70	70	70	72	72

Figure 5-7. Suitability Index Map for Sector 17



SI value	Percent of Sector Having This or a Higher SI		
	Sector 6	Sector 12	Sector 17
>72	0.4	0	0.6
72	0.4	2.6	37.9
71	2.7	2.7	39.3
70	2.8	2.8	78.1
69	2.9	2.8	78.4
68	3.5	2.8	79.6
67	3.8	3.2	80.3
66	4.0	5.1	80.3
65	4.1	5.1	80.3
64	6.0	15.8	80.3
63	6.9	16.2	81.4
62	8.2	17.4	81.4
61	8.9	17.5	81.6
60	9.3	17.8	81.6
59	9.7	18.3	81.8
58	10.1	27.7	81.8
57	10.5	27.9	81.9
56	11.1	28.6	
55	11.6	28.7	
54	11.9	28.9	
53	12.3	28.9	
51	12.7	28.9	
51	12.8	29.4	
50	14.5	29.4	
1-50	17.2	29.4	81.9
Subtotal	17.2	29.4	81.9
Screened Percent (SI = 0)	82.8	70.6	18.1
Total	100	100	100

Table 5-4. Comparison of the Suitability Index Values of Sectors 6, 12, and 17

well suited for a sanitary landfill, as indicated at the outset by the fact that 82% of the area was eliminated in the screening procedure, mostly because of thin soils. The only unscreened part which takes in more than 12 hectares (30 acres) is in the southeast quarter, and even there the SIs are not high. The best 6% of the sector has an SI range of 64 to 75. The best 10% has SI values of 58 to 75, and 7% of the sector has SI values of 30 to 58. The best suited part of the sector for a sanitary landfill is between two northwest-oriented country roads about 2 kilometers south of Kyle. The SI values there are mostly in the 60s.

Sector 12 (Figure 5-6), which is in the east-central part of the study area, is relatively flat and is underlain mostly by alluvium with thick soils. The northeast corner is underlain by clay. This sector is also not particularly well suited for a sanitary landfill, as indicated by the fact that over 70% of its area was eliminated in the screening procedure. However, most of the remaining 30% is distributed in blocks large enough to be used as landfill sites. Most of this unscreened area is in the northeast quarter of the sector. The maximum SI value in the sector is 72, and a significant part of the sector (2.6%) in the far northeast corner has this value. Overall, the best 5% has an SI range of 66 to 72. SIs of 64 or over take in about 16% of the sector, and 14% of the area has SIs of 51 to 64. Clearly, the best part of the sector for a landfill is in the northeast corner where the substrate is clay. There a large block of over 50 hectares (125 acres) has an SI value of 72.

Sector 17 (Figure 5-7) is in the south-central part of the study area. It is characterized by gentle slopes and is underlain almost entirely by clays that have thick soils. Because of its topographic and substrate uniformity, only a small range of SIs are represented in this sector. The sector is well suited for a sanitary landfill, as indicated initially by the fact that only 18% of its area was eliminated by screening. The SI values of the candidate areas are also relatively high in that the minimum value is 60. The highest SI values are from 75 to 79, but they account for less than 1% of the sector and are generally surrounded by areas having much lower SIs. Large blocks of the sector do, however, have SI values of 72. These occur in the southern half of the sector and are surrounded by large areas having an SI of 70 or 71. Overall, more than 78% of the sector has SI values of 70 or higher. The 4% that has SIs of 57 to 70 are widely scattered and generally adjoin surface water bodies. The prime part of the sector for a landfill is just southeast of the sector center, where a large block of 125 hectares (325 acres) has an SI of 72. Smaller, but nevertheless significant blocks of areas with SIs of 72 are also in the western half of the sector.

A comparison of the three sectors (Table 5-4) evaluated shows that the geologic and topographic characteristics of Sector 17 are clearly the most suitable for a sanitary landfill. More than 78% of Sector 17 has an SI of 70 or higher, whereas only 2.8% of Sectors 6 and 12 have SIs of 70 or more. These results may have been anticipated qualitatively considering the flat topography and mostly clay substrate of Sector 17. Sector 12 has a small area in the northeast corner which have SI values as high as those in Sector 17, but the characteristics of that area are about identical to those of Sector 17.

5.2.5 Verification Procedure

In order to ensure the accuracy of the results of the Screening and Evaluation Procedure, the most promising candidate areas must be verified. Only a cursory verification has been conducted. More detailed on-site investigations will still be needed before sites are actually used for a landfill. The first step of the verification consists of rechecking the most promising areas against the seven data source maps. This check reveals that one or two blocks with relatively high scores should have been screened; the largest is a block which is now occupied by the Quail Creek Country Club. The second step is to check the candidate areas on aerial photographs. This check has turned up no obvious errors. The final step consists of field visitation and cursory observation of the candidate areas. In general, all of the most promising areas appeared to be quite satisfactory for emplacement of a sanitary landfill. One exception is the large block (most of which has SI values of only 50) located just northwest of Kyle. This block is probably too close to the town, and the small stream draining the site flows in close proximity to the southern edge of the town, thus posing a potential health hazard to residents living there. Also, two of the blocks in Sector 12 are probably located too close to the Blanco River where leachate may have access to the river through the permeable channel gravels of the alluvium. In Sector 17 some of the grid squares adjacent to areas screened because of water bodies apparently should have received lower SI values because of their proximity to the water. Aside from these relatively minor problems, no large or obvious errors in the Suitability Index Maps were observed in the cursory verification.

