A

Technical Guidance Document and Program Proposal to Assess

THE WATER RESOURCES POTENTIAL OF THE DAKOTA AQUIFER IN KANSAS
A Long Term Multi-Agency Research Program

Submitted by

The Kansas Geological Survey
University of Kansas

Kansas Geological Survey
Open-file Report

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

The Dakota aquifer system is an integral part of future water-resources planning for western and south-central Kansas. It is the second most extensive aquifer in Kansas after the High Plains aquifer (Ogallala and associated alluvial aquifers). In the near future, severe depletion of the Ogallala aquifer due to overdevelopment, will cause a critical water shortage in western and northwestern Kansas. The Dakota aquifer will be the next available source of water for this region. Preliminary work by the Kansas Geological Survey, funded by a grant from the Kansas Corporation Commission, has shown that fresh and usable waters are present locally in the Dakota aquifer of northwest Kansas. At present, however, insufficient information concerning the quantity and quality of Dakota waters limits the ability of State water planners to evaluate this aquifer as a future major source of water for this region. Equally important, it is crucial to assess the potential effects of development in advance in order to avoid depletions similar to those being experienced in the Ogallala. A significant research effort is needed to develop a sound technical basis on which future water-management and planning efforts can depend.

Responding to this need, the Kansas Geological Survey is proposing to conduct a comprehensive multi-phased, multi-agency study of the Dakota aquifer system in Kansas. The proposed objectives of the Program are: (1) to develop a usable and detailed geologic framework of the Dakota aquifer and related rocks that extends from the outcrop areas in central Kansas to the Colorado and Nebraska state lines; (2) to develop a better understanding of the structural configuration of the aquifer; (3) to characterize water availability, the movement of ground water and the variation of water chemistry within the Dakota aquifer system on a regional and subregional basis; and (4) to assess the effects of various water management scenarios on the performance of the Dakota aquifer using three-dimensional mathematical simulations (ground-water models). With the completion of objectives 1, 2, and 3, addressing policy concerns and water-management plans (4) for this complex aquifer system will be possible. In an effort to deal with inter-state problems concerning the Dakota, the KGS will contact water planners and managers in adjoining states in order to address concerns dealing with joint areas.

The Dakota aquifer system has the potential for providing new or supplemental water supplies to meet current and future municipal, agricultural, and industrial demands in much of western Kansas. The major water-resource issues that concern the Dakota relate to (1) the quantity and quality of available ground water; (2) the degree of natural saltwater contamination from underlying units; (3) the potential for degradation of water quality due to shallow disposal of oil-field brines in zones beneath the Dakota; and (4) the effect of saline-water discharge on surface-water quality in central Kansas. The suitability of the Dakota aquifer for future water supplies will depend on currently unknown water-quality characteristics in much of the area and on defining hydraulically connected parts of the overall hydrologic system.

Addressing the future water-related issues involving the Dakota aquifer will require an integrated, detailed study of the geologic units, the flow of water through the system, and the variation of water quality throughout the unit. The proposed study will be conducted in several phases over a period of 14 years. The Kansas Geological Survey is willing to commit a considerable portion of its resources to ensure the successful completion of this research program. Attached to this document is a preliminary budget summarizing the resources that will be committed to this program by both the KGS and the U.S. Geological Survey. In addition, the budget stresses the need for the funding requested from the legislature in order to complete the program in a timely manner.

The first year of the Program will characterize water availability, movement, and quality in this aquifer system; create several Program water-related data bases; develop new cost-effective field techniques for acquiring information about the geologic framework in areas of sparse data coverage; and update the technical document to reflect any changes in approach or priorities that may arise as a result of the first year's work. The function of the technical document is to provide a structure for the Dakota Program that will be modified and updated to reflect the needs of those involved in the research and the Water Steering Committee.

As part of the work plan, the geographic extent of the Dakota aquifer system will be divided into subareas that will serve as the basis of future programs. The subarea projects will be conducted during years 2 through 10 of the Program. Each subarea project will address the basic questions of the geology, hydrology, water quantity, and water quality of the Dakota aquifer. After completion of all the subarea projects (years 11 through 14), the results will be combined and used to address water-management concerns on a Statewide basis.

Reports and maps will be completed at the end of each individual research effort. Project reports on the subareas of study will describe the hydrogeology and water chemistry of each part of the Dakota aquifer system in Kansas. Other reports will deal with regional geology, stratigraphy, and other aspects of the research that are not fully addressed in the project subarea reports. Short yearly summaries will present the progress made on individual research projects and any significant findings. Use of this information will permit delineation of regions of the State where usable water supplies are available in the Dakota. It is expected that these documents will aid in defining future research areas on the aquifer system and will update the technical document.

Where appropriate, project results will be added to the Kansas Water Data base. Copies of geologic data bases will be made available in paper and electronic form as needed. A final report summarizing the results of subarea-research projects will be prepared and used to assess the impacts of future water-management decisions on the Dakota aquifer system. Additionally, provision will be made to address the short-term needs of water planners and managers that might be outside the research topics of the particular subarea being investigated at the moment.

Kansas Geological Survey takes the responsibility as the lead agency for conducting and managing this long-term research program and will coordinate its efforts with other Federal, State, and local water-related agencies, where appropriate. This is in accordance with the August 3, 1987, Memorandum of Understanding related to the Dakota aquifer study between KGS and the Kansas State Board of Agriculture, Kansas Water Office, Kansas Department of Health and Environment, U.S. Geological Survey, the Groundwater Management Districts, and the Kansas Corporation Commission. KGS shall annually seek advice and recommendations from the Interagency Water Steering Committee on matters that relate to the conduct of this program and will make every attempt to incorporate the Committee's comments into the project work plans to be developed during the course of the Program. The members of the Interagency Water Steering Committee are the Director (Division of Information Systems and Communications), Director (Kansas Biological Survey), Chairman (Kansas Corporation Commission), Secretary (Kansas Department of Wildlife and Parks), Director (Kansas Geological Survey), Director (Kansas Water Office), Secretary (State Board of Agriculture), Director (State Conservation Commission), and the Secretary (Kansas Department of Health and Environment).

1.0 Introduction

This document has been created to serve two purposes. First of all, this is a proposal for research of the Dakota aquifer based on present perceptions. It is anticipated that as this program progresses, these perceptions will be modified as more is learned about this very complex aquifer system. Considerable time is spent broadly sketching what is presently known of the water resources potential of the Dakota aquifer; the historical background that has emphasized the need for a study of the Dakota (Appendices A and B; and Section 1.3); and the purpose and objectives of this long-term research program that will be conducted and managed by the Kansas Geological Survey. Highlighted in this part are the institutional arrangements that will be activated during the Program. Secondly, this is a technical document that outlines the methodologies that, at least initially, appear to be useful tools in trying to answer some of the immediate scientific and planning questions (Chapter 2.0). It is expected that these tools may have to be modified based on more detailed examination of the nature of the problems to be solved.

The Kansas Geological Survey has prepared this program plan based on many thoughtful discussions that have been held with the KGS staff and the Dakota Interagency Coordinating Committee, a group composed of representatives of Federal, State, and local water agencies. These discussions have been extremely helpful in focusing our efforts to identify issues that this program must address. Many hours of effort have gone into the review of this document by members of the Committee and by KGS Staff. Their suggestions and comments have improved and strengthened this document and the overall content of the Program.

1.1 Water Supply Potential of the Dakota Aquifer in Kansas

The Dakota aquifer system is considered crucial in the water resources planning for western and south-central Kansas by all of the water-related State agencies and groundwater management districts in Kansas. In the near future, a critical need for water will occur in those areas where the depletion of the High Plains aquifer is most severe (Appendix A). This will certainly affect the future economic well-being of much of western Kansas. As a result, a preliminary draft of the Kansas Water Plan calls for a statewide study of the Dakota aquifer for water availability. The Dakota aquifer appears to have the potential for providing new or supplemental water supplies that meet current and future municipal, agricultural, and industrial demands in much of western Kansas. East of the High Plains, the Dakota may provide supplemental water supplies of variable quality to growing municipalities where demand exceeds the supply available.

The Dakota aquifer is the second most geographically extensive aquifer system in the State. Recent estimates by Crook (1975) and Helgeson et al. (in review) indicate that the total amount of recoverable water from the Dakota aquifer statewide, irrespective of quality, ranges from approximately 500 to 750 million acre-ft. Keene and Bayne (1977) have estimated that 70 to 80 million acre-feet of water containing less than 1000 mg/l total dissolved solids and an additional 10 to 15 million acre-feet of water containing 1000 to 3000 mg/l can be obtained from this aquifer in the State.

At present, the Dakota aquifer is already an important source of water in southwestern and south-central Kansas, especially where adequate supplies are not available from overlying stream/aquifer systems or the High Plains aquifer. The Dakota is used to a moderate extent for irrigation, municipal and industrial use in Hodgeman, Ford, Finney, Kearny, Gray, Ness, Edwards, Pawnee, Barton and Rush Counties. Irrigation water use for 1985-86 was approximately 11,400 acre-ft/year. Municipal, domestic, and stock use amounted to less than 400 acre-ft/year during the same period. Well yields range from less than 30 to more than 2000 gallons/minute (GPM) in southwest and west-central Kansas. Well yields from the Dakota are generally higher in southwest Kansas where the Dakota is hydraulically connected to the overlying High Plains aquifer. However, well yields in Hodgemen and northern Ford Counties frequently exceed 700 GPM even though the High Plains aquifer is not present in these areas. No well-yield information is available for northwest Kansas.

The Dakota aquifer consists of rocks of Lower Cretaceous age that belong to the Dakota Formation. Figure 1 shows the relationship of the Dakota Formation to other adjacent Lower Cretaceous rock units in Kansas and the distribution of lithologies in schematic form. These rocks crop out in a broad band from near northeastern Washington County to central Rice County and consist of interbedded shales and sandstones. Figure 2 shows the approximate geographic extent of the Dakota aquifer in Kansas, which generally coincides with that of the Lower Cretaceous rocks. Statewide, these rocks consist of approximately 70% relatively impermeable siltstone and

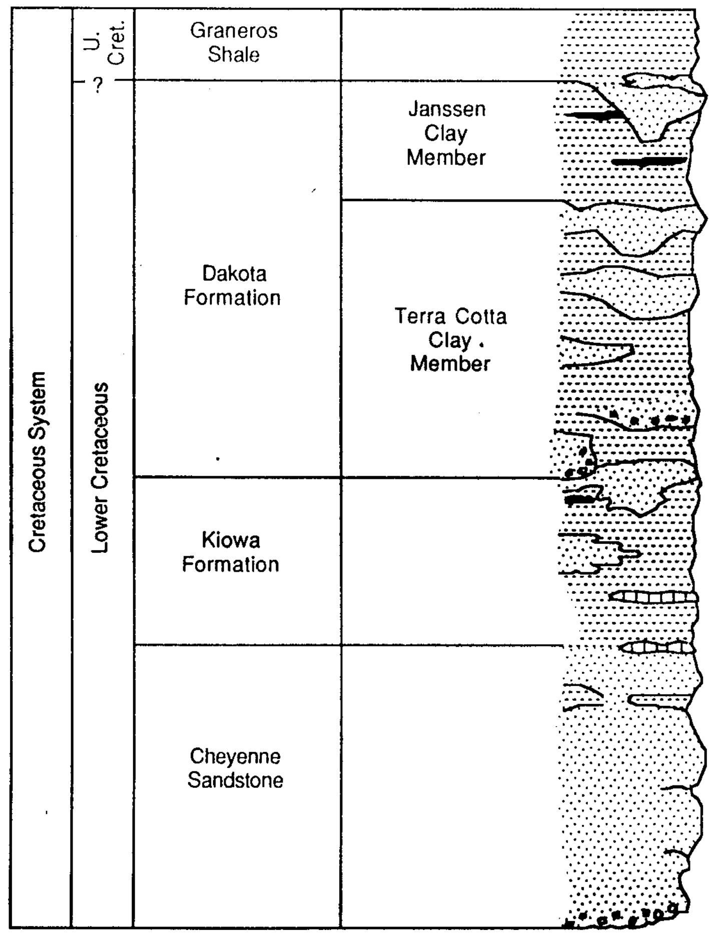

Figure 1. Stratigraphic column of the Lower Cretaceous rocks in Kansas, including the Graneros Shale. Modified from Zeller(1968).

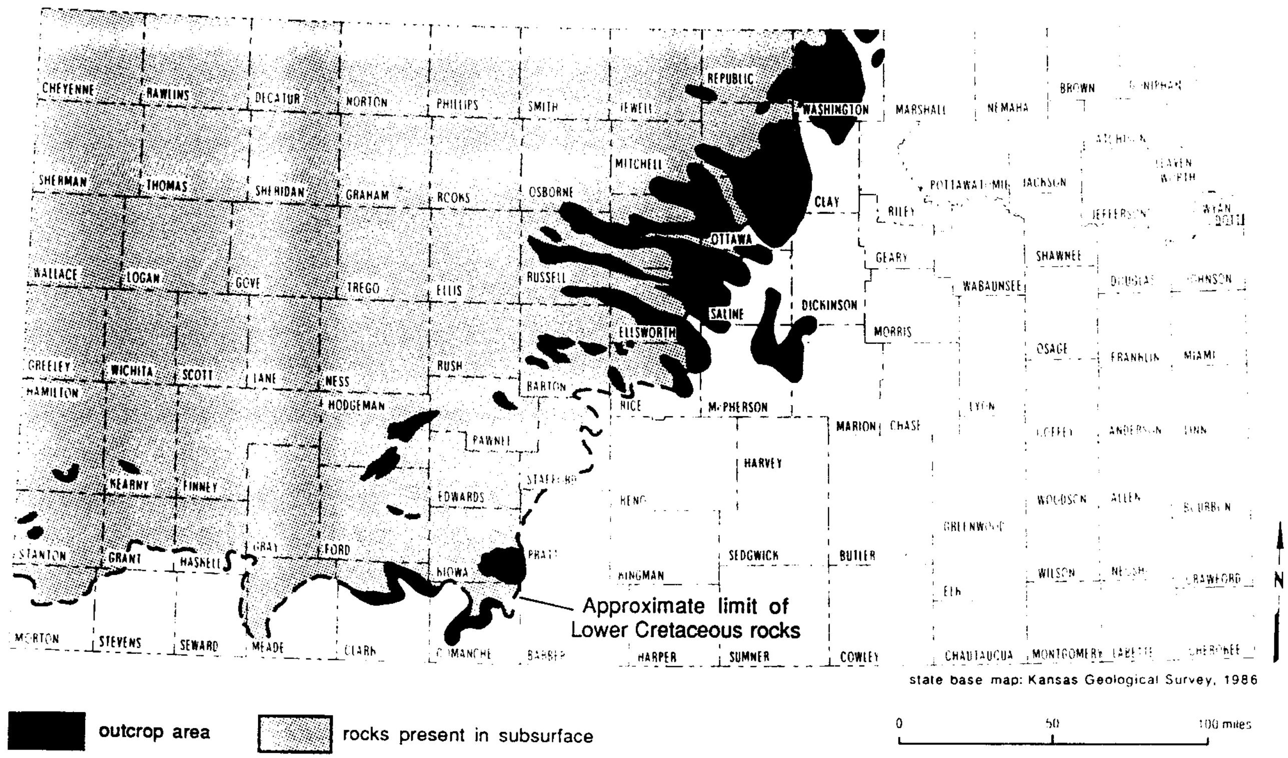

Figure 2. Geographic extent of the Lower Cretaceous bedrock aquifers in Kansas.

claystone and 30% permeable sandstone. The sandstones are thin bedded to massive and occur as irregular lenses that differ in thickness and areal extent. The ability of the sandstone beds to yield water depends largely on the areal extent, thickness, and interconnection of the sandstone beds, and on the grain size and cementation of the sand. The total thickness of the Dakota formation ranges from less than 150 ft. in north-central Kansas to more than 300 ft. in western and southern portions of the State.

