Determination of potential recharge to the Ogallala aquifer in western Kansas and associated vertical flow rates in the unsaturated zone using isotopes, inorganic chemistry data and other tracers

by

Sabine Bock

Kansas Geological Survey Open-file Report 90-33a

List of Figures

List of Tables

Introduction

The Ogallala aquifer represents the most important water resource for western Kansas. In 1988, 98.3 % of the water being withdrawn was used for irrigation; compared to this amount, domestic, municipal, and industrial usages are only of minor importance. Because the irrigated agricultural economy is solely dependent on Ogallala ground water, declining water levels due to advanced irrigation techniques since the 1960's are of serious concern. Basically, the Ogallala aquifer is being mined; with an average annual precipitation of about 460 mm to 580 mm, recharge is estimated to be only 4 mm/year to 14 mm/year (O'Connor & McClain, 1982). These recharge values are based on actual water level declines and model predictions.

The intent of the presented research was to determine: 1) at what rate is the Ogallala aquifer potentially being recharged; and 2) how important are intermittent streams, playa-like structures and lineaments for contributing recharge to the Ogallala aquifer? For this purpose an attempt was made to date the ground water and the soil water in the unsaturated zone and thus be able to distinguish between older and younger waters. Several different approaches were tried to determine the best suitable dating methods: tritium, the stable isotopes oxygen-18 and deuterium, freon, atrazine, nitrate, and standard inorganic chemistry. In addition, one well was sampled for carbon-14. The combination of the isotopes with the standard inorganic chemistry, especially nitrate clearly worked best for identifying recent recharge.

The project was started in November 1987 and divided into two phases. Phase 1 concerned the establishment of the most suitable analytical method to date the Ogallala ground water, and phase 2 expanded the sampling net and, based on the results of phase 1, concentrated more on the unsaturated zone.

The chosen study area is more or less outlined by Northwest Kansas Groundwater Management District 4 (Fig. 1).

Figure 1: Location of study area

Except for one site, all monitoring well sites are located close to lineaments, which were mapped from satellite imagery (McCauley, 1988). Three of the 11 research sites are located in the vicinity of intermittent streams, and one site is located in a playa-like structure.

A total of 15 wells, eight of which were installed as monitoring wells by the Kansas Geological Survey have been sampled throughout the study. Ground water samples were taken in November 1987 and analyzed for standard inorganic chemistry, tritium, stable isotopes, freon, and atrazine. In August 1989 and November 1989 only samples for standard inorganic analyses were collected. A carbon -14 age determination was performed on one ground water sample.

Soil water from three lysimeters was collected frequently from December 1988 to November 1989 for standard inorganic chemistry analyses, whereas tritium and stable isotope analyses were performed once. One lysimeter was sampled for tritium in three different months, March, June, and November 1989.

At three sites soil cores were taken and tritium content, particle size, calcium carbonate content, nitrate, atrazine (spot check), moisture, and porosity were determined. However, it was not possible to analyze consistently all the cores taken for these parameters.

A precipitation sample was collected in November 1987 and subsequently analyzed for tritium, stable isotopes, and freon. An additional precipitation samples was collected in October 1989 and analyzed for tritium only.

A stream sample was collected in March 1989 and tritium, stable isotope, and inorganic chemistry analyses were performed.

A tritium input function based on data compiled by the International Atomic Energy Agency was established for the study area to estimate the theoretical tritium input via precipitation over the last 36 years. Thus it became possible to predict the order of magnitude of the tritium concentration left in 1989 after radioactive decay in either the unsaturated or the saturated zone from the emissions in 1961/62 and to compare the theoretical value with actual field data.

The rate of vertical movement of soil moisture through the thick loess cover in the unsaturated zone was determined as well as the amount of precipitation that entered the unsaturated zone as recharge during the period from 1962 to 1989.

A differentiation between older and younger ground water in the Ogallala aquifer was possible and thus potential site specific rates of vertical flow in the unsaturated zone could be determined.

Chapter 1

Climate

Several factors influence the climate in Kansas:

1. Location

The state of Kansas is located between 37° N and 40° N latitude, approximately on the same latitude as Sicily. In summer the inclination of the earth on its axis causes the incoming radiation to be considerable, whereas in winter the sun's rays are more oblique and distributed over a wider surface. The longer daylight hours in the summer support the accumulation of heat during this season.

2. Land/water ratio

The closest water body to Kansas is the Gulf of Mexico, more than 5800 airline kilometers to the south. The climate in Kansas is thus continental, with great temperature differences between summer and winter.

3. Westerlies and jet stream

The state lies in the zone of the prevailing westerlies which can account for tornadoes in the summer and blizzards during the winter. The position of the jet stream, a fast moving stream of eastward moving air within the high westerlies, represents another climatic factor. It is associated with large arctic air masses that at times move out of the polar regions.

4. Altitude

Elevation in Kansas ranges from 1227 m in western Kansas to 213 m above sea level in southeast Kansas. The highest point is Mount Sunflower in western Kansas with 1227 m above sea level. The total relief in Kansas is 1014 m, rising gently from east to west at about 3 m per 1.6 km (Self, 1987). Climate differences are associated with the change in elevation, temperatures change at an average rate of 2° C per 305 m elevation.

Temperatures in Kansas can drop very suddenly in only a few hours. The lack of mountain ranges within the state allows weather systems to move in and pass very quickly.

Three climatic types can be distinguished in Kansas (fig. 2): humid subtropical, temperate continental (warm summer subtype), and middle latitude steppe (semiarid) (Trewartha et al., 1967). The study area belongs to the mid-latitude steppe climate type. Precipitation is sparse because winds from the Pacific Ocean lose most of their moisture in the Rocky Mountains before reaching Kansas. Moisture from the Golf of Mexico seldom reaches western Kansas because of the great distance between these two areas and the deflection of air masses to the east rather than to the west over the midcontinent.

Fig. 3 shows the distribution of precipitation over Kansas. Fig. 4 shows the location of weather stations in the study area and in Decatur County.

Fig. 5 depicts the annual precipitation and annual air temperature from 1958 to 1988 for three stations in the study area and another station in Decatur County. It is obvious that the precipitation increases from west to east in the study area. The northernmost station in Decatur County shows the highest amount of precipitation. The average temperatures vary according to altitude. Goodland and Colby are located on a higher elevation than Hoxie and Oberlin. Hoxie shows the lowest elevation and the highest temperature.

Fig. 6 depicts average monthly precipitation for the time period from 1958 to 1988 for the weather stations within the study area. The westernmost station in Goodland shows the lowest precipitation values, except for January and December. Higher precipitation in these months is probably due to more snowfall in that area compared to Colby and Hoxie, caused by higher elevations and a more westerly location. Snowstorms generally move in from the west into Kansas.

The easternmost station, Hoxie, shows the highest precipitation values except for June and July when Colby receives more rain.

Generally, the trend for precipitation in the study area is that of a decrease toward the west.

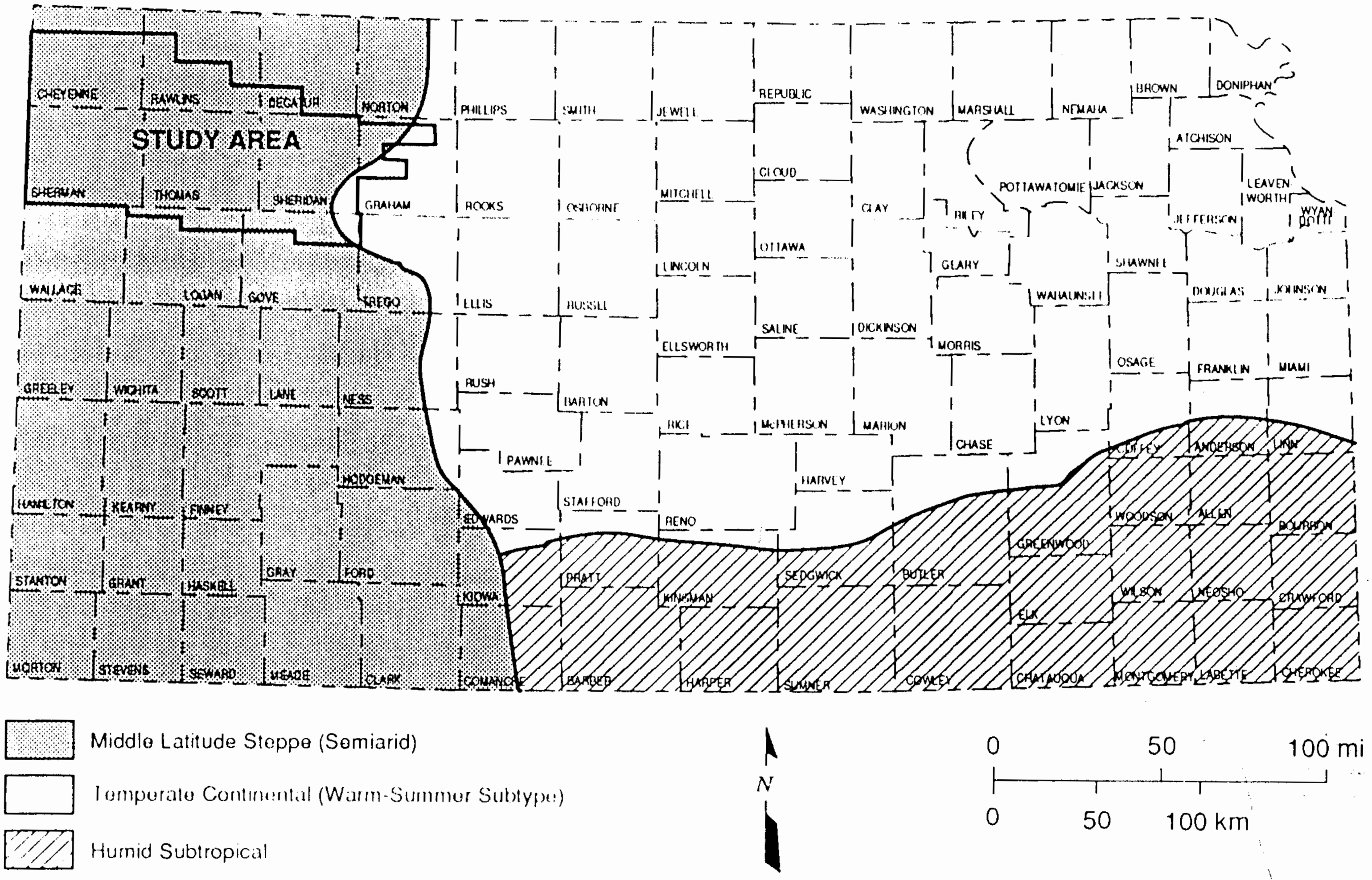


Figure 2: Climates in different parts of Kansas, modified from Self (1978)

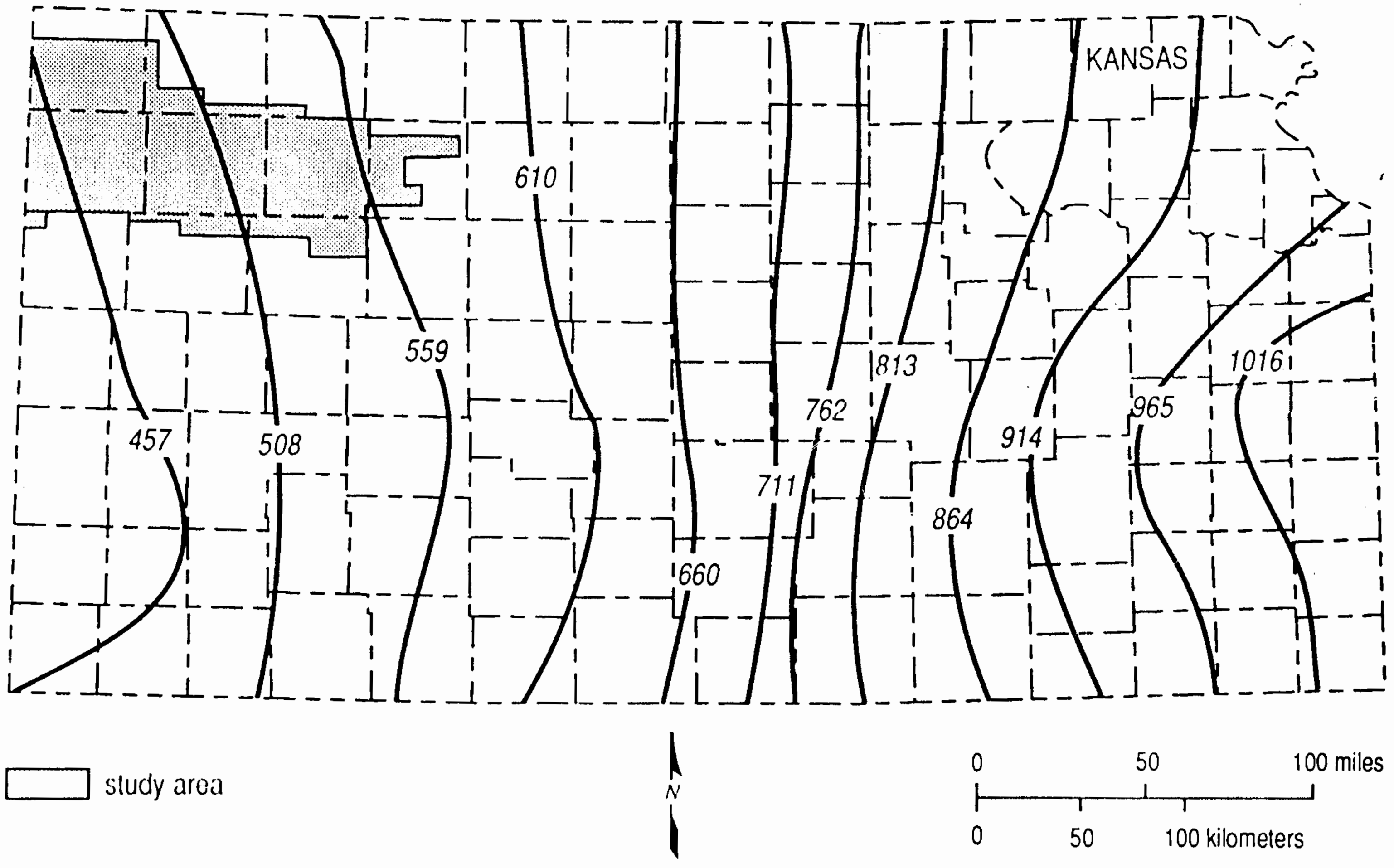


Figure 3: Study area and mean annual precipitation in mm, 1941 - 1970 (data from the Kansas Agricultural Experiment Station) modified from United States Geological Survey, 1978

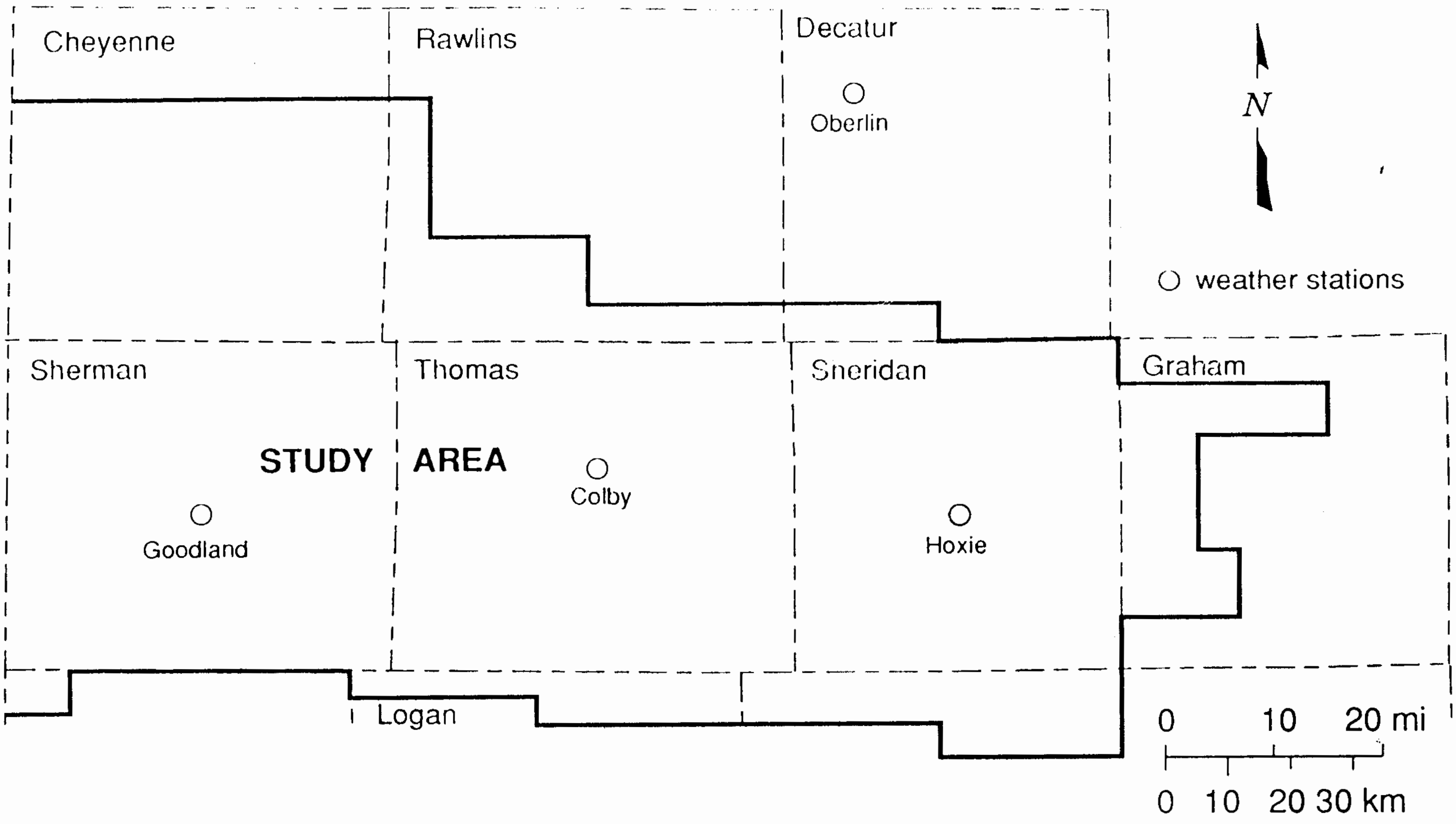


Figure 4: Weather stations in the study area

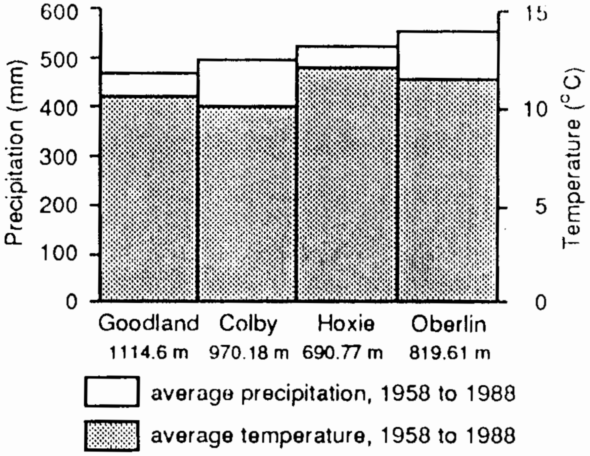


Figure 5: Average precipitation and average temperature from 1958 - 1988 in the study area

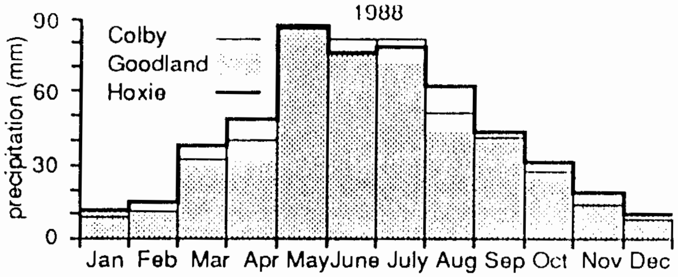


Figure 6: Average monthly precipitation in 1958 -1988 in the study area

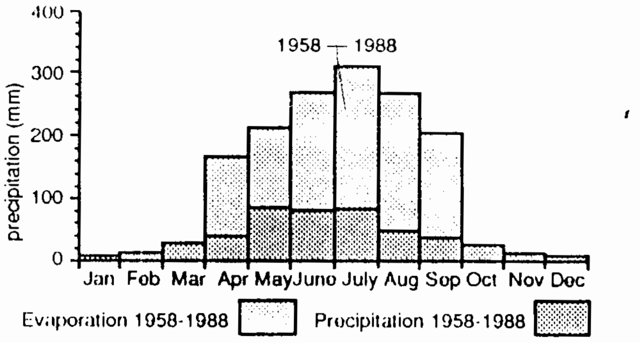


Figure 7: Average evaporation and precipitation from 1958 - 1988 at the Colby weather station

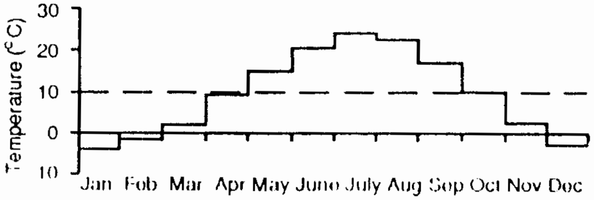


Figure 9: mean monthly air temperature at the Colby weather station, from 1958 - 1988

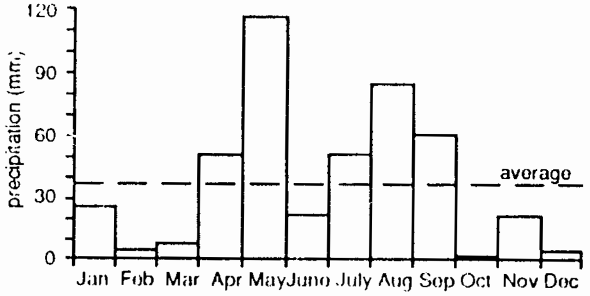


Figure 10: Precipitation in 1988 at the Colby weather station

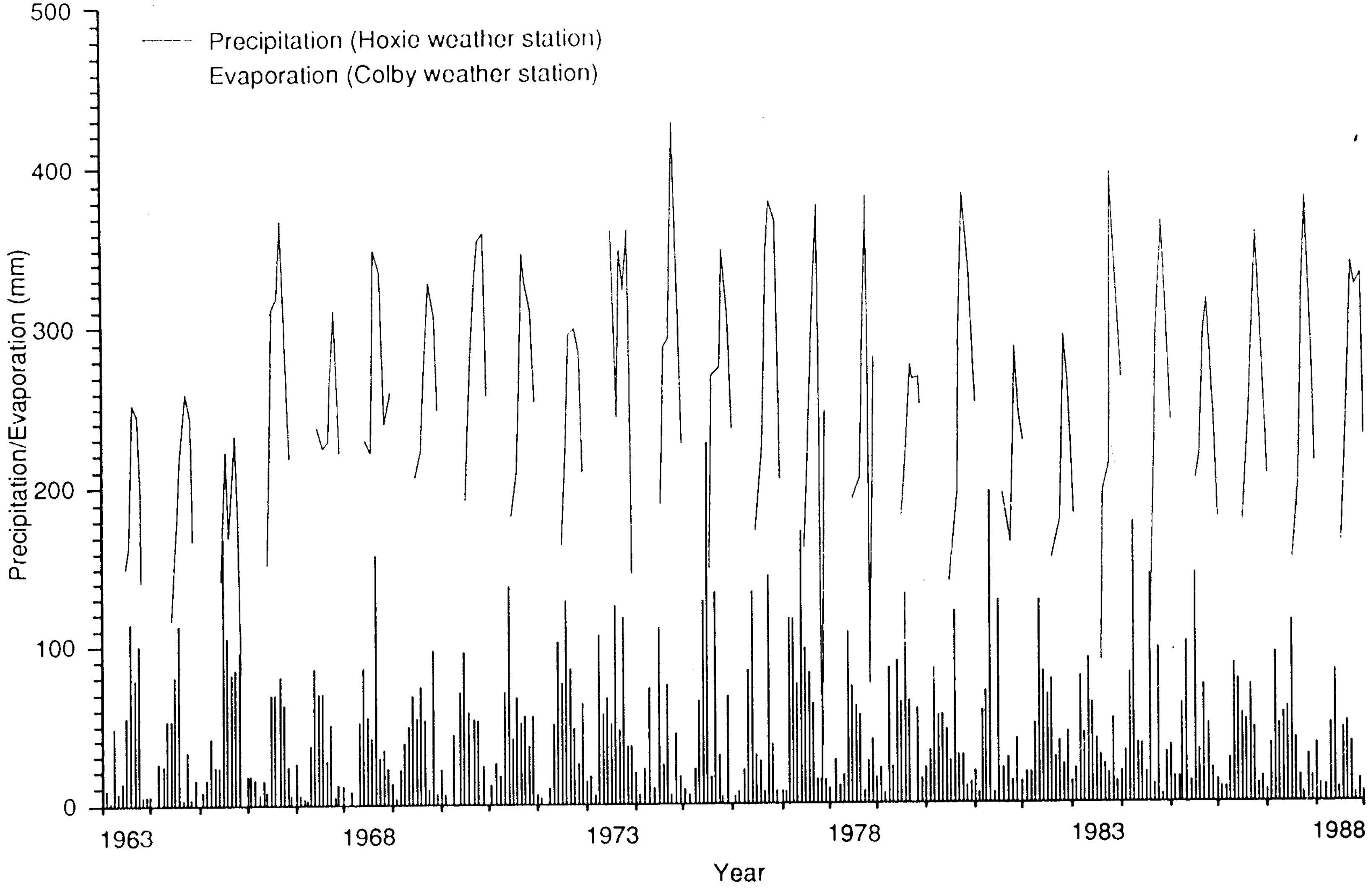


Figure 8: Precipitation and evaporation from 1963 to 1988 in the study area

Most of the precipitation falls during the summer months from May to August, however, evaporation greatly exceeds the amount of precipitation in the summer. High temperatures and brisk wind movement combined with the overall semiarid climate cause the high evaporation rate.

Fig. 7 shows average monthly precipitation from 1958 to 1988 and average monthly evaporation from April to September for the same time frame at the Colby station. Evaporation data are available only for this one station and only for a six months period. Frosts occurring from October to March prevent the collection of average monthly evaporation data for these months.

Evaporation exceeds precipitation by up to 400%, thus the necessity of irrigation for agriculture becomes obvious. Fig. 8 depicts the average monthly precipitation from 1963 to 1988 recorded at the Hoxie weather station and the average monthly evaporation for the same time period at the Colby weather station.

Recharge to the Ogallala aquifer is, based on figs. 7 and 8, is non-existent during the summer months.

Fig. 9 shows the average monthly air temperature in Colby from 1958 to 1988. The coldest month is January with an average air temperature of -3.7 °C, the hottest month is July with 24.5 °C on the average. The mean average air temperature for the 31 year period is 10.1 °C.

Mean annual precipitation at the Colby weather station from 1958 to 1988 is 492 mm. In 1988, the total precipitation was only 442 mm, the average monthly precipitation was 38 mm (fig. 10). In 1989 precipitation from January to April was only 38 mm. Drought conditions combined with a dust storm in the spring of 1989 caused great crop damages in the study area.

Chapter 2

Topography

Fenneman (1931) classified Kansas as part of the High Plains section of the Great Plains physiographic province. Fig. 11 shows the physiographic regions of Kansas.

Western Kansas, including the study area, presents itself as a broad, feature-and treeless, mostly grass covered plain, sloping gently from west to east at an average rate of 3 m to 8 m per 1.6 kilometers (Self, 1978, O'Connor & McClain, 1982). The native vegetation is short prairie grass.

Fig. 12 depicts the streams present in the study area . Only three streams are partly perennial, the South Fork Republican River, Beaver Creek, and the South Fork Solomon River. All other streams have intermittent character.

Upland areas are generally marked by numerous undrained depressions, ranging in diameter from a few feet to several miles.

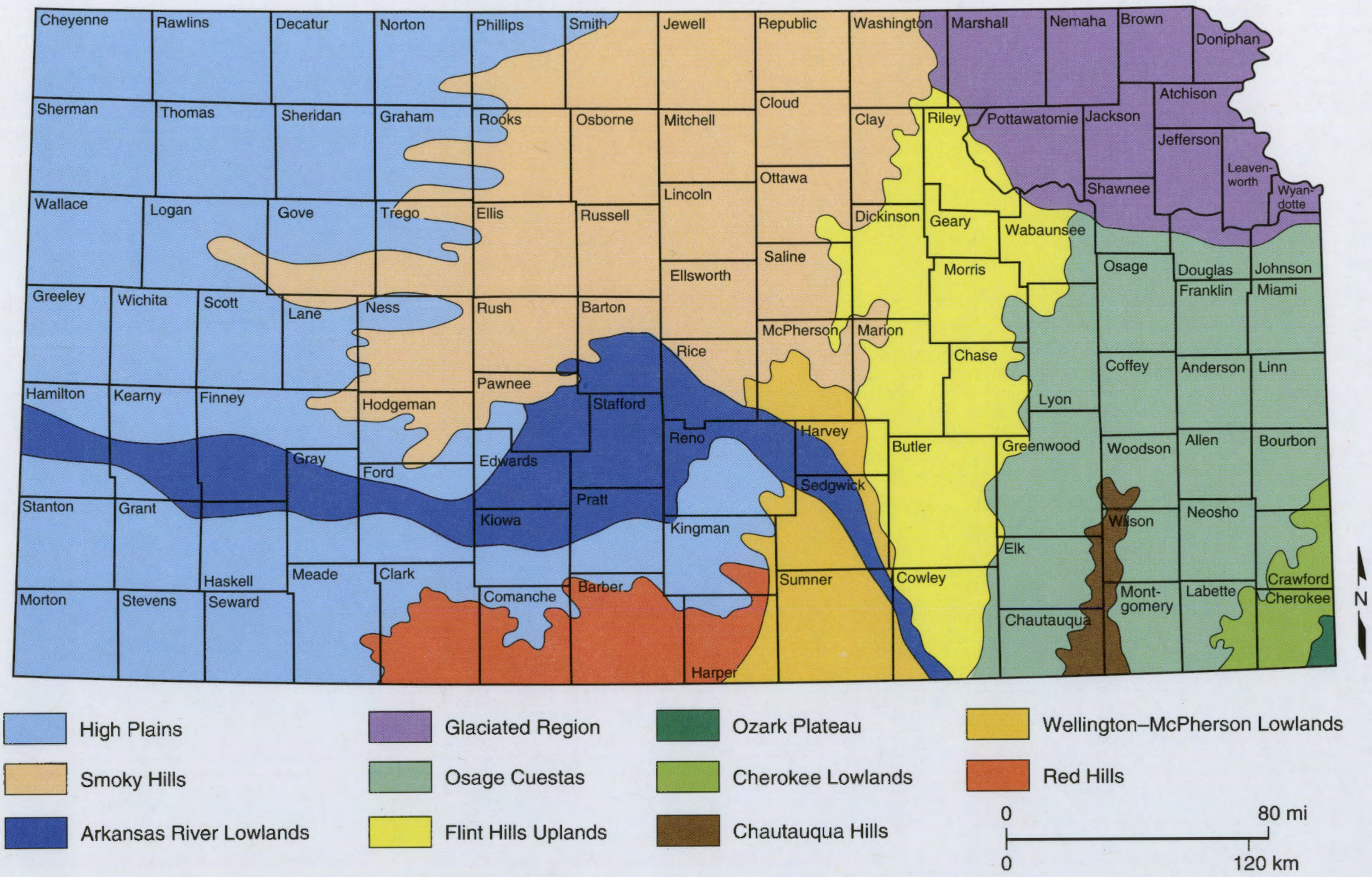
The location of the study area is shown in fig. 1. The study area coincides with the boundaries of Groundwater Management District No. 4, which overlies part of the Ogallala aquifer with at least 15 m of saturation.