5.3 Toward a Physical Land Use Plan for the San Marcos Area

The results of this chapter represent a beginning of the work required to determine land suitability for all projected urban land uses in the study area. Still remaining are not only the evaluation of the rest of the sectors for a sanitary landfill specifically, but also the multiple evaluations for many projected urban uses. The urban system concept provides a good organizational scheme for conducting suitability analyses for these projected uses. The resulting Suitability Index Maps can then be used as input which should be considered with other factors, such as locational aspects, compatibility of adjacent urban facilities and activities, and social, economic, and political conditions. By considering all of these factors planners should be able to formulate a physical land use plan. It should be emphasized, however, that the physical suitability of the land as indicated on the Suitability Index Maps should be given the highest

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6 Chapter 6. Summary and Conclusions

The procedure of this environmental geologic study has been to focus on growing urban areas and to delineate the components of urban systems and their geologic environments. These components were used as conceptual tools for development of a systematic three-part methodology for conducting environmental geologic investigation of growing urban areas. This methodology was then applied to a case study area around San Marcos in the Interstate 35 growth corridor of central Texas.

Recognition of the two conceptually distinct parts of the urban-environment interaction - the urban system and the geologic environment - makes the problem of environmental geologic analysis more manageable. The classification of the geologic environment into three broad categories (substrate, processes, and landform) appears to be conceptually sound and sufficiently comprehensive to be applicable to most of the inhabitable parts of the world. Also, the urban system organizational scheme, which uses the four categories (situs, input, output, and transportation) recognized here, apparently accounts for the urban facilities and activities having the most environmental geologic significance. The organization of the procedure of the methodology into three parts – delineation of the data sources followed by a curative and then a preventive procedure - appears to be a rational and rigorous approach to the analysis of the interaction between cities and their geologic environments.

In the derivation of the natural data source maps for the San Marcos case study area, the substrate-processes-landform scheme proved to be highly effective in organizing the geologic and geology-related phenomena having significance for urbanization. The curative part of the methodology has also apparently accounted for all the important environmental geologic conflicts in the area. The preventive part of the procedure was quite effective in determining land capability for the one projected urban land use, a sanitary landfill, for which the analysis was run. The application of this part of the methodology to the San Marcos area clearly demonstrated the advantages of this rigorous analysis. In the first place the procedure goes a step beyond the preparation of the data source maps and converts the information into an indication of land suitability for specific uses. Second, the procedure is based on an established decision-making technique, so the results (the Suitability Index Maps) are highly defensible. Finally, the results are easily understood by nontechnical people who are likely to be making land use decisions.

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Appendix. Geology of the San Marcos Area, Texas

The primary aim of this appendix is to present a geologic report to accompany the geologic maps of the San Marcos area (Plates 9 and 10). The procedure will be first to describe the regional geologic context and then to cover in turn the three major aspects of the geology of the area: stratigraphy, structural geology, and geomorphology. This report has been prepared in a very condensed form, and only the major points are covered in each topic. The geologic mapping for Plates 9 and 10 is original to this study, but most of the information in this text is derived from previous studies. These sources are too numerous to cite individually, but local studies by DeCook (1956, 1960,1963), Davis (1962), and Noyes (1957) have been relied upon heavily.

The geologic mapping was done on Agricultural Stabilization and Conservation Service (U.S. Department of Agriculture) aerial photographs that have a scale of 1:20,000. All mapping was accomplished in the field because frequent spot checking of outcrops was necessary to work out the complex fault patterns. The map information was transferred to topographic base maps by use of a mirror-type desk projector (Reed Research Model 635B). As noted in the text, U.S. Geological Survey 7-1/2 minute topographic quadrangles (scale 1:24,000) were used as base maps. The study area includes the southern one-third of the Mountain City quadrangle, all of the San Marcos North quadrangle, and the northern two-thirds of the San Marcos South quadrangle. Available subsurface data on file at the Texas Water Development Board were also examined. Most of these data are in the form of water well logs prepared by water well drillers having little training in geology and proved to be of only limited value. DeCook (1960, 1963) made the best possible interpretations of these data, so his studies are used extensively in this-report. Logs of wells drilled since these studies were published were also utilized to some extent.

A.1 The Geologic Context: Geologic Elements of Central Texas

The basement rocks of central Texas comprise two primary elements - the Texas Craton and the Oauchita foldbelt. The Texas Craton, a northwest elongated mass of Precambrian, mostly granitic rock, is the most fundamental basement element in Texas. It is bounded on the southeast by the strongly deformed and metamorphosed Paleozoic rocks of the Ouachita foldbelt. The study area lies over the Ouachita foldbelt just southeast of the boundary with the Texas Craton.

Unconformably overlying this basement is a southeast dipping wedge of Cretaceous sedimentary rocks. This wedge, which thins to the northwest, is approximately 750 meters thick in the San Marcos area. The strata of this wedge are mostly carbonate rocks and fine-grained terrigenous rocks.