These sandstone lenses were deposited as point bars and littoral deposits by westward-flowing streams, and as off-shore sand bars by currents under shallow marine conditions during the early part of the Cretaceous Period (approximately 100-110 million years ago). Due to the nature of the geologic agents that deposited these sandstone bodies their spatial distribution is extremely irregular. As a result, it is difficult to predict their occurrence without systematic study of the depositional environments represented in these rocks.

Two other Lower Cretaceous rock units underlie the Dakota Formation over much of the State. The Cheyenne Sandstone is the oldest and lowermost Lower Cretaceous rock unit in Kansas. This unit consists of interbedded sandstones and shales and is known to contain sodium-chloride brines. The Cheyenne Sandstone was used as a saltwater disposal zone by the oil industry in central Kansas until the 1970's (Don Butcher, personal communication, 1987). Above the Cheyenne and below the Dakota is the Kiowa Formation which is made up of shales and siltstones with some scattered lenses of sandstone.

This unit is generally considered to be a confining unit separating the bedrock aquifers in the Dakota from those in the Cheyenne Sandstone. The thickness of the Kiowa Formation varies widely across the State but the geologic unit is generally thickest in southern and southwestern Kansas and thinnest in the north-central part of the State where it is absent in some places.

1.2 Purpose of the Research Program

In response to a request from the Interagency Water Steering Committee, the Kansas Geological Survey is proposing to manage and conduct a comprehensive multi-phased, multi-agency study of the Dakota aquifer in Kansas. The purpose of this long-term research program is to evaluate the water resources potential of the Dakota aquifer system in Kansas, including an assessment of the impacts associated with various management plans. Comprehensive study of the Dakota aquifer will require a thorough and detailed definition of: structural geology, stratigraphy, flow properties, water quality, interactions with other aquifers and surface waters, and flow regimes on the local and regional levels. In this program the level of detail must be sufficient to be able to predict three-dimensionally the movement of water and the variations of water quality in fairly small geographic areas (approximately 50-100 square miles or less in some areas). At this scale, the characterization of the aquifer can provide enough useful data to evaluate in a meaningful manner the potential of locating usable waters and the consequences of applying various water-management plans.

1.3 Water Resources Research Needs Related to the Dakota Aquifer

At the present time a usable geologic framework for the Lower Cretaceous rocks in the subsurface of Kansas west of the outcrop does not exist. This has resulted because no attempt has been made to update and refine Merriam's (1957) publication of selected cross-sectional views of the geology of the Mesozoic-age rocks in Kansas. Since then, new data, new interpretations of the surface exposures, and new geologic techniques have been developed that will aid in the interpretation of the Lower Cretaceous rocks in the subsurface.

A review of previous work indicates that, historically, problems of nomenclature, stratigraphy, and interpretation of the depositional environments represented by the Cheyenne, Kiowa, and Dakota formations have minimized our ability to understand the geologic framework of the Lower Cretaceous rocks in the Great Plains (For a brief summary of previous work see Appendix B). Similar arguments apply to the discrimination of the other Lower Cretaceous units. Misinterpretation and confusion have also resulted from attempts to extend formational boundaries into the subsurface of Kansas beyond the outcrop without a good understanding of the depositional framework. Typically, formation tops are picked from either wireline logs or drill cuttings. However, since the petrophysical properties measured by the logging tools are not necessarily the lithologic attributes that define formational boundaries where the units are exposed in the outcrop, miscorrelation of formations frequently occurs. These are problems that can only be addresed by finding time lines and working out the lithofacies relationships within the Lower Cretaceous and then defining formational boundaries in a rational way.

A thorough understanding of the geologic framework is necessary in order to: (1) predict water availability, the flow of water and dissolved constituents in the Dakota aquifer; (2) identify areas where the Dakota aquifer is hydraulically connected with other adjacent aquifers; (3) map the depth to the top of the Dakota from the land surface; and (4) develop an understanding of the evolution of the ground-water basin.

The primary paths of water transmission through the Dakota are the sandy portions of the aquifer and the fracture systems. As a result it is important to be able to predict the distribution of the major sandstone-bearing zones within the Dakota and to locate the major fracture systems. These paths of water movement control the ability of the aquifer to release water to wells. Ground-water availability to wells will be much higher in the sandy portions of the aquifer than in the unfractured siltstone and claystone portions.

The hydraulic properties and boundary effects, such as, the size, shape, and degree of interconnection of the sandstone-bearing zones, will have an impact on the local performance of the aquifer during pumping. Drawdown in pumping wells will be directly related to the position of the flow system boundaries with respect to the well. The efficiency of the pump will decrease and the unit cost of the water to the user may increase substantially in wells located near no-flow boundaries or zones of lower permeability.

At the present time the hydraulic properties of the Dakota aquifer are largely unknown outside of a few areas in southwestern Kansas where pump tests of large-yielding wells have been conducted. The distribution of these properties is important because they affect the ground-water flow on a sub-regional and local level. Generalized regional flow directions on a multi-state basis using limited data have been presented by Helgeson et al. (in review). However, the usefulness of their potentiometric surface map is limited. For example, Swineford and Williams (1945) and, more recently, Macfarlane, Townsend, and Whittemore (in progress) have shown that the distribution of water quality and the flow directions are highly variable vertically and horizontally. In another study, Leonard and Berry (1961) have shown that different lenses of sandstone within the Dakota aquifer may have significantly different hydraulic head values depending on the degree of interconnection of the sandstones even within very small geographic areas. In light of these findings the use of two dimensional map views of the Lower Cretaceous bedrock aquifers in computer simulations of the hydrology may be inappropriate even on a regional scale. Clearly, the authors have not been able to address the three-dimensional nature of flow and chemical quality in the Dakota and other interconnecting aquifer systems.

The depth to the top of the Dakota aquifer is an important factor in determining its viability as a water supply. This parameter determines the depth to which water supply wells must be drilled before penetrating water-producing zones within the aquifer, and, thus the cost of well construction. The depth also has some bearing on the size and kinds of pumps that can be used to withdraw water from the well. The depth of the aquifer beneath the land surface and its variability will be of interest to those Kansans living in the northwest and western parts of the State where the thickness of overlying sediments above the Dakota aquifer is greatest.

Finally, a good understanding of the geologic framework is important to the interpretation of the present-day hydrology and water quality in the context of the evolution of the ground-water system. Geologic processes involving uplift, erosion, and deposition cause major changes in the regional flow of ground water and water chemistry. From the regional studies of Belitz (1985) and Helgeson et al. (in review) it is postulated that the tectonic development of the Denver basin has affected the rate of recharge to the aquifer systems within the Basin. This has caused incomplete flushing of original formation water from the Dakota, in particular. The authors did not investigate the effect of basinal development on the flow system in their study due to insufficient data. The role of these processes and their effects eastward of the Denver Basin needs to be examined in order to understand the evolution of the present-day flow system and the variability of ground-water chemical quality.

Knowledge of water quality within the Dakota Formation is limited due to the large areal extent of this unit in western Kansas and in part to the rather poor geographic distribution of analyses for water samples from wells penetrating this aquifer. Discrepancies are evident in regional assignments of various water-type classifications within the Dakota Formation in Kansas (Keene and Bayne, 1977; Lobmeyer and Weakly, 1979; Kume and Spinazola, 1985; and Leonard et al., 1983). In part these discrepancies may be the product of non-uniformity in the sampling, handling, and preservation procedures employed in the collection of water samples that later were used to establish chemical quality data considered to be representative of water in the Dakota aquifer.

Other problems exist in the usage of "in place" wells to obtain water samples from the Dakota aquifer. Such wells often have long screened intervals designed to maximize yield. The water chemistry from samples collected from these wells represents a composite of all the water-bearing zones contributing to the well. Thus, these regional sampling programs do not provide direct information regarding changes in water quality vertically within the aquifer at various locations within the system. Another uncertainty in regional sampling of existing wells is the question of integrity of the well casing and assurance that water is not being conducted downward from the surface or near surface to the well screen.

Macfarlane and Townsend collected water samples during the summer of 1987 at a site north of Hays, Kansas in which observation wells had been completed at various depths in the Cretaceous rocks. They also carried out a sampling of existing wells in the north-central Kansas area which were believed to be producing water from the Dakota aquifer. Preliminary results of this work indicate a vertical variation in water quality in the Cretaceous rocks at the

Hays site and the possible influx of surficial water into several of the wells sampled in the regional study. The presence of hydrogen-sulfide in some of the samples suggests that reducing environments may exist in portions of the Dakota aquifer system in Kansas.

In order to evaluate spatial variability within the Dakota aquifer in Kansas, it would be desirable to establish a set or nest of multiple completion monitoring wells in the Dakota Formation along selected traverse lines. Data from these monitoring sites could be combined with those obtained in regional sampling programs of existing wells to evaluate the regional quality and potential use of ground water in this system. In addition to major constituent analyses, determination of other selected elements such as bromine, iodine, boron, lithium, and the stable isotopes of hydrogen, oxygen, and sulfur may shed light on the origin and movement of water in the aquifer system. Constituents such as ammonium ion, hydrogen sulfide, and dissolved iron and manganese should be monitored to evaluate regional variations in the oxidation-reduction character of the hydrogeochemical system and point to potential water quality problems arising from the presence of undesirable trace elements.

The quality of water available in the Dakota aquifer system ultimately determines its value for various uses. The chemical quality of the ground water should be assessed with respect to current quality standards for different uses in order to protect the present state of the aquifer and to project its potential value given improvements in water treatment.

No comprehensive use assessment of water quality in the Dakota aquifer system has been made, largely because there is little available data on the chemical characteristics necessary for such an evaluation. Although the salinity of the water is the major factor in a use assessment, there are several other constituents and properties that must be considered. The quantity of data on minor constituents and properties, such as trace metals and radioactivity, for which standards exist is much less than that for major constituents.

Primary standards for major and minor constituents exist in order to protect "good" quality drinking water. To ensure the quality of Dakota water all of the necessary major and minor constituents should be determined. The mineralogy and chemical environment of certain portions of the Dakota system are such that the maximum contaminant levels for some of these constituents might be exceeded. For instance, small amounts of uranium-bearing minerals are known to occur in fluvial channel deposits of the Lower Cretaceous Series. Decay of the radioactive isotopes of uranium could lead to waters exceeding the radioactivity standards for drinking purposes. Fluoride concentrations commonly exceed 2 mg/L and can be as high as 7 mg/L in waters currently pumped from the Dakota (Lobmeyer and Weakly, 1979; Kume and Spinazola, 1985; Townsend, personal communication). In comparison, drinking water standards are 1.8 to 2.0 mg/L fluoride for waters with a similar range of temperature. The high fluoride values occur in parts of the aquifer where ion exchange has decreased the concentration of dissolved calcium to low levels, probably allowing the dissolution of small amounts of the mineral fluorite and fluorapatite. High concentrations of arsenic and selenium may also exist in local portions of the aquifer strata. This could occur where minerals containing higher contents of these elements are found in conjunction with changes in water chemistry in alluvial sediments deposited in oxidizing conditions in contact with those deposited in reducing environments.

High concentrations of other minor and trace constituents that may be present could be undesirable for agricultural uses, such as irrigation and livestock watering, and various industrial purposes. Waters for agriculture and industry generally must meet fewer standards than for human consumption, although some standards for particular uses may be more stringent.

Understanding the geochemical controls on water quality in the Dakota aquifer is needed to improve the search for sources of fresh water within the system, guide the construction and operation of wells to reduce plugging problems, and assess the effects of freshwater withdrawals and brine introduction on water quality and aquifer permeability. The primary factor in geochemical controls on water quality is water-rock interaction within the Dakota aquifer and between the Dakota and adjoining units. Determination of the spacial distribution of water types in conjunction with local stratigraphy should aid in determining the chemical equilibria controlling water quality during mixing of different water types. This in turn will aid in predicting possible adverse effects on the Dakota aquifer.

Exploration for usable water within undeveloped portions of the Dakota aquifer system requires stratigraphic, hydrogeologic, and geochemical information. Predictions of water quality in areas without chemical information and based solely on extrapolation of concentration contours from existing data will probably be inaccurate in many cases. A geochemical understanding of the water-rock interactions could improve predictions of spatial changes in water quality.

Variation in water chemistry between units is also an important consideration in assessing the effects on wells caused by mixing waters during pumping. Precipitation of calcium carbonate or iron oxyhydroxides caused by mixing of waters of different chemistry can plug a well screen or reduce the permeability of the aquifer. Problems related to mixing due to pumping stresses on the aquifer could be reduced by considering appropriate hydrogeological and geochemical data during the construction and operation of the well. Corrosion is another problem related to the interaction of well materials with varying water chemistries. The design of and materials selection for wells can reduce corrosion problems if the applicable geochemical data are available and used.