The study area covers a total of 12740 km^2. Only five bigger communities are located within this area: Goodland, Colby, Hoxie, Oakley, Bird City, and St. Francis (fig. 13).

In 1984 Goodland and Colby were the only towns with a population greater than 5000, the total population of northwest Kansas at that time was 43130 (Socolofsky & Self, 1988). According to a 1987 population estimate, the population in northwest Kansas is declining (Helyar, ed., 1988).

Agriculture is the most important source of income in northwest Kansas. In the nine county area encompassing the study area a total of 4648 farms existed in 1987, with a combined area of 22460 km^2 (Helyar, ed., 1988).

Generalized Physiographic Map of Kansas



Kansas Geological Survey
The University of Kansas
1930 Constant Avenue
Lawrence, Kansas 66047

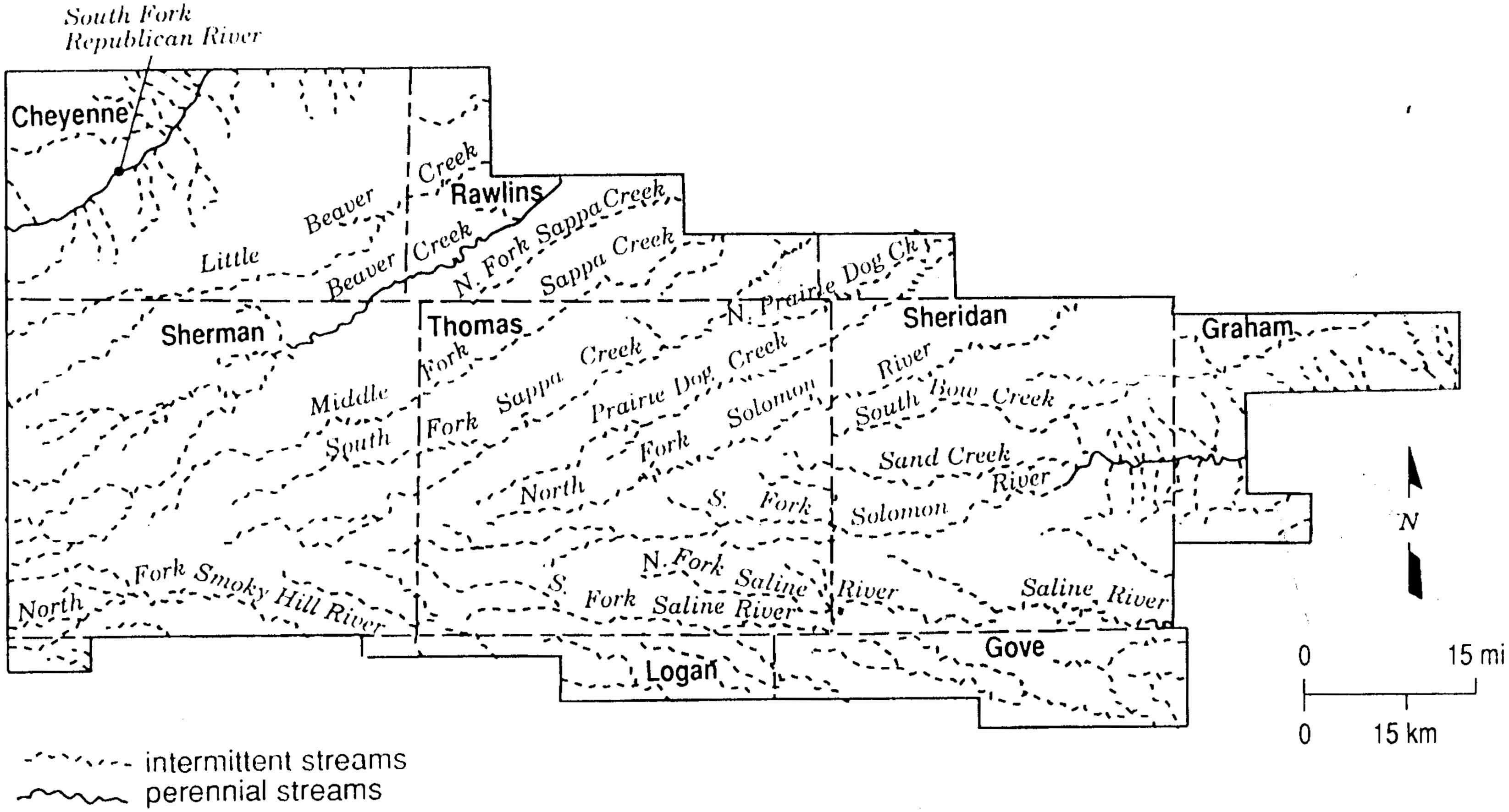


Figure 12: Surface drainage in the study area

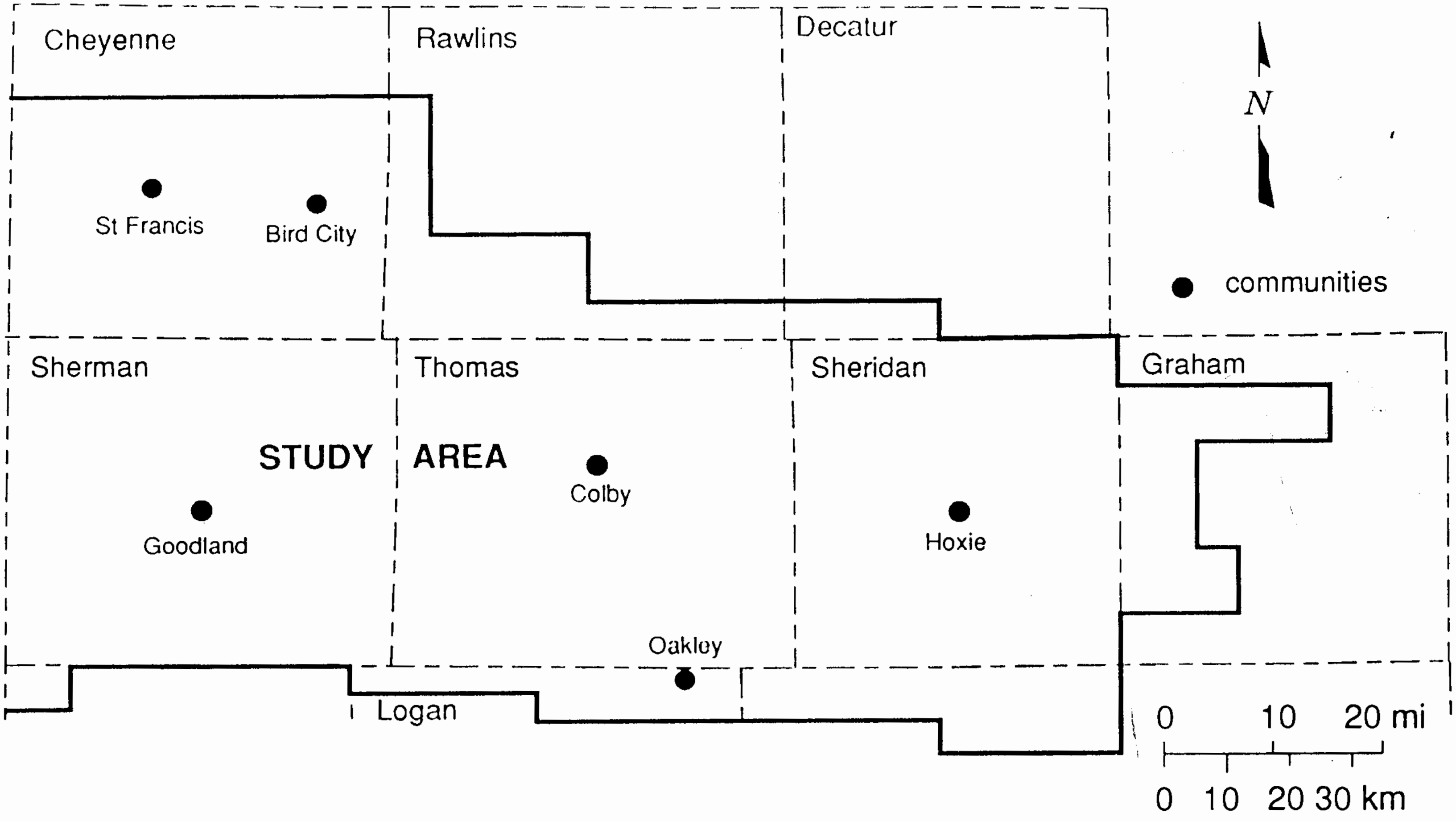


Figure 13: Communities in the study area

Wheat is the main product, corn is raised under irrigation and sorghum is the usual substitute to wheat production.

Livestock production is the smallest in this region compared to the rest of the state (Socolofsky & Self, 1988), probably due to the semiarid climate.

Chapter 3

Geology

General Geologic History of Kansas

A very extensive summary of Kansas geology is given by Merriam (1963) and in Zeller (1968). In the following, a short and basic overview of Kansas geologic history is presented.

Kansas is situated on the southern extension of the Canadian shield, in the so-called "Central Stable Region" (Eardley,1949) of the North American continent (Fig. 14). Due to this stability, which prevailed since the end of the Precambrian the sequence of sedimentary rocks covering Kansas attains a maximum thickness of only about 2900 m.

The relative stability is also shown by the surface geology map of Kansas (Fig. 15). The cross section depicts nearly horizontally bedded stratigraphic units dipping gently towards the east. The uniformity is only interrupted at the Nemaha Anticline, where the strata are bent upwards to as much as a 5° angle in the surface beds (Merriam. 1963). However, the structure is much more pronounced in the subsurface. The Nemaha Anticline is a prominent paleozoic structure, which extends from Nebraska all across Kansas into Oklahoma and is still tectonically active. Of the 43 earthquakes recorded in Kansas since 1811, 24 had epicenters within Kansas and 10 were very close to the axis of the Nemaha Anticline (Merriam, 1963).

Typically, most of the rocks comprising Kansas geology were deposited in a shallow-shelf environment. During the early Paleozoic era, Kansas was above sea level, but in the middle Cambrian time the land submerged slowly and an interior sea covered the area until uplift in the Ordovician began. Dolomites, sandstones and limestones were deposited, unconformably overlying the Precambrian bedrock. Throughout much of the Paleozoicum the sea level fluctuated and thus the paleozoic stratigraphy is characterized by alternating marine/non-marine sediments. Much of these limestones, dolomites , shales and sandstones deposited during the marine intervals were eroded during times of uplift, only

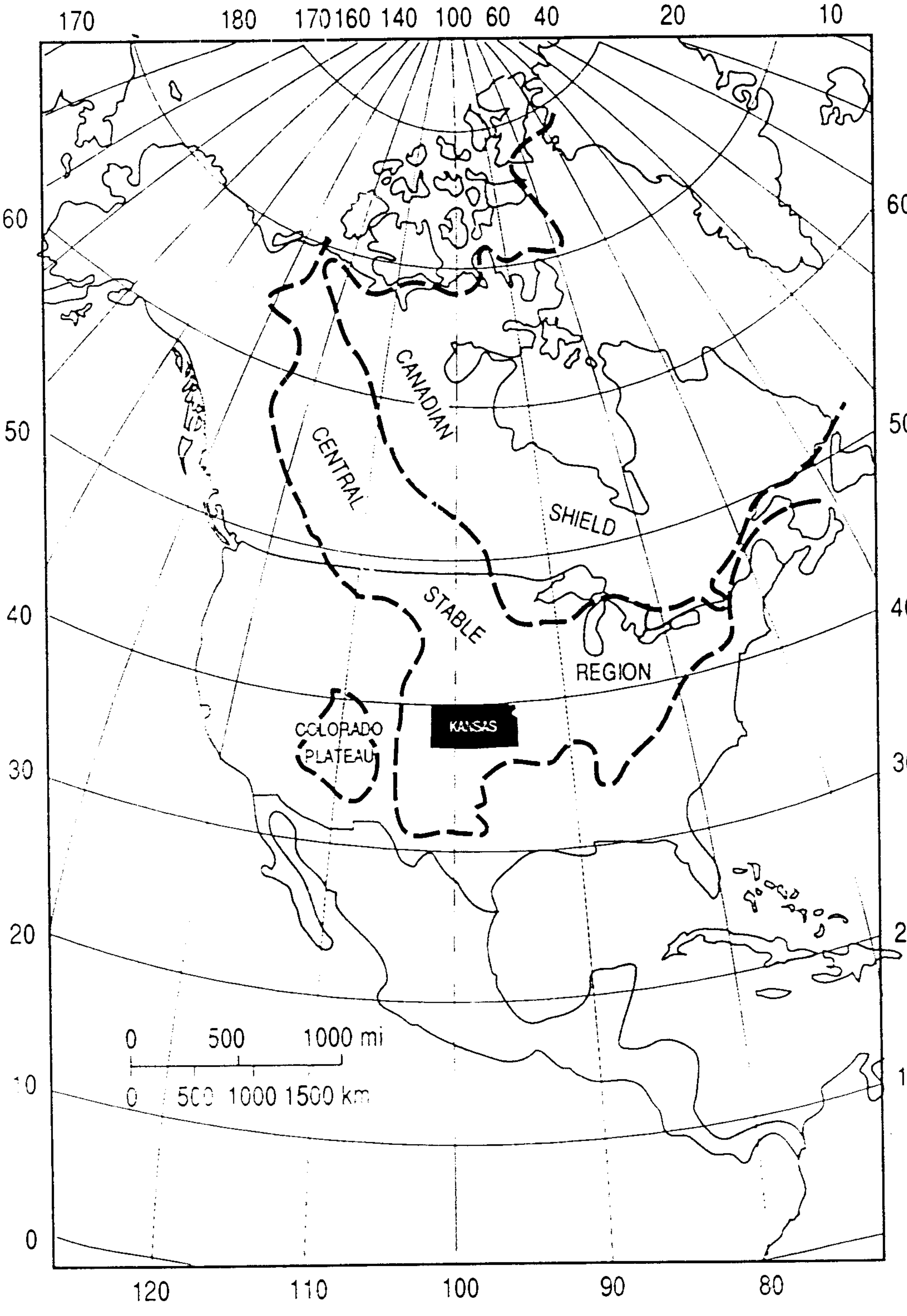
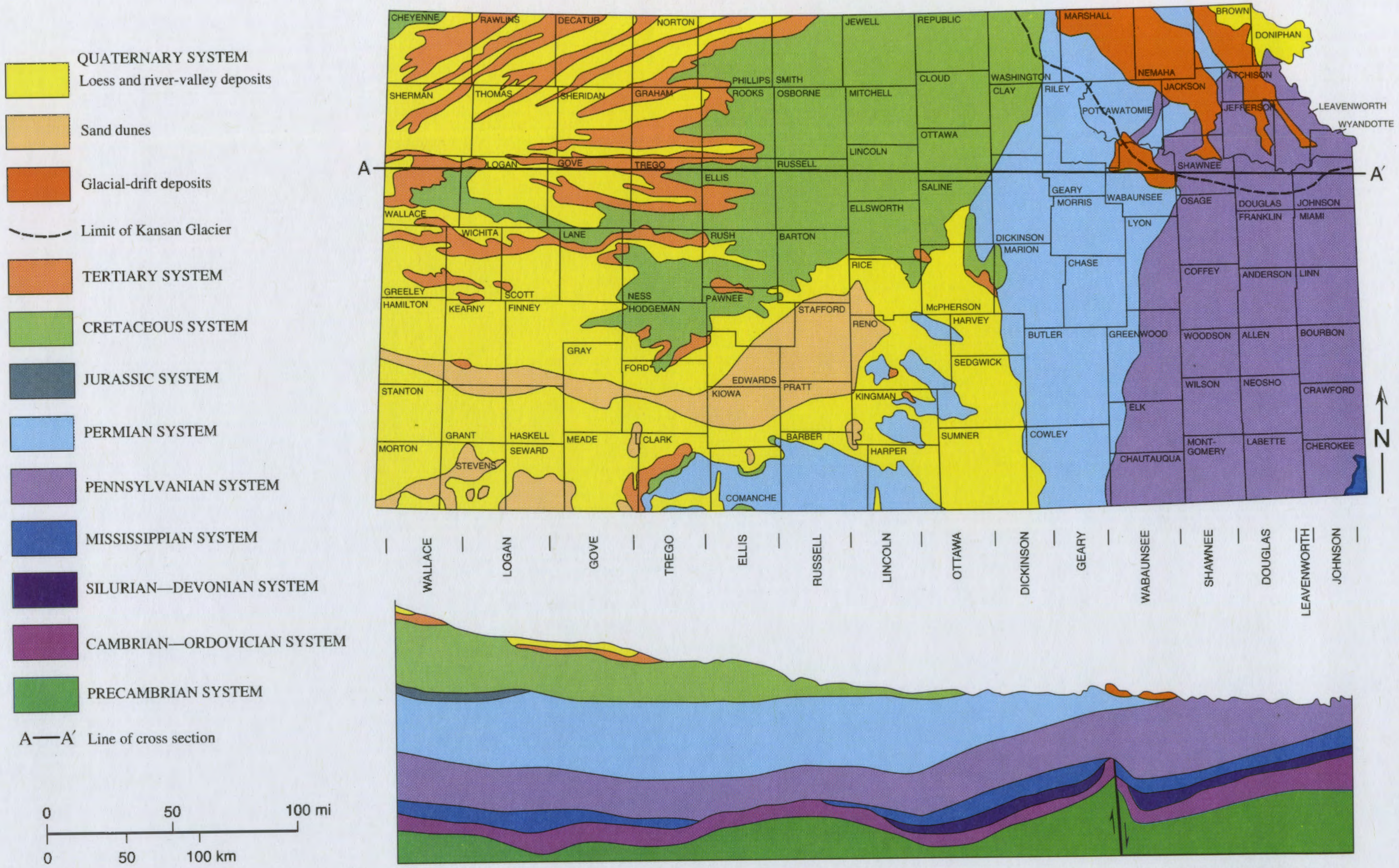


Figure 14: Kansas as part of the Central Stable Region, modified from Eardley (1951) and Merriam (1963)

Generalized Geologic Map of Kansas



Geologic cross section below I—70

Kansas Geological Survey
The University of Kansas
1930 Constant Avenue
Lawrence, Kansas 66047
www.kgs.ukans.edu

January 2000

structural and stratigraphic basin-fills were preserved. Coal and Lignite deposits were formed periodically during all of the middle and upper Pennsylvanian. Currently, these deposits are mined in southeast Kansas.

During the Permian, regression dominated over transgressive phases and red shales, sandstones, beds of salt, anhydrite, and gypsum were deposited.

A pronounced unconformity marks the beginning of the Mesozoicum. The area was uplifted and remained above sea level during Triassic and early Jurassic times. In the late Jurassic the sea transgressed again. Deposits of this era are very rarely found in Kansas. The geologic cross section (Fig. 15) shows strata this age only in western Kansas. This is probably due to the fact that the Jurassic transgression did not last long. It was followed by an uplift either at the end of the Jurassic or the beginning of the Cretaceous. Again a sequence of marine and non-marine depositional cycles followed.

The remainder of the Cretaceous period is characterized by marine conditions and hundreds of meters of limestone, chalk and shale were deposited. The only Cretaceous deposits cropping out locally in the study area are the Pierre Shale and the Niobrara Chalk. Overall the sediments of this period are very similar to the ones deposited during the Paleozoicum, except for one peculiarity. Many Mesozoic deposits include Bentonite beds, which indicate that volcanic ash was blown periodically into the seas in which deposition took place.

The Cretaceous sea withdrew and subareal erosion began over most of the Great Plains area, creating a plain-like surface with a low topographic relief (Frye, 1945). The unconformity between the Upper Cretaceous Pierre Shale and the Tertiary Ogallala Formation documents this erosional process.

In the early Tertiary extensive uplift in the Rocky Mountain area took place and streams flowing eastward deposited clastic sediments in the area. The earliest Tertiary deposits in Kansas are assumed to be Pliocene in age. As deposition proceeded existing bedrock divides were eventually buried and an aggradational peneplain was formed. It merged westward with the erosional surface in the Rocky Mountains and extended eastward to the Flint Hills, which formed a divide in east-central Kansas. It is assumed that the streams shifted laterally on this surface due to the rapid filling of the channel beds (Frye, 1945, Prescott, 1953). Another uplift occurred resulting in eastward tilting of the plain, and the streams started to dissect the peneplain.

A sharp erosional unconformity generally marks the boundary between Tertiary and Quaternary.

During the Pleistocene worldwide climatic changes caused major continental and alpine (Rocky Mountains) glaciers to develop. Four major glacial events, which are contemporaneous with the Guenz, Mindel, Riss and Wuerm glaciations in Europe, are recognized. They are, listed from older to younger: Nebraskan, Kansan, Illinoisan and Wisconsinan. In between each of these glaciations the climate was warmer than present days temperatures, conditions remained stable and soil formation could take place. The four interglacial stages are listed from older to younger: Aftonian, Yarmouthian and Sangamonian after the respectively occurring paleosoils, and Holocene. Figs. 11 and 15 show the ice termini of the four glaciations. Only the Nebraskan and the Kansas glaciers reached northeast Kansas and left deposits behind.

Not much is known about the Nebraskan glaciation and the subsequent interstadial, because of its great age and the masking and erosion of Nebraskan deposits by sediments of other glacial events. It is assumed that Nebraskan related deposits filled in most of the pre-glacial valleys (Frye & Leonard, 1951). The Kansan glaciation again changed the established drainage patterns and produced the ones active today. Illinoisan and Wisconsinan glaciers did not reach Kansas, they stopped about 200 km to the north in Iowa (Dort,1985).

Since the early 1960's it is recognized, that during all the four major glaciations multiple advances and retreats of the continental glaciers occurred and that the conventional four stage single advance model is not valid (Frye & Willman, 1963, Reed et al., 1966, Bayne, 1969, Dort, 1965, 1966a, 1966b,1985, Reed & Dreeszen, 1965, Reed et al., 1965).

During all four glaciations loess deposition took place. The Wisconsinan Peoria loess covers most of the upland areas in Kansas, especially in the western part of the state. Research concentrated on this loess unit, because of its accessibility, areal extent and thickness. But radiocarbon dates from Pleistocene deposits are still very rare in Kansas compared to other states (ex. Nebraska, Iowa, Illinois), so that direct correlation in many cases is not yet possible.

The Quaternary period in general shows a history of alternating deposition and erosion. Alluvial deposits, Pleistocene and Holocene in age, are represented mainly by valley-fill , terrace and floodplain deposits. Holocene dune sands are more or less confined to the south-central Kansas area and parts of southwest Kansas.

In recent times the land surface has been modified by erosion as well as alluviation.

Geology of the Study Area

Fig. 16 shows the surface geology of the study area and fig. 17 depicts the most important stratigraphic units in northwest Kansas.

In the following, the outcropping rock units in the study area are described, with emphasis on those units, which influence the water quality and water availability of the Ogallala Aquifer, i.e. the Tertiary Ogallala Formation itself and the overlying deposits, comprising Pleistocene loess and Holocene alluvium.

Cretaceous System

The thickness of Cretaceous deposits in Kansas is about 914 m (O'Connor, 1968). In the study area only Upper Cretaceous rocks crop out locally. They are :

1. The Niobrara Chalk of the Colorado Group
2. The Pierre Shale of the Montana Group

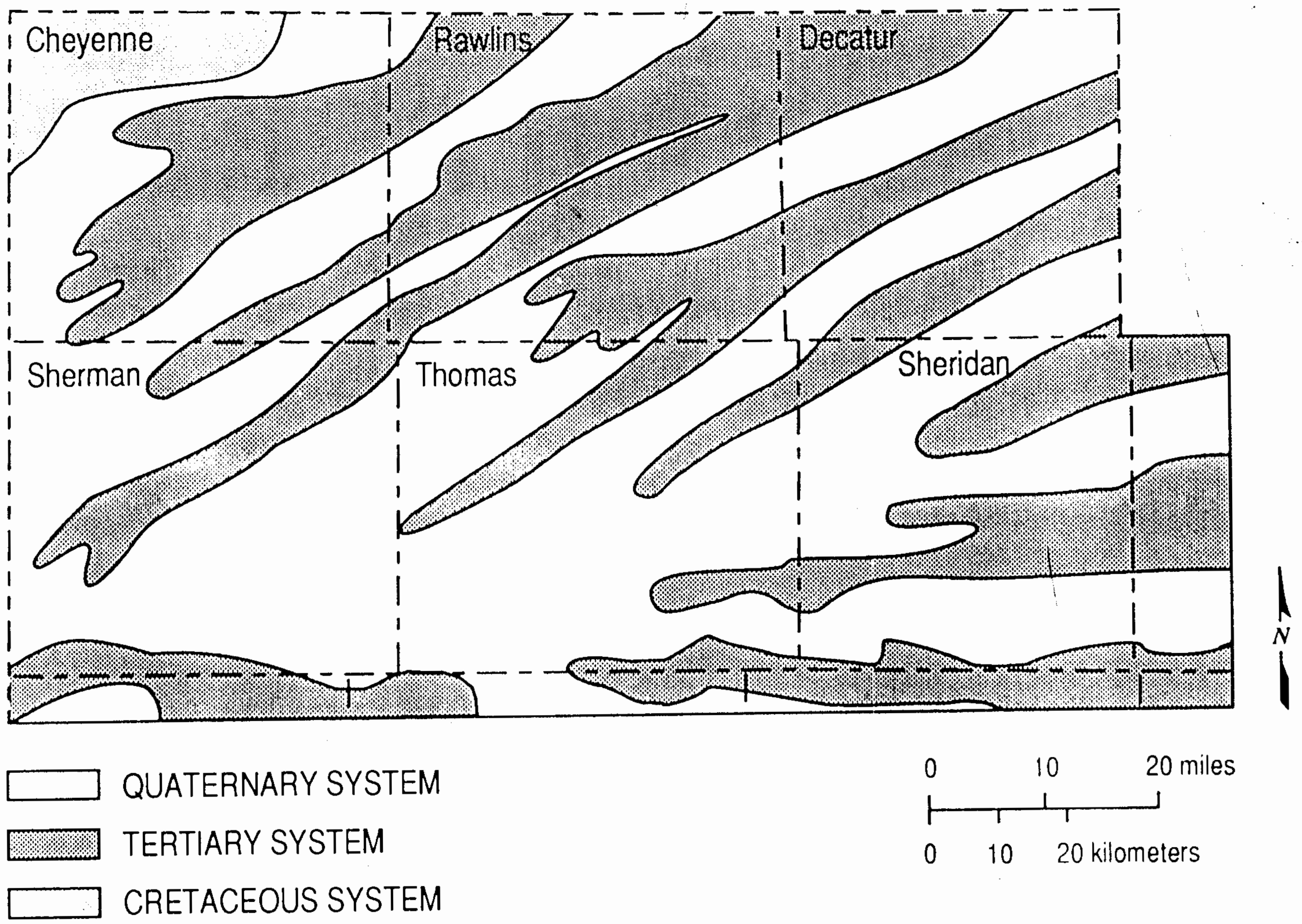


Figure 16: Surface geology of the study area

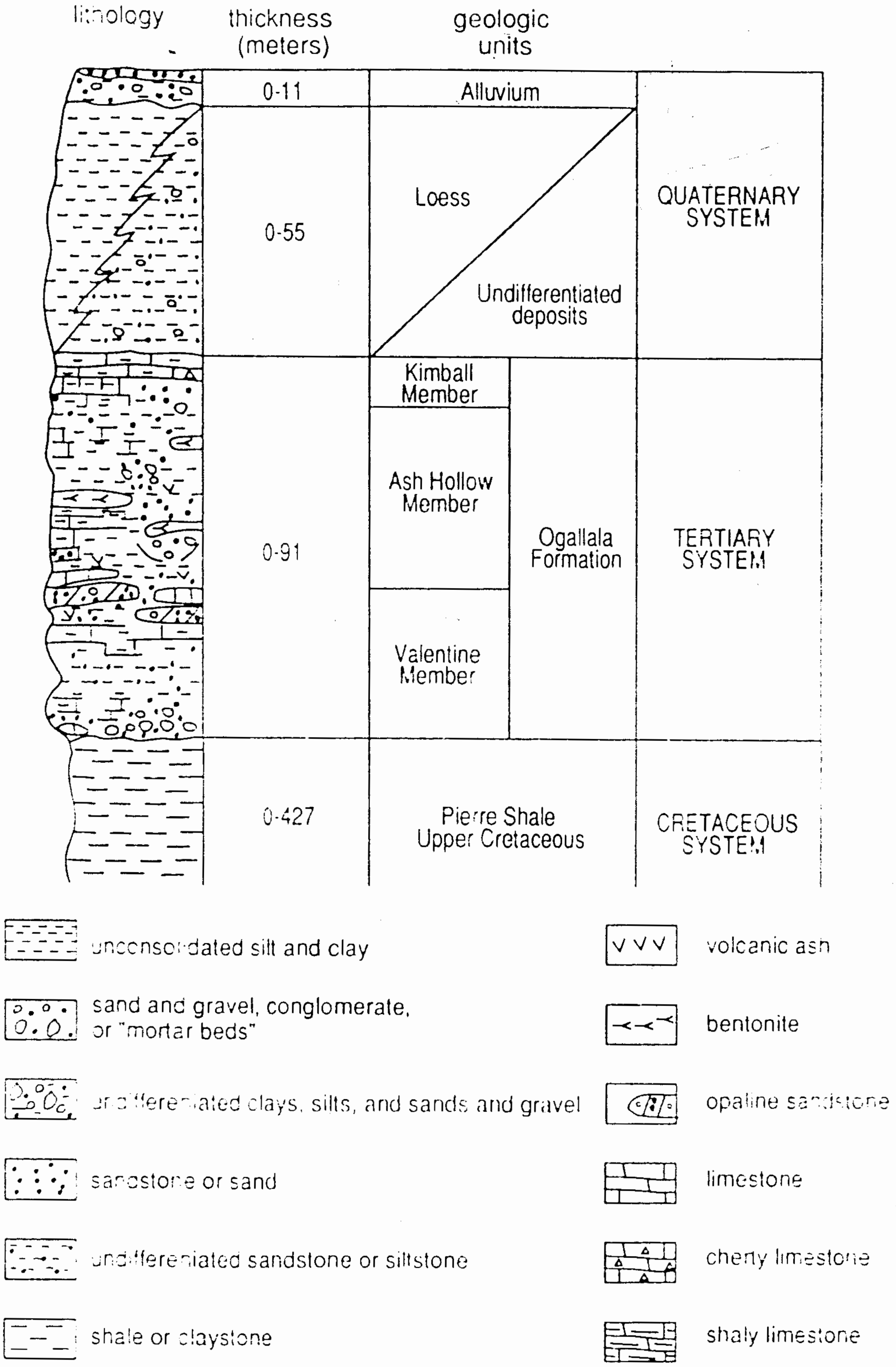


Figure 17: Stratigraphy of Northwest Kansas

Both these rock formations are confined to five counties in the study area : Cheyenne County, Wallace County, Logan County, Gove County, and Graham County.