The Cretaceous wedge is intensely faulted along the Balcones fault zone, which extends in an arcuate band from Del Rio to north of Waco. The location of the fault zone closely follows the line of crustal weakness along the boundary between the Ouachita foldbelt and the Texas Craton. Displacement across the zone is downward to the southeast, and the zone is in a graben-like relation to the Luling-Mexia fault system, which is located further toward the Gulf Coast. The regional dip across this hinge-line fault zone increases from about 1.9 to 5.7 meters per kilometer northwest of the zone to about 9.5 to 18.9 meters per kilometer southeast of the zone. The displacement across the zone is maximum between Austin and San Antonio. Most of the faulting is believed to have occurred during the Miocene, and no well documented instances of fault movement have been recorded in historic times.

The topographic expression of the fault zone is well developed in the San Marcos area. The faulting of the soft, clayey Upper Cretaceous strata downward against the more resistant carbonate units of the Lower Cretaceous has resulted in the development of the east-facing Balcones Escarpment. The elevation across this fault-line scarp about doubles from about 150 to about 300 meters.

Uplifting of the west side of the Balcones fault zone has caused faster erosion there, and the result has been the exposure of generally older rocks there than east of the zone. However, the rate of erosion west of the scarp had been slowed considerably by the resistant Edwards Group carbonate rocks, thus giving rise to a relatively flat, elevated surface known as the Edwards Plateau.

A.2 Stratigraphy

Because of the emphasis of this study on the surface and near-surface bedrock, only rock units that crop out will be described. As shown on the geologic maps (Plates 9 and 10), the bedrock in the San Marcos area comprises mostly Cretaceous sedimentary rocks, and most of the Texas Cretaceous stratigraphic section is exposed in the area. Several gravel deposits of Quaternary age are also present in the area, but their discussion is deferred to the geomorphology section of this appendix.

Most of the Texas Cretaceous strata were deposited in shallow marine environments on a broad shelf that extended inland from about the middle of the present Gulf Coastal Plain. The dominant lithologies of the strata are limestones, dolomites, and marls. Most of the upper part of the section is composed of terrigenous clays. Highly uniform lithotopes over large areas of the shelf give rise to rock-stratigraphic units which may change materially in thickness and composition regionally but are relatively uniform in areas as large as a 15-minute quadrangle. Some of the rock-stratifigraphic units thin southward across the San Marcos area, owing to the influence of a subtle Cretaceous positive tectonic element, the San Marcos Platform, between New Braunfels and San Antonio. None of the units, however, show appreciable lithologic changes across the area. Each of the stratigraphic units cropping out in the area are described very generally in ascending order in the following paragraphs. For detailed descriptions and measured sections of these units, the reader is referred to DeCook, 1956, Noyes, 1957, DeCook, 1960, Davis, 1962, or DeCook, 1963.

A.2.1 Glen Rose Formation

The oldest rock-stratigraphic unit exposed in the San Marcos area is the Glen Rose Formation. It crops out in the northwest corner of area in the canyon of the Blanco River, where the upper 12 to 15 meters are exposed. The strata consist of finely crystalline dolomite interbedded with dolomitic limestone and dolomitic marl. Individual beds range from 0.6 meters to several meters in thickness (Davis, 1962). Because of its small area of occurrence, this formation does not have great significance for this study.

A.2.2 Walnut Formation

The next formation in ascending order is the Walnut, which was distinguished by Davis (1962) but was included by Rose (1972) in the overlying Kainer Formation. The Walnut crops out on the bluffs of the Blanco canyon in the northwest part of the area. Davis (1962) recognizes the Bull Creek and Bee Cave Members in ascending order. The Bull Creek is 12.0 meters thick and is mostly a massive limestone and dolomite. The Bee Cave is 2.5 meters thick and is a nodular marl. Like the Glen Rose, the Walnut Formation is not particularly significant to this study, and it is included with the overlying Kainer Formation on the geologic map.

A.2.3 Edwards Group

The Edwards Group is the next rock-stratigraphic unit. Although this unit has been elevated in rank to a group comprising the Kainer (below) and the Person (above) Formations (Rose, 1972), it will be described here as a group primarily because both formations serve as part of the important Edwards aquifer. The Edwards is a nearly pure carbonate unit with beds of hard limestone, dolomite, and all gradations between these two lithologies. Isopachous maps by Rose (1972) indicate a thickness of about 100 meters for the Kainer and 43 to 49 meters for the Person in the San Marcos area. The two formations are lithologically similar and are difficult to distinguish unless the distinctive marker bed (the Regional Dense Member) at the base of the Person crops out. For this reason, and because of the intense faulting, no section has yet been measured in the area. The Kainer and Person have been mapped separately on the geologic map where it was possible to distinguish between them. Elsewhere, the Edwards is mapped as undifferentiated.

The Edwards is one of the most important rock units in the area. It underlies most of the area west of the Balcones Escarpment and therefore determines the physical properties of the substrate in that area. More importantly, this unit is the aquifer which supplies the significant quantities of ground water in the area and provides the flow from San Marcos Springs. The outcrop area west of the escarpment, because it provides much of the recharge to this aquifer, should be subjected to rather tight land use restrictions. The Edwards is different both in lithology and in the chemical quality of its contained water on either side of the "bad-water line" shown on the Resources map (Plate 3). This line approximately demarks the downdip limit of freshwater circulation. West of the line the water is potable (although somewhat mineralized), and the rock has been greatly altered by the rapidly circulating water. East of the line the water is highly mineralized and is charged with hydrogen sulfide. The rock there has not been subjected to the solution, collapse, and recrystallization effects that are characteristic of the aquifer part of the formation, and it is more typical of a deeply buried petroliferous limestone. Two oilfields a few miles southeast of San Marcos have produced a combined total of about 270 million barrels of oil from the Edwards.