Pumping withdrawals can cause introduction of waters from other portions of an aquifer or adjacent strata into the zone being pumped. In areas where stream-aquifer interactions are substantial, surface waters could be drawn into the subsurface. If the units from which waters are mixed have appreciably different water chemistry, degradation of water quality could result. Differences in the pH, oxidation potential, and dissolved gas concentrations between introduced and native ground waters can cause water-mineral reactions that significantly change ground-water chemistries. Ion exchange can alter the dissolved constituent concentrations of waters passing from one strata to another. Drinking water standards exist for many of the constituents that could be affected by changes in the water-mineral equilibria in Dakota rocks, including fluoride, arsenic, selenium, barium, iron, and manganese. A knowledge of these potential problems could be used in well construction and operation to minimize adverse effects or to forecast possible water-quality changes needing treatment.

Use, management, and protection of ground-water resources in the Dakota aquifer system require a knowledge of the quantity and quality of waters recharged to and discharged from the system. Geochemical methods are used to identify recharge types and sources, to locate discharge areas, and to determine the effects of recharge on the aquifer water quality and the effects of discharge on the quality of overlying ground and surface waters. Such studies also help in the hydrologic estimation of recharge and discharge flow rates.

Water quality in the Dakota varies from potable to saline (Keene and Bayne, 1977). Occurrences of highly saline water in the Dakota aquifer and in the overlying surface waters may be caused by upward movement of brines from underlying regional aquifers (Hargadine et al., 1979; Jordan et al., 1964; U.S. Public Health Service, 1949). Figure 3 shows the areal extent of the saltwater intrusion problem in the Dakota aquifer and overlying surface waters in central Kansas.

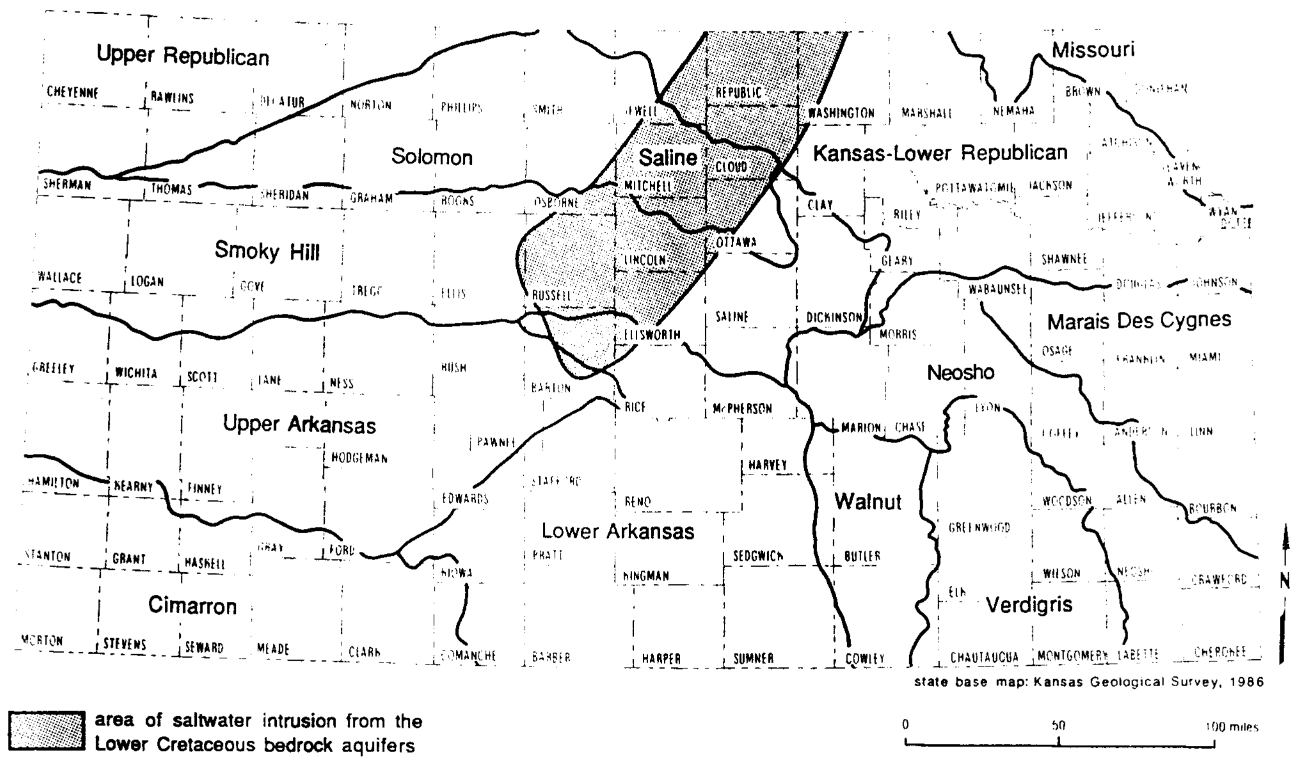

Figure 3. Areas of saltwater intrusion associated with the Dakota and associated Lower Cretaceous aquifers.

Figure 4 is a composite profile of water quality from some test drilling in Russell County. These saline intrusion areas possibly signify the location of ground-water discharge zones of intermediate or regional scale ground-water flow systems (Toth, 1984). The origin of these saline waters may be derived from several sources: cross-formational flow between units, rock/water interactions between the clays in the Dakota and pore waters, relict waters entrapped at the time of deposition, or dissolution of small amounts of evaporites in the strata. Knowledge of the brine source can be used to determine whether cross-formational flow between units is occurring or if brines injected into a lower aquifer are migrating upward. Throughout central Kansas the Permian Cedar Hills Sandstone is being used for brine disposal. Determination of cross-formational flow between the Dakota Formation and the underlying Permian is necessary for predicting the viability of the Dakota aquifer for future water uses.

Research is also needed to address certain water planning and management issues related to the Dakota aquifer. The important water planning and management issues that need to be addressed are questions such as, what are the potential hydrologic impacts of increased ground-water withdrawals on the Dakota and other hydraulically interconnected aquifers, how much water can be withdrawn from the Dakota aquifer without causing severe water quality changes or depletions, what will be the impact of curtailing or diminishing reservoir releases that now are used to maintain acceptable levels of surface water quality in the Kansas River basin,

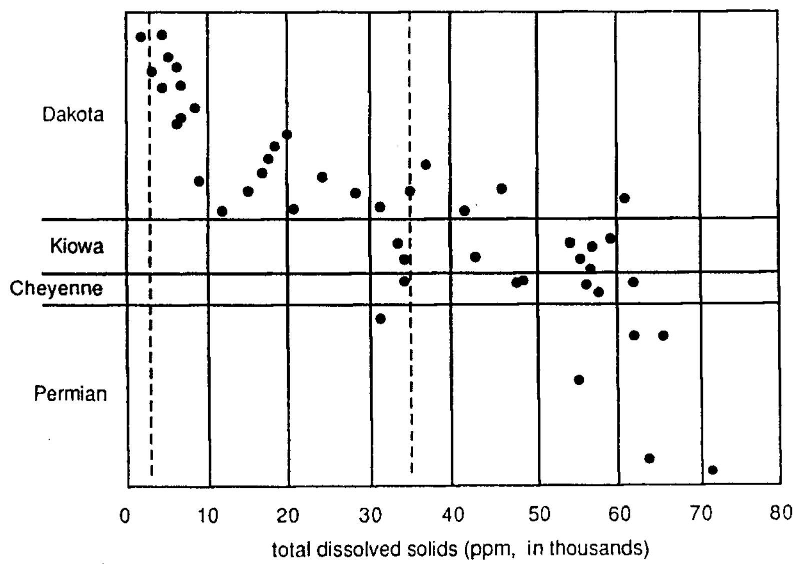

Figure 4. Composite water quality profile of the Lower Cretaceous and Permian bedrock aquifers in Russell County, generalized from test drilling Dashed vertical lines show the 3000 ppm and 35,000 (sea water) ppm concentrations. Modified from Swineford and Williams (1945).

and what are the potential effects of oil-field brine disposal in other subjacent injection zones within the State? These water management questions have heretofore not been addressed in a meaningful way due the lack of data on the Dakota aquifer. One study has been conducted by the U.S. Geological Survey to assess the potential hydrologic impacts of increased water use of the Dakota aquifer in southwest Kansas (Watts, 1985). However, the results of this study should be considered somewhat preliminary since the mathematical simulation of the Dakota, Cheyenne, and High Plains aquifers was supported by limited data on the material properties of the aquifers involved. More recently, the U.S. Geological Survey's CMRASA Program has tried to make some projections on the impact of further use of the Dakota aquifer within a nine state study area that includes Kansas (Helgeson et al., in review). The results of this study though useful are very general and cannot provide sufficient detail about the aquifer system to allow management decisions to be made for smaller subregions with particular problems.

1.4 Objectives of the Research Program

The overall objectives of this Program are:

(1) To develop a usable stratigraphic framework for the Dakota Formation and related Lower Cretaceous rock units in the subsurface of Kansas extending from the outcrop area in the central part of the State to the Colorado and Nebraska state borders. Completion of this objective is necessary in order to begin to understand the distribution of the major rock units and

especially the major sandstone-bearing zones within the Lower Cretaceous. With this information it will be possible to evaluate ground-water availability over the region, the spatial variability of the flow directions, properties and water quality.

(2) To develop a better understanding of the structural configuration of the aquifer in order to locate areas where the the bedrock may be sufficiently fractured to allow significant vertical movement of fluids into or out of the Dakota aquifer and to identify areas where other bedrock aquifer systems may be hydraulically connected with the Dakota or other Lower Cretaceous bedrock aquifers. This will be particularly useful information for identifying recharge and discharge sources and avenues of vertical movement within and between aquifer units. This information will also be useful for determining the depth from land surface to the top of the Dakota aquifer and its thickness.

(3) To develop subregional and regional three-dimensional views of the movement of water within the Dakota aquifer and other Lower Cretaceous bedrock aquifers, paying particular attention to the heterogeneity of the aquifer units involved. Addressing and resolving the water resource issues related to the Dakota aquifer system depends on defining and understanding the system's basic hydrogeology. Consequently, determination of the three-dimensional flow system must be done in order to take into account: (1) the complex nature of water flow and water

chemistry in the Dakota aquifer; (2) the upward movement of saline waters across clay-shale aquitards within the Kiowa Formation; and (3) hydraulic interconnections with saltwater bearing bedrock aquifers in the Permian and with fresher waters in the High Plains and stream/aquifer systems.

(4) To assess the effects of various water management scenarios on the Dakota aquifer in Kansas using three-dimensional flow and mass-transport models. With the completion of an operational three-dimensional flow and mass-transport model it will be possible to address policy concerns and water management plans that may affect the Dakota aquifer. By simulating future development of water resources, management plans focusing on optimal use under a given set of constraints can be formulated to wisely use the waters of the Dakota aquifer for the long-term benefit of the State.

1.5 Multi-Agency Involvement (Federal, State, and Local)

In accordance with the August 3, 1987 memorandum of understanding (MOU) between KGS, the water-related State regulatory and planning agencies, the ground-water management districts, and the U.S. Geological Survey, KGS takes the responsibility as the lead agency for conducting and managing this long-term research program and will work cooperatively with the above mentioned groups. Furthermore, where appropriate KGS will develop with and be a party to cooperative agreements for the conduct of research projects with the U.S. Geological Survey. KGS retains the right to negotiate the schedule and terms of any agreements between KGS and the U.S. Geological Survey. The U.S. Geological Survey will coordinate all proposed research activities that pertain to the Dakota aquifer study with KGS to avoid duplication. KGS shall seek advice and recommendations from the Interagency Water Steering Committee on any matters that relate to the conduct of this program and will make every attempt to incorporate the Committee's comments into the Plan of Study for the Program.

1.6 Expected Results

The results of this program will be the project reports and maps that will be produced from the individual projects undertaken to accomplish the objectives of the Program and the periodically updated data bases that will be available in hard copy or electronic form. Project reports and journal articles will be prepared promptly at the completion of each project and all data bases that were accessed during the project will be updated to reflect the results of the project. It is expected that these reports will be used to guide succeeding research projects in the Dakota aquifer. All subarea project reports will be published by KGS and made available to the public and other Federal, State, and local agencies. Results of projects involving the U.S. Geological Survey, that are not subarea project reports, may also be published by the U.S. Geological Survey. Where appropriate project results will be added to the Kansas Water Data Base and will be used to add to and update a KGS Dakota aquifer data base that will be developed for the purposes of the Program.

1.7 Expected Length of the Program

The expected length of this program is fourteen years assuming continuous funding by the State of Kansas. The exact length of time required to complete the Program will depend on the levels of funding available to do the work.

2.0 Approach and Overall Program Design

2.1 Opening Statement

A comprehensive study of the Dakota and other Lower Cretaceous bedrock aquifers will require definition of the geologic framework, petrophysical and hydraulic properties of the porous media, flow regimes, interactions with other aquifers and surface waters, and water quality. The distribution of these parameters must be known vertically as well as laterally on the regional and subregional level. Fulfillment of these needs is necessary because the aquifers are complex geologically. This complexity impacts directly the flow of ground waters in these aquifer systems and, as a result, the distribution of water quality.

A review of previous hydrogeologic investigations shows that the ability to interpret this complexity has been hampered historically by oversimplified and frequently erroneous views of the nature of the geologic framework. Previous projects have been conducted in these Lower Cretaceous bedrock aquifers without taking into account the fully three-dimensional nature of the movement of ground waters and dissolved constituents within and between the discontinuous lenses of sandstones in these rocks. In this program the need for predictability of the aquifer characteristics, fluid flows, and water quality can only be effectively met by adopting an integrated program of geologic and hydrologic study of these aquifers. The important point is that predictability is the essence of this study. We must be able predict the behavior of the aquifer system if we are to manage and plan for the rational use of this resource in the future.

KGS will be working closely with other Federal, State and local water-related agencies to design and complete this program in a timely manner. However, at the outset it should be made clear that such a program is of necessity a long-term effort requiring careful documentation and investigation of an extensive and complex system. Certain elements will require attention throughout the duration of the project, including such items as acquisition and monitoring of observation well sites, "piggyback" borehole geophysical logging, and incorporation of project results into computer simulations of the movement of water and constituents in the Lower Cretaceous aquifers. Shorter term studies within the framework of the overall program will provide results pertaining to particular regions or areas of pressing concern. The long and the short-term aspects of the program should be mutually supportive and jointly contribute to a comprehensive evaluation of the entire system.