Niobrara Chalk

The Niobrara Formation was named by Meek & Hayden in 1862 from exposures near the mouth of the Niobrara River in northeast Nebraska. The formation was divided into two members by Logan (1897): the lower Fort Hays Limestone member and the upper Smoky Hill Chalk member. Together they can attain considerable thickness: Hodson (1963) reports about 213 m thick deposits for Wallace County.

Outcrops of the Fort Hays Limestone are only reported for Gove County , where it is exposed along parts of the Smoky Hill River and attains a thickness of 0.9 m to 1.8 m (Hodson & Wahl, 1960). In general, thickness ranges from 12 m to 26 m (Merriam, 1963). The Fort Hays Limestone member is a massively bedded, white-grayish chalk or chalky limestone, and is characterized by a large species of Inoceramus (O'Connor, 1968). Because it is more resistant to erosion than the overlying Smoky Hill Chalk and the underlying Carlile Shale, the Fort Hays Limestone often form cliffs.

The Smoky Hill Chalk member conformably overlies the Fort Hays Limestone and is much more common in outcrops in the study area. It comprises thinly bedded chalky shales and chalk, although massive beds can occur locally. The color is light to dark grey, but the chalk weathers to white, pink, yellow and brown, due to the commonly found concretions of limonite and pyrite. Weathering of the 30 m to more than 183 m thick chalk beds (Hodson & Wahl, 1960, Prescott, 1955) produces spectacular landscape features: colorful canyons and ridges are formed, such as Castle Rock and Monument Rock in Gove County. The Smoky Hill Chalk member is characterized by an abundance of fossils. Bones of aquatic reptiles, sharks teeth and invertebrate fossils, notably Inoceramus, are common. Thin beds of bentonite occur throughout the formation.

Pierre Shale

The Pierre Shale belongs to the Montana Group and represents its only member in Kansas. It is the uppermost Cretaceous formation present in this state and overlies conformably the Niobrara Chalk. Meek & Hayden used the term Pierre Shale first in 1862 for exposures in South Dakota. Williston (1897) was the first to recognize the Pierre Shale in Kansas, but not until 1931 was it described in detail (Elias, 1931).

Most of the Pierre Shale in northwest Kansas is covered by the Tertiary Ogallala Formation, only along streams one can generally find good outcrops. Thickness in the study area ranges from 5 m at its eastern limits in Graham County (Prescott, 1955) to 427 m in Cheyenne County (Prescott, 1952).

Elias (1931) divided the Pierre Shale Formation into six members. In descending order they are: Beecher Island (about 30 m thick), an unamed member of about 152 m to 183 m thickness, Salt Grass Shale (18 m thick), Lake Creek Shale (61 m thick), Weskan Shale (52 m thick), and Sharon Springs Shale (47 m thick). The thicknesses are reported by O'Connor (1968). The Pierre Shale generally is a dark-grey to black, thinly bedded shale, which weathers to coffee-brown and a lighter grey color. Thin beds of bentonite occur throughout as well as pyrite, marcasite and limonite concretions. Selenite crystals are usually found in abundance along cracks. Except for concretions and thin chalk beds the Pierre Shale is non-calcareous.

Tertiary System

Ogallala formation

Tertiary (Neogene) deposits in Kansas are represented by only one formation, the Ogallala Formation. The name Ogallala was coined by Darton in 1899 from outcrops near the town of Ogallala in Keith County, Nebraska.

The outcrop area of the Ogallala Formation has a north/south extension of more than 1287 km and a maximum lateral extension of 644 km from Wyoming across Nebraska

(Frye et al., 1956), and thus represents the largest area of more or less continuously exposed non-marine deposits on the North American continent. Paralleling the Rocky Mountains the Ogallala Formation is present in parts of South Dakota, Nebraska, Wyoming, Colorado, Kansas, New Mexico, Oklahoma and Texas. Nebraska is nearly totally covered by these deposits, all type localities of the Ogallala Formation and its members are situated here.

Fig. 18 shows the distribution of the Ogallala Formation in Kansas. The formation is more or less confined to the western part, but a few deposits are known from central Kansas. This indicates that originally a far more extensive area was covered and then lost due to erosion (Merriam, 1963).

The thickness of the Ogallala Formation varies considerably. In northwest Kansas thicknesses vary from a featheredge to 122 m in Wallace County (Hodson, 1963). Average thickness in the study area is about 50 m (Frye, 1945, Prescott, 1952, Prescott, 1953, Bayne 1956, Walters, 1956, Johnson, 1958, Hodson & Wahl, 1960, Hodson, 1963, Hodson, 1969).

The Ogallala Formation was deposited unconformable over Cretaceous bedrock during late Miocene and Pliocene times in pre-existing valleys by east or southeast flowing streams originating in the Rocky Mountains. Based on the clastic ratio pattern (sand/shale) the drainage pattern during deposition of the Ogallala Formation parallels in general older channels cut into Cretaceous bedrock (Merriam, 1963). Merriam & Frye (1954) recognized four of these ancient stream valleys in western Kansas (Fig. 19): The northernmost valley extends eastward from southern Cheyenne County to western Phillips County, another valley trends eastward from central Wallace County along the present Smoky Hill River valley, a third valley reaches from southeastern Wallace County across northern Wichita, Scott, Lane, and Ness counties to the southeast, and the fourth valley extends southeastward from the southeast corner of Greeley County to the present day Arkansas River valley.

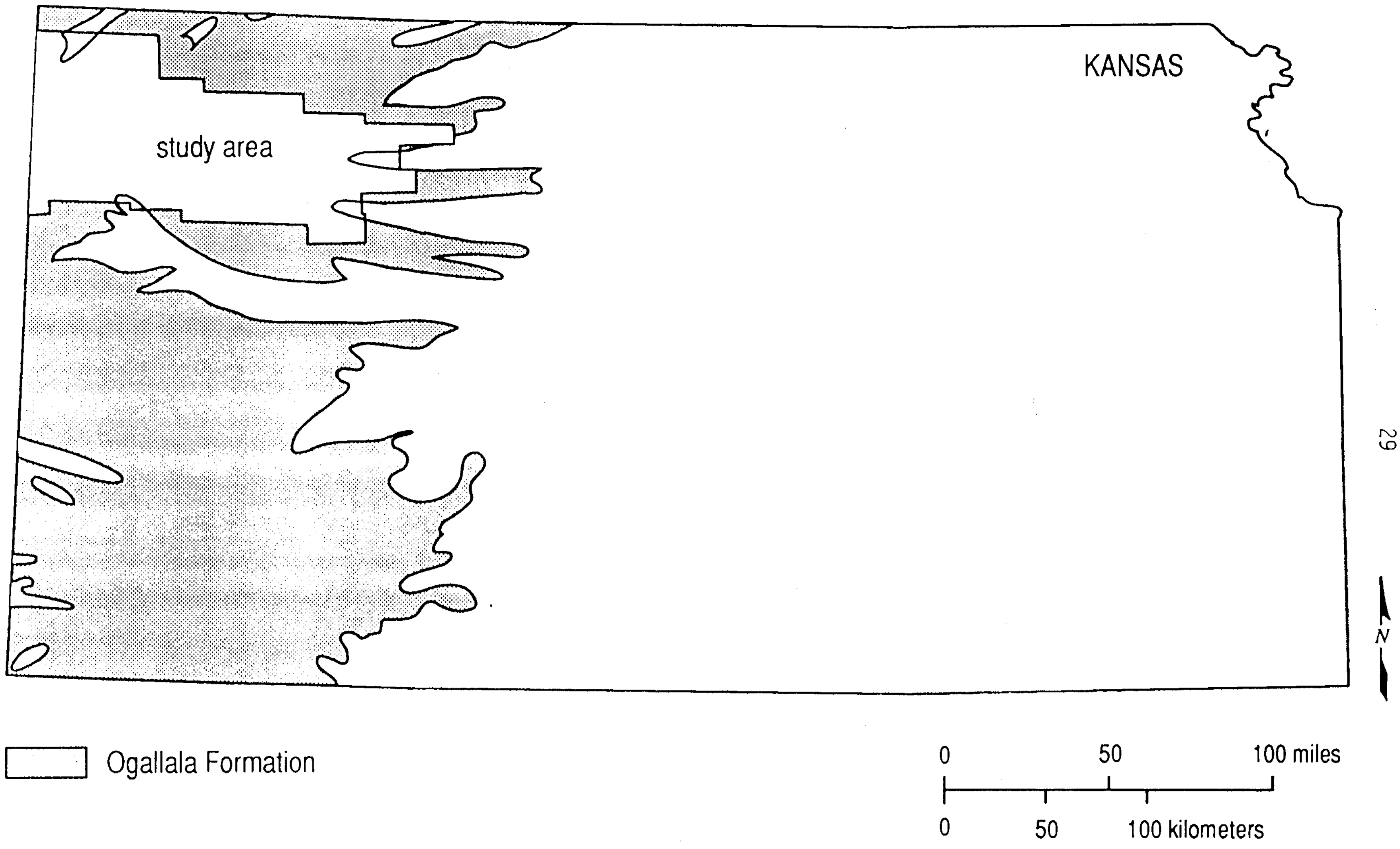


Figure 18: Distribution of the Ogallala Formation in Kansas

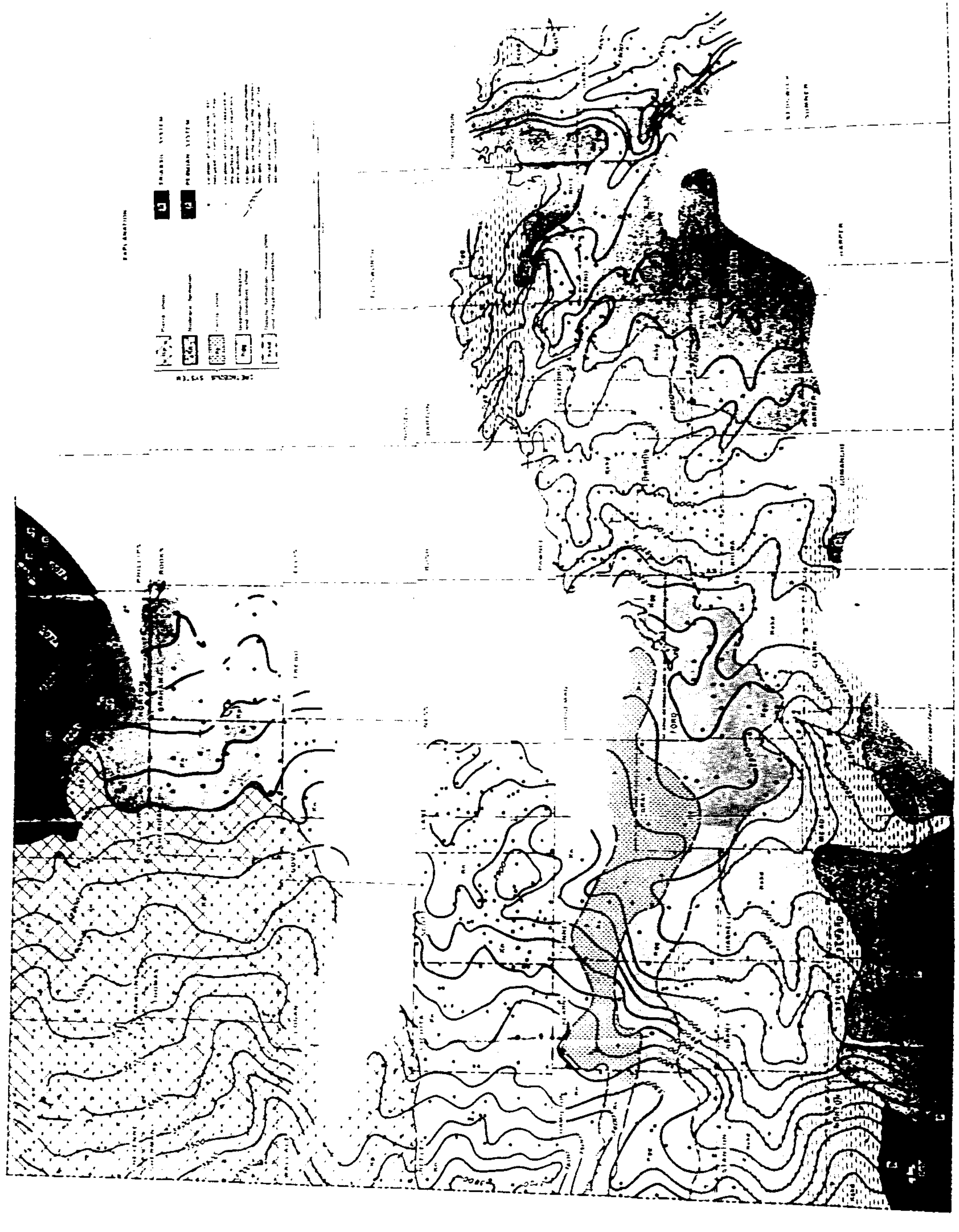


Figure 19: Ancient stream valleys in western Kansas, adapted from Merriam and Frye (1954)

Generally, the pre-Ogallala topography represented a widespread, gently sloped erosional surface that reached from the Rocky Mountains as far as east-central Kansas. In northwest Kansas the bedrock surface generally slopes to the east or northeast, whereas in west-central Kansas easterly directions prevail. The local bedrock relief can be considerable: it ranges from 61 m to 122 m (Smith, 1940, Frye & Leonard, 1952).

Smith (1940) saw the cause for deposition of the Ogallala Formation in a combination of climatic change and tectonic factors: a semiarid climate together with contemporaneous uplift in the Rocky Mountains and possible up-and downwarping in the adjacent plains area resulted in the deposition of the fluviatile, Tertiary sediments. Thus he followed Darton (1920) in combining interpretations of Haworth (1897), who correlated the deposition of the Ogallala Formation with uplift in the Rocky Mountains, and Johnson (1901), who held only climatic changes responsible. Based on the stratigraphy throughout the Ogallala Formation Frye et al. (1956) conclude that erosion and differential structural movements of small magnitude at different times during the late Tertiary coincide with the deposition of the Ogallala Formation.

Opinions vary regarding the mode of deposition. Soon after it was suggested by Hay (1890) and Williston (1895) that the Ogallala Formation originated as a lacustrine deposit, this theory was dismissed in favor of a predominantly fluviatile deposition (Gilbert, 1896, Haworth, 1897, Johnson, 1901). Ever since, this theory remained undisputed. In addition, minor eolian contributions were suggested (Smith, 1940). Johnson's (1901) theory of the Ogallala Formation being a composite alluvial fan deposit was dismissed by Smith in 1940, on the grounds that in Kansas the thickness of deposits increases away from the source, i.e. the Rocky Mountains. He instead described the formation as a warped and dissected piedmont alluvial plain deposit, which was gradually deposited throughout time. For the next 40 years this mode of deposition was adopted in subsequent publications. Frye et al. (1956) in their extensive description of Ogallala Formation stratigraphy in Kansas agreed, that the oldest sediments were deposited at the bottom of the valleys, whereas successively younger deposits filled these valleys and finally merged over bedrock divides forming a coalescent alluvial plain, which reached from the Rocky Mountains to the Flint Hills of east-central Kansas. Streams probably shifted laterally on this surface, resulting in the formation of many lakes (Frye, 1945, Prescott, 1953). At the beginning of the Pleistocene stream rejuvenation caused by renewed upwarping dissected the plain. Both the Rocky Mountains and the plains area were affected simultaneously, and the Ogallala Formation was arched (Smith, 1940). In 1957, Frye & Leonard claimed that this single depositional cycle concept is valid for the Ogallala Formation of the entire Great Plains region. Only in 1980 a different mode of deposition was suggested. Seni (1980) postulated that the Ogallala Formation in Texas originated in several stages from three overlapping, low gradient,wet alluvial fan lobes. Yet another depositional scheme was published in 1984 by Diffendal for the panhandle area of Nebraska. Here a complex sequence of cut and fill sediments is present. Fig. 20 depicts the concept of Frye & Leonard versus the concept of Diffendal.

No new data have been presented for Kansas thus far.

The source of the sediment being mainly the Rocky Mountain area, the deposits of the Ogallala Formation consist of igneous and metamorphic rock fragments, such as pebbles of granite, quartzite, and pink feldspar. But Cretaceous limestone fragments are also recognized, indicating local sources in Kansas as well as sedimentary rock sources in eastern Colorado.

Frye et al. (1956) describe the Ogallala Formation as a heterogenous complex of clastic deposits with virtually no distinctive marker beds that are traceable either laterally or vertically. Except for a limestone at the very top of the formation, the individual beds are characteristically lenticular and commonly do not show sharp contacts between lithologies, but gradual transitions (Smith, 1940). The texture ranges from coarse gravel and sand through sand, silt, and marl to clay (Frye, 1970). Sorting is generally poor to moderate, and channeling and crossbedding are very common features (Smith, 1940, Prescott, 1953).

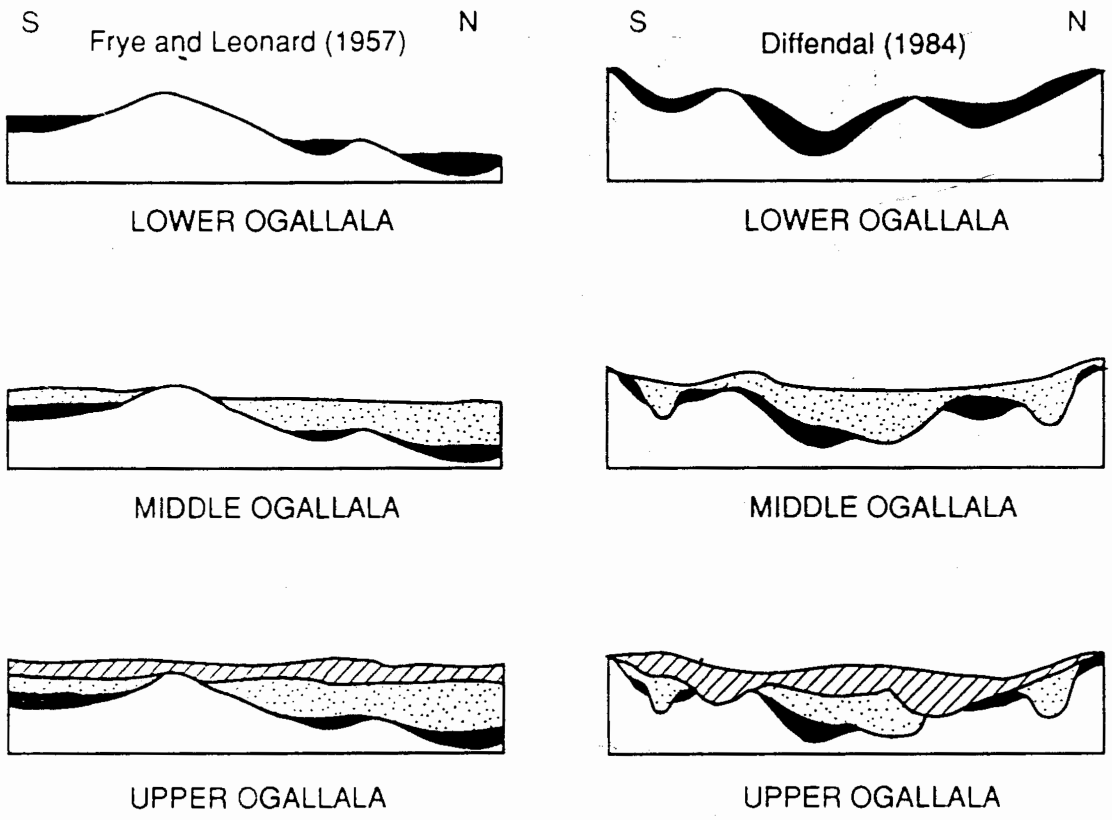


Figure 20: Conceptual models for the deposition of the Ogallala formation, modified from Diffendal (1984)

Colors of deposits can be light grey, tan, white, olive grey and red brown. The sediments can be loose, friable or compact, with cement of either silica or carbonates. The latter is by far the more common cement and considerations have been made as to the origin of the calcium carbonate. Smith (1940) postulates that the source is mainly the Rocky Mountain area itself and in situ weathering after deposition. One of his arguments against the Cretaceous limestone and chalk deposits of eastern Colorado as a source is the greater abundance of carbonate cement in the upper parts of the formation, which were deposited after the Cretaceous sediments to the west were almost covered by debris from the mountains. According to Smith (1940) the principal source should also coincide with the area of the most rainfall to facilitate weathering and subsequent transport of the carbonates, which would point to the Rocky Mountains. Here Paleozoic limestones and calcic minerals in crystalline rocks could be the origin of the carbonates.The calcium carbonate is not only present in form of cement, but occurs also as nodules, caliche lenses and beds. Prescott (1952) reports caliche beds from a few centimeters to 9.4 m thick for Cheyenne County. Most of the calcium carbonate was probably deposited at or near the water table; because of fluctuating ground water levels, caliche was deposited at various positions throughout the Ogallala Formation (Bayne, 1956).

Correlation of beds was and is done mainly by opalized hulls of grass seeds and fruits from other plants. These are widespread and very abundant in certain horizons and thus more useful than the rare silicified bones of fossil vertebrates (plain dwelling mammals) or fossil molluscs. Although 14 species of molluscs have been identified from Ogallala sediments in northwest Kansas (Frye et al., 1956), their preservation is generally poor: Commonly only imperfect external molds are found.

Another especially good aid to stratigraphic correlation is the presence of ashbeds. They can be differentiated by their petrographic characteristics such as chemical composition, thickness, shape, color and refractive indices of the glass shards. Ten ashbeds have been described in the Ogallala Formation of northern Kansas and six have been given formal names (Swineford et al., 1955). The thickness of the ashbeds ranges from 30 cm to 6.7 m (Frye et al., 1956).

Besides fossil seeds and ashbeds distinctive rock types can also be helpful in differentiating between beds in the Ogallala Formation:

Opaline sands seem to occur only in the lower part of the formation, below the zone of the ashbeds. which are the source of the silica (Frye & Swineford, 1946). These cemented sands are also called "Ogallala Quartzite", because of their resemblance with true quartzite when fine or medium sands are cemented. However, they loose this resemblance when coarse sands or gravels are bonded by the opaline silica. Generally, this "Ogallala Quartzite" displays a dark green color.Walters (1956) reports a thickness of up to 7 m of this particular deposit in Rawlins County.

Chert can be found in the upper part of the formation 3 m to 4.6 m below the capping limestone and may be "genetically related to the stable surface that developed on the alluvial plain after termination of the Ogallala deposition " (Frye et al., 1956). Although the origin of the chert is not quite clear, it may serve locally as a marker.

Bentonitic clay beds are known from positions at or near the base of the Ogallala Formation (Elias, 1931). They could be the weathering product of volcanic ash (Elias, 1931) or the alteration from ash to Montmorillonite could have been related to high ground water levels, the magnesium being provided by nearby Cretaceous marine shales (Frye et al., 1956).

Beds of diatomaceous marl including mollusc shells and altered soil horizons may serve as indicators of depositional environments. Stratigraphically, they have little value because they occur throughout the formation.

Lugn (1939) divided the Ogallala Formation in Nebraska into four members. In ascending order they are: Valentine, Ash Hollow, Sidney gravel, and Kimball. In Kansas only three of these members are recognized. the Sidney gravel is here included in the basal part of the Kimball. Generally, these members are distinguished based on their lithologic, faunal and floral content. Volcanic ashbeds are also used for stratigraphic purposes.

A description of the three members of the Ogallala Formation recognized in Kansas follows.

Valentine

This lowermost member of the Ogallala Formation was named from exposures near Valentine, Nebraska. The thickness in Kansas ranges locally up to 30 m, but thins eastward to about 9 m and less (Frye et al., 1956).

The Valentine comprises mainly fine to medium sand, relatively well sorted. and some feldspathic gravels.

Cementation by silica formed green opaline sandstone, called "Ogallala Quartzite". Irregular cementation by carbonates occurs as well.

Also present are beds of soft, fresh water limestone, volcanic ash lentils. Greenish grey bentonitic clays are found especially at the base. Locally, Cretaceous rocks are incorporated, reflecting a local source.

The overall color of these deposits is greenish grey to grey. Frye et al. (1956) assumed that deposition was rather uniform and took place at a low rate. Based on the greenish color of the sediments, caused by ferrous iron, the great abundance of branchiate snails, and the local alteration of volcanic ash to montmorillonite, they also state that the water table remained near the surface during deposition.

Because the Valentine represents the bottom filling of Cretaceous stream valleys, its outcrops are not as common as those of the Ash Hollow or Kimball members.

Ash Hollow

The name Ash Hollow was derived from Ash Hollow Canyon in the North Platte River valley, Keith County, Nebraska. Most of the Ogallala Formation exposures in northern Kansas are represented by this member. In contrast to the Valentine, which was confined to bedrock valleys, the Ash Hollow filled those valleys, transgressed over all but the highest bedrock divides and its upper part can be assumed to have spread out over most of northwestern Kansas (Frye et al., 1956).

The thickness of this part of the Ogallala Formation can reach up to 40 m (Frye et al., 1956).

The lower part of the Ash Hollow is confined to the same bedrock valleys as the Valentine, indicating that to that time the streams were still trending eastward. The known easternmost extension of the Ash Hollow is in McPherson County in east-central Kansas, where it is assumed to make up the lower part of the Delmore Formation (Williams & Lohman, 1949, Hibbard, 1952).

Fine to coarse sand, silt and gravel are the main constituents of this member of the Ogallala Formation.

Loose cementation is due to calcium carbonate, generating the so-called "mortar beds". This name originated from the use of this material as natural mortar for sod houses by the early settlers. Partly, these cementation zones may have been soil caliche, formed in the middle to late Ash Hollow. "As some of these "caliche " zones are separated by only a few feet of noncalcareous silty sand, it is judged that, locally, increments of sedimentation six feet thick or thicker accumulated rapidly and were preceded and followed by periods of surface stability sufficiently long to permit the development of deep, mature lime-accumulating soils containing caliche zones several feet thick" (Frye et al., 1956). Development of these soils could occur, because at the end of the Ash Hollow laterally shifting streams left large portions of the alluvial plain untouched for a considerable amount of time (Smith, 1940).

Fresh water limestones, deposited in shallow, quiet ponds, and sands and gravels bonded by calcareous cement due to the action of ground water make up the rest of the calcareous material of the Ash Hollow.

Opal cementation occurs as well, but is less common.

Ash beds are concentrated more in the lower part of the Ash Hollow. There are at least ten separate beds, six of which are named (Swineford et al., 1955): Calvert, Rawlins, Fort Wallace, Dellvale, Reager and Reamsville. According to Frye et al. (1956) eight of the ten ashbeds are definitely to be placed in the Ash Hollow. However, in his mind the Calvert bed belongs to the upper Valentine, and one unnamed bed can not be placed with certainty. Merriam (1963) classes all ten ashbeds as Ash Hollow.

Compared to the Valentine, the colors of deposits change gradually from greenish grey to red and tan throughout the Ash Hollow. In the upper part of the section green colors are absent. This difference in color may have been caused by a gradual lowering of the water table during deposition entailing different effects of surface weathering (Frye et al., 1956).

Generally, there is a lack of crossbedding and the sorting is poorer in the Ash Hollow as in the Valentine. This could indicate rapid but intermittent sedimentation, as is shown by the caliche zones as well.

The input of local bedrock into the deposits is much less than in the Valentine.

Kimball

The uppermost and thinnest member of the Ogallala Formation was named after Kimball County, Nebraska. Due to erosion only isolated remnants of this member are left, but because sedimentation was not confined to any bedrock valleys and deposition occurred on a plain-like surface, the Kimball had the most widespread geographic distribution of all the Ogallala Formation members.

The rate of deposition greatly decreased so that the average thickness in northern Kansas is only about 9 m (Frye et al., 1956).

Locally, the basal part of the Kimball is made up of lenticular channel gravels, which occur more consistently in Nebraska and were therefore given member status in that state: the Sidney gravel member.

Medium to fine sands and silts predominate in this section. They are rich in calcium carbonate which increases towards the top of the sequence, culminating in the so-called "cap rock", "algal limestone" or "Ogallala climax soil", a dense, sandy limestone characterized by concentric, wavy laminae and pisolithic structures. It contains quartz and feldspar grains and locally granitic and other igneous fragments as well.