A.2.4 Georgetown Formation

The Edwards Group is overlain by the Georgetown Formation, which is from 9 to 12 meters thick in the San Marcos area. The contact between the Edwards and Georgetown is sharp and distinctive and is probably disconformable. DeCook (1956), in a description of a measured section around Sink Creek just north of San Marcos, indicates that this formation includes beds of shale, marl, argillaceous limestone, and limestone. The Georgetown crops out in several fault blocks in the intensely faulted zone along the Balcones Escarpment, but does not include large outcrop areas.

A.2.5 Del Rio Clay

The Del Rio is about 15 meters thick and is composed of a clay-shale almost uniformly through this thickness. In the unweathered state these clays are composed dominantly of kaolinite and illite with a small admixture of mixed layer illite-montmorillonite. In the weathered zone, however, the illite and mixed layer clay are converted into highly plastic montmorillonite. The contact of the Del Rio with the underlying Georgetown is usually obscured by mass movement of these clays. The formation is characterized by gypsum veinlets (at the outcrop) and by abundant specimens of the distinctive small oyster, Ilmatogyra arietina. A thin (about 0.3 meter) bed of Ilmatogyra lumachelle occurs at about the middle of the formation. Like the Georgetown, the Del Rio crops out in irregular polygonal fault blocks in the vicinity of the Balcones Escarpment. Despite the small total area of outcrop, this formation has considerable implications for this study, as noted in the text.

A.2.6 Buda Formation

The next formation in ascending order is the Buda, which is a relatively hard, nodular limestone in the lower part and a hard, resistant, thick-bedded limestone in the upper part. It is about 15 meters thick in the San Marcos area. The Buda, like the underlying Del Rio and Georgetown, occurs chiefly in fault blocks in the intensely faulted zone along the escarpment. The hard limestones of this formation often form a resistant cap on hills that are flanked by the less resistant Del Rio Clay. The contact between the Del Rio and Buda is usually obscured by slump failure of the Del Rio out from under the Buda.

A.2.7 Eagle Ford Formation

The Eagle Ford Formation, which is about 7.5 meters thick, overlies the Buda Formation. The Eagle Ford has three distinct parts - a lower bentonitic shale about 2.1 meters thick, a middle calcareous, flaggy sandstone or siltstone unit that is about 1.2 meters thick, and an upper shale having a thickness of about 4.2 meters. The lower contact between the lower shale and the upper Buda limestones is sharp and distinct. The contact with the overlying Austin Group can seldom be seen because of slumpage of the upper shale out from under the more competent beds of the Austin. The Eagle Ford, like the subjacent formations above the Edwards, occurs in fault blocks along the Balcones Escarpment, and it also occurs more prominently in the bluffs of the Blanco River in the eastern half of the San Marcos area. Despite the competent flaggy beds in the middle of the Eagle Ford, this formation is considered a clay unit for the purposes of this study.

A.2.8 Austin Group

The Austin Group has been elevated in recent years from formation to group status and has been subdivided into several formations. However, it has been mapped in this study as a single unit because the lithologic differences between the various formations are not in general great enough to be highly significant for environmental geologic purposes. DeCook (1963) reports a thickness of about 49 to 55 meters in the vicinity of San Marcos, but the upper contact is not exposed in the area. The lithology is chiefly an argillaceous or chalky limestone.

The Austin underlies a large area in the eastern half of the Kyle section of the study area on both sides of the Blanco River. It also crops out in a step fault block between the San Marcos Springs and Comal Springs faults southwest of San Marcos. Interestingly, the Austin also occurs in a fault block in the western part of the Kyle section not far from the highest elevation in the area. Because of its large area of outcrop in the northern half of the area, the Austin is very significant to this study.

A.2.9 Taylor Group

The Taylor Group, which is the next rock-stratigraphic unit in ascending order, has a thickness of about 90 meters in the San Marcos area. Like the Austin Group, the Taylor has in recent years been elevated to group status and has been divided into three formations (Young, 1965). These formations are the Sprinkle (lower), Pecan Gap (middle), and Bergstrom (upper). All three formations are composed of smectitic mudstone and are distinguished primarily on the basis of calcium carbonate content; the Pecan Gap is more calcareous and more resistant to erosion than the underlying Sprinkle or the overlying Bergstrom Formation.

The formations of the Taylor Group crop out extensively in the area east of the Balcones Escarpment. The Sprinkle was recognized in only one location southwest of San Marcos, but the Pecan Gap underlies almost all of the rest of the area east of the scarp. The Bergstrom is in contact with the Pecan Gap along an inferred northeast-oriented Balcones fault and occurs in the southeast corner of the area. Because of its wide areas of occurrence and poor engineering properties, the Taylor Group as a whole is very significant to this study.