The goal of the first year project in the Dakota Program is to develop a research plan that fulfills the information needs of State water-resources managers and planners. In order to accomplish this goal, it is necessary to characterize ground-water quality, movement, and availability in the Dakota aquifer of western Kansas. As part of this effort, it is also desirable to evaluate the methods and concepts used in previous investigations of this complex aquifer system. To assist in this statewide characterization, new data bases will be developed from the data collected by Federal, State and local agencies. This characterization and evaluation process will allow an assessment to be made of the status of research on the Dakota aquifer. The concerns of the various State and local water agencies will be actively solicited and used to help define the information needed to make future decisions dealing with water in the Dakota aquifer. At the end of the first year, the results of the characterization and evaluation, together with the definition of information need, will provide a basis for developing future research projects in the Dakota Program and for updating this technical guidance document.

As part of the development of the work plan, the geographic extent of the Dakota aquifer system will be subdivided into subareas that will be studied sequentially to determine the geologic framework, hydrology and water chemistry. Figure 5 shows one possible arrangement of subareas. The order of study of the hydrogeology of these subareas will be established according to priority needs or by the existence of current programs. Ultimately, results from all subarea projects will be combined into an overall aquifer system evaluation. Each subarea project is expected to last approximately two to three years time depending on the amount of information available, the size of the subarea, and the level of funding.

Finally, attention will be paid to developing methods of transferring the concepts and information derived from the study to the various user groups in a timely manner. As part of the reporting process, water-related information will be used to update the Kansas Water Data Base at the completion of each project. Prior to the beginning of each project a schedule of the tasks to be completed and

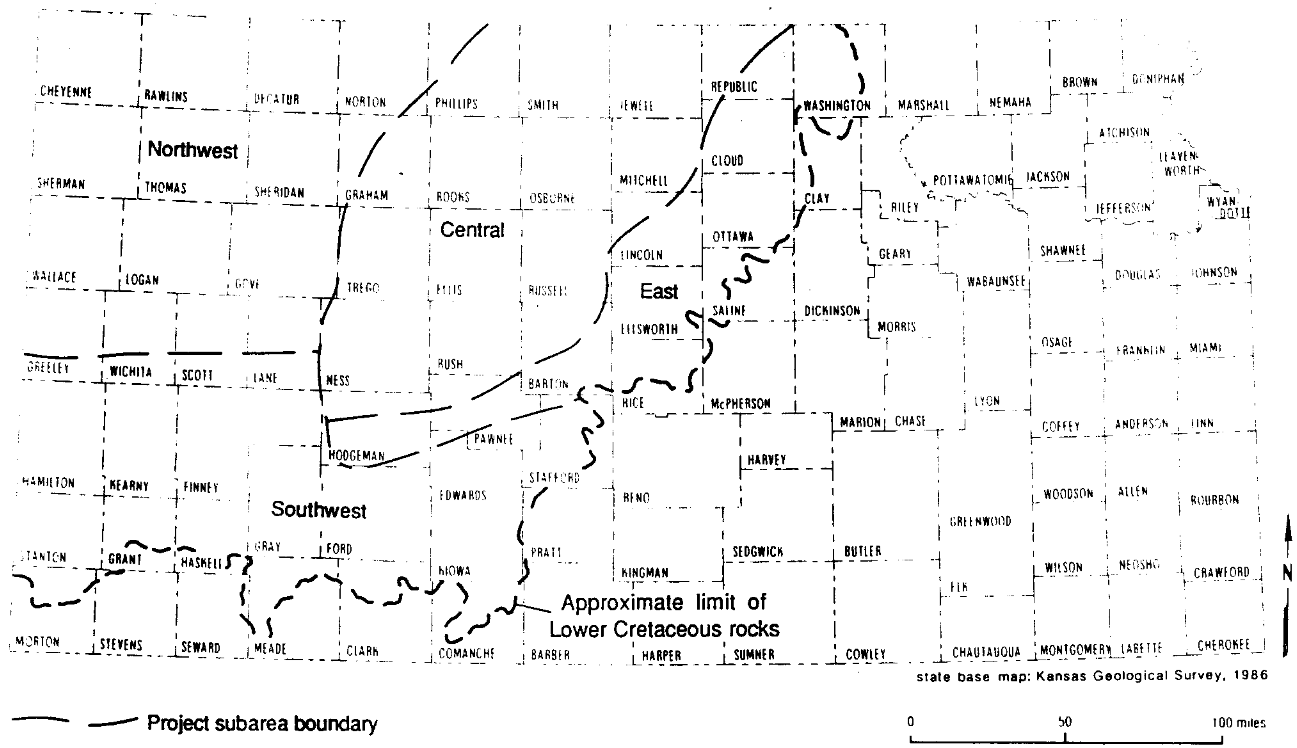

Figure 5. One possible arrangement of project subareas.

the costs will be developed. This will provide KGS and other State agencies with the technical background, estimates of the costs to be engendered, information on specific interagency coordination needs, and a timetable.

The following subsections of this proposal describe in detail the methodologies that will be used to study the Dakota aquifer. Figure 6 is a listing of the major Program elements in generalized form that will be undertaken and a proposed timetable for their accomplishment.

2.2 Methodology

2.2.1 Database Development

Geologic and hydrologic databases will be developed and organized into a database management system with geographic information system (GIS) capabilities. In this format the data will be more useful to the various research efforts in the Lower Cretaceous of western Kansas and will facilitate transfer of information and results to the various user groups outside the research community.

The geologic information to be input in a database form is expected to be diverse. Sources will include but, but not be limited to, formation tops from petroleum industry scout cards, wireline and driller's logs, and logs produced from an examination of drill cuttings, seismic data, and maps of surface geology and interpreted remote sensing data. The data will be used to produce structure contour, isopach, and lithofacies maps, cross-sections, and data

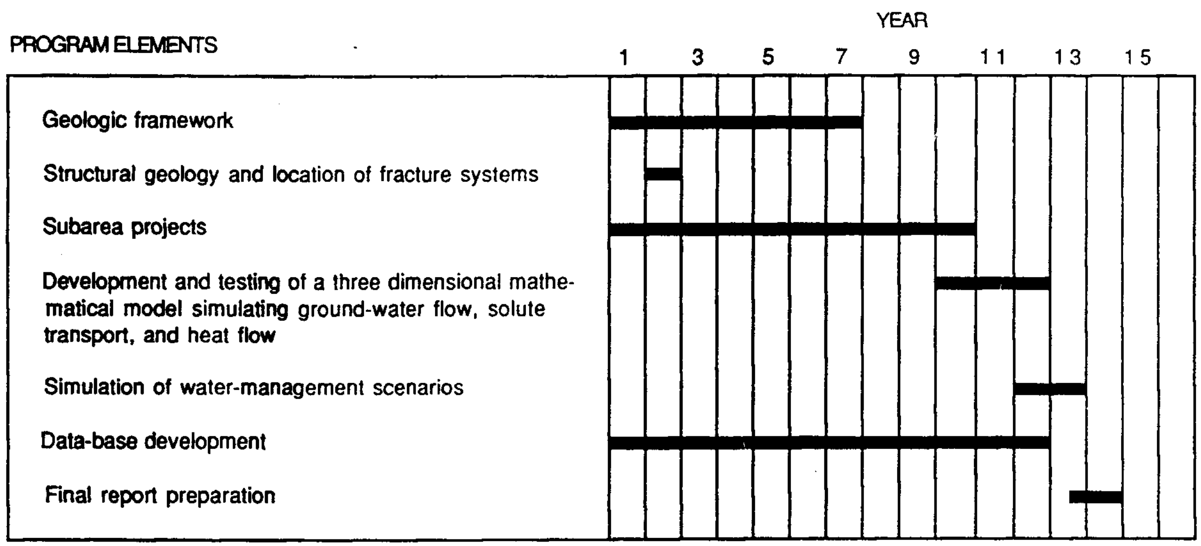

Figure 6. Timing of the major elements of the Dakota aquifer Program.

summaries in tabulated form. Each database will be updated and modified as new information becomes available during the Program.

A wireline (borehole geophysical) log database will be developed primarily to establish the regional stratigraphic framework of the Lower Cretaceous and adjacent rock units. It is expected that the most common logs that will be available are gamma-ray, resistivity, and porosity (either neutron, sonic, or density) logs. These logs will be digitized from paper copy or input directly into computer storage if already in digital form on tape. In this form the data can be used to estimate petrophysical properties and to perform lithofacies analysis or three-dimensional geologic modeling of properties described below.

As the Dakota Program proceeds, it is anticipated that there will be opportunities, when oil companies are drilling in areas of interest to the Program, for KGS to "piggyback" well-logging runs of specialized suites of tools. Under this option KGS will request the drilling company to suspend drilling operations long enough to allow a private company to log zones of interest in the shallow part of the hole being drilled. KGS will reimburse the driller for any costs associated with the "piggyback" operation. This will allow important information to be gathered for the Program that might otherwise be unavailable.

The hydrologic data base will also, of necessity, be diverse and will include, but not be limited to, well information pertaining to location, construction, water levels, and chemical quality, results of pump tests or other hydrologic testing, stream flow, pertinent geologic information, and water use data. During the life of the Program the database will be used to produce maps and cross-sections of potentiometric surfaces of the confined aquifers, water-table configuration of the shallow unconfined aquifers, variations in concentration of selected constituents, and geochemical facies mapping.

2.2.2 Geologic Framework

2.2.2.1 Stratigraphic Boundaries, Depositional Systems and Lithofacies

In order to understand the flow of water through the Lower Cretaceous bedrock aquifers it is necessary that there exists a thorough understanding of the geologic framework. This is a consequence of the variability of the geologic processes responsible for the deposition of these units in marine and non-marine environments. To accomplish this, the stratigraphic boundaries between formations must be extended from the outcrop into the subsurface of western Kansas to define the relationship between the geologic units. Additionally, interpretations of the facies distributions must be made in order to develop some predictive capability about the extent of individual facies. This capability will be critical since the sandstones were deposited under a diverse set of environmental conditions within a transgressive-regressive-transgressive cycle of deposition.

The fundamental basis for understanding the lithology, geometry, and lateral relationships of time-equivalent rock units in sedimentary basins is correlation. To correlate, in the geologic sense, is to establish the temporal equivalency of two or more rock units regardless of their composition. Conventionally, geologists correlate rock units of similar character from well to well across a sedimentary basin. In some cases correlation of rock types is coincident with correlation of time surfaces. Most often, however, correlation of similar rock types is not coincident with correlation of time surfaces. To overcome this problem and to place diverse rock units within a time framework, geologists utilize independent data sets such as fossil content or, less commonly, isotopic ages of the rocks themselves. Having established a time framework by some independent method, rock units of similar or diverse physical properties are grouped and correlated.

There exist several practical and theoretical limitations to establishing time lines within stratigraphic sequences from independent data sets. Of these, the two most important are the degree of temporal resolution obtainable and the frequent absence of fossils or datable minerals within many rock types. Even if the latter problem is exempted, the former always will prove a severe limitation.

In the absence of an accurate high-resolution time frame, correlation by rock type often results in false correlations and, consequently, inaccurate description and prediction of the geometry and distribution of rock types within a basin. This, in turn leads to failure to predict the three-dimensional extent of lithofacies in the subsurface.

A major breakthrough in the analysis of sequences of rocks in a sedimentary basin would be achieved by establishing a new conceptual approach and methodology to extract time surfaces directly from the rock units themselves. Accurate correlation of rock units within a high resolution time framework would provide the control necessary for accurate understanding of the stratigraphic architecture of a basin and the geometry of reservoir rock units within it. Consequently, the ability to predict the extent of lithofacies in the subsurface would be preserved.

Accomplishment of this goal has important ramifications beyond that of accurate correlation of sampled rock units. First, accurate understanding of explored parts of a basin enhances the ability to predict the character and distribution of rock units in unexplored parts of a basin by employing geological intuition or standard geological models. Second, and more significantly, it is possible to develop numerical models which simulate the deposition of specific rock types across a basin within time increments. Models are capable of simulating complex geological processes, so that, the interaction of various factors affecting the nature and distribution of facies can be evaluated (Reading, 1978). Such models simulate observed stratigraphic geometries and rock compositions within discrete time intervals. Then, they can be applied to predict deterministically the geometriés and rock compositions within unexplored portions of the basin.

Modeling studies by Cross (personal communication, 1987) show that the fundamental building block of marine shelf to coastal-plain stratigraphic sequences is the progradational event, or the seaward advance of the shoreline and adjacent environments during a geologically short time interval. During progradation, shallow-water environments move seaward over and progressively replace deeper water environments (Figure 7).

In vertical profile at a single geographic position, a progradational event is expressed as a shallowing-upward succession of rock types, or lithofacies. At varying positions within a basin a progradational event is represented by vertical successions of different lithofacies. For example, a vertical succession of shallow marine to coastal-plain sediments deposited in the shallow part of a basin reflects the same progradational event as a vertical succession of deep to moderately deep marine sediments deposited in the deep part of the basin (Figure 7).

An episode of progradation is essentially synchronous throughout the sedimentary basin. The sediments deposited during a progradational event are lithologically diverse but are genetically related by their equivalence in time. These packages of temporally equivalent strata are termed genetic sequences. Genetic sequences are bounded at the top and bottom by time surfaces, which may in part coincide with erosional surfaces, and may be correlated across sedimentary basins regardless of changes in lithology of rock units within them. The essence of establishing accurate correlations among rock units of diverse lithologies is the recognition of the initiation and termination of these genetic sequences.

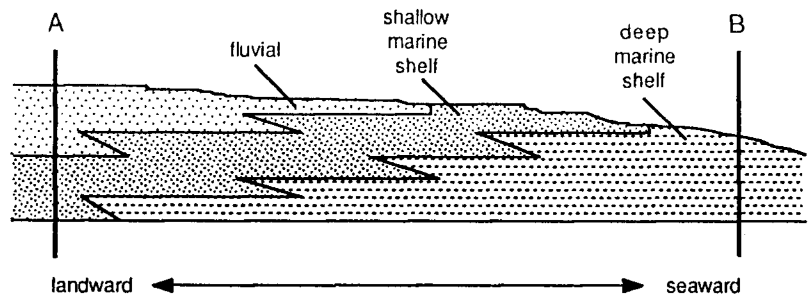

Figure 7. Hypothetical cross-section of a progradational event.