The origin of this limestone horizon was long disputed. Elias (1931) described it for the first time and suggested that it was formed in an extensive lake by algal activity to form an algal limestone. Another hypothesis was formation in a series of disconnected lakes, the environment being more a back swamp area or abandoned channel segment (Theis, 1936). In 1956, Frye et al. found that the limestone does not contain any fossil remains and thus postulated an inorganic soil forming process on a stable surface over a considerable amount of time.

The upper limestone is, due to erosion, not present everywhere, but where it exists it represents an excellent marker bed for the end of the Ogallala deposition and the boundary between Tertiary and Quaternary deposits.

The thickness of the "cap rock" ranges from 46 cm in Rawlins County (Walters, 1956) to 1.2 m in Cheyenne County (Prescott, 1957).

Silification in the Kimball does not occur as frequently as in the Ash Hollow. Opal and chert in this member are assumed to be secondary replacements of calcium carbonate, indicated by color, type of replacement, associated clay minerals and stratigraphic relations (Frye et al., 1956). The source of the silica is, according to Frye et al. (1956), more likely to be on or near the alluvial surface than being derived from volcanic ashbeds in the formation itself, and transportation as well as deposition occurred by downward percolating meteoric waters. Volcanic ash deposited directly at the surface or silicates derived from weathering of feldspars may have provided the source.

The Kimball shows a greater degree of uniformity as far as lithology and thickness are concerned. This effect is caused by a lack of locally controlled depositional features. Deposition occurred on a coalescent plain, no bedrock valley controlled the direction of flow, thus the depositing rivers were free to shift according to gradient~~, sed~~iment load and water volume.

Color of the sediments in the Kimball is commonly a light grey.

Overall, the Kimball member of the Ogallala Formation is less permeable and fossiliferous and shows more calcium carbonate cementation than the Valentine and Ash Hollow.

Quaternary System

The Midwest and the central Great Plains region of the United States represent the most extensive thick loess deposits in the western hemisphere. In an area extending more than 1610 km from east to west and more than 804 km from north to south, most upland areas are covered with loess (Frye, Willman, Glass, 1968). The youngest loess, named the Peoria loess, covers more than 65% of the land surface of the State of Kansas (Welch & Hale, 1987).

Pleistocene loess mantles a large part of the upland areas in western Kansas. Only where stream erosion occurred are the underlying Tertiary or Cretaceous sediments exposed. The average thickness of loess in the study area is 15 m to 18 m.

Three major loess units are recognized in Kansas:

1. Loveland loess, deposited during Illinoisan time
2. Peoria loess, deposited during Wisconsinan time
3. Bignell loess, deposited either at the end of the Wisconsinan or in the beginning of the Holocene, although recent radiocarbon dates indicate deposition during

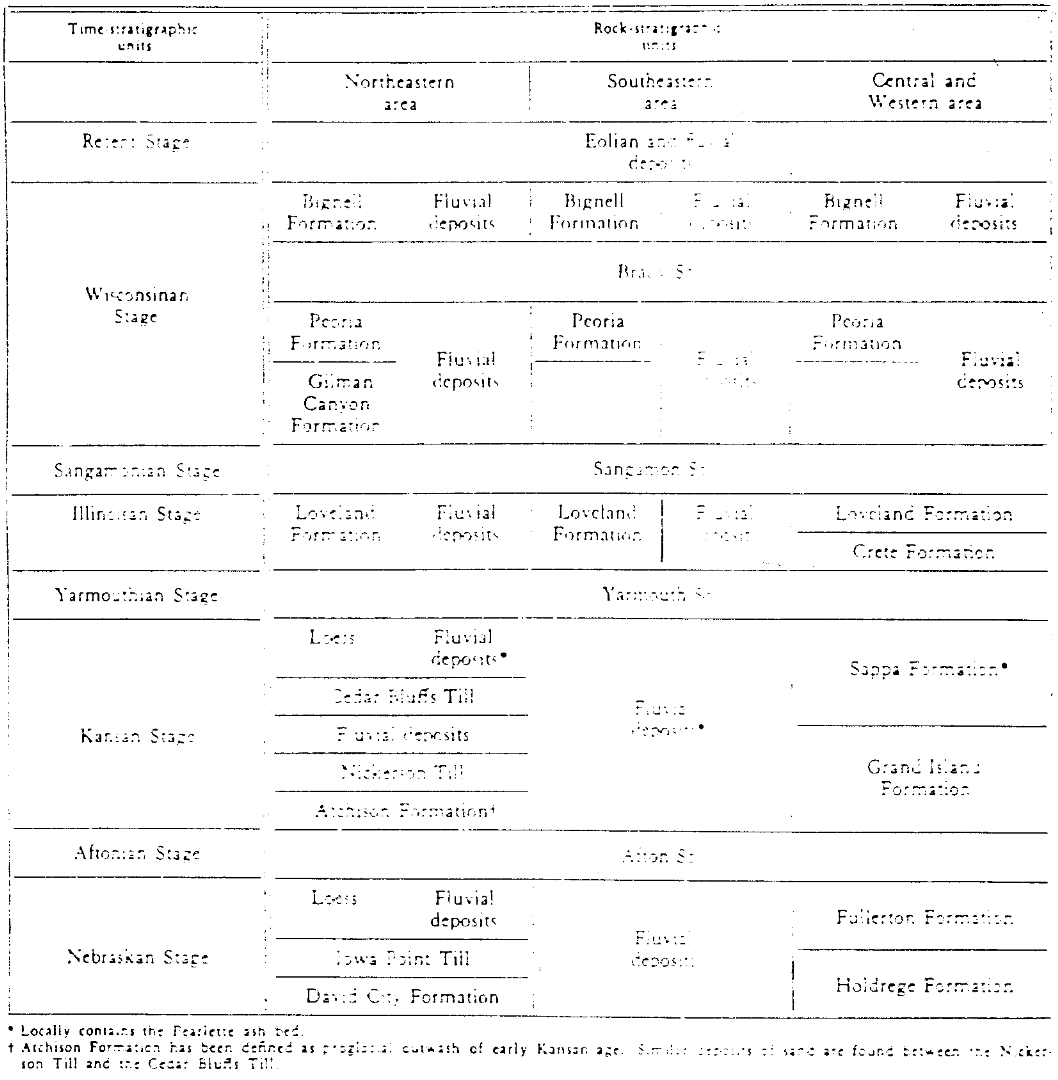
the Holocene (Lutenegger, 1985, May, 1989)

Fig. 21 shows the time-stratigraphic positions of all the above mentioned loess units, according to Bayne & O'Connor, 1968. The position of the Bignell loess is controversial: Based on radiocarbon dates Ruhe (1983) states. that the Bignell loess may be Holocene in age. Strong morphological and chemical resemblance with the underlying Peoria loess could also allow interpretation of the Bignell loess as a reworked product of the Peoria loess (Frye & Leonard, 1951).

Loveland loess

Loveland loess, the oldest loess unit recognized in Kansas, was named by Shimek (1910) after the type locality near Loveland. Iowa. Frye & Leonard (1951) describe this loess at the type section as massive, and consisting of fine sand and silt, the upper part being leached of calcium carbonate, the lower part being unleached and containing calcium carbonate nodules due to illuviation. The overall color of this loess unit is reddish-tan to tan. Fossils. mainly molluscs, have been found elsewhere in the Loveland loess, but are rare in Kansas. The upper part of this loess unit displays a distinct reddish brown to pink color caused by weathering and is called the Sangamon paleosol. This soil developed during an interglacial in times of relative stability under a probably more humid and warmer climate than todays as indicated by the red color. This blocky textured, highly clayey soil horizon is widely used as a marker bed, differentiating between the Illinoisan and Wisconsinan. In western Kansas the Sangamon soil is relatively thin and compact. Bayne (1956) reports a maximum thickness of 1.2 m for the Sangamon soil in Sheridan County, and Prescott (1952) reports 1.8 m in Cheyenne County. At the type section in Iowa the Sangamon soil is 7.6 m thick (Frye & Leonard, 1952).

Minor soil developments within the Loveland loess unit (Frye & Leonard. 1954) suggest periods of stability during Illinoisan time.



Time-stratigraphic units	Rock-stratigraphic units					
	Northeastern area		Southeastern area		Central and Western area	
Recent Stage	Eolian and Fluvial deposits					
Wisconsinan Stage	Bignell Formation	Fluvial deposits	Bignell Formation	Fluvial deposits	Bignell Formation	Fluvial deposits
	Brady Soil					
	Peoria Formation	Fluvial deposits	Peoria Formation	Fluvial deposits	Peoria Formation	Fluvial deposits
	Gilman Canyon Formation					
Sangamonian Stage	Sangamon Soil					
Illinoian Stage	Loveland Formation	Fluvial deposits	Loveland Formation	Fluvial deposits	Loveland Formation	
					Crete Formation	
Yarmouthian Stage	Yarmouth Soil					
Kansan Stage	Loess	Fluvial deposits*	Fluvial deposits*		Sappa Formation*	
	Cedar Bluffs Till					
	Fluvial deposits				Grand Island Formation	
	Nickerson Till					
	Atchison Formation†					
Aftonian Stage	Afton Soil					
Nebraskan Stage	Loess	Fluvial deposits	Fluvial deposits		Fullerton Formation	
	Iowa Point Till				Holdrege Formation	
	David City Formation					

* Locally contains the Pearlette ash bed.

† Atchison Formation has been defined as proglacial outwash of early Kansan age. Similar deposits of sand are found between the Nickerson Till and the Cedar Bluffs Till.

Figure 21: Classification of Pleistocene series in Kansas (Bayne and O'Connor, 1968)

The distribution of Loveland loess over Kansas is discontinuous and patchy compared to the Peoria loess, although it is well developed in northern and central Kansas.

Peoria loess

Wisconsinan eolian deposits have been divided into 2 loess units: the lower Gilman Canyon Formation and the upper Peoria loess. The Gilman Canyon Formation is named after its type locality in Nebraska and is described as dark gray, humus enriched, non-calcareous and 30 cm to 1 m thick (Reed & Dreeszen, 1965, Dreeszen, 1970). The top of the Gilman Canyon Formation marks a weakly developed interstadial soil horizon. For western Kansas the Gilman Canyon Formation has not been described.

The overlying Peoria loess represents the thickest loess unit in Kansas and the best preserved one. The name Peoria was coined by Leverett (1898) after the type locality near Peoria, Illinois. Within the Peoria three distinct molluscan faunal zones are recognized: a basal, lower, and upper zone (Leonard, 1951). Because it shows leaching, Frye & Leonard (1952) concluded that deposition of the basal zone was slow. It is assumed that the silt was first incorporated into the A horizon of the Sangamon soil; but eventually the rate of deposition exceeded the rate of leaching and the loess became more calcareous. Regarding the overall rate of deposition, opinions differ: evidence for episodic deposition is, for example, found in Iowa, where the loess includes dark, organic rich bands, which are believed to be incipient soils formed during periods of slower deposition (Daniels et al., 1960. Ruhe et al.. 1971). Frankel (1957) also assumes the occurring zonation and preservation of fossils in the Peoria loess of Nebraska as being evidence for episodic deposition. In Kansas, however, no well developed paleosols or other unconformities are found. and it is assumed that the Peoria loess here represents a continuous deposit. The occurring faunal zonations are attributed to a change in the rate of deposition rather than a complete break (Welch & Hale, 1987).

The Peoria silt is of eolian origin, massive, homogenous, tan to light yellow colored and calcareous. Large amounts of very fine sand can occur in the Peoria silt , indicative of periods of high winds during deposition (Prescott, 1952). The Peoria attains great thickness in northwest Kansas: average thickness here is between 6 m and 12 m, however, thicknesses of up to 27 m in Cheyenne County (Prescott, 1952) and 24 m in Rawlins County (Walters, 1956) have been recorded. The overall mineralogy of Peoria Loess shows a dominance of quartz, feldspars, volcanic ash shards, carbonates and micas in the silt fraction; the clay mineralogy is made up of montmorillonite, illite, calcite, quartz and feldspar and a trace of kaolinite (Swineford & Frye, 1951).

Bignell Loess

The Bignell loess is the youngest loess unit found in Kansas and was named by Schultz & Stout (1945) from exposures along the Platte River near North Platte, Nebraska. As mentioned above, its appearance and chemical characteristics are very similar to the Peoria loess, although the Bignell loess is generally more friable and less compact. The only certain way to distinguish between these two loess units in the field is the presence of the Brady soil, developed on top of the Peoria loess, and/or the sparse but distinctive molluscan fauna of the Bignell loess (Leonard, 1951). The Brady soil is regionally traceable only in northwest Kansas, where its occurrence is closely associated with the Bignell loess. However, compared to the distribution of the Peoria loess, the Brady soil and the Bignell loess represent a very discontinuous deposit, even more patchy than the Loveland loess.

Bayne (1956) describes the Brady soil in Sheridan County as being generally thicker than the modern soil horizon and of dark brown color, except in areas where it was developed under poor drainage conditions: in those areas the color is grey or even black. The thickness of Brady soil in Sheridan County is commonly about 30 centimeters but it can reach a maximum of 90 cm. Its presence is generally confined to upland areas.

The Bignell loess - where it is present in the study area - shows a thickness of a few centimeters to a maximum of 1.5 m (Bayne, 1956, Walters, 1956, Prescott, 1952, Prescott, 1955, Hodson & Wahl, 1960, Prescott, 1953).

Source of loess

For the last 50 years the source of loess in Kansas has been debated. Most of the research was done on the Peoria loess, because of its easy accessibility as a surficial deposit, its nearly continuous distribution throughout the state and its considerable thickness. The Loveland loess is also widespread, but of patchy occurrence and is visible only in outcrops. Sources for the Loveland loess are probably very similar to those of the Peoria loess. The youngest loess in Kansas, the Bignell loess, seems to occur only in central and western Kansas, so that there is no direct relationship with the last continental glaciation.

Three requirements have to be fulfilled before loess deposition can take place:

1. Presence of a deflating area, i.e. a continuous source of silt.
2. Presence of an inflating area, i.e. an area either morphologically suited for loess accumulation and/or an area with grass dominated vegetation to act as a catchment area for the windblown silts and to prevent subsequent removal.
3. The wind has to blow from one direction.

As far as the source of loess is concerned, three theories have been developed over the years:

1. Glacial (alpine/continental) outwash river floodplains.
2. Desert regional sources (areas of sand dunes).
3. Regional fluvial and eolian erosion of the Ogallala Formation.

A glacial outwash loess source was favored by Frye & Leonard (1952), they recognized the Missouri, Platte and Arkansas rivers as major contributors. The Missouri River served as a source for northeastern Kansas, the Platte River in Nebraska provided silty material for northern, central and western Kansas, and the Arkansas River contributed coarser, more sandy sediments to areas in southwest and south central Kansas. A decrease of particle size and thickness away from these rivers supports this conclusion. Mathematical models (Waggoner & Bingham, 1961, Frazee, Fehrenbacher & Krumbein, 1970) predict a thinning of loess as well as a decrease in grain size with increasing distance from the presumed source.

A desert regional source was suggested by Lugn (1960). He assumed the Nebraska Sand Hills to be the major contributor to Kansas Peoria loess, based on a decrease in particle size as well as in thickness away from the Sand Hills to the southeast. In his view, the Sand Hills today represent remnants of the Tertiary Ogallala Formation, the sand being left behind as dune sand after wind erosion of the silts and clays under an arid climate. He stated that the major rivers contributed only little sediment to the loess deposition. However, fossils indicate a boreal climate during Wisconsinan time and in addition radiocarbon dates suggest that the Nebraska Sand Hills may be Holocene in age, which would preclude them as a source for Peoria loess.

Reed & Dreezsen (1965) favor an eolian/fluvial source of the Peoria loess, derived from erosion of the Ogallala Formation: From test hole data in the Sand Hill region in Nebraska they conclude, that before Wisconsinan time the landscape showed hills and valleys due to stream erosion of the Ogallala Formation. The valleys were subsequently filled with sediments grading upward into finer material, which was reworked during the middle/late Wisconsinan by eolian processes. The sand was deposited in dunes (Sand Hills) and the silts were blown to the southeast. Reed & Dreezsen's theory differs from Lugns only in as much as the origin of the Sand Hills is concerned.

One theory by itself does not explain the differences in thickness and distribution of Peoria loess in Kansas. More than one source had to be present. Therefore, Welch & Hale (1987) conclude, that loess in the western half of the state was derived:

a. from the Sand Hills in Nebraska as well as from regional dunes in eastern

Colorado and south central Kansas,

b. from alpine glacial outwash sediments - derived from the Rocky Mountain area - of the floodplains of the Platte and Arkansas rivers,

c. from floodplain material from non-glacial rivers, such as the Arikaree, Republican, Solomon, Saline, Smoky Hill, Pawnee and Cimarron rivers.

In the northeastern part of Kansas the loess is mainly derived from continental - glacial outwash of the Missouri River and non-glacial rivers such as the Big Blue. The volume contributed by each source is unknown.

The unique geographic location of Kansas between continental glaciers to the northeast and alpine glaciers to the west probably also contributed to the unevenness of loess deposition in this state. Caused by differences in microclimate, distribution of deposits from the alpine glacial source could have been out of phase with deposition of sediments derived from the continental glacier (Welch & Hale, 1987).

Alluvium

The alluvial deposits in the High Plains area consist of valley-fill, terraces, and flood plain deposits, both Pleistocene and Holocene in age. Partially, these undifferentiated deposits of gravel, sand, silt and clay represent reworked sediments of the Tertiary Ogallala Formation and/or from Cretaceous bedrock. Materials imported from the Rocky Mountains by fluvial processes during the Pleistocene are also common.

The average thickness of alluvial deposits in northwest Kansas is about 12 m (Bayne & O'Connor, 1968), but the Alluvium can attain much greater thickness: 21 m in Wallace County (Hodson, 1963) and 30 m in Gove County (Hodson & Wahl, 1960) have been reported.

Chapter 4

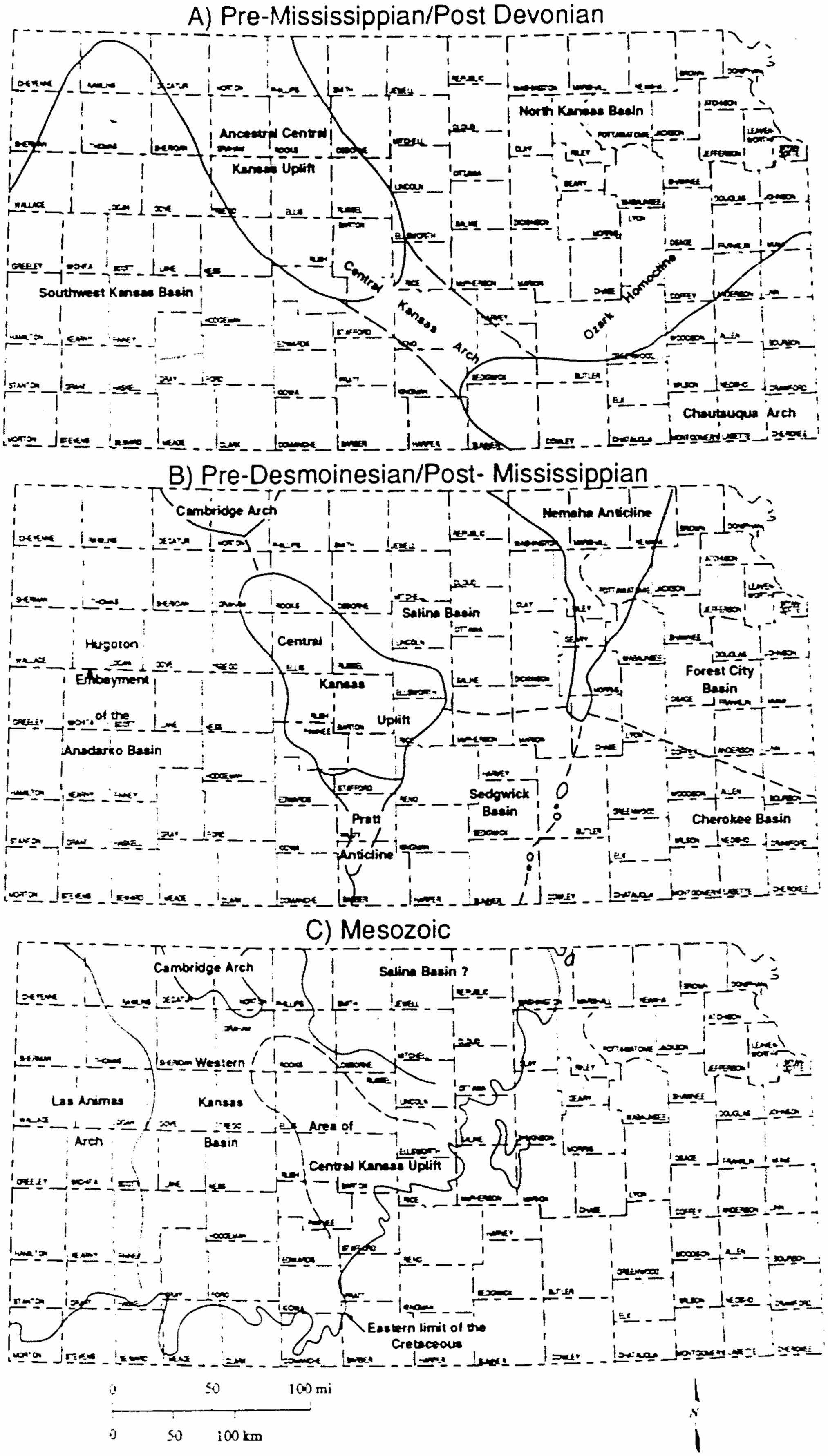
Tectonic framework of the study area

Fig. 22 shows the major structural features of Kansas for different time periods. The study area is part of four structures: the Central Kansas Uplift, the southern extension of the Cambridge Arch, the Hugoton Embayment of the Anadarko Basin, and the Las Animas Arch.

Between the Desmonian and Mississippian regional arching occurred along a northwest/southeast axis, the so-called Ellis Arch developed (Frye, 1945). This anticlinal feature was affected by several periods of uplift (Merriam, 1963), and finally developed at the end of the Mississippian or during early Pennsylvanian time into the Central Kansas Uplift and the Cambridge Arch, which separate the Hugoton Embayment in the west from the Salina and Sedgwick basins to the east (Fig. 22). Arching of the uplift continued through Pennsylvanian and early Permian time, resulting in a tilt of the area toward the Hugoton Embayment. The crest of the structure has Pennsylvanian beds overlying Precambrian rocks, on the flanks pre-Pennsylvanian beds are upturned, truncated and overstepped by Pennsylvanian strata (Merriam, 1963).Trending northwestward, the Central Kansas Uplift is the most prominent structural feature in Kansas. It has an approximate areal extent of 14.763 km^2 (Merriam, 1963) and lies entirely within the state.

Separated from the Central Kansas Uplift by a saddle structure, the Cambridge Arch represents the northwest extension of the latter. Structural movements along this feature occurred parallel to those of the Central Kansas Uplift and then again in Mesozoic time, continuing through the Cretaceous and later (Lee & Merriam, 1954). Together with the Central Kansas Uplift the Cambridge Arch shows an arcuate trend of uparched features. In plan view the beds are convex to the southwest. Several smaller anticlinal and synclinal structures parallel the Cambridge Arch.

The Hugoton Embayment is a large, shelf-like extension of Oklahoma's Anadarko Basin into western Kansas (Maher & Collins, 1948). An increase in the thickness of



A) Pre-Mississippian/Post Devonian

B) Pre-Desmoinesian/Post- Mississippian

C) Mesozoic

Figure 22: Tectonic framework of Kansas, modified from Merriam (1963)

sediments to the south and toward the axis of the structure, indicates the general dip of beds. The Hugoton Embayment as a major structural unit occupies about one third of the entire state of Kansas (Merriam, 1963). Structural development continued to be active through Pennsylvanian and Permian time (Lee & Merriam, 1954). Cretaceous beds in the area of the Hugoton Embayment, foremost beds in the Niobrara Formation, show many small, tension-type faults and fractures. They seem to be especially numerous in Wallace County (Johnson, 1958).

The Las Animas Arch is located mostly in eastern Colorado, only its easternmost extension reaches into western Kansas. It separates the Denver Basin from the Hugoton Embayment and the later Western Kansas Basin. Until the late Cretaceous, the Las Animas Arch had little effect on the regional structure in western Kansas. As a result of the mainly post-Cretaceous activity along the Las Animas Arch, Cretaceous bedrock in northwest Kansas dips generally 3 m to 6 m per 1.6 km to the northeast, although locally dips to the east or the north are observed as well (O'Connor & McClain, 1982).

Concurrent with the orogeny in the Rocky Mountains during the late Tertiary were small differential epirogenetic movements (Frye, et al., 1956).

In the Pleistocene differential uplift caused arching of the Ogallala beds and a general tilt to the east. Elias (1931) observed gentle folding in the Ogallala Formation in Wallace County which reflect in the Cretaceous strata.

More recent structural epirogenetic movements are documented by occurring earthquakes mainly along the Central Kansas Uplift and the Nemaha Anticline in eastern Kansas (Merriam, 1963).

Chapter 5

Mineral Resources in the study area

Mineral resources in the study area are not very extensive. The most important source of income is agriculture. Of the non-fuel resources sand and gravel is the most important one.

Oil and Gas

Oil and gas wells exist in nearly every county of the study area with production of oil outweighing the gas production. However, most of the oil and gas resources of Kansas are located and being exploited in central Kansas along the Central Kansas Uplift and in the eastern part of the state, so that overall production in the study area is comparatively low. Generally, oil and gas producing strata in northwest Kansas are the Cambrian/Ordovician Arbuckle Group and the Pennsylvanian Marmaton and Kansas City-Lansing groups. Some Mississippian rocks yield oil and gas as well.

Only 9.83% of the 58.823.981 barrels of oil produced in the entire state of Kansas in 1988 come from counties in the study area (Kansas Geological Survey, 1989).

Sand and Gravel

Among the non-fuel mineral commodities sand and gravel is most widely produced in the study area. Numerous open pit operations yield sand and gravel associated with the Tertiary Ogallala Formation, but also from alluvial and terrace deposits. The materials are used for road construction and surfacing and as an aggregate for concrete.

Smoky Hill Chalk

The Upper Cretaceous Smoky Hill Chalk is sometimes used as a building stone but more often county roads are surfaced with the crushed material.

Ogallala "Quartzite"

Very rarely is the Ogallala "Quartzite" used as a building stone anymore but where it is present in outcrops it is sometimes mined for road material.

Mortar beds of the Ogallala Formation

In 1963 Wallace County was the only county in the study area where this material was commercially mined (Hodson, 1963). The diatomaceous marl can be used as paint filler and whiting substitute. As a building stone the marl is not suitable because it shows differential weathering due to different hardness in the marl beds.

Volcanic ash

Volcanic ash is a mineral source of minor importance. It is not mined commercially in the study area but in Norton County it is mined for use as an abrasive element and as a filter for clarification of cooking oils. In former times it was used as a mineral filler in road construction.

Chapter 6

Hydrology of the Study Area

Surface Waters

Northwest Kansas belongs to the Missouri River drainage basin. The majority of streams flow to the northeast following the general slope of the area.

Only three perennial streams are recognized in the study area: the South Fork Republican River, Beaver Creek, and the South Fork Solomon River (Fig. 12). All of these streams have intermittent character over long distances before they become perennial by intersecting the ground water table.

Numerous intermittent streams are present in the study area. The majority of them were perennial before the onset of irrigation, which lowered the water table considerably. Now they carry water only during and shortly after precipitation events. However, not much run-off is produced by precipitation events, unless they are either of longer duration, which is rare, or short with very heavy rainfall so that the dry soil can not quickly absorb the moisture. Loess, which covers most of the upland areas in northwest Kansas, and in which the soils are developed, acts like a big sponge soaking up moisture, when rainfalls are not too heavy or when the area is under snow cover and the ground is not frozen.

Seeps and springs are rare in the study area, because of the deep water table. Since irrigation began most of the springs went dry and are now above ground water level. Active springs can still be found along the discharge boundary of the Ogallala aquifer, mostly in the very eastern part of the study area (Graham County) and along the perennial streams.

The majority of the numerous intermittent ponds is present in Sherman, Thomas, and Cheyenne counties. During and after precipitation events, the ponds will hold water for a short period of time and serve as a water source for cattle.

The presence of intermittent ponds and the larger sized depressions is attributed to various causes, including solution-subsidence, wind scour, differential erosion-deposition, differential compaction, and the wallowing of buffalo (Self, 1978).

Ground Water

High Plains Aquifer System

The High Plains aquifer system which is considered by Gutentag & Weeks (1980) to consist of one or more hydraulically connected units of late Tertiary or Quaternary age, is considered a single hydrologic unit. The Tertiary Ogallala Formation comprises the major part of the High Plains aquifer system, which underlies a total of 450789 km^2 (Stullken et al., 1985) in eight states: Wyoming, South Dakota, Nebraska, Colorado, Kansas, Texas, Oklahoma and New Mexico. 80% of the this area, i.e. 347060 km^2 (Weeks, 1986), is underlain by the Ogallala Formation, which is thus the principal geologic unit of the High Plains aquifer (Fig. 23).

In the study area, the term High Plains aquifer system is more or less synonymous with the term Ogallala Aquifer, because Ogallala deposits represent the major water bearing formation.

In 1980 the total volume of drainable water in storage in the High Plains aquifer was estimated to be 4 x 10^{12} m^3 (Gutentag et al., 1984). According to Weeks (1986) this amount is divided among the eight states overlying the High Plains aquifer system as follows: 65% of the ground water in aquifer storage are in Nebraska, where recharge and saturated thickness are greatest due to the presence of sand dunes, about 12% are in Texas, Kansas holds 10%, Colorado 4%, Oklahoma 3.5%, South Dakota and Wyoming 2% each, and New Mexico 1%.