A.2.10 Corsicana Formation

The youngest Cretaceous formation in the San Marcos area is the Corsicana Formation of the Navarro Group. Outcrops of this formation were observed in the far southeast corner of the area where the formation apparently overlies the Bergstrom in normal stratigraphic contact. A regional dip of about 19 meters per kilometer was assumed when this contact was drawn.

A.3 Structural Geology

The San Marcos area lies over the Balcones Escarpment in an intensely faulted part of the Balcones fault zone. This zone, as noted earlier, is a system of mostly normal faults having a net displacement downward to the east and southeast. At first glance, the part of the geologic map northwest of the escarpment (Plates 9 and 10) has the appearance of a shattered mirror or pane of glass, but with closer study a definite pattern emerges. In general, the faults of major displacement strike about N30°E. Near the northern margin of the area the Mustang Branch and Mountain City faults are step faults across which the Austin Group is 224 displaced downward to the southeast to about the same level as the Edwards Group. A third step fault, the Kyle fault, is located about 7 kilometers to the southeast near Kyle. It has displaced the Pecan Gap Formation down to about the level of the Austin Group. A similar relationship exists near the western margin of the San Marcos section of the area. Three step faults (an unnamed zone of faults, the San Marcos Springs fault, the Comal Springs fault) have displaced the Pecan Gap Formation downward to the southeast to an elevation lower than the Edwards Group. The two step fault zones in the northern and southern parts of the area are not aligned with each other, but are offset by about 4.6 kilometers. The complex faulting and outcrop pattern between these zones is the result of the adjustment of the intervening area to their en echelon relationship. The offset of the zones can be seen quite clearly in the Balcones Escarpment as shown on the satellite photo in the Frontispiece. In broad outline, the Edwards Group outcrops on the upthrown side of the southern set of step faults give way northeastward to progressively younger strata that are on the downthrown side of the Mustang Branch and Mountain City step faults (R. O. Kehle, personal communication). Figure A-1 shows in simplified diagrammatic form the ramp between the en echelon step faults. This ramp, instead of bending smoothly, as shown in the diagram, from the upthrown side of the southern fault zone to the downthrown side of the northern zone, has been intensely faulted and fractured, resulting in the mosaic of gravity fault blocks west of the Blanco River in the Kyle section. Unfortunately, a key part of the transition has been covered by alluvium of the Blanco River. This relatively straightforward picture is complicated somewhat by the intensely faulted graben-like downfaulted wedge in the west-central part of the Kyle section. Similar but somewhat smaller ramp-like structures can also be seen along the Balcones Escarpment near the eastern margin of the Kyle section. Three en echelon faults (the Kyle fault, the San Marcos Springs fault, and an unnamed fault between these two) separate two ramps which dip northeastward. Outcrops on these ramps change northeastward from the Austin Group to the Pecan Gap Formation, but the exact nature of the transition is obscured by alluvial cover.

Another interesting structural feature along the escarpment is the relatively undisturbed monolithic block upon which the northwestern half of San Marcos is built. This block is encircled by intense faulting but has not itself been appreciably disturbed except for a slight eastward tilt which may be a result of regional dip. The block stands quite high topographically on the divide between Sink Springs and Purgatory Creeks.

Southeast of the Balcones Escarpment the Balcones faulting does not appear to be as intense as northeast of the scarp. However, this apparent difference is due to the difficulty in recognizing and mapping faults in the clay terrane rather than to the absence of faults. Not only is it almost impossible to observe faults in the soft, uniform Upper Cretaceous clay units, but the structure is further obscured by the thick black soils that have developed on the clays. More than likely, intense faulting like that northwest of the scarp has also occurred southeastward to the Mexia

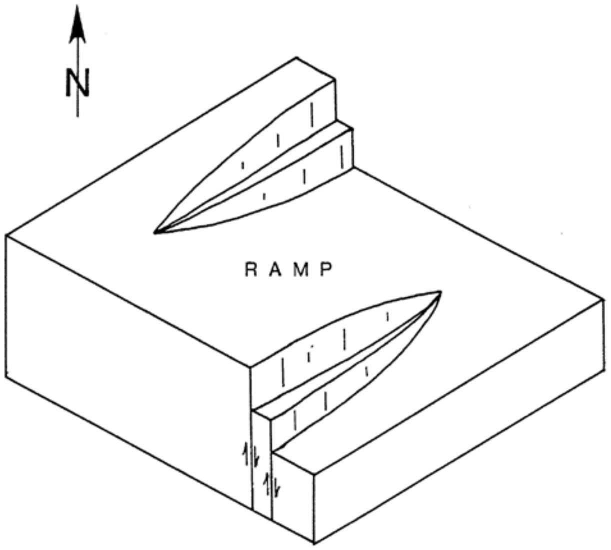

Figure A-l. Diagram Showing the Ramp Between Two En Echelon Fault Zones

If this block were eroded to a level surface, the strata exposed in the ramp would become progressively younger northeastward.

fault zone (Keith Young, personal communication). The major faults shown on the geologic map southeast of the escarpment are taken from previous work (chiefly DeCook, 1960, 1963 and Barnes, 1974), and their existence is inferred primarily from subsurface data rather than surface mapping.