Because stratigraphic sequences of marine shelf to coastal-plain environments are composed of multiple progradational events, it is necessary to be able to distinguish one event from another. Otherwise it would be impossible to distinguish one time surface from another and correlations would be inaccurate. Preliminary results of Cross's numerical simulations suggest that this may be accomplished by recognizing an hierarchial stacking geometry of progradational events. It appears that progradational events are arranged systematically in three geometric patterns as a direct consequence of the interactions of the fundamental controls discussed previously. Relative to the direction of progradation, these patterns are forward-(or basinward) stepping, backward-(or landward) stepping, and vertical stacking.

Accompanying these geometric stacking patterns are changes in the thickness and lateral extent of particular lithofacies. For example, shallow marine sands of the shoreface environment are thin and widespread during forward-stepping phases, thick and laterally restricted during vertically stacked phases, and very thin and extremely restricted during backward-stepping phases. By contrast, lithofacies representing fluvial and coastal-plain environments attain maximum thickness during backward stepping phases and are thinnest during forward-stepping phases. A good field example of this may be the Rocktown Channel sandstone in central Kansas where vertical stacking of the channel sands occurs in a deltaic sequence of finer grained sediments and lignites.

Research to extend time surfaces landward beyond the coastal-plain has been successful but few attempts have been made to correlate time surfaces from the marine into non-marine environments. Using paleosols and coals in the Pennsylvanian section, Busch (1984) has been able extend time surfaces from marine to non-marine depositional environments. This is possible because soils located on upland surfaces during the Pennsylvanian formed under relatively stable climatic conditions. These sedimentary features are preserved as a result of the occurrence of progradational events nearby that have altered the climate and the distribution of depositional environments. Kraus (1987) has been able to correlate paleosols in the Eocene sediments deposited in part of the Big Horn Basin in Wyoming. She has found paleosols preserved in the alluvial sediments to be useful in determining changes in the relative rates of sediment accumulation associated with climatic change and tectonic activity in the vicinity of the study area.

Recognition of genetic sequences at all levels within this hierarchy forms the basis for establishing time lines time correlations, and hence formational boundaries, that are independent of lithofacies and for accurately establishing the depositional architecture of a basin within time slices. Moreover, if the existing numerical simulations are reasonably correct, it should be possible to develop more sophisticated models capable of predicting deterministically the thickness and spatial distribution of different lithofacies tracts within individual events.

In order to unravel the geologic framework of the Lower Cretaceous in Kansas, fieldwork will begin in the outcrop areas to determine in some detail the lateral extent of the time surfaces along the outcrop and the style of sedimentation in central and southwestern Kansas. Concurrently, geologic information will be obtained about these units in the subsurface by looking at cores, wireline logs, and well cuttings in order to extend three-dimensionally the correlations made along the outcrop in central Kansas.

Based on this preliminary phase of the project methodologies for identifying and correlating genetic sequences will be developed and used to do an analysis of the Lower Cretaceous west of the outcrop. Work in the deeper subsurface will proceed using available suites of wireline logs and cores, where possible. Once correlations have been established along several lines across western Kansas from marine to coastal-plain to non-marine settings, then formational boundaries can be extended into the subsurface. Additionally, simulations of the depositional systems will be generated to predict deterministically the geometry and composition of lithofacies within the Lower Cretaceous. The results of these simulations together with well-log or core data will be used to fill-in the interpretations of lithofacies within between the lines of correlated wells extending across the State.

2.2.2.2 Geostatistical Analysis and Modeling

The Lower Cretaceous rocks of Kansas are highly complex geologically due to the wide range of marine and non-marine processes responsible for their deposition. This complexity is manifested in the extreme lateral and vertical variability of rock properties present in the Lower Cretaceous. In order to be able to estimate the rock properties the three-dimensional pattern of variation must be understood and a mathematical framework to describe the variation must be found. The most efficient way to do this is a three-dimensional digital format. Although computers have been used for geologic data storage for many years, the data structures employed and the graphics produced have been exclusively one- or two-dimensional. It has not been possible to organize geologic information in a manner that allows for true three-dimensional modeling and analysis.

The kernel of the geologic modeling problem lies in the ability to estimate the geologic properties of an arbitrary x-y-z location from known information scattered randomly within the limits of the volume of interest. The problem of three-dimensional geological estimation has been addressed in two widely differing contexts. The first of these involves the use of regionalized variable theory and the application of three-dimensional kriging procedures. These have been very successful in modeling reservoirs (Delfner et al., 1983). Unfortunately, kriging requires a relatively high density of observations, at least along a limited number of traverses at different orientations through the volume of interest. Unless such data are available, semivariograms that characterize the rates of change of geological properties with distance cannot be estimated reliably and predictions of lithologies and other properties cannot be made. This technique is more appropriate on a local scale where there is a sufficient density of data available. In addition the estimation process is computationally extravagant and probably cannot be used routinely for detailed three-dimensional modeling from a regional framework. However, the recent development of space transforms promises to greatly improve the computability of such massive simulation and estimation problems, although the methodology is still in an embryonic stage (Christakos, 1987).

A much simpler procedure has been suggested by Doveton, Zhu, and Davis (1984). They approximate the petrophysical variation expressed in well logs with high-order polynomial curves. These curves capture the gross aspects of vertical lithostratigraphic variation while sacrificing small-scale details that are unlikely to be laterally continuous. (Vertical resolution can be increased by segmenting the well logs at stratigraphic boundaries.) The polynomials are interpretable as moments of vertical variability, and can yield conventional forms of geologic maps widely used in petroleum exploration (Krumbein and Libby, 1957).

Lateral variation may also be expressed as a polynomial expansion of the geographic coordinates of the well locations, yielding trend surface maps. These are routinely used in petroleum exploration to express the dominant components of structure and lithology. Since the curves describing vertical variability at individual wells also are polynomial expansions, the two can be combined and solved simultaneously. This will yield a true three-dimensional model in which the modeled property can be evaluated at any x-y-z location.

The polynomial model will extend throughout the entire three-dimensional extent of the space being evaluated. Cross-sections and maps can be constructed showing variation on any arbitrary plane through the solid space, at any orientation, spacing, or level. It is even possible to compute tilted slices through the solid to display, for example, the geology along an inclined fault plane. A simple slice through the model is made by holding one geographic variable constant, systematically varying the other two variables through their range, and evaluating the model equation for the dependent variable. The result will be a contoured map of cross-section drawn perpendicular to the geographic axis held constant. Doveton, Zhu, and Davis (1984) provide several examples of such slices. If desired, sections can be calculated along arbitrary curved or bent lines whether or not these include well locations.

The three-dimensional model described by Doveton, Zhu, and Davis (1984) expresses variation of two geological properties - structure and percent shale in a sandstone-shale sequence. A complete three-dimensional geological model must express many additional properties simultaneously, such as lithology, structure, porosity, fluid content, and hydraulic conductivity (intrinsic permeability for a homogeneous fluid). Multiple geological variables can be accommodated in the model in two ways. Expanding the single model equation into canonical form allows the inclusion of multiple properties, although at a great increase in complexity of the equations. Such an extension has not been attempted before and it is not known if sufficient resolution can be retained in the canonical formulation.

A more practical alternative may be to express the geologic properties of interest as a set of independent or quasi-independent models. For example, variation in a lithologic component could be described by one model equation, variation in porosity by another, and variation in fluid composition by a third. The models would have common independent variables, the geographic coordinates, which would tie them together. Any or all of the properties could be evaluated simultaneously along specified sections or planes, or at arbitrary points within the solid space. It may be necessary to evaluate some components by subtraction from unity in order to provide constraints on the model. In a unit comprised of sandstone and shale, for example, only one lithologic component should be modeled and the other found by subtraction of the proportion of shale expressed as a fraction from unity. Otherwise, use of two independent models may yield estimates of sandstone and shale which do not sum to unity.

Some important geologic properties do not exist as continuous variates but rather are in the form of discrete ordinal or nominal properties. The development of new data analysis methods allows discrete data to be treated by variance-minimizing algorithms such as those considered here. So-called "regression-like" procedures are now available that should be directly applicable (Reynolds, 1985).

Wrigley (1977) has suggested that logit transforms will allow trend surface analysis to be made of discrete data, and presumably his methods can be extended as part of a three-dimensional modeling process.

An alternative procedure might involve calculation of nominal and ordinal equivalents of moments, and use of discrete regression-like modeling equations (Nerlove and Press, 1973). This approach would be novel, and it is not known whether it would be superior to extensions of the logit procedures devised by Wrigley. Evaluation of these two alternatives will require experimentation. It is possible that one method may be computationally or predictively superior to the other for certain types of discrete geologic data. Fortunately, either approach should be fully compatible with the moments modeling method used for continuous data, and results should be easily incorporated into a multivariate geologic model.

Polynomial model equations presume that the property being described is continuous everywhere within the volume enclosed by the model. Obviously, faults, pinchouts, and other discontinuities are violations of this assumption. If it can be assumed that the modeled property extends without change across the plane of a fault, except for a displacement, faulting can be included in the model relatively easily. However, if the presence of a fault or pinchout affects the spatial distribution of a property (such as pore fluid composition), modeling will be much more complex.

It is expected that the early stages of this project will begin at the end of the subsurface and field stratigraphic studies described above. Final design and specification of the modeling software will be undertaken in close cooperation with other project leaders in the Dakota aquifer Program. Detailed information on the geology, and the petrophysical and hydrologic properties of the rocks, the areas to be modeled, the scales at which the models are to operate, and the required resolutions are needed in order to write detailed specifications. As a practical matter, information must also be provided on the specific computing resources available, the size and structure of data files, characteristics of database management systems to be used, and the characteristics of the graphics display units to be employed.

Although the conceptualization and design of the modeling process are the most critical aspects in development of the software, experience suggests that the greatest programming effort will have to be devoted to interfacing with, and managing, the already-existing geological data files. This task will be greatly simplified using efficient database management software with geographic information system (GIS) capabilities.

Development of the three-dimensional geologic modeling system will take place in a series of phases. Completion of a phase constitutes a project milestone, a time when accomplishments of the phase can be reviewed and detailed strategy compiled for the succeeding phase. Listed below are the various phases of the project described above in sequential order (note that phase 2 involves two different but concurrent activities):

Phase 1 Definition of the three-dimensional model and the framework in which it is to operate.

Phase 2 Evaluation of alternative three-dimensional modeling procedures.

Initial design of interfaces to Lower Cretaceous and database management system.

Phase 3 Design and implementation of an initial three-dimensional model.

Phase 4 Demonstration and revision of initial model.

Phase 5 Graphical output and interactive control, design, and programming.

Phase 6 Final installation and testing.

Phase 7 Operational testing, training, and documentation.

2.2.3 Location of Geologic Structures and Fracture zones

Geologic structures, particularly fractures, are important hydrologic features because they act either as conduits facilitating the lateral and vertical movement of fluids or as barriers to flow that may result in relative hydraulic isolation of waters in the subsurface. As a result, these features may have considerable influence on interaction with other aquifers and surface waters, the variation in material properties, and water quality and availability. Kolm and Peter (1984), working in South Dakota, mapped lineaments from satellite imagery in areas underlain by Lower Cretaceous bedrock aquifers. They found these linear features to be correlated with water chemistry, potentiometric, and geothermal anomalies in these aquifers.

Locating geologic structures and fracture zones in the subsurface can be most efficiently done by integrating several techniques: (1) mapping the configuration of geologic markers in the subsurface; (2) mapping and field-checking of lineaments observed in remote sensing imagery of the study area; and (3) application of surface geophysical techniques, in particular seismic methods. The results of applying one method will be compared with those of the other methods and with the nature of the materials comprising the Lower Cretaceous, including water availability and water quality. Lineaments will be compared with the top configuration and seismic data to determine if subsurface structures are reflected at the surface in the form of lineaments. Additionally, the seismic data will be used to "fill-in" where sparse control is evident from the data distribution or to do seismic stratigraphy for delineating seismic facies.

In this project, the first two techniques will be used in a reconnaissance of the project subareas to locate regionally significant structural features in the subsurface. Maps of the configuration of various geologic markers in the Lower Cretaceous and adjacent units will be used to show the orientation of various sedimentary bedrock units in the subsurface as well as structural and stratigraphic relations, and depth to the top of Dakota and other Lower Cretaceous formations from the surface. Remote sensing imagery will be used to map lineaments which may be related to the pattern of jointing in the rocks or faulting associated with events that have occurred since the deposition of the Lower Cretaceous units. Once these features have been mapped, they will be field-checked to determine their structural significance.

In areas where the field data are sparse or more detailed study is appropriate, seismic surveys will be run to obtain the necessary level of detail for this study. Seismic reflection methods have been used by petroleum exploration companies for the past 60 years to determine subsurface geologic structure to depths of several thousand feet. Refinements in seismic reflection technology in the past twenty years have allowed for examination of stratigraphic variations by seismic methods. Work at KGS has refined the resolution capability of the method to be very effective at depths of less than 1500 feet. Because much of the Lower Cretaceous present in Kansas occurs at depths less than 1500 feet, the methodology exists to examine both the gross geologic structure and the stratigraphy of the Lower Cretaceous bedrock units. A preliminary assessment must be carried out in the field on some test cases to determine the suitability of the method for this purpose.

2.2.4 Hydrology and Water Quality of the Dakota Aquifer

2.2.4.1 Definition of Regional Flow Systems and Development of Ground-water Flow Models

Studies of regional ground-water flow systems have shown that the potential energy distribution and flow patterns of formation fluids in a rigid rock framework are produced by elevation differences of the water table. This is a direct consequence of the hydraulically continuous nature of the rock framework considered over geologically significant periods of time (so-called steady-state conditions). Consequently, in an idealized ground-water basin under steady state conditions, fluctuations in the topography (relief) modified by variations in rock permeability are responsible for the differentiation of local, intermediate, and regional flow systems.

The evolution of sedimentary basins, involving uplift, deposition, and erosion, causes major changes in basin hydrodynamics and hydrochemistry of basinal fluids. Transient flow conditions induced by geologic processes acting over finite periods of time produce changes in the flow system at a rate that depends on the diffusivity of the rock framework (Toth, 1984). The duration and magnitude of these changes is directly related to modifications in the flow system boundary conditions caused by the geologic processes acting on the ground-water basin. Thus, an overprinting of a more recent pattern of ground-water movement on a relict flow system may occur as a result of tectonic movements or changes in topography in a ground-water basin. Toth has shown that the time of adjustment may be geologically significant, on the order of millions of years, if aquitards of substantial thickness are present in the subsurface.