For a long time the High Plains aquifer was regarded as an inexhaustible supply of water. When development began on the High Plains in the late 19th century, the early settlers used windmills to pump shallow ground water from hand dug wells. Until the

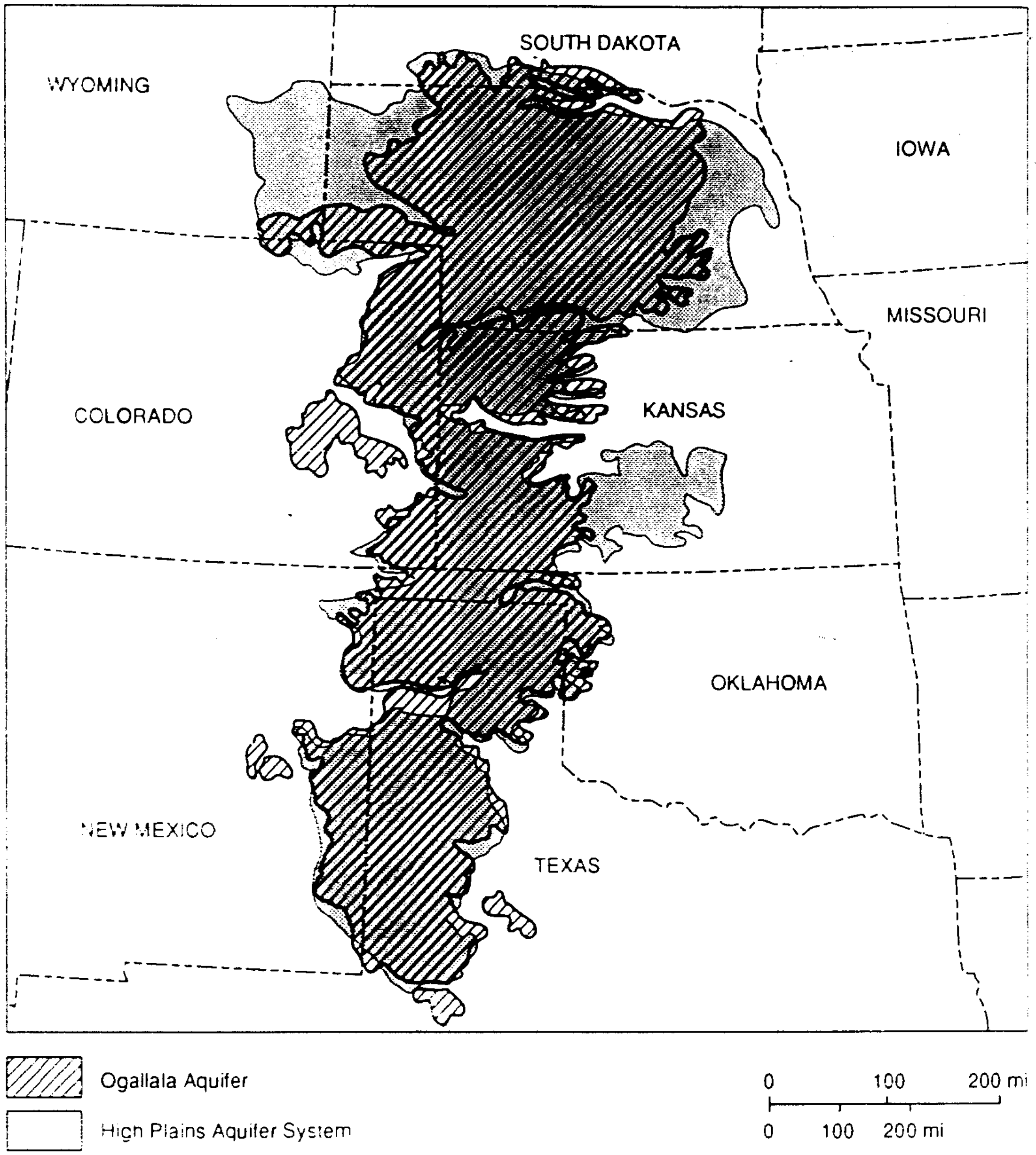


Figure 23: The Ogallala aquifer as part of the High Plains aquifer system, modified from Weeks (1986) and Merriam (1963)

1930's the agriculture in the High Plains was under a "boom and bust" cycle: With enough precipitation agriculture flourished on the fertile soils, but recurring droughts destroyed everything. During the so-called "dust bowl" that coincided with the Great Depression in the 1930's many settlers had to leave the High Plains. However, spurred by the drought, technological advances in well drilling techniques, pumping technology and cheap available energy, ground water irrigation developed rapidly after the 1930's. The second world war interrupted this process, but after it was over one of the most productive and stable agricultures established itself in the High Plains. By 1949, 8094 km^2, mostly located in the Southern High Plains, were irrigated (Weeks & Gutentag, 1984). Most irrigation wells were drilled in areas, where the ground water level was less than 30 m below land surface. In the 1960's the development of efficient power plants for turbine pumps allowed the installation of deeper wells. In addition, the center pivot irrigation system was developed, making land available for irrigation which was previously not suitable.

Annual ground water pumpage for irrigation increased from about 4.0 x 10^9 m^3 during 1949 to nearly 2.2 x 10^{10} m^3 during 1980, representing about 30% of the ground water used for irrigation in the United States (Weeks & Gutentag, 1984). The report published by Camp Dresser & McKee, Inc. et al. (1982) lists an increase in irrigated acreage in the High Plains area from 14.164 km^2 in 1950, mostly situated in Texas and Nebraska, to more than 60703 km^2 in 1980, which represents an average annual increase of about 1619 km^2 in 30 years.

About 20% of the irrigated land in the United States is located in the High Plains (Weeks & Gutentag, 1984). Fig. 24 shows irrigated acreage and estimated ground water pumpage in the High Plains from 1949 to 1978.

Approximately 95% of the water withdrawn from the High Plains aquifer system is used for irrigation (Weeks et al., 1988). Compared to this figure, the amount of water needed for domestic, industrial and municipal usages represents only a minor factor.

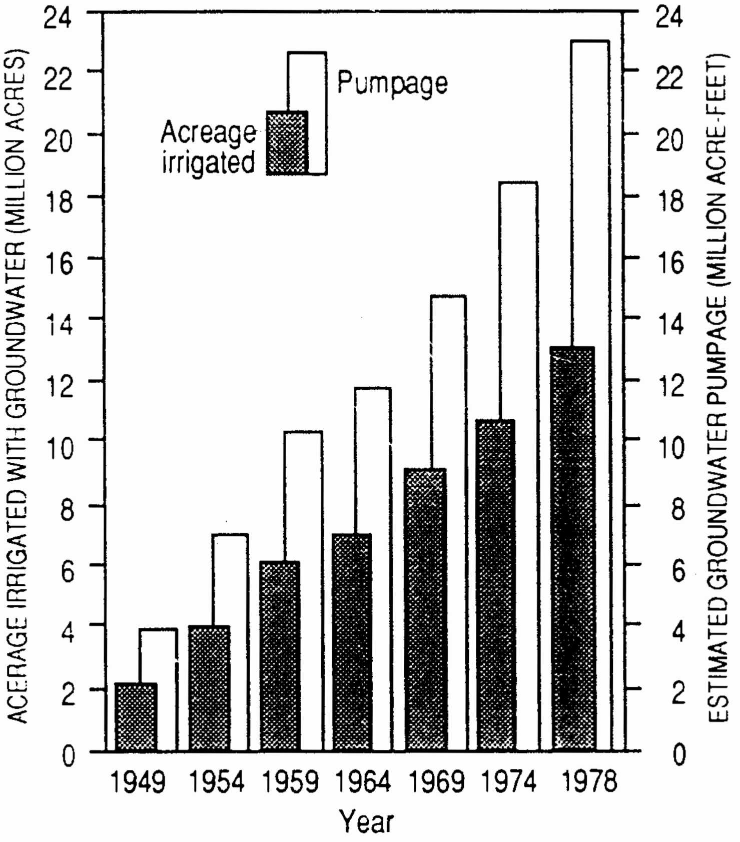


Figure 24: Irrigated acreage and estimated ground water pumpage in the High Plains from 1949 to 1978, modified from Weeks (1986)

Following Nebraska and Texas, the state of Kansas is the third largest water consumer. Kansas, Nebraska and Texas together account for about 88% of the total water pumped.

Although improved irrigation techniques reduced the per acre application by 30% from 2466 m^3 of water to 1726 m^3 (Camp Dresser & McKee, Inc. et al., 1982), the significant increase in irrigation over the last 30 to 40 years has caused severe water level declines in the High ~~Plains~~ aquifer system.

Fig. 25 shows the water level changes from pre-development to 1980. The largest area of decline occurred in Texas, exceeding 15 m of decline. Locally, the water table declined here as much as 61 m (Luckey et al., 1981).

The later onset of irrigation development in the northern half of the High Plains aquifer system, combined locally with more favorable recharge conditions, is probably responsible for a lesser water level decline in this area.

Weeks et al. (1984, 1988) attribute water level rises in Nebraska to return flow from surface water irrigation and leakage from canals and reservoirs, whereas rises in Kansas and Oklahoma are said to represent recovery from abnormally low water levels during the drought of 1933 to 1940. According to their figures, a total of 12950 km^2 of the High Plains aquifer showed water level declines in excess of 3 m, and more than 31080 km^2 showed declines in excess of 15 m. In only 1% of the total area underlain by the High Plains aquifer system significant water level rises (more than 3 m) occurred, whereas severe declines (more than 3 m) occurred in 29% of the area (Weeks et al., 1984, 1988).

From pre-development to 1980 the total volume of ground water in storage in the High Plains aquifer system was depleted by 2.05×10^{11} m^3, 16% of the removal occurred in Kansas and 70% in Texas (Weeks et al., 1988).

Due to this depletion, not only the water levels declined but the saturated thickness changed concurrently. Changes in saturated thickness are directly related to changes in well yields. Negative changes mean a decrease in water availability and an increase in pumping lifts, which can cause a significant cost increase regarding the operation of irrigation wells.

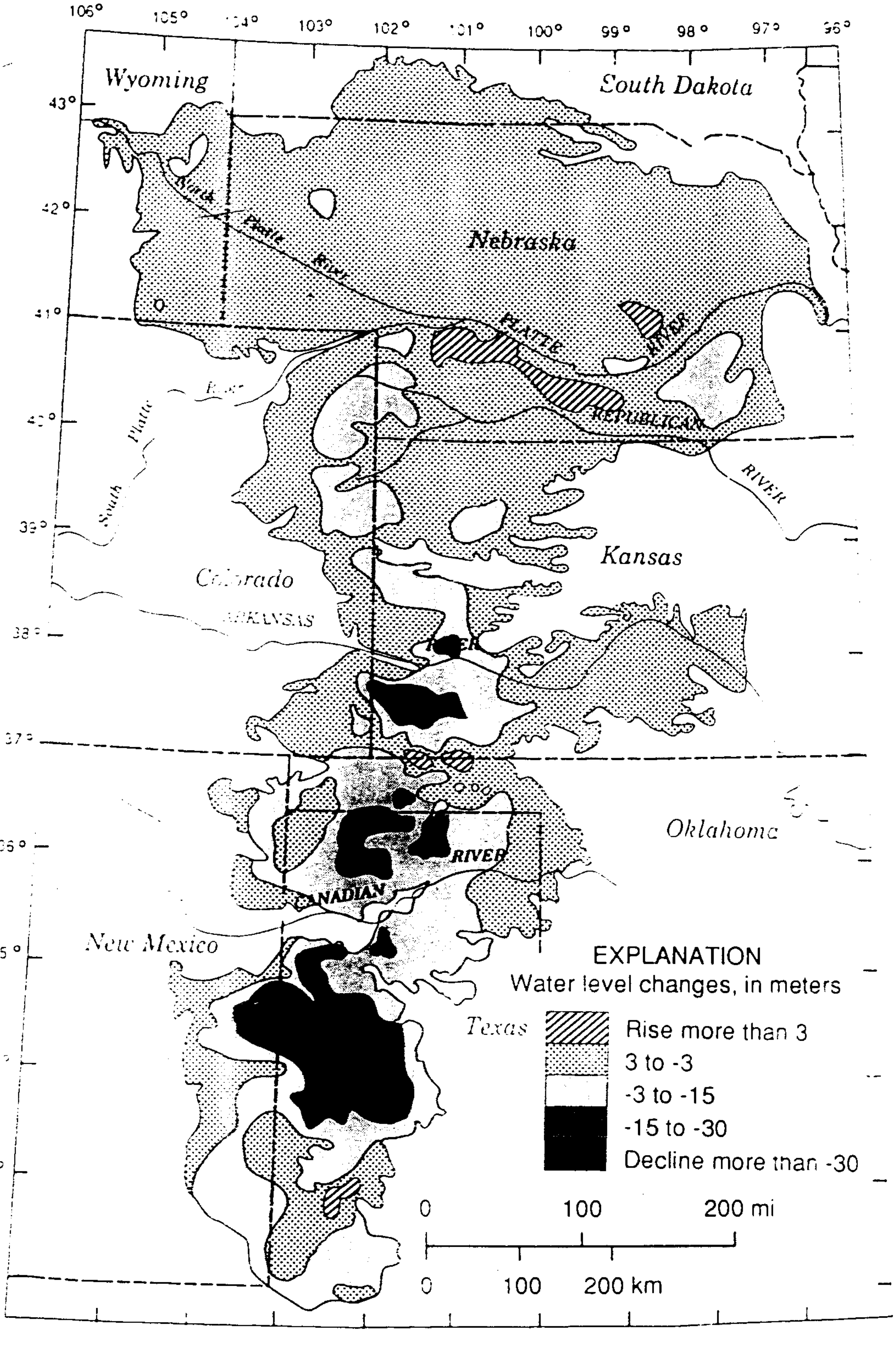


Figure 25: Water level changes in the High Plains aquifer, pre-development to 1980 modified from Weeks et al. (1988)

Fig. 26 shows the saturated thickness of the High Plains aquifer system from pre-development to 1980. Significant increases in saturated thickness (more than 10%) occurred in only 1% of the area, decreases of more than 10% and more than 25% occurred in 25% and 8% of the area, respectively (Weeks et al., 1988).

Areas of significant decrease generally coincide with areas being under irrigation for a long time. In Texas and New Mexico large scale irrigation operations began about 1940, whereas in Colorado, northwest Kansas, Nebraska and Wyoming most of the irrigation development took place since 1960.

Increases in saturated thickness are due to the same processes described above for the increase of water levels.

Fig. 27 shows the saturated thickness in the High Plains aquifer system in 1980. Average saturated thickness was 61 m, but areas with up to 305 m saturated thickness are known from Nebraska; about 46% of the aquifer system had less than 30 m of saturated thickness (Weeks et al., 1988, Weeks, 1986).

Declining water levels and decreasing saturated thickness indicate that the High Plains aquifer is basically being mined: water is withdrawn at a much faster rate than recharge can occur.

Precipitation and seepage from streams are the main contributors to recharge to the generally unconfined aquifer system. But because evaporation greatly exceeds precipitation (Figs. 7 and 8), only a very minor amount of the latter infiltrates the ground and eventually reaches the ground water table. Exception are areas with sandy soils which are characterized by high permeability, low field capacity and rapid infiltration rates.

Recharge estimates range from 0.6 mm per year in Texas to 152 mm per year in areas of dune sands in Kansas and Nebraska (Gutentag et al., 1984). Luckey (1984) estimated the average annual recharge to the High Plains aquifer over the entire area of the aquifer system by model simulation. The resulting value was 152 mm per year. About 80%

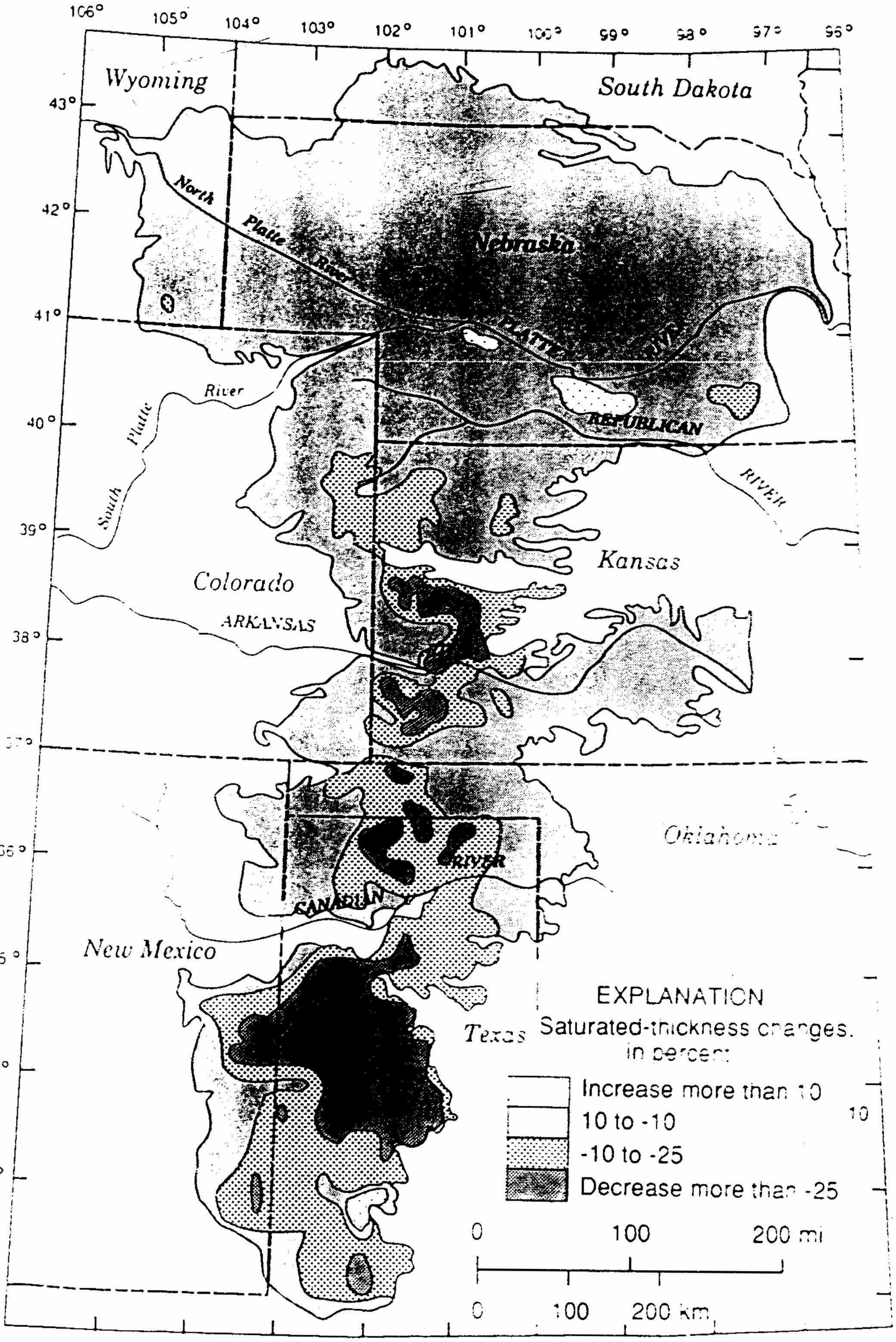


Figure 26: Saturated thickness changes from pre-development to 1980 in the High Plains aquifer, modified from Weeks et al. (1988)

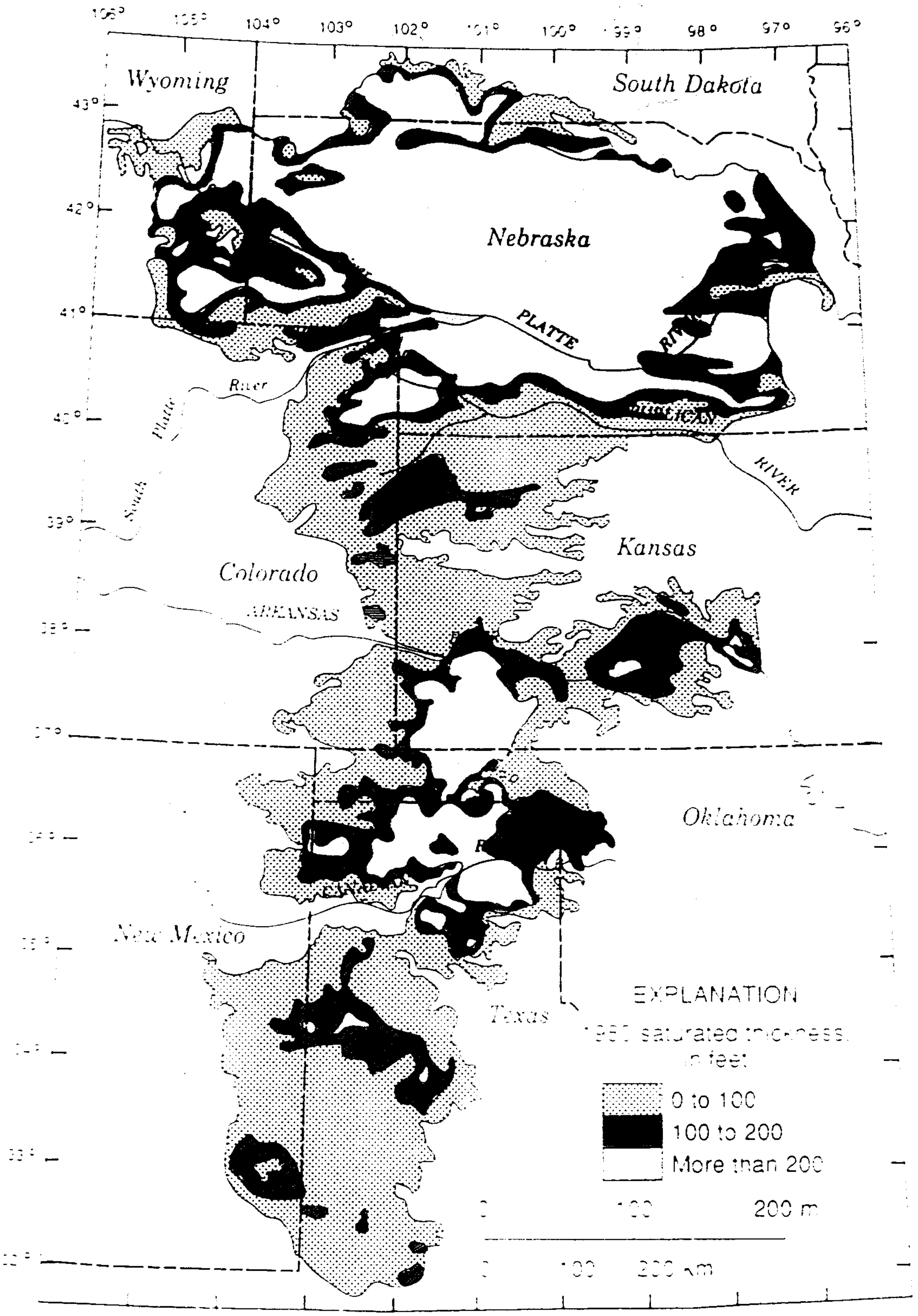


Figure 27: Saturated thickness of the High Plains aquifer in 1980, modified from Weeks et al. (1988)

of this recharge occurs north of 39 degrees latitude, where dune sands are present and evapotranspiration is low.

Ground water flow in the system is generally from west to east following the slope of the water table. Based on aquifer properties and the regional ground water gradient, the velocity of ground water flow is about 30 cm per day (Weeks, 1986).

Hydraulic conductivity and specific yield can vary horizontally as well as laterally, because they depend on the characteristics of the sediment. Both properties control the flow of ground water in an unconfined aquifer.

The hydraulic conductivity for 68% of the High Plains aquifer system is 9.25×10^{-5} m/sec to 34.7×10^{-5} m/sec (Gutentag et al., 1984), although it can be as high as 10.5×10^{-4} m/sec for individual lithologic units and averages 20.8×10^{-5} m/sec (Weeks, 1986, Weeks et al., 1988).

The value for specific yield is 15% on the average and can range from 3% to 35% for individual lithologic units (Weeks, 1986, Weeks et al., 1988). For 76% of the aquifer system Gutentag et al. (1984) give a specific yield value of 10% to 20%.

Water quality in the High Plains aquifer system is generally suited for irrigation, but is locally not of drinking water quality. Concentrations of sulfate, chloride, selenium, fluoride, nitrate and dissolved solids can exceed the United States Environmental Protection Agency's (1976, 1977) primary and secondary drinking water standards.

Fluoride concentrations of more than 2 mg/l are widespread in the High Plains aquifer and are derived from fluoride minerals in the sand, gravel and volcanic ash deposits that comprise a large part of the aquifer. Underlying Cretaceous rocks, especially from the Lower Cretaceous period, add fluoride as well.

85% of the water stored in the High Plains aquifer contains less than 500 mg/l dissolved solids and about 27% contain less than 250 mg/l dissolved solids (Weeks et al., 1988).

High concentrations along the streams are caused by irrigation return flow which is highly mineralized due to flushing and consecutive transport of the salts accumulated in the soils by evaporation processes. The shallow aquifer along the streams is very susceptible to these contaminations.

Concentrations of more than 500 mg/l dissolved solids in Texas and New Mexico are caused by the Lower Cretaceous bedrock in these areas, which was deposited in a deep marine environment (Weeks et al. 1988). Water in these rocks is highly mineralized.

The Ogallala Aquifer in the Study Area

The High Plains aquifer in Kansas comprises the Tertiary Ogallala formation and alluvial deposits of Quaternary age. In northwest Kansas, including the study area, Quaternary water bearing deposits are of minor importance as a water resource. Only the alluvium along streams yields water to wells. The principal water source are the Tertiary deposits of the Ogallala formation, i.e. the Ogallala aquifer.

In general, most of the characteristics of the High Plains Aquifer system, as outlined in the previous paragraph, are also applicable to the Ogallala aquifer in western Kansas.

In the following, the Ogallala aquifer in the study area and in northwest Kansas in general is described in greater detail.

The Ogallala aquifer in northwest Kansas overlies low permeability Lower Cretaceous bedrock, which represents a "no-flow" boundary according to Stullken et al. (1985). However, hydraulic connection may occur sometimes along fracture zones.

The aquifer is generally unconfined with ground water flowing from west to east according to hydraulic head differences. The slope of the water table follows the slope of the bedrock which averages about 0.24% (Stullken et al., 1985).

On a regional scale the aquifer may appear homogenous in its properties but on a local scale variations can be considerable due to the diverse lithology of the Ogallala formation.

Very few pump test data are described in the literature. Data in the old county reports, mostly compiled during the 1940's and 1950's are not considered to be very reliable, because of the techniques and equipment used at that time, and often the duration of the tests and the screened depth of the respective wells are not mentioned.

Stullken et al. (1985) summarizes some of the older pump test data in the Ogallala aquifer. For counties included in the study area, transmissivity values range from 223 m^2/day to 4.926 m^2/day, and hydraulic conductivity values vary from 10.4 x 10^{-5} m/sec to 15.6 x 10^{-4} m/sec. Numbers for storage coefficients, which are identical with specific yield in an unconfined aquifer, are not reported.

Stullken et al. (1985) also estimated hydraulic conductivity and specific yield of the Ogallala aquifer in Kansas based on 1612 well logs. Fig. 28 and Fig. 29 show the results. For northwest Kansas the estimated hydraulic conductivity averages 22 x 10^{-5} m/sec to 43 x 10^{-5} m/sec, the specific yield for the same area ranges from 10 to 25%.

Unpublished pump test data from the files of the Kansas Geological Survey and the United States Geological Survey provide information on 35 aquifer tests of Ogallala wells in the study area. Transmissivity values range from 403 m^2/day to 6170 m^2/day, specific conductivity values vary from 7.6 x 10^{-5} m/sec to 13.8 x 10^{-4} m/sec, and storage coefficients range from 1 x 10^{-11} to 0.16. The data were obtained by using the Theis method.

It is evident that large variations in aquifer properties occur in the Ogallala aquifer throughout northwest Kansas, reflecting the diverse lithology of the water bearing Ogallala formation.