The total vertical slip (throw) across the study area from the upper contact of the Glen Rose in the Blanco River canyon to the inferred contact between the Taylor and Navarro Groups in the southeast corner of the area is about 415 meters. An unknown part of this displacement is due to regional dip. The displacement on the major faults in the area is difficult to estimate because the blocks on either side of the faults are themselves usually broken up by cross faults. The individual blocks are often displaced by differing amounts. Also, the blocks are usually tilted and bent, which further increases the difficulty of estimating displacements. Despite these problems some very general estimates of displacements on the major faults or fault zones can be made. The minimum throw on the combined Mustang Branch and Mountain City faults equals the thickness of the stratigraphic interval between the Edwards and Austin Groups, and amounts to about 50 meters. The Hidden Valley fault, which is reported to have a throw of about 60 meters in Comal County (George, 1952), has a highly variable throw in the San Marcos area. The upper contact of the Glen Rose is apparently displaced only about 9 meters at one point in the Blanco River canyon, but it is displaced by more than 15 meters at another point in the canyon. DeCook (1963) states that this fault dies out to the northeast. The Morton Ranch fault has maximum displacement along a segment where the Austin Group is faulted down against the Person Formation, and the minimum displacement there is about 50 meters. Davis (1962) estimates the maximum displacement of this fault to be between 80 and 110 meters. DeCook (1956) estimates the throw of San Marcos Springs fault to be a minimum of about 90 meters. Comal Springs fault decreases in displacement northeastward across the area. The throw is estimated to be about 120 meters near the west edge of the San Marcos section and about 100 meters near San Marcos. Because of the en echelon relationship of some of these faults, their displacements sum to a value greater than the total vertical throw across the area.

An interesting structural feature southeast of the Balcones Escarpment is the inferred breached dome-like structure between Hunter Road and Interstate 35 southwest of San Marcos. A lone outcrop of the Sprinkle Formation observed near the center of this feature was found to be completely surrounded by outcrops of the Pecan Gap Formation. The interpreted structure, which assumes a reversal of dip near the Comal Springs fault of the type described by Cloos (1968), is advanced as the simplest explanation for these observations. An earth resistivity traverse was made parallel to McCarty Lane by an Engineering Geology class of the University of Texas at Austin to clarify the structural picture at this location, but the results were relatively inconclusive. The interpretation depicted proved to be compatible with the resistivity observations, but an alternative interpretation which proposes additional faults and a horst-like structure is equally likely. The reversal-of-dip explanation is used here to avoid depicting a minimum of two additional inferred faults, neither of which can be satisfactorily connected to known faults.

A.4 Geomorphology

The primary physiographic element in the San Marcos area is the Balcones Escarpment. As noted in the text, the elevation about doubles westward across the scarp within the limits of the area, and the landforms are different on either side. East of the scarp the topography on the soft Upper Cretaceous clays of the Blackland Prairie is gentle and rolling with low rounded hills. West of the scarp the rugged limestone terrane of the dissected eastern margin of the Edwards Plateau is known as the Texas hill country.

A.4.1 Fluvial Processes

The dominant geomorphic processes in the area at present are the fluvial processes. One of the more interesting aspects of the fluvial geomorphology of the area is the geologic history of the Blanco River. Woodruff (Baker and others, 1974) described evidence indicating that the Blanco formerly flowed eastward out of the Kyle section into what is now the drainage basin of Onion Creek. He proposed that the scarp (90°) bend in the course of the river in the north-central part of the Kyle section may be an elbow of capture. This elbow was created when the Blanco was diverted by a small stream that was eroding headward more or less normal to the Balcones Escarpment. A faintly visible trace of a short segment of the precapture course of the Blanco can be seen on aerial photos about 1.6 kilometers northeast of the capture elbow on the present divide between Onion Creek and the Blanco River. The increased gradient resulting from the capture may have been the primary cause of the incision of the Blanco to form the canyon where the river flows through the resistant Edwards Group limestones.

Evidence for a second capture of the Blanco can also be found south of Kyle, where terrace gravels cap the Austin Group uplands. This terrace stands about 12 to 15 meters above the present floodplain of the Blanco. Koenig (1940), who has studied this terrace, reports a maximum thickness of 12.8 meters for the gravels of this terrace. A thickness of no more than about 4.6 meters was observed during this study. The terrace is deeply dissected and retains none of its original landform, but it clearly indicates that the Blanco formerly flowed eastward south of Kyle into the present drainage basin of Plum Creek (Koenig, 1940). This former course of the Blanco is also clearly indicated east of the Kyle section on the Seguin sheet of the Geologic Atlas of Texas (Barnes, 1974). The alluvial gravels in this former valley are more resistant to erosion than the surrounding Upper Cretaceous clays and have resulted in an inversion of topography (Victor Baker, personal communication). The gravels now cap hills that are higher than the 'surrounding clay terrane.