The role of these geologic processes and the more recent effects of man will be examined in the Dakota and other related Lower Cretaceous bedrock aquifer systems of Kansas on the eastern flank of the Denver Basin. This will be done in conjunction with underlying and overlying systems in order to: (1) understand and predict the mechanisms of ground-water circulation and water quality changes in these systems; (2) analyze the interactions between the Ogallala and Dakota aquifer systems. Under number 1, the flow system and the resulting variations in water chemistry will be analyzed in the context of the geologic development of the east flank of the Denver Basin and areas to the east in Kansas. Coupled flow and mass transport models will also be used to evaluate the effects of ground-water use and oil-field brine disposal on the system.

These tasks will be accomplished with the help of cross-sectional, two-dimensional (areal), and three-dimensional ground-water flow models employing steady-state or time-dependent boundary conditions, as needed. Two-dimensional flow models will be employed in the early stages of the project to integrate the results of previous studies with data generated from the present investigation during the second year of the project. These models will be used as a means of updating project results and hypothesis testing to guide later investigations. Cross-sectional flow models will be used to integrate the results of hydrologic observations collected from specific multiple completion monitoring wells located along lines of cross-section traversing the extent of the Lower Cretaceous in Kansas. These models will also be used to assess the effects of geologic processes on the flow system and the impact of present day interactions between adjacent aquifers on the flow system. Toward the end of the project, three-dimensional models will be used to describe the flow system and mass transport. Both the cross-sectional and three-dimensional flow models will be developed for steady-state and time-dependent boundary conditions and source terms. Transient conditions will be used to assess the effects of tectonic development and erosional/depositional loadings on the ground-water basin on present conditions in the Dakota aquifer and on a shorter time scale the present and future effects of man on the system. A number of multi-dimensional ground-water solute and energy transport models are available for this purpose, such as CFEST, FE3DGW, SWIFT, SWIP2, SUTRA, TERZAGHI, USGS-3D, INTERA, and HST3D. Prior to the selection of a model, a critical evaluation will be conducted to determine model suitability for this part of the project. The selected model will provide the basis for simulating water management scenarios and assessing their future consequences in western Kansas.

The prerequisites for the successful application of the modeling effort are a thorough understanding of: (1) the geologic framework; (2) the boundary conditions governing the flow system; (3) geologic history of the basin; and (4) a well-documented hydrologic and hydrochemical data base, including fluid pressures and densities, hydraulic properties, water chemistry, and temperatures within the basin. The geologic framework and geologic history needs are addressed previously in this proposal. In order to meet the hydrologic needs for the modeling effort hydrologic data associated with specific points in the system are needed as a consequence of the geologic complexity of the sandstone and shale sequences in the Lower Cretaceous. Furthermore, these observation points should be arranged in a logical manner, such as along lines of cross-section that trend parallel to the regional ground-water flow directions of the ground-water system. These requirements can be met by constructing several series of monitoring sites arranged along selected lines.

Each monitoring site will consist of a multiple completion monitoring well that will be used to observe hydrologic conditions within the Lower Cretaceous and adjacent aquifer systems in a single borehole. This will be done by first perforating the casing at the desired levels in the subsurface and then placing standpipe piezometers in the borehole, gravel packing the screened intervals, and cementing off between the gravel pack zones within the steel casing. Within a steel cased 5-1/2 in. OD well it is possible to place three 1-1/2 in. OD piezometers downhole. Within an 8-5/8 in. casing it is possible to put four such piezometers downhole. Each piezometer can then be used to monitor fluid pressures and water quality, and can be used to perform hydrologic testing for materials properties. These monitoring sites will be visited periodically to obtain fluid pressure measurements and water samples, and to perform hydrologic testing described below under 2.2.4.2.

It is anticipated that most of the monitoring sites will be constructed from abandoned oil or oil-field brine disposal wells that will be "taken over" by KGS during the time span of the Program or drilled and cased by contract for KGS. Three lines of cross-section consisting of four to ten monitoring sites arranged along lines of various length should provide adequate coverage. Selection of the general location of the lines of cross-section will be based on a review of the hydrologic data base compiled from previous studies of Lower Cretaceous hydrogeology compiled at the beginning of the project. Prior to taking over responsibility for these wells the owners will be required to provide adequate documentation of well construction and cementing, records of the geologic units encountered by the driller at the time the well was constructed, and any other pertinent information, such as repairs that have been done on the well since its construction.

2.2.4.2 Estimation of Flow Properties

One of the major goals of this investigation of the Lower Cretaceous bedrock aquifers is to construct a mathematical model of the flow system that will allow the impact of various water management scenarios to be assessed in a rational framework based on the physical processes occurring in the subsurface. Though mathematical modeling is a technology that is in common use in hydrogeology (Bachmat et al., 1980), its viability for quantitative prediction of responses to future planned activities is still unclear (e.g. Alley and Emery, 1987). A primary reason for this is that the flow-model parameters are often just a product of the fitting process and not necessarily related to the properties of the geologic materials under investigation. Therefore, when extrapolation to future conditions is attempted, the model is often just a rough, at best, approximation of reality (Klemes, 1986).

In order to construct a model more closely tied to the physical properties of the porous media, a major effort will be made here to relate the parameters of the model to actual or estimated properties of the geologic materials. This will be done by: (1) conducting single well recovery (slug) tests of piezometers at each monitoring site in the deeper subsurface and pump tests, where possible, in the shallow subsurface; and (2) extending the results of this work by using the properties data, the scale of the testing methodology used to collect the data, petrophysical parameters measured on borehole geophysical logs, and any other local geologic or sedimentological information to develop multivariate relationships that can be used to estimate the materials properties of untested zones in the Lower Cretaceous and other bedrock units. Resistivity and porosity logs, in particular, will be analyzed for measures of pore volume and geometry in sandstone beds. These properties can be linked directly to the permeability of granular sediments (Hearst and Nelson, 1985; Doveton 1986; and Freeze and Cherry, 1979). Pore space characterizations will be interpreted in terms of grain fabric. The results should have implications not only regarding depositional systems and diagenetic processes, but potential relationships with permeability. Wendt et al.(1986) used linear multiple regression techniques to predict the permeabilities of sandstone and shale sequences in uncored wells on the north slope of Alaska with some success using parameters similar to those mentioned above in the estimation process.

Slug tests of the piezometers at the monitoring sites and at other localities in the western part of the State will be conducted using techniques developed for determining horizontal component of permeability (Earlougher, 1977) and the horizontal and vertical components of permeability of the geologic materials between measurement points in a single borehole (Burns, 1969; Prats, 1970; and Hirasaki, 1974). Pump tests will be conducted and analyzed using standard methodologies and new techniques presently being developed at KGS that take into account non-uniform conditions in the aquifer (Butler, 1987b).

For this study, several practical as well as theoretical considerations must be acknowledged and dealt with accordingly. Individual cells of the flow model will be quite large due to the size of the modeled area. The so-called scale effect (e.g. Dagan, 1986; Haldorsen, 1986; and Weber, 1986) will therefore be an important consideration in the comparison of core, slug test, and pump test values of material properties. As a result, the scale effect needs to be incorporated in the spatial analysis of the properties data. Flow properties obtained from the laboratory analysis of core plugs or from slug test responses may be very poor estimates of the properties at a larger scale, given the magnitude of the small-scale property variations that can be expected and the effects of fracturing. Pumping tests are probably the best approach for estimation of the flow properties at the scale of a model cell, though they are impractical in deep confined aquifer systems such as the Lower Cretaceous bedrock aquifers in northwest Kansas where the depth to the top of the Dakota exceeds 1000 feet and properties data are sparse. In this area of the State, slug tests results or data from cores will be the only means of estimating permeability and storativity of the aquifer materials.

Another problem already alluded to previously involves the connectivity of the sandstone bodies. Fogg (1986) has shown that property estimation is strongly dependent on the connectivity of the major sandstone bodies. The question of sandstone body connectivity and how to estimate it will thus be an important focus of this work. Similarly, the impact of fractures on the Lower Cretaceous flow system must also be assessed. Hydrologic testing in conjunction with seismic and log analysis can help address these questions, but further research is required.

2.2.4.3 Pilot Studies to Analyze the Effect of Local Heterogeneities on Aquifer Performance

Conventional aquifer testing methodology assumes that flow and transport properties are uniform in space. Recent work (Butler, 1986, 1987a, in press) has begun to address the issue of the ramifications of this assumption for pumping tests in non-uniform aquifers. In order to make some meaningful statements about flow and transport conditions within the Lower Cretaceous system, the effects of local heterogeneities on aquifer behavior must be examined in considerable detail. This examination will initially be in the context of a theoretical analysis of flow and transport in simple geometrical configurations that can be treated analytically (e.g. Butler, in press). These analytical solutions will better our understanding of behavior in non-uniform aquifer units. They will also allow us to assess the applicability of conventional testing methodology in non-uniform conditions of the type found in the Lower Cretaceous system. For conditions in which the traditional testing approaches are of limited usefulness, new methodologies will be developed based on the insight gleaned from the analytical solutions. Variable rate pumping tests (Butler and McElwee, 1987b) and pulse testing are two approaches presently being developed that hold much promise for the definition of flow properties in the non-uniform conditions faced in this investigation. The latter stage of this work will involve applying the developed techniques to investigations of flow and transport behavior in local areas. The goal is to develop and apply a methodology that can be readily employed to better define the local flow and transport properties of the Lower Cretaceous bedrock aquifers.

2.2.4.4 Water Quality in the Dakota Aquifer

Water chemistry can assist in interpretation of certain types of hydrologic flow regimes. The water chemistry of the Dakota system is complex. There are several types of water occurring throughout the state: calcium-bicarbonate water in the outcrop zone; sodium-chloride waters in the deeper portions of the system; and sodium-bicarbonate and calcium-sulfate waters in the poorly-defined transition zone. Defining the areal boundaries of water types is difficult due to the lack of knowledge concerning the stratigraphy and structure of the aquifer units. For example, chemical water types might differ vertically from one unit to another. Thus, present designation of the general chemical character of aquifer subregions could be dependent on the particular stratigraphic horizons for which water chemistry data exist. More information is needed on the mineralogy of the strata to determine whether the salinity and chemical character have been generated mainly within the aquifer units and/or in underlying and overlying units of the basin.

Also, minor constituent and isotopic analyses of waters needed to determine saltwater sources in the aquifer and from adjacent strata are sparse.

Previous studies of the Dakota aquifer in other states suggest that stratigraphic pinchouts, fractures, and the occurrence of overlying shales above the Dakota may result in conditions favoring the presence of poor-quality water in this aquifer (Benz et al., 1961; Peter, 1984; Leonard et al., 1984). In most of these studies, the Dakota aquifer does not contain sufficient quantities of evaporite minerals to produce high chloride or sulfate waters. The source of the saltwater must be from either man-induced contamination or from migration of fluids from other sources. Standard chemical analyses are useful for identifying the general differences in water types and in some cases for distinguishing between natural and oil-field brines (Leonard, 1964). However, trace element ratios and the isotopic composition of waters are much more useful for defining the sources of the waters. For example, mixing curve methods based on Br/Cl, I/Cl, and B/Cl have been used to differentiate saltwater sources contaminating ground waters, and to estimate percentage contributions from a mixture of fresh waters and two salinity sources (Whittemore et al., 1981; Whittemore, 1984).

Isotopes such as oxygen-18, deuterium, sulfate-34, and strontium-87 have been used to evaluate the possibilities of cross-formational flow between units and to define the regional ground-water flow system in basin studies (Kreitler et al., 1985; Land and Prezbandowski, 1981; Krothe, 1980; Hitchon and Friedman, 1969; Clayton et al., 1966). The isotopic signature of shallow ground water is a reflection of the precipitation in the local recharge area. The isotopic signature of deeper waters may be different due to infiltration time, rock-water interactions, or long residence time due to regional flow versus local flow systems. Evaluation of the isotopic composition of shallow and deep ground waters indicates the occurrence of waters of different origins and distinguishes the degree of mixing that is occurring among these waters (Lambert, 1978; Clayton et al., 1966; Krothe et al., 1982). Isotopic techniques have been utilized in such projects as analyzing the movement, origin, and age of pore waters in sediments; determining if the origin of saline waters is due to mixing of different water or to rock-water interactions; and evaluating the role of fracture flow on the mixing of different waters (Desaulniers et al, 1981; Fritz and Frape, 1982; Dutton, 1987).

A work plan for the study of water chemistry in the Dakota Formation is a multifaceted program. There are many aspects that must be considered when defining a program of study. Some of these include the assessment of the available water quality for different uses both in the areas where Dakota waters are currently withdrawn and in those areas where there may be potential future use; determining the sources of Dakota waters and the role that cross-formational flow between adjacent units may play in affecting the overall water quality of the Dakota aquifer; determine the present effects of oil-field brine disposal in the Dakota and adjacent strata on the current water quality of the Dakota aquifer;

determine recharge and discharge zones for the Dakota system; and determine the geochemical factors governing the present water quality of different units within the Dakota system and adjacent units. These objectives compose the core of a plan of study involving the Dakota formation. Listed below is a plan of study to evaluate several of these objectives simultaneously throughout the multi-year program of study of the aquifer.

Objectives:

Ground-Water Quality Assessment

1. Assess the ground-water quality for different uses in those aquifer areas where Dakota aquifer waters are presently used and for which chemical data are available.
2. Assess the general potential useability of ground waters in the undeveloped portions and reassess the value of the waters for different purposes in the presently developed portions of the Dakota aquifer based on additional sampling and analysis of ground waters.

Use of Water Chemistry to Identify Hydrogeologic Boundaries

1. Determine the natural origin of the water and salinity in different units of the Dakota aquifer system and in adjacent and overlying strata.
2. Determine the present effect of oil-brine disposal on the quality of waters in the Dakota aquifer.