With the onset of irrigation since the 1950's and major advances in irrigation techniques since the 1960's, water levels and saturated thickness started to decline

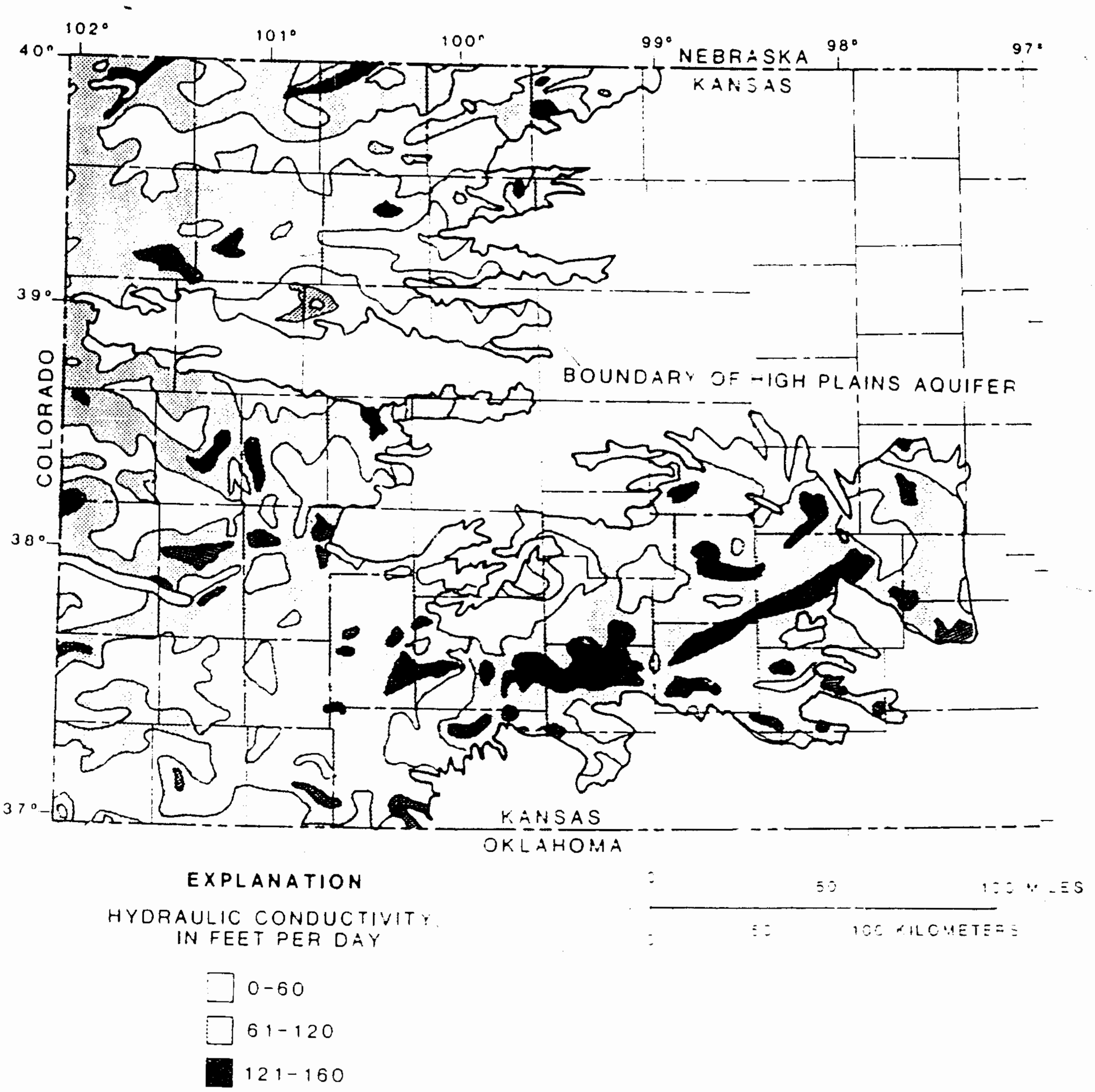


Figure 28: Hydraulic conductivities of the High Plains aquifer in Kansas, modified from Stullken et al. (1985)

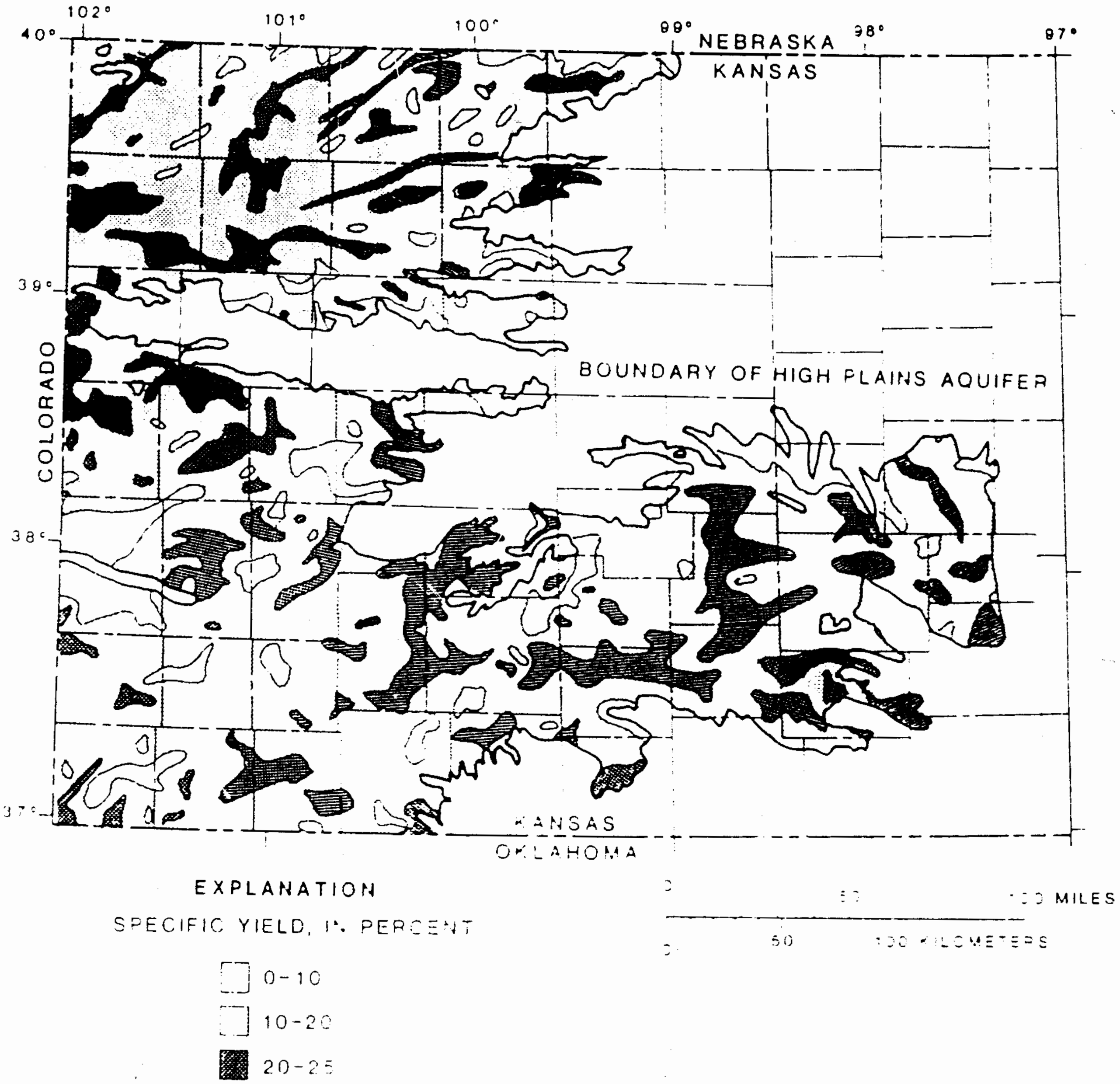


Figure 29: Specific yield of the High Plains aquifer in Kansas, modified from Stullken et al. (1985)

seriously in northwest Kansas and continued to decline to the present. Fig. 30 depicts the decline in depth to water for a well in Thomas County for the period from 1947 to 1988.

Basically, the Ogallala aquifer is being mined, withdrawal of water by far outweighing recharge to the aquifer. Because the irrigated agricultural economy is solely dependent on Ogallala ground water the declining water levels are of serious concern. It is one of the primary tasks of the Groundwater Management District in northwest Kansas to enhance better management of the resource. The change from flood irrigation to the center pivot irrigation system helped in reducing the amount of withdrawal from the Ogallala aquifer, but eventually it may become necessary to return to dry land farming practices in northwest Kansas, because it will be too expensive and too inefficient to pump water out of the declining aquifer.

Table 1 lists the appropriated water rights as of September 18, 1989 for the study area. Water rights for a total 3531 wells were appropriated, 3412 of which were irrigation wells. 1.09×10^9 m^3 of water, i.e. 98.39% of the total volume appropriated, were appropriated for irrigation, which does not mean that this amount was actually pumped. This number represents the maximum pumpage allowed for irrigation. Municipal, industrial, and stock water wells are of only minor importance.

Table 1: Appropriated water rights in the study area

Use type	Number of wells	Volume of water appropriated (m^3)	% of total
Irrigation	3412	1.09×10^9	98.39
Municipal	73	11574418	1.04
Industrial	19	2803102.2	0.25
Stock water	26	2745274.5	0.25
Recreational	1	715140	0.06
Total	3531	1.11×10^9	99.99

Water use data for 1989 have not been processed yet. The reported water use for the study area in 1988 is listed in table 2. The figures were kindly provided by the

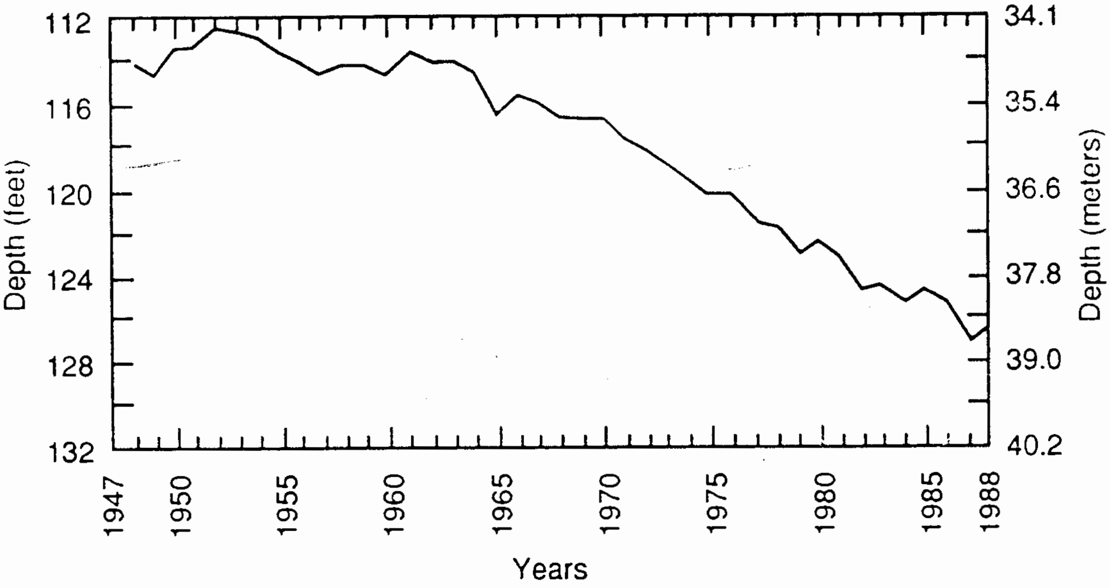


Figure 30: Water level decline in a well in Thomas County, Kansas, redrawn from Geiger et al. (1988)

Groundwater Management District. A total of 6.4 x 10^8 m^3 of water were used. 98.3% of this amount was used for irrigation and 1.35% for municipal purposes, i.e. drinking water. Usages for stock water, domestic, industrial and recreational purposes were all less than 1%.

Table 2: 1988 water use in the study area

Use type	Volume of water used (m^3)	% of total
Irrigation	6.26 x 10^8	98.3
Municipal	8593726.4	1.35
Stock water	146205.4	0.23
Domestic	9888.7	0.002
Industrial	198574.6	0.03
Recreational	332910	0.05
Total use	6.37 x 10^8	99.96

The difference in numbers between the maximum amount of water appropriated (1.1 x 10^9 m^3) up to September 1989 and the total amount of water used in 1988 (6.4 x 10^8 m^3) is partially due to the existence of old water rights. Water rights do not expire. There may be no well anymore at a given location, but the appropriated water right to pump so many m^3 of water still exists. In addition, many farmers use the system of rotation irrigation, comparable to crop rotation. They have more than one irrigation well, but do not use all their wells every year, depending on the kind of crops they grow on the particular fields.

Table 3 gives an overview of averages of: a)water level changes from 1950 to 1988, b)% saturated thickness changes from 1950 to 1989, c) the change in saturated thickness for the same time period reported in meters. d) water level changes from 1988 to 1989, and e) depth to water in 1989 for nine counties included in the study area (Townsend, et al. 1989). The counties which are only partially inside the boundaries of the study area, i.e. Cheyenne, Rawlins, Decatur, Graham, Gove and Logan counties, were

Table 3 : Average water level changes from 1950 to 1989 and from 1988 to 1989, changes in saturated thickness and depth to water in the study area

County	Water level change 1950-1989 (m)	Water level change 1988-1989 (m)	Change in saturated thickness 1950-1989 (%) Ogallala/Quaternary	Change in saturated thickness 1950-1989 (m) Ogallala/Quaternary	Depth to water Ogallala/Quaternary
Cheyenne	-2.77 (35)	-0.35 (45)	-9.1 (29)/-9.6 (5)	-3.26 (29)/-0.6 (5)	50.6 (32)/4.05 (5)
Decatur	-0.33 (30)	+0.05 (30)	+0.6 (11)/-7.1 (16)	-0.03 (11)/-0.61 (16)	31.9 (12)/6.3 (16)
Gove	-2.04 (3)	-0.4 (18)	-12.3 (3)/	-2.04 (3)/	24.2 (10)/4.4 (1)
Graham	-0.58 (12)	-0.12 (22)	-0.4 (10)/	-0.43 (10)/	28.8 (15)/7.0 (3)
Logan	-3.88 (4)	-0.04 (12)	-13.25 (4)/	-3.73 (4)/	35.7 (9)/3.3 (1)
Rawlins	-2.04 (25)	-0.65 (27)	-7.7 (14)/-18.4 (9)	-2.16 (14)/-1.8 (9)	43.5 (16)/5.9 (9)
Sheridan	-6.1 (31)	-0.12 (44)	-21.12 (24)/-13.5 (4)	-7.3 (24)/-1.98 (4)	61.9 (24)/5.6 (4)
Sherman	-8.1 (51)	-0.29 (58)	-17.9 (47)/-2.o (1)	-8.29 (47)/-0.61 (1)	45.2 (52)/2.2 (1)
Thomas	-4.6 (40)	-0.44 (52)	-13.6 (39)/-7 (1)	-4.6 (39)/-1.52 (1)	47.7 (47)/4.2 (1)

( ) = number of observation wells

included as a whole in the table, whereas Wallace County was not included at all, because it contributes the least area to the study area.

Water level changes from 1950 to 1989 as well as water level changes from 1988 to 1989 are based on wells completed in the Ogallala formation and in Quaternary deposits. Depth to water as well as % change in saturated thickness from 1950 to 1989 and saturated thickness changes in feet for the same time frame are reported separately for Ogallala wells and Quaternary wells. The number of observation wells each average value is based upon is given in parentheses.

The greatest water level changes for the period from 1950 to 1989 occurred in Sherman, Sheridan, and Thomas counties. The Ogallala aquifer in these counties also shows the highest values for saturated thickness (Fig. 31). A broad band of saturated thickness reaching up to 55 m in Sherman County crosses the study area from west to east, mostly influencing the afore mentioned counties. Thus irrigation is by far more common here than in the other counties of the study area, causing the large declines of the water table.

The saturated thickness map (Fig. 31) also shows the discharge boundary of the Ogallala aquifer in northwest Kansas. This boundary reaches through Wallace, Logan, Gove, and Graham counties and Cheyenne County in the northwest. This means that the Tertiary deposits of the Ogallala formation are thinning out in these areas, saturated thickness of the deposits declines accordingly and irrigation is not as common. Thus the water level declines here are not as severe.

Jenkins & Pabst (1975) list areas suitable for irrigation overlying 15 m of saturated thickness and estimated water in storage for six counties in northwest Kansas: Cheyenne, Decatur, Rawlins, Sheridan, Sherman, and Thomas counties (Table 4). These data are based on saturated thickness in 1973 in this area, but the general trend is still true.

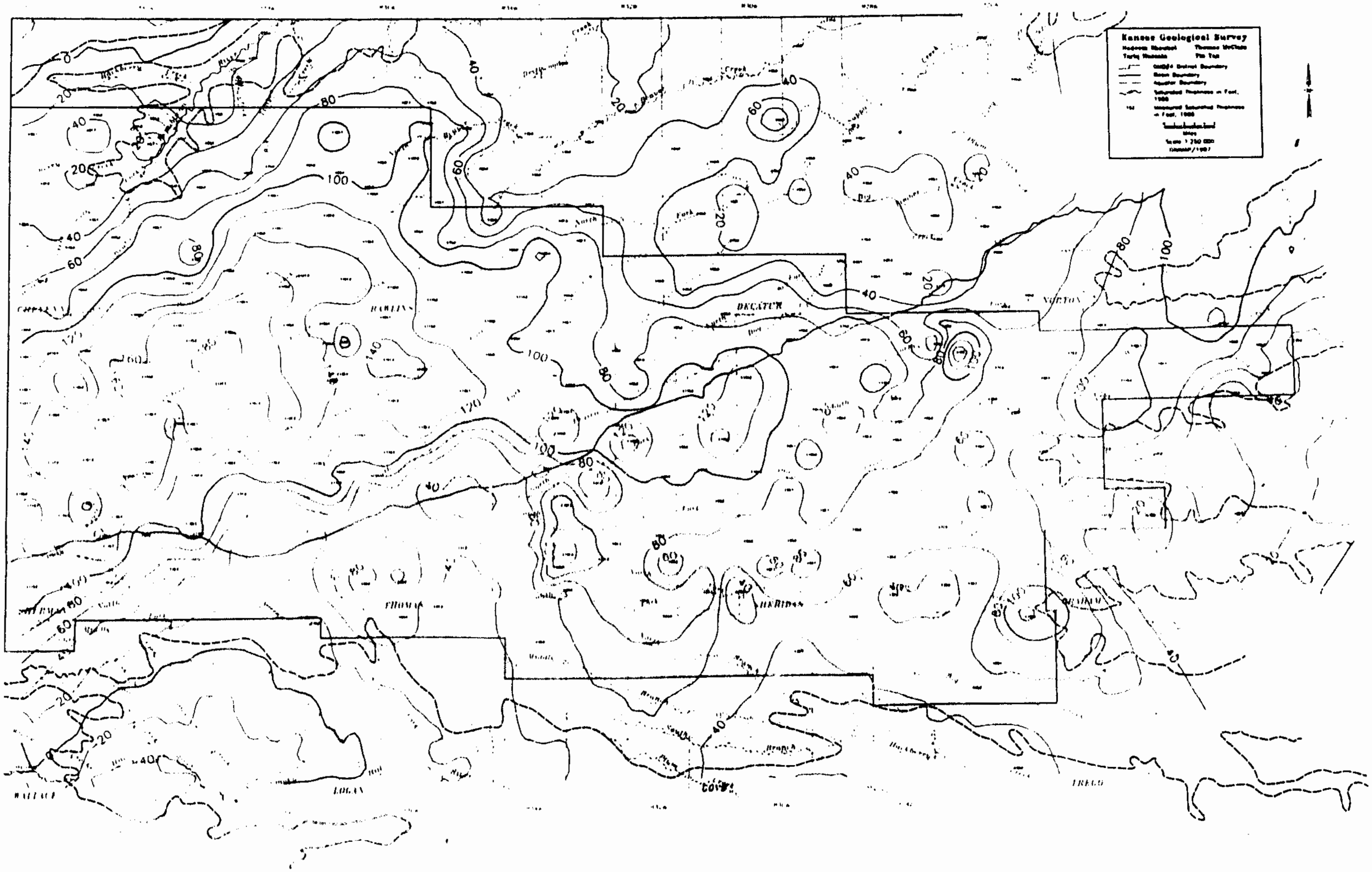


Figure 31: Saturated thickness of the Ogallala aquifer in the study area in 1986 (in feet)

Table 4: Total area, area suitable for irrigation overlying 15 m of saturation, and estimated volume of ground water in storage for counties in the study area in 1973

County	Total area (km^2)	Area suitable for irrigation and overlying 15 m of saturation (km^2)	Estimated water in storage (m^3)
Cheyenne	2660	1191	1.11×10^{10}
Decatur	2328	311	3.70×10^{9}
Rawlins	5382	803	9.86×10^{9}
Sheridan	2313	1243	1.23×10^{10}
Sherman	2732	1878	2.22×10^{10}
Thomas	2771	1917	1.60×10^{10}

Sheridan, Sherman and Thomas counties show the most amount of water in storage and the most area suitable for irrigation overlying 15 m of saturation. 69.1% of the total area in Thomas County is suitable for irrigation and meets the saturation criterion. For Sherman and Sheridan counties the numbers are 68.7% and 53.8%, respectively.

Cheyenne County shows 44.8% of the entire county as suitable for irrigation and overlying 15 m of saturated thickness, one of the reasons being the discharge boundary of the Ogallala aquifer crossing the county. Although the county has only 9% less area suitable for irrigation than Sheridan County and the difference in water in storage is only 1.2×10^9 m^3 irrigation seems to be not as common in Cheyenne County. The water level decline from 1950 to 1989 in Cheyenne County is 2.8 m on the average compared to a decline of 6 m in Sheridan County (Table 3).

Rawlins and Decatur counties show the least amount of suitable land for irrigation: 14.9% and 13.3%, respectively.

For comparison the ground water in storage based on saturated thickness in 1977 (O'Connor & McClain, 1982) is listed in table 5 for counties in the study area. All 1977 data are lower than the 1973 data in table 4, indicating a water level decline. The great difference in numbers for Sheridan County may be due to the numbers and locations of wells used for generation of the data as well as to individual contouring.

Table 5: Estimated volume of ground water in storage in the study area in 1977

County	Volume of water (m^3)
Cheyenne	8.13×10^9
Decatur	3.56×10^9
Graham	3.45×10^9
Rawlins	3.83×10^9
Sheridan	5.00×10^9
Sherman	1.71×10^{10}
Thomas	1.3×10^{10}

From table 4 and table 5 it becomes obvious that the counties with the greatest water level decline coincide with the counties with the most irrigation.

Saturated thickness declines simultaneously with the water table. The average % change in saturated thickness for all eight counties together is 17%. Only one county, Decatur County, shows a positive change of 0.6% for the Ogallala aquifer (table 3). However, the average water level decline from 1950 to 1989 for Decatur County includes an average decline of 5 cm for the 11 Ogallala wells monitored. The change in saturated thickness in feet from 1950 to 1989 is also negative for the Ogallala wells. These facts imply an error in the data base used for the calculation of the % saturated thickness change for the Ogallala wells in Decatur County.

Compared to the other counties listed in table 3, Decatur County apparently uses very little ground water. Not many wells seem to tap the Ogallala aquifer in this county, probably because of low saturated thickness values (generally below 15 m) and an average depth to water of 32 m. Most ground water used apparently comes from alluvial wells as indicated by the decline of 7.1% for saturated thickness from 1950 to 1989 and an average water level decline of 0.5 m for the same period compared to a decline of only 5 cm in the Ogallala wells.

Prairie Dog, Sappa and Beaver creeks are partially perennial in Decatur County (Fig. 12), which provides an additional water source and may also influence the amount of ground water pumped. Precipitation could also be a factor. The weather station in Decatur County recorded higher precipitation rates here than in Thomas, Sherman or Sheridan counties (Fig. 5).

The data for Graham County (table 3), except for the depth to water, are entirely based on Ogallala observation wells. No data for Quaternary wells were available. Here as well as in Decatur County the water level decline over the 39 year period is minimal: 30 cm. Little irrigation, caused by saturated thickness values generally lower than 15 m, the discharge boundary of the Ogallala aquifer crossing the county and the presence of a perennial stream may be the cause.

Water level changes from 1988 to 1989 are, with the exception of Decatur County, all negative. The average decline over the entire nine county area is 30 cm. The spatial distribution of the declines varies considerably, depending on withdrawal rates, precipitation and recharge in the individual counties. The maximum decline of 0.65 m occurred in Rawlins County, followed by Thomas, Cheyenne, Gove and Sherman counties. 1988 and the first half of 1989 were exceptionally dry, which explains these great declines occurring in just one year. Fig. 32 shows the 1987/1989 water level contours in the study area.

Average depth to water in 1989 was 41.05 m in the Ogallala wells and 4.8 m in the Quaternary wells. These numbers are of course dependent on the topography, but they indicate the general status quo.

Fig. 33 shows water level changes from March 1989 to December 1989 in the wells used for this study. Well locations are depicted in Fig. 34. All wells shown are completed in the water bearing Ogallala formation. Except in the wells of site 11, all water level measurements were made using an electric tape. The water level at site 11 exceeded the reach of the electric tape, so that a chalked steel tape had to be used. All measurements are reported in meters below land surface.

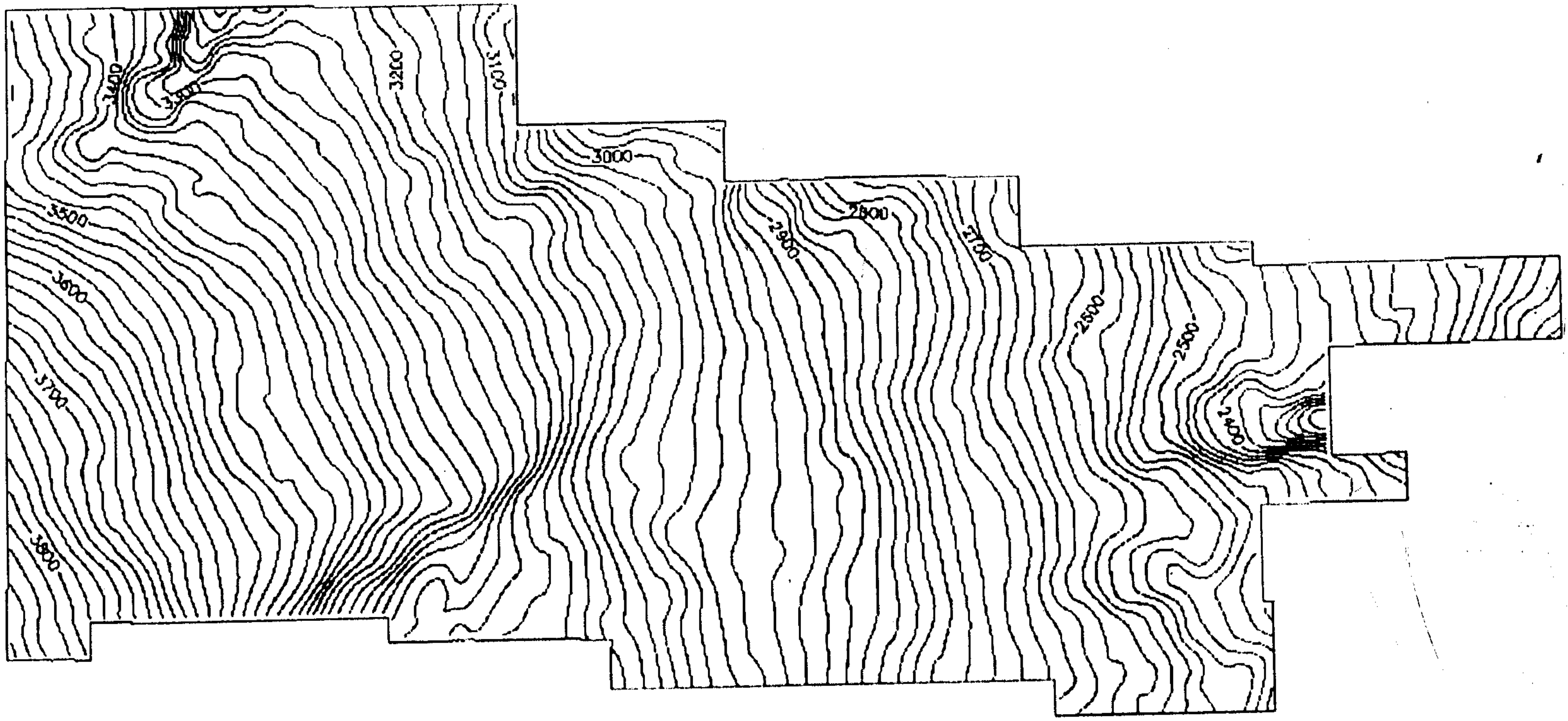


Figure 32: Water levels of the Ogallala aquifer in the study area, 1987-1989, in feet above sea level

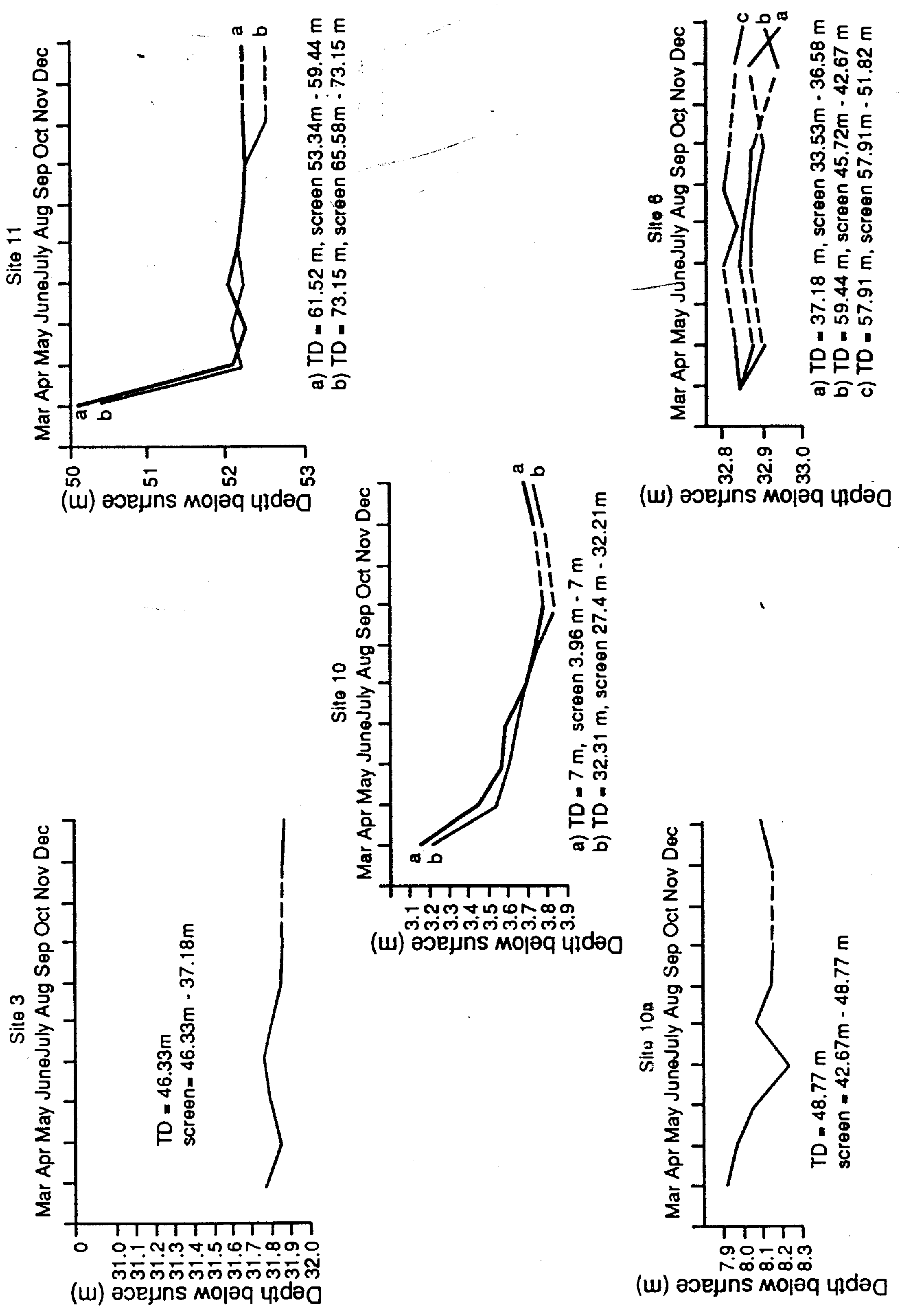


Figure 33: Water level changes from March to December 1989 in monitoring wells in the study area

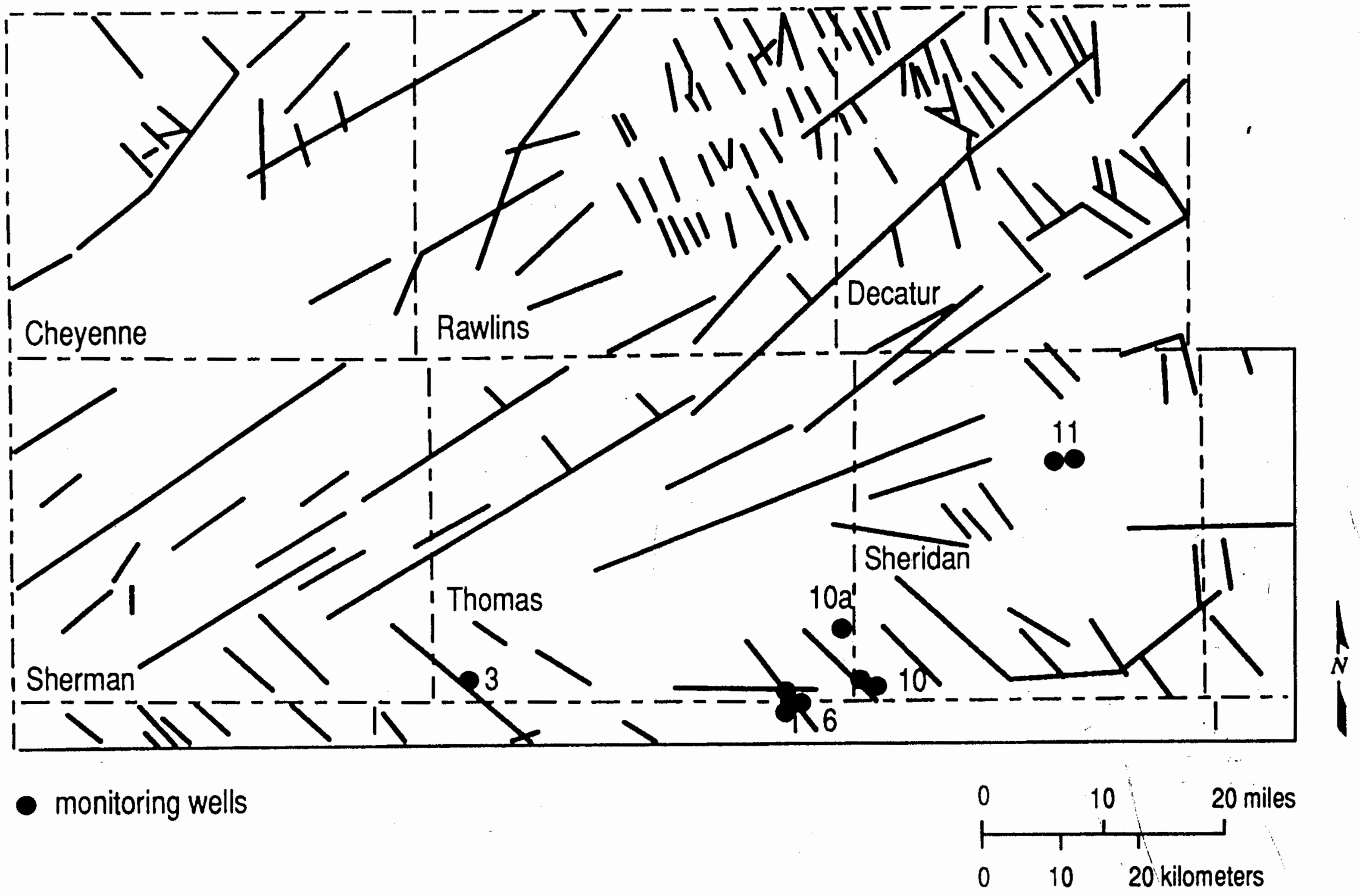


Figure 34: Water level monitoring wells in the study area

Only one well was measured at sites 3 and 11, whereas at sites 6, 10, and 12 up to three wells screened at different depths of the aquifer were present.