The present Blanco River and associated features also display several interesting characteristics. About 4.2 kilometers west of Kyle the narrow canyon of the river abruptly opens to a floodplain having a width of about 1.6 kilometers. The river has a meandering course within the limits of this floodplain, which remains relatively constant in width downstream to about Interstate 35. East of the Interstate the floodplain again increases in width, to about 5.8 kilometers. These abrupt changes in floodplain width are attributed to changes in bedrock resistance to erosion. The widening of the gorge to a floodplain west of Kyle occurs at almost the exact point that the river crosses a fault which marks the downstream limit of the hard Edwards Group limestones. Apparently the sidecutting action of the river is more effective in the less resistant post-Edwards strata downstream from this point. Interestingly, there is also a sharp nickpoint in the river at the same site. An old gravel terrace on the upland west of the river indicates that this location has marked a sharp change in the river's behavior from a primarily downcutting to a sidecutting stream for some time in the geologic past. The second sudden broadening of the floodplain at the Interstate occurs at another change in bedrock resistance, where the nonresistant Pecan Gap clays are downfaulted against the more resistant Austin Group chalks and limestones.

The Blanco has incised slightly and has cut into or through the floodplain alluvium. As a result the flat surface along the river is no longer a floodplain in the normal sense of the term, but is rather an "infrequently flooded surface" (Victor Baker, personal communication). The river has cut into bedrock for most of its course downstream to Interstate 35, exposing in the alluvium a thickness of about 6 meters of gravel overlain by about 3 meters of sand, silt, and clay (see Figure 3-6 in text). Because of the exclusively carbonate rock source area, the gravel is composed chiefly of limestone clasts with a lesser amount of chert and dolomite. The succession of gravel overlain by fine-grained sediment is interpreted to be a normal channel gravel - overbank mud sequence. The deposition of this sequence at a particular location probably occurs during the passage of a meander loop which is eroding into the bedrock slightly. As a result, the preexisting alluvium at the location is entirely removed as the meander passes, and only one channel - floodplain sequence is preserved at the location. This process, which explains the presence of only one sequence in most places, is highly idealized and is not realized everywhere on the floodplain, resulting in several variations on the most commonly observed succession.

Downstream from Interstate 3S, the river probably has not cut through the alluvium along most of its length. Several abandoned channels can be identified in the floodplain almost from its beginning west of Kyle by tonal changes in large scale air photos. The present course of the river near the confluence into the San Marcos River has apparently been assumed relatively recently, as indicated by the steep slopes in the weak Pecan Gap clays along the cut bank there.

A minor but interesting fluvial geomorphic feature of the area is just south of San Marcos, where an example of stream piracy in action can be seen. In UTM 3304-601, the 580-foot contour line clearly indicates a connecting channel between Willow Springs and Purgatory Creeks. Longitudinal profiles of these creeks downstream from this channel show a gradient of about 3.8 meters per kilometer for Willow Springs Creek and a gradient of about 1.9 meters per kilometer for Purgatory Creek. The U.S. Army Corps of Engineers (1971, p. 20) reports that water from Purgatory Creek flows through the connecting channel into Willow Springs Creek when the Purgatory Creek discharge exceeds 120 cubic meters per second (4,200 cubic feet per second). It seems clear that the higher gradient Willow Springs Creek is in process of capturing the flow of Purgatory Creek at this natural channel. If these streams were left undisturbed by urbanization, erosion during 232 times of flood would almost certainly deepen the channel, and within a few hundred years all of the flow of Purgatory Creek would be diverted into Willow Springs Creek.

A.4.2 Karst Processes

Karst processes have been important on the Edwards Group carbonate rocks in the western part of the San Marcos area. The present climate in the area is not conducive to karst processes, however, and the karst features as a whole appear to be undergoing destruction by stream dissection. Many dolines nevertheless remain on the uplands some distance away from the major rivers where the dissection is most rapid. The relatively flat upland in the northwest corner of the Kyle section appears to be a fairly good remnant of the Edwards Plateau surface and has dolines in sufficient abundance to be termed a karst plain.

As noted in the text the most important karst process from an anthropocentric point of view is the recharge to the Edwards aquifer. Some of this recharge takes place by direct infiltration and through sinkholes in the uplands, but most recharge is believed to occur in the beds of intermittent streams (L. J. Turk, personal communication). An example of this stream recharge is depicted in Figure 3-7 in the text.

Abundant caves are a prominent karst feature associated with the Edwards Group. One cave, Wonder Cave, is operated commercially, and several others have been named, explored, and mapped. One of the more interesting caves is Dugger Cave (Tarbutton Cave), which is located near the Blanco River channel in UTM 3316-604. This cave has a vertical entrance, and the base flow of the Blanco is prevented from being diverted into the cave only by a lip of bedrock and cemented gravel alluvium about 0.9 meters high between the river level and the cave entrance. During flood stages, when the water overtops the lip, part of the river's flow is diverted into the cave, thus becoming recharge to the Edwards aquifer. Interestingly, although small passages of the cave extend under the Blanco channel (Bill Russell, Texas Speleological Survey, personal communication), an appreciable part of the river's base flow is apparently not lost to the cave.

Dugger Cave is probably the furthest downstream point of recharge from the Blanco River to the Edwards aquifer.