3. Assist in the determination of flow relationships within the Dakota system and recharge and discharge directions and rates to and from adjacent strata.
4. Determine the locations and effects of stream/Dakota aquifer interactions on water quality in the Dakota and affected streams and assist in quantifying these relationships.
5. Utilize isotope and trace element methodologies to determine potential cross-formational flow zones between the Dakota and adjoining units.
6. Use major constituents, trace elements, isotope analyses, and structural and areal photography data to locate fracture flow and potential mixing of water zones.
7. Use standard chemical techniques such as specific conductivity and chloride analyses to evaluate high salinity zones as potential discharge zones from the Dakota.
8. Use of isotope analysis of clays in cores to compare with ground waters in some areas to evaluate the local depositional history of the rocks.

Geochemical Controls on Ground-Water Chemistry

1. Determine the geochemical factors governing the present water quality of different units within the Dakota aquifer system and adjoining strata.
2. Predict the water quality of the Dakota aquifer in undeveloped areas based on coupling a knowledge of the geochemical controls

with mineralogic, stratigraphic, and hydrogeologic information for the areas.

3. Assess the potential effects of mixing waters from different aquifer units, and in areas of stream-aquifer interactions, from surface waters, to form precipitates reducing well capacity, to corrode wells, and to change concentrations of constituents important in determining water use. Apply the results to guidelines for water well construction in the Dakota aquifer.

Spatial Distribution of Ground-Water Quality

1. Determine the spatial distribution of currently available water quality data in order to define areas of limited data for future investigation.
2. Evaluate the quality and source of available data for research purposes.
3. If data is not available for associated units (such as Cheyenne, Kiowa, and Cedar Hills) help in formulating criteria and locations for future drilling and well installation projects.
4. Use water-quality data in conjunction with stratigraphy to determine whether cross-formational flow is occurring throughout the study areas.

Work Plan Elements:

Year 1:

1. Compile the chemical data presently available for assessing the quality of Dakota ground waters in different areas for use in

agriculture (crops and livestock), for drinking purposes, and by various industries appropriate to Kansas.

2. Assess the acceptability of Dakota ground waters for various uses in different portions of the aquifer based on the available data.

3. Compile and examine the quality of hydrochemical information presently available that includes data useful for geochemically characterizing waters in the Dakota system, adjacent underlying and overlying aquifers and other strata, and overlying surface waters. Besides major constituent values, this data includes concentrations of minor and trace elements, particularly bromide, iodide, boron, and lithium, and hydrogen, oxygen, and sulfur isotopes.

4. Check on availability of drilling and completion information concerning existing wells in Dakota Formation to try to confirm that the Dakota (or other units) are the sole water-supply units for the well.

5. Find geophysical logs in areas of usable water data to verify depths and thicknesses of units.

6. A report summarizing the quality of available data and the assessment of water quality for various uses.

Year 2 through 10:

1. Determine the additional data necessary for substantial improvements in water use assessment in the areas where water is presently withdrawn and in the regions now undeveloped.

2. Design a sampling and analysis plan based on the results of work plan item no. 1 above and coordinated with other sampling and analysis plans in the overall Dakota Program. The plan would involve existing wells and new observation wells needed.
3. Assist in the installation and sampling of new observation wells and the sampling of existing wells using the sampling plan of work plan item no. 2. Determine the chemical characteristics necessary for use assessment in the sampled waters.
4. Assess the general potential useability of ground waters in the undeveloped portions and reassess the value of the waters for different purposes in the presently developed portions of the Dakota aquifer based on the results of work plan item no. 3.
5. Develop an overview of the origin, recharge, and discharge of ground waters in the Dakota system based on the available hydrochemical studies and data. Include discussion of any oil-brine contamination of the aquifer observed and the effects of stream-Dakota aquifer interactions on water quality. This report will be coordinated with related hydrologic studies of the Dakota Program.
6. Determine the additional information necessary to substantially improve the identification of water origin, and recharge and discharge relationships within the Dakota system as well as from and to adjacent strata and overlying surface waters.
7. Design a sampling and analysis plan based on the results of work plan item no. 6 and coordinated with other sampling and

analysis plans in the overall Dakota Program. The plan would involve existing wells and new observation wells needed.

8. Describe the origin of waters and identify and assist in quantifying the recharge and discharge relationships within the Dakota system, in adjacent strata, and in stream/Dakota aquifer interactions. Assess the current and potential affects of oil-brine disposal in Permian strata on water quality of the Dakota aquifer. This report will be written in coordination with related stratigraphic and hydrologic studies of the Dakota Program.

9. Coordinate water data with stratigraphy in order to evaluate possibilities of cross-formational flow.

10. Determine the geochemical factors controlling ground-water quality in the Dakota system. This will include using water-quality computer models such as WATEQF to determine equilibria relationships, and models such as PHREEQE to evaluate potential mixing scenarios between units.

11. Use statistical methods to evaluate trends in data and associations of various hydrologic properties with chemical data.

Interdisciplinary Cooperation:

Initial collection of data, sampling of existing wells, installation and sampling of new observation wells will be conducted in coordination with related projects in the Dakota Program in the Kansas Geological Survey, and in the U.S. Geological Survey. The initial and final reports will be integrated with those of other investigators in the Dakota Program to produce a coordinated document on the Dakota system. Information management and transfer will be coordinated with the Technical Information Services Section of the KGS. The following State agencies will be consulted on topics related to each subproject: the Kansas Department of Health and Environment on drinking water-use assessment, water and observation well construction and operation, and oil-brine disposal; the Kansas Board of Agriculture on agricultural water-use assessment and water well construction and operation; the Kansas Water Office on water-quality planning; and the Kansas Corporation Commission on industrial water-use assessment and oil-brine disposal; Kansas State University-use of isotope laboratory should such a center be established.

2.2.5 Simulation of Water Management Scenarios

One of the primary objectives of this research program is to evaluate the potential of the usable water resources in the Dakota aquifer in Kansas and to develop proper strategies for its exploitation. These strategies should be developed and tested subject to the policies of the Kansas Water Office and minimization of their impact on the quality and quantity of the resource.

In proposing management strategies for any resource, first the quantity, location, and the quality of the resource must be known. Clearly, there is no point in striving for a better management policy if little or no resource exists and uncertainties in its quality and accessability are substantial. The products of the previous elements of this proposal are aimed at providing information on the quality, quantity, and accessibility of waters from the Dakota aquifer. It is anticipated that these results will be incorporated into a model of the system that will serve to synthesize this information. However, no matter how much effort is put into the identification of the characteristics of this water resource, there will always exist some uncertainty about its nature and the porous medium that it flows through. In addition to these uncertainties, other uncertainties concerning factors such as the demand for water and the recharge to the aquifer are also present. In any management strategy, these uncertainties must be addressed and incorporated into the strategy.

Assuming that aquifer properties are properly identified, and the quality and quantity of water available in the aquifer are documented, two different approaches may be investigated for the management of the resource. In one approach, a set of pumpages may be assumed as the management strategy to simulate the effect of such a strategy on the quantity and quality variations of the resource. In another approach, a management model may be formulated to find out the optimum potential of the system for ground-water withdrawal. In this approach the uncertainties in the parameters in the system and demands may be incorporated into the management model. If the mean and standard deviation of the parameters and demands can be estimated, the chance constraint programming approach (Wagner and Gorelick, 1987; Heidari, 1985) may be used to arrive at the optimum steady-state pumping strategy. Then, the impact of such a strategy on the chemical quality may be evaluated by either velocity vector analysis (Wilson et al., 1986) or by a mass transport model (INTERA, 1983). In this study, the steady-state simulation of the impact of different pumpage strategies will be performed and evaluated. A management model that considers the uncertainties in aquifer parameters as well as the uncertainties in demand will be constructed and applied to a portion of the aquifer. The impact of the management strategies on the water quality will be assessed using velocity vector analysis. The development and testing of a management model based on mass transport will be done if possible.

2.3 Transfer of Information, Data base Management, and Display

Initial development of project data bases will utilize the existing FORMS utility on the KGS Data General MV/20000 computer. This utility provides full screen applications development for data entry and management. KGS is currently evaluating data base management systems (DBMS). A relational DBMS should be placed on-line during the first year of the program. This will enhance capabilities to associate multiple attributes with point, line, or area features. The Technical Information Services Section of KGS will provide instruction and supervision for transfer of all project data bases into the new DBMS. In the event this is not possible during the first year, temporary access to the U.S. Geological Survey DBMS and Geographic Information System (GIS) will be arranged until the KGS systems are fully operational.

An essential element for transfer and display of information generated in a large regional study is the facility to produce high quality maps integrating feature attributes with base map data. KGS has long been recognized as a leader in the area of computer-assisted mapping. Operations are based on the Geodata Interactive Management Map Analysis and Production (GIMMAP) system developed by KGS staff. Analytic capabilities of the system currently relate to topologic analysis of the digitized data for system data base structuring and metric analysis, such as distance, length, and area measures of mapped features. Base map data have been digitized from USGS 7.5 minute quadrangle maps. Coverage of the study area is complete for State and county boundaries, township and range lines, section corners, primary surface-water hydrology, State and Federal highways, railroads, and county seats.

The automated cartography capabilities of KGS have been used in numerous research projects in conjunction with software for geologic or hydrologic analysis and interpretation of data. However, the cartographic and interpretive software have not been incorporated into an integrated, geologically oriented, interactive information system. Such an integration will be undertaken as the information needs of the Dakota aquifer Program are more clearly defined during the early stages of research.

3.0 Total Program Budget and Personnel Requirements

	New Legislative Appropriation To KGS	New Legislative Appropriation For USGS	KGS Matching Funds	USGS Matching Funds
PERSONNEL				
12 Scientists			1,581,126	
3 Drillers			86,535	
Secretarial Support			136,775	
Administrative Support	136,775			
Student Research Assistants (9 Mo 50% FTE - 3 Mo 100% FTE)	595,276			
SUBTOTAL	732,051		1,804,436	
FRINGE BENEFITS				
Permanent Staff 21%	28,726		378,929	
Student Research Assistants (0.7% 9 Mo - 8% 3 Mo)	21,549			
SUBCONTRACTS				
USGS		850,000		850,000
Colorado School of Mines	69,660			
TRAVEL	315,000			
SERVICES				
Computer Time	176,800			
Water Analysis			67,500	
Water Analysis for Isotopes			10,215	
Monitoring Site Construction	125,010			
Installation of 3 5-1/2 in. Steel -Cased Boreholes	45,000			
Seismic Studies	499,500			
Wireline Logging	110,025			
X-Ray Mineralogy			17,010	
SUBTOTAL	956,335		94,725	
RESEARCH SUPPLIES			43,540	
EQUIPMENT				
Air Pump Unit	7,000			
Pump/Slug Test Monitoring Equip.	15,000			
TOTAL	2,145,321	850,000	2,321,630	850,000

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Appendix A: Use and Availability of Ground Waters from the High Plains Aquifer: Past, Present, and Future

The availability of water resources and the semi-arid climate of western Kansas have always played a dominating role in the economic development of that region (Miner, 1986). Annual rainfall amounts over the western half of Kansas range from 18 inches near the Kansas-Colorado border to 27 inches in the central part of the State. Even though most of the precipitation falls during the growing season, high rates of evaporation and erratic rainfall patterns limit the amount of water available to plants. As a result, farmers living in the western part of the State have had to rely on irrigation methods to supply the necessary water for crops. Miner points out that ditch irrigation began as early as 1873 when George Allman dammed the Smoky Hill River near Fort Wallace and constructed a mile-long irrigation canal for watering crops. Also, at about this time the use of ground water for irrigation is first mentioned in the writings of several people living in the western part of the State.

Up until the late 1950's and early 1960's the demand on the water resources of western Kansas was very small compared to the volume available for use. The High Plains aquifer system contained high-quality water and in some areas up to 600 feet of saturated thickness existed. Many of the streams in western Kansas flowed year round except during drought periods.

At this time the introduction of new high capacity pumps, combined with plentiful supplies of cheap fuel for pumping, changed this picture drastically. Consumption of ground water for irrigation increased dramatically and true mining of the ground-water resources of western Kansas began. This accelerated use of water resources has greatly affected both the quantity and quality of ground and surface water resources in western Kansas. The average rate of water withdrawal for the High Plains aquifer is about fifteen times the rate of natural recharge. Consequently, ground-water level declines are being experienced all across western Kansas in varying degrees of severity. By 1981, water levels in the High Plains aquifer had declined as much as 150 feet since pre-development in some places (U.S. Geological Survey, 1983). In some localized areas in west-central Kansas the High Plains aquifer has been effectively dewatered. Overdevelopment of the High Plains aquifer has caused some irrigators in southwest Kansas to turn to the Dakota aquifer as an alternate source of water. Many of the western Kansas streams no longer flow year round because they are receiving diminished base flow contributions from the High Plains aquifer.

Recognizing the need to manage and conserve the ground-water resources of Kansas, the Legislature passed the Ground-water Management District Act in 1972. This piece of legislation allowed the formation of ground-water management districts (GMDs) based on local initiative. GMD's 1, 3, and 4 each have a slightly different plan for managing the water resources within their boundaries. Each of the Districts has experienced at least a 10 foot decline in saturated thickness of the High Plains aquifer between pre-development and 1980. The Northwest Ground-water Management District, GMD 4, allows a depletion rate by individual irrigators not to exceed 2% of the saturated thickness per year. A variation of this policy is practiced in the Southwest Kansas Ground-water Management District, GMD 3, where the aquifer depletion rate is not to exceed 40% of the saturated thickness in 25 years. Each of these Districts also employs a fixed well spacing that is independent of the rate of depletion. West-Central Ground-water Management District, GMD 1, uses a well spacing requirement based on the percent decline in saturated thickness using 1950 well measurements as a baseline for computing depletion.

Farther east, water supply availability in many of the stream/aquifer systems is affected by the implementation of soil and water conservation practices and by the depletion of the High Plains aquifer system. The Smoky Hill, Saline, and Solomon river systems have been affected to the point that reaches downstream of the High Plains aquifer are receiving greatly diminished influxes of water. These diminished inflows are having serious consequences for the operation of Cedar Bluff, Kirwin, Keith Sebelius, and Webster Reservoirs.