These water level measurements are only intended to show the general trend regarding the behavior of the water table. Measurements were only taken once a month and the time between measurements differs from month to month. However, all water levels were either measured on the same day or on two consecutive days in each month. Water levels in well clusters were always measured on the same day. Some of the fluctuations in the water levels may have been caused simply by small errors reading the tape. Only one measurement per well was taken, which especially regarding measurements with a steel tape may represent a source for errors.

The average water level decline in the nine wells monitored from March to December 1989 is 63.44 cm.

The well at site 3 is screened from 37.2 m to 46.3 m below land surface and shows a water level decline of only 7 cm, although there is an irrigation well about 800 m to the north of it. The irrigation well was probably not operating during the time period the water level measurements were taken. The location of the well in a playa-like depression may influence the rate of recharge and thus the decline of the water level.

At site 6 three wells were monitored, all of them completed in different parts of the aquifer. Well 6a is screened from 33.5 m to 36.6 m below land surface, well 6b is screened from 47.7 m to 45.7 m below land surface, and well 6c is screened from 51.8 m to 57.9 m below land surface. Wells a and b were installed in a well nest, well c is located 3.3 m away. A difference in elevation between the well nest and well c may explain the higher water level in well c. Water levels in wells a and b declined 8 cm and 7 cm, respectively, whereas well c shows the same water level in March as in December.

The water level in the well monitored at site 10a declined 17 cm from March to December 1989. The relatively sharp decline of 18 cm from May to June in this well may be due to the pumpage of a stock well located about 30 m away from the monitoring well.

But more likely the use of a steel tape instead of an electric tape for measuring the water level was the cause. The steel tape was only used for the June measurement. The sharp decline from May to June and the nearly identical rise from June to July may attest this use of a different measuring device, especially since all the other measurements show a more or less smooth decline of the water level throughout the period monitored.

The two wells monitored at site 10 are 2 m apart and are screened at a depth from 4 m to 7 m and 27.7 m to 32.3 m, respectively. Both wells show a more or less identical decline in water levels, the difference from March to December being 49 cm in the shallow well and 51 cm in the deep well. This amount of decline is fairly close to the afore mentioned average decline of 30 cm for the entire nine county area in which the study area is located.

Site 11 is the only site measured consistently with a steel tape because of its deep water level. This may account for some of the adverse fluctuations of about 7 cm to 8 cm observed in the hydrograph for the period from April to June. The wells are installed in a well nest, so no morphological differences influence the measurements. Screened intervals are from 53.3 m to 59.4 m below land surface in well 11a, and from 68.6 m to 73.1 m below land surface in well 11b.

It is certainly not the best method to use a chalked steel tape in a two inch well, because condensation tends to occur along the inner walls of the casing wetting areas on the tape that could be mistaken for a water level reading. Also, the water on the tape tends to dry off very fast due to the high evaporation rate and this too may introduce small errors reading the tape.

The most striking feature of the hydrograph is however the parallel decline of nearly 2 m from March to April. Fig. 35 depicts the location of irrigation wells in the vicinity of the site. Most of the wells are situated to the northeast, east, and southeast of the site, the closest ones being about 1.6 km away. The sharp decline of the water level can thus be attributed to the onset of the irrigation season sometime during the month of March. It

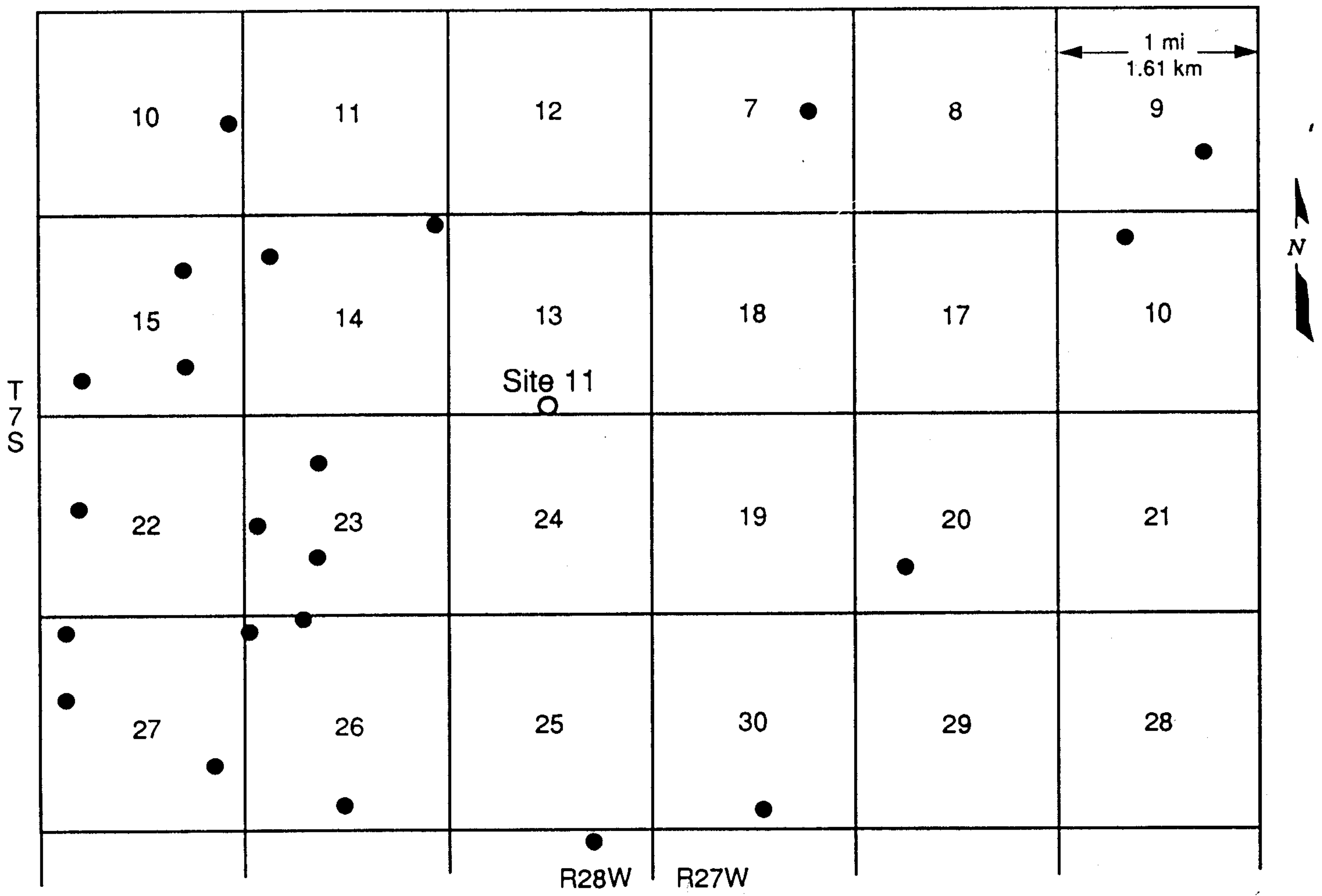


Figure 35: Irrigation wells in the vicinity of site 11

seems that the influence of the cones of depression is reflected in the behavior of the water table.

In December and October the difference between water levels in wells a and b is 28 cm. An error in reading the measuring tape seems to be unlikely, because that would mean that the identical error was made twice, in October and in December. A 4.9 m thick clay lens is present in the area between the screens of the two wells, i.e. between the end of the screen in well a and the beginning of the screened interval in well b. However, it is peculiar that the clay lens effects the water levels only as of October and not before. A possible explanation may be this: Until the end of September the majority of irrigation wells around the site were pumping and water levels in wells a and b were influenced simultaneously by the cones of depression. By the end of September only the well(s) influencing well b either continued pumping or were just started for pre-irrigation. The clay lens inhibited the drawdown to extend to well a. Thus as of the end of September a perched water table becomes recognizable at this site.

The water level in well b declined 24 cm more than the one in well a over the period monitored. Well a declined 2.04 m from March to December, whereas well b declined 2.28 m. Water levels in both wells were higher in December than in October. It can be assumed that water levels will continue to rise until April 1990 when the next irrigation season begins.

Seven of the nine wells monitored show a slight water level rise from October to December, which is probably due to a decrease in ground water demand. The main irrigation season generally ceases in September and not many farmers in this area pre-irrigate their field for the next growing season.

In general, the Ogallala aquifer in northwest Kansas loses water due to discharge to wells, streams, springs, and evaporation and evapotranspiration where the water table is very shallow.

Discharge to wells accounts for the biggest ground water loss, whereas perennial streams and flowing springs are very rare in the study area. The South Fork Republican River in Cheyenne County and the South Fork Solomon River in eastern Sheridan County and Graham County are the only perennial streams in the study area.

The intermittent streams generally run only during and shortly after rainfall events for short periods of time, thus contributing water to the aquifer.

The Saline River south of Hoxie in Sheridan County, an intermittent stream, was observed to carry water for a few months in 1989. Standard inorganic chemical analyses performed on a water sample taken March 27, 1989 indicate baseflow. The stream went dry sometime between the middle of April and very early June.

Recharge to the Ogallala aquifer in northwest Kansas is mainly from precipitation. All water exceeding crop requirements and field capacity of the soils eventually reaches the ground water table. However, loess has a large field capacity of about 26% to 29% by weight (Meyer et al., 1953). Loess deposits, which mantle most of the upland areas in northwest Kansas, can thus absorb large volumes of water and will significantly reduce the amount of water reaching the water table. On the other hand, as will be pointed out later, macropore flow may circumvent this behavior.

Recharge to the aquifer is also taking place by irrigation return flow. But for the study area this just means that water previously pumped for irrigation purposes from the Ogallala aquifer is partly being returned to it. Thus it represents no real gain as far as recharge is concerned. No surface irrigation practices are used in the study area.

Some recharge is derived from ground water inflow along the Kansas/Colorado border (Stullken et al., 1985, O'Connor & McClain, 1982), with flow occurring from areas with higher hydraulic heads in Colorado to areas with lower pressure heads in Kansas.

Estimates of recharge rates for northwest Kansas vary: 7 mm/year to 14 mm/year in Gove, Logan, and Wallace counties (McClain et al., 1975), 6 mm/year in the entire northwest Kansas area (Jenkins & Pabst, 1975), and from 4 mm/year to 14 mm/year for all of western Kansas, including northwest Kansas (O'Connor & McClain, 1982). The Groundwater Management District of northwest Kansas uses 9 mm/year for a recharge figure, including 3 mm/ year from irrigation return flow (Bossert, 1990, pers. comm.).

Recharge along streams and in areas of undrained depressions is regarded to be above normal, although no specific figures are cited in the literature.

Ground Water Quality

Ground water derived from the Ogallala formation in northwest Kansas is generally of very good quality, suitable as drinking water and for irrigation purposes. Locally, fluoride concentrations can exceed the U.S. Environmental Protection Agency primary drinking water standards, but all other constituents are usually well below recommended limits.

Because of the great depths to water, Ogallala ground water is not easily contaminated. However, point source pollution due to commercial feed lots, septic tanks, sewage treatment ponds, landfills, oil field disposal wells, back syphoning of irrigation wells and improper well construction and grouting procedures can occur if proper care is not taken.

Low precipitation and recharge rates as well as the extensive loess cover reduce the risk of contamination but can not eliminate it. The most likely cause of long term changes in the quality of Ogallala ground water is irrigation combined with chemigation, i.e. generally speaking pollution caused by agricultural practices.

Nitrate problems which are very common in central and south central Kansas due to the presence of sandy soils in that area, are thus far of no concern in northwest Kansas.

Hathaway et al. (1979) reported on ground water analyses from 315 pumping irrigation wells in Cheyenne, Decatur, Gove, Logan, Rawlins, Sherman, Sheridan, Thomas and Wallace counties and the western half of Graham County, an area including the study area. They found that the ground water is a calcium-bicarbonate to calcium-magnesium-bicarbonate type water. In the western part of northwest Kansas, where Pierre Shale represents the bedrock, the ground water tends to be more of a calcium-magnesium-bicarbonate type water, whereas in areas where Niobrara Chalk underlies the Ogallala formation, i.e. in the eastern part of northwest Kansas, the ground water is generally a calcium-bicarbonate type water. A transition toward sulfate type waters seems to occur in the shallow alluvial ground waters. Water derived from alluvial deposits generally is of poorer quality compared to Ogallala ground water with concentrations of mainly calcium, sodium, magnesium, sulfate, and chloride being elevated.

Long term irrigation with Ogallala ground water does not induce a detrimental effect on the soils. The water is described as being of medium salinity-low alkali hazard (Hathaway et al., 1979).

A detailed discussion of the standard inorganic analyses performed on ground waters sampled in the study area during the period from November 1987 to August 1989 is given in chapter 8.

Chapter 7

Analyzed constituents

Tritium

Tritium or ^3H is a slightly radioactive hydrogen isotope and has the least natural abundance of all the hydrogen isotopes: about 10^{-16} % (Vinogradov et al., 1968). For comparison, protium and deuterium make up 99.984 % and 0.0156 %, respectively.

The tritium concentration generally is reported in TU (tritium units), where 1 TU equals 1 tritium atom per 10^{18} hydrogen atoms and corresponds to 3.2×10^{-12} curie tritium/liter water (Rauert, 1971).

When the radioactive nature of tritium was discovered in 1939 (Alvarez & Cornog, 1939), it was thought unlikely to detect the isotope in nature. In 1946 Libby postulated the natural production of tritium by cosmic ray interaction, and in 1949 tritium concentrations in atmospheric hydrogen were measured for the first time in the vicinity of Hamburg (Faltings & Harteck, 1950). In 1951 von Grosse et al. proved the existence of tritium in Norwegian lake water.

Tritium is produced naturally in the atmosphere, lithosphere and hydrosphere. By far the main production of tritium occurs in the upper atmosphere by the interaction of cosmic ray neutrons with nitrogen atoms according to the reaction $^{14}N+n \rightarrow {}^3H+{}^{12}C$ (Libby, 1946). A reaction of protons with oxygen atoms according to $^{16}O+p \rightarrow {}^3H+{}^{14}O$ (Ferronsky & Polyakov, 1982, Vinogradov et al., 1968) can produce tritium as well.

Various rates of production are can be found in the literature. Fireman (1953) was the first to publish an average production rate of tritium in the atmosphere. According to his calculations the rate was 0.1 to 0.2 tritium atoms/cm^2/sec. Subsequently rates of 0.123 tritium atoms/cm^2/sec (Kaufman & Libby, 1954), 0.14 tritium atoms/cm^2/sec (Begemann & Libby, 1957), 1.06 tritium atoms/cm^2/sec (Begemann, 1959), 0.6 tritium atoms/cm^2/sec to 1.3 tritium atoms/cm^2/sec (Wilson & Fergusson, 1960), 0.2+/-0.5 tritium atoms/cm^2/sec (Teegarden, 1967) were published. Begemann (1962) mentioned the calculations of Craig

& Lal (1961) and Lal & Peters (1962) as being the most reliable. Their values of 0.5+/-0.3 tritium atoms/cm^2/sec and 0.25 tritium atoms/cm^2/sec are also the ones cited and used in the more recent literature (ex. Freeze & Cherry, 1979, Faure, 1977, Dincer & Davis, 1967).

According to Vinogradov et al. (1968), the rate of production is highest at an altitude of 10 km, i.e. in the troposphere. However, Begemann (1962) states that 66% of all cosmic ray produced tritium is derived from the stratosphere, and only 34% are produced in the troposphere. Job (1970) assumes a maximum tritium concentrations in the range of 20-25 km altitude, based on the distribution of ozone and strontium-90 in the stratosphere.

In the lithosphere tritium is produced by neutrons derived from spontaneous fission of uranium and more importantly by bombardment of alpha particles from the decay of uranium and thorium in rocks (Morrison & Beard, 1949). The generated neutrons react with lithium traces in rocks according to $^6Li+n \rightarrow {}^3H+{}^4He$ and form tritium (Kaufman & Libby, 1953, Vinogradov et al., 1968).

The tritium production from terrestrial sources is very small, Kaufman & Libby (1954) give a production rate of 0.001 tritium atoms/cm^2/sec for a layer of igneous rocks 1 km deep.

The production of tritium in the hydrosphere due to the reaction with lithium is even smaller and can be considered negligible. The great abundance of light hydrogen isotopes acts as a sink for the neutrons, thus preventing their absorption by lithium (Kaufman & Libby, 1954).

Tritium decays by beta-emission to ^{3}He, the particles having maximum energies of only 18 KeV. The health hazard induced by tritium is thus negligible, the maximum permissible concentration in water is 0.003 μc/ml above natural background (U.S. Atomic Energy Commission, 1960). One curie unit corresponds to 3.7 x 10^{10} disintegrations per second, equivalent to the radioactivity of 1 g of radium. Most tritium will pass through the body in the matter of a few weeks and will not become fixed in bones or organs (Davis & DeWiest, 1966). The biological half-life of tritium ranges from 5 - 11 days (Job, 1970).

Different publications cite different half-lives for tritium, ranging from 12.43 years (Ferronsky & Polyakov, 1982) to 12.6 years (Vinogradov et al., 1968, Rauert, 1971, Athavale et al., 1980). Begeman (1962) gives a half-life of 12.3 years, which is adopted by Freeze & Cherry (1979), and Fontes (1980) list 12.35 years as a half-life.

In the calculations done for this study a half-life of 12.3 years was used for tritium.

The natural background of tritium in precipitation is largely dependent on the sample location. It can vary from roughly 5 - 20 TU (Larson, Delcore & Offer, 1987). An average of 8 TU was found in Chicago precipitation (Kaufman & Libby, 1954, Begemann & Libby, 1957). Brown (1961) found a mean value of 15 TU based on his studies in the Ottawa Valley, Canada. The average tritium concentration in precipitation on the North-American continent is 6+/-2 TU according to Craig & Lal (1961). Roether (1967) analyzed German wines made from grapes grown before the onset of thermonuclear bomb testing, the results indicated 5.5+/-0.7 TU as a mean value of tritium concentration in precipitation. Many authors tend to give a range of tritium concentrations rather than a specific value: 5-20 TU (Payne, 1972), 4-25 TU (Gat, 1980), ≤ 20 TU (Fontes, 1980), and 0.1-10 TU (Suess, 1969).

The amount of tritium in precipitation is governed by several factors.

1. Seasonal variations: A pronounced tritium increase can be observed in late spring/early summer, whereas a minimum tritium concentration in precipitation occurs in late fall and winter. Precipitation samples collected in Sindorf/W-Germany from March 1960 to December 1961 indicated a maximum of about 200 TU in May and June and a minimum of about 20 TU in November 1960 (Israel et al., 1963). According to Roether (1967), the tritium concentration generally is greater by a factor of 5 in spring/early summer compared to the winter minimum.

This trend in increasing and decreasing concentrations parallels the ones of strontium-90, caesium-193, and ozone (Job, 1970). The cause for this seasonal behavior is a larger exchange of air masses between troposphere and stratosphere in the spring, due to a general change in air circulation in the atmosphere during this time. Tropospheric upwinds in the equatorial region rise to the stratosphere, follow the temperature gradient to higher latitudes, and subsequently sink back to the troposphere. Tritium is thus carried from the stratosphere down to the troposphere and rains out with precipitation.

2. Latitude effect: The exchange of tritium between stratosphere and troposphere occurs mainly at higher latitudes. A gradient of tritium concentrations in precipitation is present from the equator to the polar regions. The tritium fall-out maximum is located around 55 °N latitude, according to data published by Thatcher & Payne (1965). The IAEA (1967) gives an approximate latitude of 50 °N for the maximum concentration of tritium in precipitation.

3. Continental effect: Air masses over continents are much more enriched in tritium than air masses above oceans. Also, there is a general increase in tritium with increasing distance from the coast (fig. 36).

Oceans act as a sink for tritium. Tritiated water vapor is diluted by uprising, more or less non-tritiated vapor derived from the ocean surface waters; seawater has a tritium concentration of 1 TU (Job, 1970). In addition, molecular exchange between the vapor phases takes place. Thus the moisture depleted in tritium coming in from the oceans causes low tritium concentrations in precipitation in coastal areas.

Over the continents a part of the tritium rained out by precipitation is gained back by evaporation. According to Ferronsky & Polyakov (1982) the re-evaporated moisture has approximately the same tritium content as the atmospheric fall-out. Additionally, no molecular exchange with non-tritiated water or vapor phases takes place over the continents.

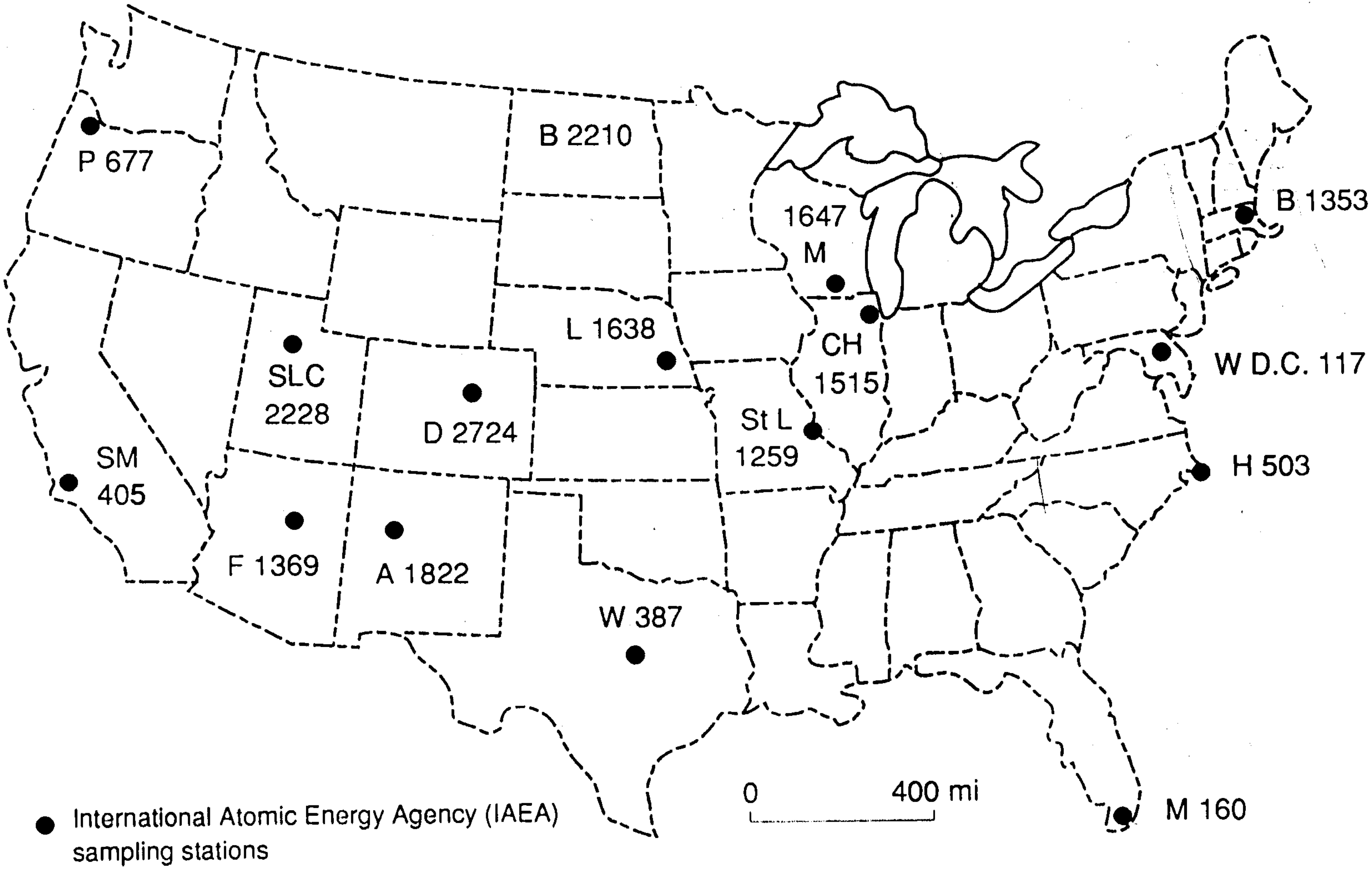


Figure 36: Mean annual Tritium fallout in 1964 in TU

Besides being produced by natural sources, tritium in large amounts was injected into the atmosphere by thermonuclear bomb tests since 1952. Tests were undertaken mainly by the U.S., the U.S.S.R. and the U.K.

Up to about 1957 the energies of the explosions were not very high and altitudes at which the explosions took place were intermediate. Thus the tritium emitted generally did not reach the stratosphere, but fell out with precipitation over a short period of time. Grant-Taylor & Taylor (1966) give a time frame of 1 - 2 months before the tritium content in precipitation subsided to pre-bomb levels.

Starting with the U.S. "Hardtack" test series in summer of 1958 in the Bikini area of the Pacific, high altitude tests - 4 to 7.5 km - began (Ferronsky & Polyakov, 1982). The 1961/62 test series by the U.S. and the U.S.S.R. released two times the energy of all the tests during 1954 to 1958, and due to the explosions taking place at high altitudes, a large amount of tritium was stored in the stratosphere. Ferronsky & Polyakov (1982) mention a value of up to 200 kg of tritium being stored in the stratosphere. Fergusson (1965) lists a release of 173 megatons tritium due to the thermonuclear explosions from 1954 to 1958, whereas the 1961 tests injected 120 megatons, and the 1962 tests injected a total of 217 megatons. Accordingly, the tritium content of precipitation in 1963 was 2 to 3 orders of magnitude greater than the normal background level (Fontes, 1980). The highest tritium measurement for a single month was recorded in April 1963 at White Horse , Yukon: 10.000 TU (Thatcher & Payne, 1965).

Fig. 36 depicts the tritium distribution in precipitation in 1964 for different locations within the U.S.. The data were compiled by the IAEA (International Atomic Energy Agency), which monitors stations throughout the world on a monthly basis for tritium, deuterium, and oxygen-18.

After the moratorium on atmospheric testing agreed upon by the U.S. and the U.S.S.R., tritium levels in precipitation slowly subsided until tests carried out by France and China in the late 1960's injected more tritium into the atmosphere. But the amount of tritium released by these later tests is insignificant compared to the tests in 1961/62.

The mean residence time for tritiated water in the atmosphere apparently varies. According to Libby (1956) stratospheric fission products have a mean residency of 10 years, however, in 1959 he mentioned a mean stratospheric halflife of less than 1 year for artificially injected tritium. A 10 year atmospheric residence time is also assumed by Martell (1963) for tritium injected by the Soviet test in 1961. Rauert (1971) postulates an average residence time of 2 years in the stratosphere before tritium reaches the troposphere and is subsequently rained out in a few weeks. Gat et al. (1962) observed a mean residence time of 3 years for stratospheric tritium injected during or prior to 1959/61. For the tritium injected by the U.S. "Castle" test in the spring of 1954 Begemann & Libby (1957) calculated a total 40 days atmospheric residence time. In 1956 Begemann postulates 40 days as being the "mean wash-out time" of the atmosphere, more or less up to the altitude of the troposphere. Brown & Grummitt (1956) observed a halflife of 35 days for wash-out of tritium injected by the Pacific tests in 1954 based on the tritium content in Ottawa precipitation. The mean residence time in the troposphere is given as 5 to 20 days by Gat (1980). More recent authors tend to give a range of residence time values for tritium in the stratosphere rather than a specific number, mostly from 1 to 10 years (Faure, 1986, Gat, 1980).