Sink Springs is a vertical, water-filled cave in UTM 3308-603 near the channel of Sink Springs Creek (see Figure 4-26 in text). The water level in the cave is near the ground surface and is at the level of the potentiometric surface of the Edwards aquifer. The cave received its name because it takes water from Sink Springs Creek during flood flow (or did before a small dam was constructed between the cave and the creek) and apparently has been known to flow in historic time (Robert Knispel, local resident, personal communication). It is possible that the discharge of San Marcos Springs issued from Sink Springs before the Edwards was breached at the discharge point at Spring Lake, but little or no evidence can be advanced to support this idea. Two other noteworthy observations can be made concerning the location of San Marcos Springs. First, it may not be fortuitous that the springs are located at the margin of the undisturbed monolithic block under northwestern San Marcos described earlier. Second, the springs are situated at a large-displacement fault where the Pecan Gap Formation has been downfaulted into contact with the Person Formation. At other points along the scarp, this displacement is distributed over two or more step faults, giving rise to a fault block having the Austin Group at the surface between the Edwards and the Pecan. Gap. That is, outcrops of Austin occur between the Edwards and the Pecan Gap on either side of the springs along the Balcones Escarpment, but the Austin has been faulted out at the springs location.

In addition to these karst features in the Edwards Group, two sinks are present in the Austin Group chalks and limestones near the south-central part of the Kyle section. They are of interest primarily because sinks have not heretofore been reported in the Austin Group in central Texas (Keith Young, personal communication). These sinks, as well as karstic features in other post-Edwards strata (such as Academy Cave and the Devil's Smokehouse, both of which are developed in the uppermost Buda Formation) have almost certainly resulted from roof collapse of large caverns in the Edwards. The dolines are thus created by a kind of natural stoping process from caverns in the Edwards upward through the stratigraphic section rather than by solution of post-Edwards limestones. Figure 3-8c in the text shows a cross-sectional view of a sinkhole in which this type of collapse has occurred.

A.4.3 Mass Movement

Mass movement of somewhat different types is active on either side of the Balcones Escarpment. East of the scarp, the weak Upper Cretaceous clay units are undergoing slumping and creep that give rise to the low, gently rolling hills. West of the scarp, a major type of mass movement is the calving off of large limestone blocks on cut banks of streams. Hills that are flanked by the Del Rio Clay and capped by the overlying Buda Formation often have large blocks of limestone from the Buda sliding down the hillside on the weak Del Rio. The best examples of such large sliding blocks are northwest of San Marcos in UTM 3308-599 and 600, where a hill is developed on a fault block of Del Rio Clay. This hill was apparently originally protected from erosion by a Buda cap, but this cap has become fragmented and broken up into large blocks. These blocks are sliding down the hill radially away from the hilltop and are now found at varying elevations on the hillside. Another notable example of the failure of the Del Rio out from under the Buda are two large slump blocks that are developed on the cut bank of the Blanco River at Five-mile Dam. The blocks are composed of Buda and Eagle Ford strata and have collapsed because of undercutting of the Del Rio Clay at the river level.

A.5 Summary

The bedrock units in the San Marcos area are Cretaceous sedimentary strata composed primarily of carbonates and fine-grained terrigenous rocks. The lithology and physical properties of the rocks are chiefly a function of the depositional conditions and source areas that were extant during deposition of the Cretaceous section, and the present occurrence and distribution of the rock units are controlled by the Balcones faulting in conjunction with the shape of the present erosional surface. Fluvial, karstic, and mass-movement processes are the dominant agents that have given rise to the existing geomorphic features, and they continue to shape the land surface today.

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Vita

Thomas Walter Grimshaw, the son of Claude and Phyllis Grimshaw, was born in Chamberlain, South Dakota on March 23, 1945. He attended several public schools in South Dakota and graduated from Washington Senior High School in Sioux Falls in June, 1963. He entered the South Dakota School of Mines and Technology in September, 1963 and received a Bachelor of Science degree in Geological Engineering from there in June, 1967. In September, 1967 he entered The University of Texas at Austin (UT) and received a Master of Arts degree in Geology from that institution in January, 1970. He entered on active duty in the U. S. Army in February, 1970 and received an honorable discharge with the rank of Captain in April, 1972. He then commenced study for the Ph.D. at UT and completed the degree in 1976.

After receiving the Ph.D., Dr. Grimshaw worked for many years in the area of environmental protection and cleanup, both in technical services (geology, groundwater hydrology, environmental geology) and in project and organization management. During this timeframe, he managed projects and organizations for several of the foremost environmental consulting firms in the U.S., including Radian, International Technology, Shaw, and RMT.

During his years with environmental consulting firms, Dr. Grimshaw extended his organization and project management interests into profit center management, systems development and implementation, program development (securing projects from clients), organization development, and international consulting. He also served as Associate Director for Environmental Programs at the Bureau of Economic Geology, the Texas state geological survey and second largest research unit at The University of Texas at Austin.

In recent years, Dr. Grimshaw shifted his career from environmental protection, compliance, and cleanup services to energy policy formulation and analysis. In this transition he changed his affiliations from major environmental service organizations to university-based energy policy entities – the LBJ School of Public Affairs, the Energy Institute, and the Center for International Energy and Environmental Policy, all at UT. This transition began with a masters degree at the LBJ School and continued with adjunct faculty and research fellow assignments at the LBJ School and other UT organizations.

Dr. Grimshaw developed an interest in cold fusion in about 2005 with preparation of an LBJ School Conference Course paper, which later evolved – with additional research – into a Professional Report on energy policy approaches to cold fusion development. He is currently managing and performing several projects for a major corporate client on various aspects of cold fusion phenomena.

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