Depletion of water resources has also affected the continued growth of the larger municipalities in western Kansas, most notably Hays and Russell. Hays is a major urban center in northwest Kansas located on the Big Creek flood plain in Ellis County. The population of Hays in 1986 was 16,301 according census data. Hays presently withdraws water from the Big Creek and Smoky Hill River stream/aquifer systems. During the last thirty years Hays has grown considerably and has increased its use of water over time. During the period from 1951 to 1982 the average daily water use rose from 0.847 to 2.010 million gallons per day (MGD) and the maximum monthly water use rose from 35.94 to 92.43 million gallons. In a recent study by the U.S. Army Corps of Engineers average daily water use and maximum daily water use are expected to increase by 1.15 MGD and 3.14 MGD over the next 50 years, respectively. In light of these developments, the City has made several attempts to secure additional water supplies in the Saline River valley, the High Plains aquifer, and farther upstream on Big Creek. More recently (Summer, 1987), Hays has contracted with a consultant to look for additional water supplies in the Dakota aquifer in Ellis County and some test drilling has been done to evaluate some possible sites for future hydraulic testing. It is clear that the future demand for water cannot be supported by the available sources in the Big Creek and Smoky Hill valley well fields.

Recently, an intensive ground-water use control area was declared in the Smoky Hill River Valley by the Chief Engineer, Division of Water Resources, that includes both the Hays well field at Schoenchen and Russell's well field at Pfeiffer. This action was taken out of concern that the stream/aquifer system in the Smoky Hill River Valley was over-appropriated for use. The Smoky Hill Task Force found that the demand for water frequently exceeds the supplies available in the river valley. The Task Force also found that no water is being released from Cedar Bluff Reservoir due to drastic depletions in the rate of inflow to the reservoir. As a result in the vicinity of the Hays and Russell well fields the stream bed is dry most of the year and the saturated thickness in the alluvium is diminished as much as 40% much of the year.

Western Kansas will likely face several serious economic and social problems in the coming decades as a result of water shortages. Areas of the High Plains aquifer where the saturated thickness is either small or negligible will continue to grow in size especially during times of drought. Most experts agree that some form of severe drought is likely to occur at least once during the 1990's. It is also clear that some regions of the High Plains aquifer are going to be more seriously affected than others. Specifically, the northwest and west-central portions of Kansas will be effectively dewatered first because of a lack of significant recharge from precipitation or from interactions with other aquifers. In other areas where the water table is closer to the surface, the soils are more permeable, or the High Plains is receiving recharge from other aquifers, the depletion rate will be slower.

Appendix B: Summary of Previous Research on the Dakota and Related Aquifers in Kansas.

Geologic Investigations Focusing on Stratigraphy and Depositional Environments

Studies focusing on the stratigraphy and depositional environments of the Lower Cretaceous have been conducted along the outcrop and in the subsurface of Kansas, Nebraska, and Colorado since the late 1800's. Only the most recent of these investigations will be mentioned here in this short review. Excellent summaries of the nomenclatural history of the Lower Cretaceous are given by Latta (1946), Merriam (1963), and Franks (1966).

Since the Dakota group was defined by Meek and Hayden (1861) the name has been applied in different ways and in different places to various sedimentary sequences composed of Lower Cretaceous sandstones and shales. These studies have largely dealt with rocks exposed at the surface. The Cheyenne and Kiowa have been recognized as formations since they were defined by Cragin in 1889 and 1894, respectively (Latta, 1946). The Dakota has been officially recognized as a formation by the Kansas Geological Survey since 1942 when the term was restricted to cover the sequence between the base of the Graneros Shale and the top of the Kiowa Formation. Plummer and Romary (1942) subdivided the Dakota Formation into two members, the Janssen Clay member above and the Terra Cotta Clay member below, based on field work along the outcrop in central Kansas.

Somewhat later an investigation by Swineford and Williams (1945) was conducted to determine the eastern extent of the Cheyenne Sandstone in the subsurface in part of Russell County. As part of their work they determined some diagnostic features of the Cheyenne that could be used to discriminate this unit from the underlying Lower Permian age Cedar Hills Sandstone and the overlying Kiowa and Dakota Formations in that area. This study was conducted at the request of the State Board of Health out of concern that insufficient geologic criteria were being used to approve the shallow disposal of oil-field brines in the Cheyenne Sandstone. Swineford and Williams examined drill cuttings and the light and dark fractions of insoluble residues of the drill cuttings. They found that differences in grain size and roundness of the sandstones and the composition of the insoluble residue suite could be used to locate formational boundaries in the part of Russell County they investigated. However, they did not try to extend their correlations to the outcrop east of their study area.

Merriam (1957) renamed the formation the Omadi in an attempt to correlate the Kansas Lower Cretaceous rock section with the same section as defined farther north in Nebraska. He defined three members which are, from oldest to youngest, the Cruise, the Huntsman, and the Gurley. In this scheme, the Dakota was elevated to group status including, from oldest to youngest, the Cheyenne, the Kiowa, and the Omadi Formations. These formational names were applied to the subsurface by Merriam (1957; 1963) and used to show the stratigraphic relationships between the various Mesozoic-age rock units in the subsurface of western Kansas. This terminology has not been adopted by the Kansas Geological Survey.

Stratigraphic relations between the Dakota and Kiowa Formation were studied by Franks (1966) along the outcrop in central Kansas. Later work by Franks (1975) recognized the close relationship between interpretation of depositional environment and the stratigraphic boundaries between the formations. Previously, Twenhofel (1920, 1924) and Tester (1931) had concluded that the two formations were conformable and gradational laterally and vertically. This conclusion was based on the occurrence of sandstones containing leaf fossils similar to those found in the in Dakota below rocks containing fossils characteristic of the Kiowa. The concept of the intertonguing of the two units led to the development of a large scale deltaic model of sedimentation involving the two formations.

Franks' field mapping of the outcrop areas shows the contact between the two units to be disconformable locally. In some cases, sharp contacts abruptly separate, Dakota clay rocks from sandstones and clay rocks in the Kiowa and, in other instances, basal sandstones in the Dakota rest on interbedded sandstones and clay rocks in the Kiowa. This is illustrated schematically in Figure 8 using a the cross-section of Lower Cretaceous geology in Central Kansas. Franks has interpreted the upper part of the Kiowa to be part of a regressive sequence of interbedded shales and sandstones. The upward increase in grain size and increase in kaolinite in the Kiowa marks the onset of regressive conditions. In the Dakota, the occurrence of conglomeratic sandstones and red-mottled clay rocks at the base of the Dakota signifies the development of alluvial depositional systems on top of the Kiowa.

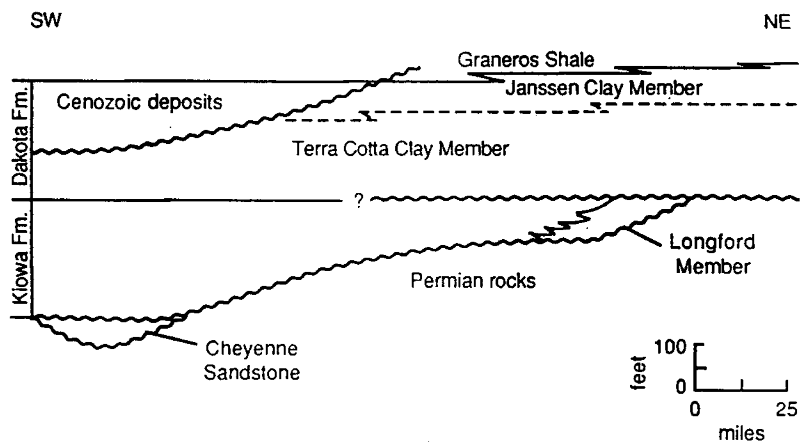

Figure 8. Schematic geologic cross-section of the Lower Cretaceous along the outcrop, central Kansas. Modified from Franks (1975).

This interpretation is consistent with a transgressive-regressive model of sedimentation that has been proposed for the deposition of the Cheyenne, Kiowa, and Dakota sequence of formations in Kansas (Franks, 1975). The Cheyenne and Kiowa Formations record a northeastward transgression of the sea across Kansas. Sedimentation was governed by the kind and rate of supply of sediment to the basin and the rate of subsidence during early Kiowa time (Franks, 1980). These rocks were deposited in and near the eastern margins of the Early Cretaceous epicontinental sea that spread over the southern Western Interior.

Near the Lower and Upper Cretaceous boundary in the upper part of the Dakota in north-central Kansas, clay rocks of the Jannsen member are interbedded with lenticular sands of the Rocktown Channel sandstone. These rocks are interpreted as having been deposited in a deltaic complex under the influence of a transgressing Graneros sea (Franks, 1975; Siemers, 1971, 1976). The Rocktown Channel sandstone body has been divided by Siemers into two major subfacies, grading within approximately 30 miles from a highly sinuous distributary channel into estuarine and delta-front sandstones. A lower cross-bedded sandstone subfacies is 54 to 66 feet thick and 900 to 1800 feet wide and is more less confined to a sinuous, elongate v-shaped trough whereas the upper flat-bedded subfacies forms an elongate tabular-shaped unit which caps the unit below. These rocks reflect an increasingly marine character to the style of sedimentation in the upper part of the Dakota westward of the outcrop as the upper part of the Dakota intertongues with the Graneros in northwest Kansas (Hattin, 1965).

Franks (1975) interpretation of the geologic framework along the outcrops shows a progressive overlapping of older Lower Cretaceous stratigraphic units on the Cretaceous-Permian boundary from southwest to northeast across Kansas. The Cheyenne Sandstone is present only in southern Kansas and does not extend very far northward of the outcrop in the subsurface. This contradicts the earlier work of Merriam (1957) which shows that the Cheyenne Sandstone is present in much of the subsurface of western Kansas. However, Franks (1979) points out that the lower part of the Kiowa Formation, the so-called "Longford member", resembles and has been confused with the Cheyenne Sandstone. These rock units are not time equivalent even though they are similar in aspect (Scott, 1970). To the north of the Cheyenne outcrop the unit pinches out and the Kiowa Formation rests directly on the Cretaceous-Permian boundary. Near the Nebraska-Kansas border, in the north central part of the Kansas, the Kiowa is not present and the Dakota rests directly on the Lower Permian.

Hydrogeologic Investigations of the Dakota Aquifer Related to Kansas

Many KGS and U.S. Geological Survey reports dealing with the hydrogeology and water quality of the Dakota and other Lower Cretaceous bedrock aquifers in Kansas have been prepared over the years. KGS reports of studies dealing with the hydrogeology of the Dakota aquifer are: (1) the Bulletin Series covering parts or all of those Kansas counties located within the areal extent of the Dakota

Formation; (2) the Irrigation Series containing the results of ground-water quality reconnaissance and hydrogeologic investigations in Kansas, in particular the results of Keene and Bayne (1977), Lobmeyer and Weakly (1979), Gutentag et al., (1981), and Kume and Spinazola (1985); and (3) the Chemical Quality Series containing ground-water chemical quality data on the Dakota aquifer in the Ground-water management districts of Kansas. Reports by the U.S. Geological Survey appropriate to this review are: (1) the numerous Open-file reports that contain the data collected by USGS and some reports, most notably Watts (1985); and (2) the professional papers that will result from the work of the CM RASA Program on the Dakota and associated aquifers. Additionally, there are many unpublished reports from State agencies and theses from universities that pertain to the Lower Cretaceous bedrock aquifers in Kansas, including a review by Crooks (1975) and the results of a modeling study of the Dakota and associated aquifers in and around the Denver-Julesburg Basin by Belitz (1985).

Perhaps the most important study of the Lower Cretaceous bedrock aquifers has been conducted recently under the U.S. Geological Survey's CM RASA Program (Helgeson et al., in review). They have prepared a report that discusses the regional hydrogeology and water chemistry of the Lower Cretaceous bedrock aquifers (renamed the Great Plains Aquifer System) in a multi-state 170,000 square mile area that includes parts of Kansas, Nebraska, Wyoming, Colorado, New Mexico, and Oklahoma (including all of the Denver-Julesburg Basin).

This investigation was conducted by compiling existing geologic, hydrologic, water use and water chemistry information about the Lower Cretaceous and other interacting aquifers from the literature into several databases. Sources of data included published and unpublished reports of all the state water agencies in the project area and USGS District Offices, data from the petroleum industry, and the water well industry. No attempt was made to gather new data from field work to fill in where the existing data bases were deficient. From the compiled data a mathematical simulation of ground-water flow within the Lower Cretaceous bedrock aquifers was produced using a four-layer computer model. Hydrologic properties of the various hydrostratigraphic units were input into the model that were regionally representative of the aquifer materials and the water chemistry.

Helgeson et al. have concluded that the Lower Cretaceous bedrock aquifer system is in general underpressured in the Denver-Julesburg Basin of northeastern Colorado, southeastern Wyoming, and western Nebraska. This has occurred for two reasons: (1) recharge from the west is restricted due to faulting along the Front Range on the west side of the Denver-Julesburg Basin and (2) the eastward rate of flow in the aquifer out of the Basin toward discharge areas increases due to eastward increases in the permeability of the aquifer. The eastward increase in permeability of the Lower Cretaceous has been interpreted to be the result of lowered effective stresses on the aquifer materials. This is due to a progressive thinning of the overlying sedimentary section eastward of the axis of the Basin. In the center of the Basin the ground-water flow system may be stagnant due to the extremely low permeability of the sandstones and the lack of continuity of the sandstone lenses. Belitz (1985) has arrived at similar conclusions concerning the regional flow of ground waters in the Denver-Julesburg Basin from his modeling studies.

The primary ground-water flow path in the Dakota aquifer is from the southern outcrop areas in southwest Kansas, southeastern Colorado and northeastern New Mexico northeastward almost parallel to the orientation of the Lower Cretaceous outcrop in Kansas and Nebraska to discharge areas in northern Kansas and Nebraska. Recharge to the Lower Cretaceous bedrock aquifers comes from leakage from overlying units where the Dakota aquifer is in contact with the High Plains aquifer and through fractures in the confining units, from underlying bedrock aquifers in contact with the Lower Cretaceous, and from precipitation in the outcrop areas.

In their evaluation of the Lower Cretaceous bedrock aquifer system, Helgeson et al. note that the variations in water chemistry appear to be related largely to the degree that the Lower Cretaceous units have been flushed of their formation waters. Calcium-bicarbonate and mixed cation-mixed anion type waters are found near the outcrop areas whereas sodium-chloride type waters are contained in the Lower Cretaceous bedrock aquifers where these rocks are more deeply buried and have not been flushed by recharge waters, and are being recharged by saline waters from the underlying Permian. The data used to characterize the deeper portions of the aquifer were insufficient or non-existent in northwest and central Nebraska due to the lack of data from those areas.