Tritium input function for the study area

Two precipitation samples were collected in the study area. In November 1987 the amount of tritium in precipitation was 14.9+/-1.2 TU, and in October 1989 the concentration was 26+/-8 TU.

Based on these two samples, a background level of about 20 TU during the period of potential recharge to the aquifer is assumed for the study area. Recharge takes place mainly in fall and winter when the ground is not frozen, and in spring. The maximum late spring/early summer tritium concentration mentioned above would thus generally not effect the tritium content in recharge to the Ogallala aquifer, unless rains in late spring/early summer would exceed the rate of evaporation. The 30 year average of precipitation and evaporation (fig. 7) shows that in general evaporation outweighs precipitation during the summer.

The network of sampling stations for tritium in precipitation operated by the IAEA does not include a station in Kansas. The closest monitor stations to the study area are Denver, Colorado, and Lincoln, Nebraska. These stations are also located in the directions (north and west) most of the frontal systems approach northwest Kansas during the period of late fall to late spring, the time when precipitation most likely becomes recharge to the Ogallala aquifer.

However, in 1968 the Denver sampling program was abandoned. As a substitute the sampling station in Salt Lake City, Utah, was chosen in order to obtain a westerly component for tritium input in precipitation for the study area.

The station with the longest record providing information regarding tritium concentrations in precipitation is Ottawa, Canada. The record starts in 1952, whereas the Denver, Lincoln, and Salt Lake City stations began to operate in 1964.

Fig. 37a shows tritium concentrations in precipitation for Ottawa, Lincoln, and Salt Lake City, unweighted for precipitation, and fig. 37b depicts the tritium for the afore mentioned stations weighted for precipitation collected at the respective stations. The tritium as well as the precipitation data were taken out of IAEA publications (1969, 1970, 1971, 1973, 1975, 1979, 1983, 1986). The following equation was applied for weighting of the tritium concentrations:

Weighted mean tritium concentration =

$$\frac{\sum \text{(monthly precipitation x monthly isotope concentration)}}{\sum \text{(monthly precipitation)}}$$

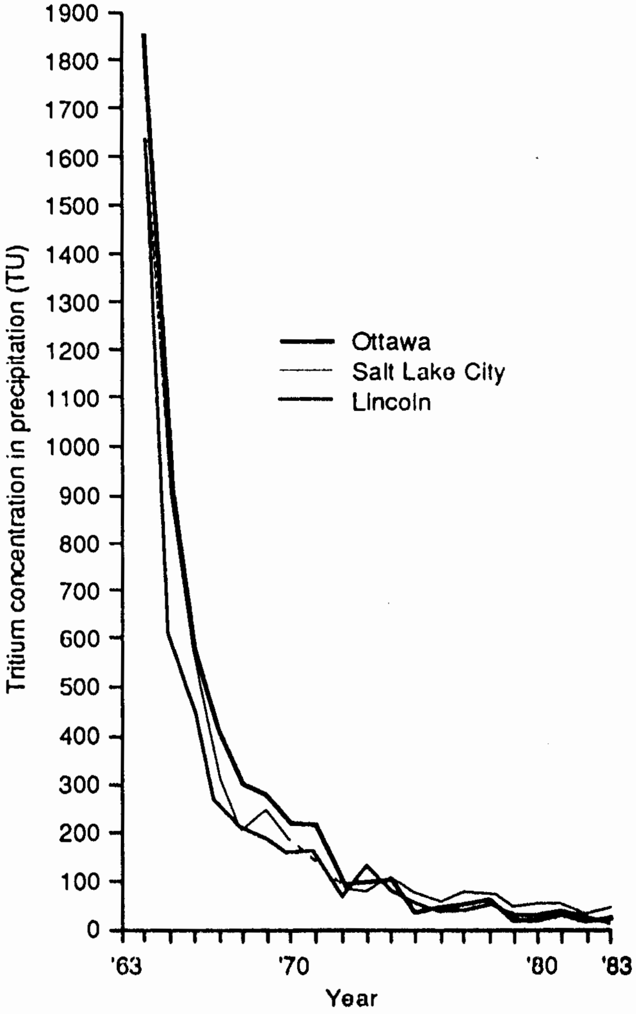


Figure 37a: Average Tritium concentration in precipitation (TU), unweighted

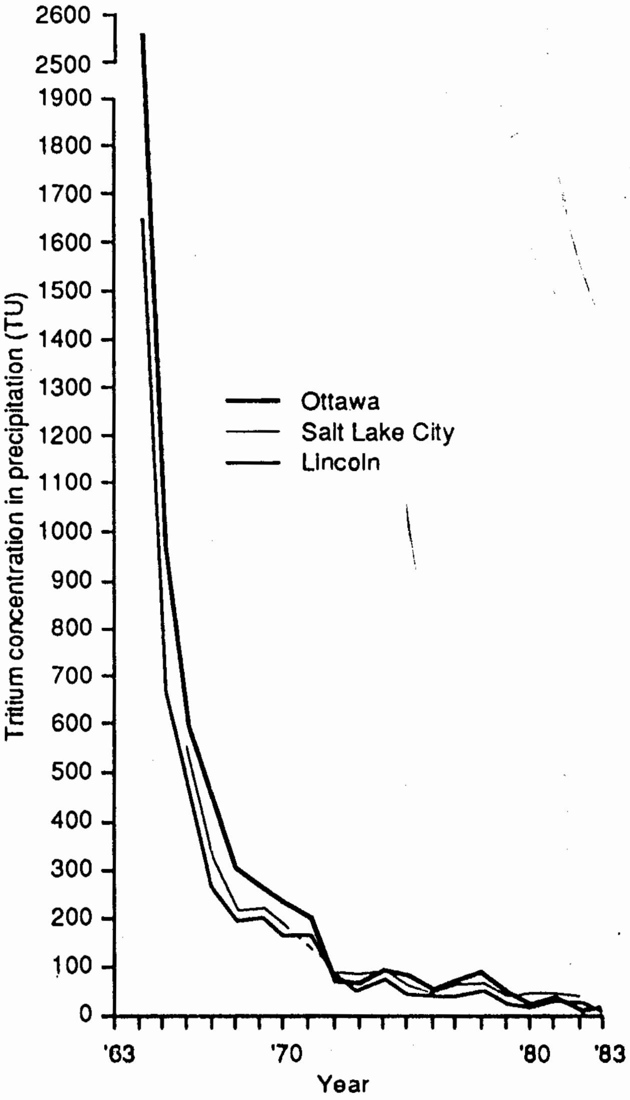


Figure 37b: Tritium concentration in precipitation (TU), weighted

It is obvious that the trend at all three stations remains the same, even after the tritium data are weighted. Lincoln and Salt Lake City are located roughly on the same latitude, 40.82 °N and 40.77 °N, respectively. Ottawa is located farther to the north, at 44.42 °N latitude.

The highest concentrations of weighted tritium are displayed by the Salt Lake City station, possibly caused by a high evaporation rate and its proximity to the Nevada test site.

However, the data from the stations Lincoln, Salt Lake City, and Ottawa are spaced close enough to derive an approximate tritium input function for the study area.

Fig. 38 depicts the weighted mean tritium concentrations in precipitation from 1953 to 1984 for the combinations Hoxie-Denver/Lincoln, Hoxie-Lincoln/Salt Lake City, and Hoxie-Ottawa. The total yeraly tritium concentrations from Denver, Lincoln, Salt Lake City, and Ottawa were weighted for precipitation at Hoxie, the closest weather station to site 11, the site most closely studied. Thus it is possible, to estimate the tritium input function for that particular area and the study area in general.

The trend in tritium concentration in precipitation for all three combinations is identical from 1964 onward. For the time period from 1953 to 1963 only tritium data from the Ottawa station were available. The Hoxie-Ottawa curve shows the peak tritium concentration in precipitation in 1963 with 3597 TU, and because the general trend for all three stations is the same after 1964, this is assumed to represent an approximate value for the peak tritium input in precipitation for the study area.

In order to correct a measured concentration of tritium for radioactive decay, the following equation was applied:

$$\mathrm{TU\,corr.} = \frac{\mathrm{TU\,measured}}{\left(\dfrac{\Delta t}{t_{1/2}}\right) \times 2}$$

where: Δt = the difference in years between the time of sample collection and the time for which the decayed tritium concentration is to be calculated,
$t_{1/2}$ = tritium half-life

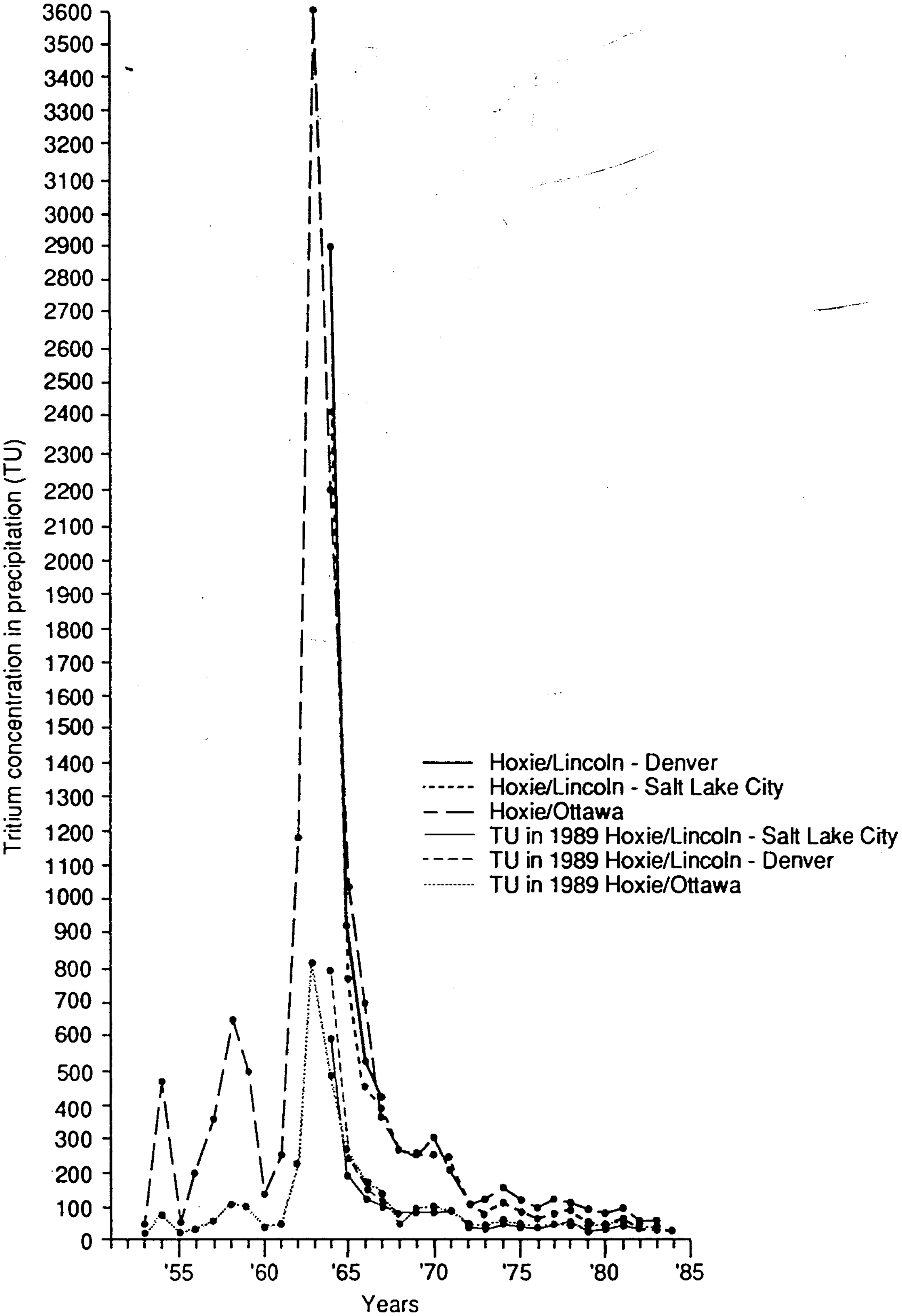


Figure 38: Mean annual tritium concentrations in precipitations from 1953 - 1984 for different combinations of recording stations and the respective tritium concentrations left in 1989 after radioactive decay

Fig. 38 also shows the concentration of tritium that would be left in 1989 after radioactive decay. The residual peak tritium concentration would now be about 815 TU.

The peak started to develop in 1962, the tritium concentration in precipitation at that time was 1193 TU in the study area. High energy thermonuclear tests during the years 1961/62 caused the tritium peak, indicating a time lag of about 1 year before the full effect of the tests documented itself in precipitation.

Fig. 39 depicts precipitation, evaporation, and the tritium content in precipitation for 1963 in the study area. To calculate the tritium concentration in precipitation, data from the Ottawa station were weighted for precipitation recorded at the Hoxie weather station. The mean annual weighted tritium concentration in precipitation of 3657 TU is shown as well as the tritium content of 831 TU left in 1989 after radioactive decay. Both, the 1963 and the 1989 tritium average do not take evaporation into account. From April to September, the months when evaporation was measured, the amount of precipitation always was smaller than the amount of evaporation. Thus only from October to March could tritiated precipitation possibly have infiltrated the ground. Based on this assumption, the highest monthly input into the unsaturated zone could was 4141 TU in March. This value is weighted for precipitation at the Hoxie weather station.

In 1964 the situation is similar (fig. 40). Evaporation from April to September exceeds precipitation, the highest amount of tritium possibly entering the unsaturated zone in a single month is 3029 TU in February.

In 1965 precipitation exceeded the amount of evaporation in June, i.e. only 7.2 % of the precipitation exceeded the amount of evaporation.

Assuming evaporation to be less than the amount of precipitation from October to March, tritium input into the unsaturated zone took place mainly during this period. Excluding the months where evaporation rates exceed the amount of precipitation, and assuming conditions favorable for infiltration from January to March and from October to

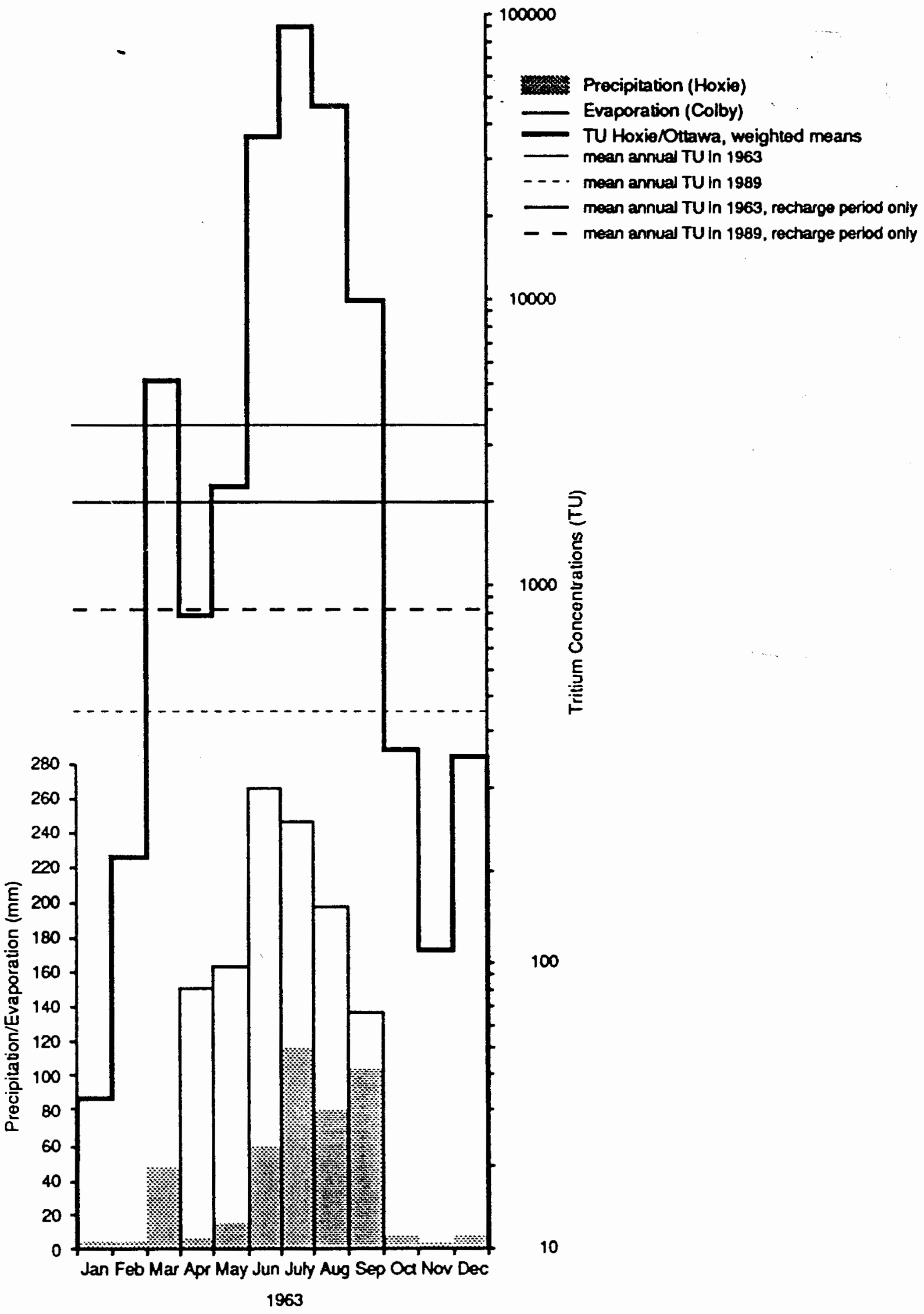


Figure 39: Monthly precipitation, evaporation, and monthly weighted tritium content in precipitation interpolated from data for Hoxie/Ottawa. Weighted means for tritium concentrations are given as well as the average tritium concentration in 1989, left after radioactive decay since 1963.

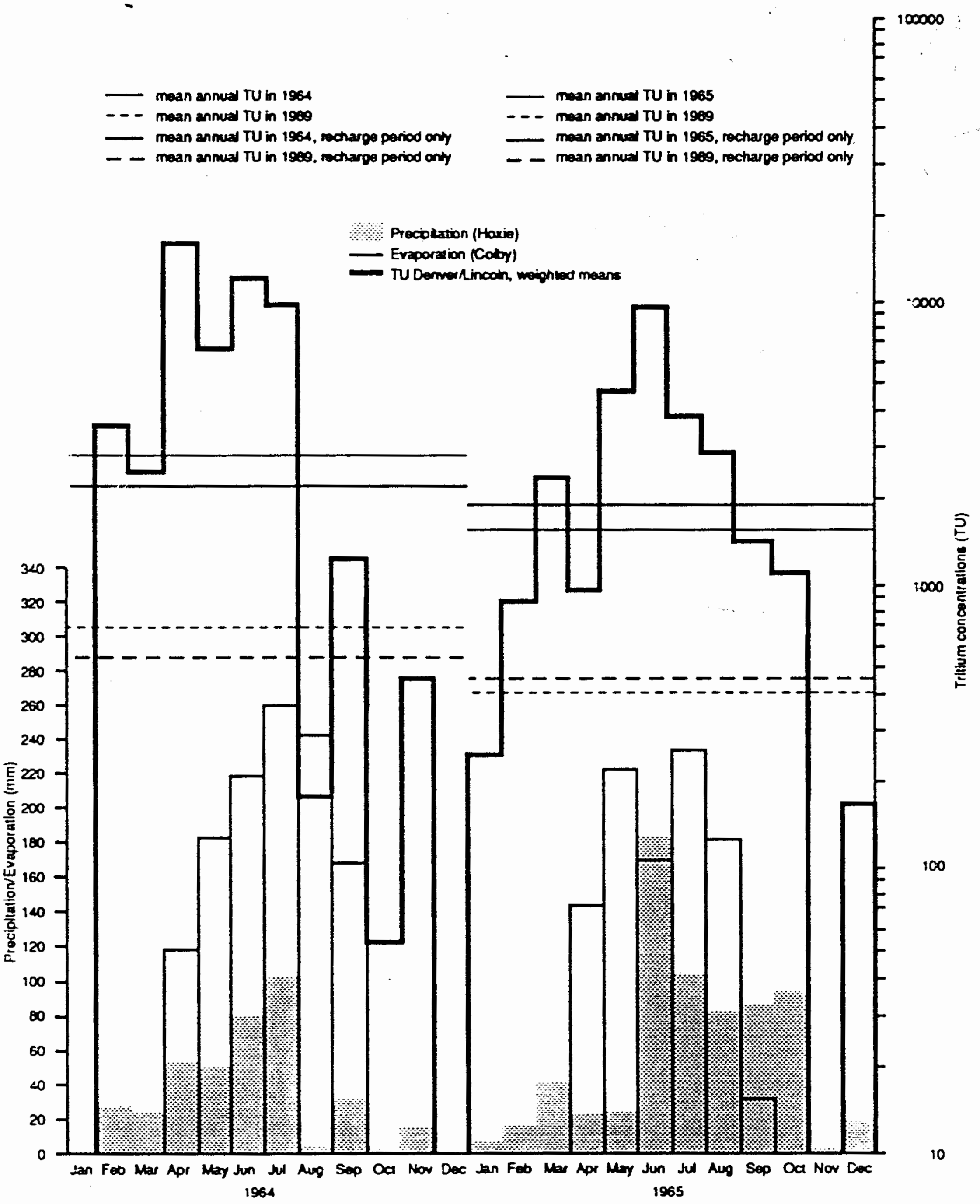


Figure 40: Monthly precipitation, evaporation and monthly weighted tritium content in precipitation interpolated from data for Denver/Lincoln. Weighted means for tritium concentrations are given as well as the average tritium concentration in 1989, left after radioactive decay since 1964-1965.

December, the following total tritium input into the unsaturated zone results for the study area: 775 TU in 1962, 2008 TU in 1963, 2291 TU in 1964, 1899 TU in 1965. The tritium input for 1965 includes tritium input in the month of June in addition to the period from January to March and October to November. The afore mentioned values represent only very rough estimates, because they were calculated under the assumption that no evaporation takes place from October to March, which is probably not quite correct. But no evaporation data were available for this period. At the same time any enrichment of tritium by evaporation was also neglected. The uptake of tritium by plants was not accounted for as well, however, this factor probably does not amount to much.

Applying a halflife of 12.3 years, tritium concentrations left in 1989 after radioactive decay would be 170 TU left from 1962, 457 TU left from 1963, 542 TU left from 1964, and 468 TU left from 1965.

Table 6 lists the tritium concentrations left in 1989 after radioactive decay from 1953 to 1984, taking only precipitation from October to March into account.

For comparison fig. 39 and fig. 40 also show the weighted tritium concentrations left in 1989 from the fall-out in 1963, 1964, and 1965 assuming uniform recharge over the respective years, i.e. without taking evaporation rates into account. As one would expect, the mean tritium concentration in precipitation for a whole respective year is greater than the amount calculated for the six months period from October to March. The values are 265.2 TU left from 1962, 831 TU left from 1963, 680 TU left from 1964, and 399 TU left from 1965.

Fig. 38 indicates that the tritium concentrations in precipitation abruptly started to increase in 1962 and dropped very sudden in 1965. Thus it is possible to average the tritium concentrations for these four years to obtain one peak tritium value. Doing so results in the concentration of 409 TU that could be present in the unsaturated zone in 1989 after radioactive decay, assuming the tritium is still in transit, thus depending on the thickness of the unsaturated zone. However, as mentioned above, this number only represents a very rough estimate.

Table 6: Tritium concentrations left in 1989 from precipitation during the period from 1953 to 1984 (recharge period only)

Year	Tritium concentration (TU) in 1989
1953	5.4*
1954	26.0
1955	5.2
1956	13.9
1957	18.0
1958	53.9
1959	113.0
1960	22.0
1961	58.5
1962	170.0
1963	457.0
1964	542.0
1965	468.0
1966	94.7
1967	56.7
1968	59.4
1969	47.5
1970	135.8
1971	32.6
1972	19.7
1973	22.0
1974	21.1
1975	16.5
1976	20.1
1977	23.0
1978	27.9
1979	13.8
1980	18.1
1981	21.3
1982	19.5
1983	13.7
1984	14.6

*From October to December 1953 only

Oxygen-18 and Deuterium

Both, oxygen-18 and deuterium are stable isotopes and occur naturally. Similar to tritium, as part of the water molecule they are not influenced by chemical or biological effects that may influence dissolved constituents in water. Thus they represent useful conservative tracers.

10^{16} water molecules with the normal isotopic composition $H_2{}^{16}O$ contain about 2000 molecules $H_2{}^{18}O$ and about 320 molecules $HD^{16}O$ (Craig & Gordon, 1965).

In 1929 oxygen-18 and oxygen-17 were discovered in natural materials (Giauque & Johnston, 1929). Accurate measurements regarding the natural abundances of oxygen isotopes succeeded with the arrival of improved mass spectrometry techniques. Nier (1950) published the currently accepted values for the relative abundance of isotopes in air oxygen: O^{16} = 99.759‰, O^{17}=0.0374‰, O^{18}=0.2039‰, resulting in an O^{18}/O^{16} ratio of about 1:489. However, the oxygen-18 content of air oxygen can vary as much as 10‰ depending on location (Gat & Gonfiantini, 1981). Thus in 1961 oxygen as a standard for atomic weights was dropped and replaced by Carbon-12.

Deuterium or ^2H was discovered by Urey in 1931. He named the newly found isotope deuterium, because it has nearly twice the mass of hydrogen. In 1934 Urey received the Nobel price for his discovery. Maximum limits of deuterium variations have been found to be about 70‰, the high value being caused by the large mass differences between deuterium and protium (Ferronsky & Polyakov, 1982, Faure, 1986).

Oxygen-18 and deuterium both are usually reported relative to the reference standard established by Craig (1961): Standard Mean Ocean Water (SMOW). The isotopic data are expressed as the relative ratio to the more abundant isotope. In the case of oxygen-18 the ratio of $^{18}O/^{16}O$ and for deuterium the ratio of $^2H/^1H$ is reported. Written in a general form the following equation is valid:

$$\delta\ ^{18}O = \left[\frac{\text{Rsample}}{\text{Rstandard}} - 1\right] \times 1000$$

The unit is parts per thousand or permil (‰). A negative δ-value indicates a sample depleted in the heavy isotopes with respect to the standard, a positive δ-value characterizes a sample enriched in the heavy component.

The various isotopic species of water have different vapor pressures and freezing points, based on a difference in mass between oxygen-16 and oxygen-18 and protium and deuterium. This difference in thermodynamic properties causes a difference in isotopic composition of waters in the hydrologic cycle.

The process by which a change in isotopic composition occurs is called fractionation. From a hydrological point of view, the fractionation occurring during condensation and evaporation is most important, because these two processes are the most relevant ones to cause changes in the isotopic composition of precipitation.

The lighter isotopes of oxygen and hydrogen display a higher volatility than the heavier species, caused by higher vapor pressures. Thus when water is evaporated an enrichment in the heavy isotope component of the remaining water takes place, whereas the resulting water vapor is depleted in respect to heavy isotopes.

Dansgaard (1964) listed a fractionation factor of 1.08 for HDO and of 1.009 for $H_2{}^{18}O$, and concludes that vapor in equilibrium with water is depleted about 80 % in deuterium and 9 % in oxygen-18, relative to the water. However, evaporation processes in nature do not take place under equilibrium conditions (Craig et al., 1963, Ehhalt & Knott, 1965, Gat, 1970). The enrichment of the remaining water is thus partly caused by kinetic fractionation. Under non-equilibrium conditions, evaporation occurs so rapidly, that the fractionation factor is influenced by the diffusion velocities of the isotope molecules in the surface layer of the water and in the surrounding air (Ehhalt et al., 1963).

In the process of condensation of water, i.e. for example when rain drops are formed in a cloud by condensation of water vapor, the liquid phase becomes enriched in heavy isotopes, whereas the remaining vapor phase is continuously depleted in the heavy isotope component.

Kirshenbaum (1951) was the first to suggest that atmospheric precipitation is formed by a Rayleigh-type process at liquid-vapor isotopic equilibrium, i.e. the process is slow and the condensate is removed immediately without further interaction with the vapor phase.

The fractionation factors of deuterium and oxygen-18 are highly temperature dependent. Riesenfeld & Chang (1936) reported ratios of vapor pressures, i.e. fractionation factors, of $H_2{}^{16}O$ to $H_2{}^{18}O$ to be 1.008 at 25 °C and 1.001 at 0 °C. For both, oxygen-18 and deuterium the fractionation increases with decreasing temperatures. This temperature dependency leads to various effects, all of which were verified on a global scale by Dansgaard (1964) based on data collected by the IAEA and the World Meteorological Organization (WMO).

1. Altitude effect: The higher the altitude, the more depleted precipitation becomes in heavy isotopes. This effect is related to orographic precipitation. Moist air masses ascend and condensation takes place when the temperature decreases. The preferential rain-out of heavy isotopes causes depletion of the remaining vapor in the heavy component. Thus the precipitation becomes subsequently lighter and lighter in isotopic content.
Large variations regarding the isotopic composition of precipitation can occur during one rain fall caused by temperature changes in the zone of atmospheric condensation in addition to isotopic depletion (Freeze & Cherry, 1979).

Eichler (1966) reported an altitude effect of -3‰ per 100 m for deuterium in the "Mittelgebirge" in Germany, and Moser & Stichler (1970) found the same value analyzing fresh snow samples collected in the Alps. Bortolami et al. (1979) found an altitude effect of about -0.3‰ per 100 m for oxygen-18 and a value close to -2.5‰ per 100 m for deuterium in the region of the Maritime Alps in northern Italy. A value of -0.44‰ per 100 m altitude above sea level for oxygen -18 is given by Foerstel & Huetzen (1982) for Germany.

According to Gat & Gonfiantini (1981) gradients of 0.15 to 0.5‰ per 100 m for oxygen-18 and gradients of 1.5 to 4‰ per 100 m for deuterium are considered to be typical, the values depending on climate and topography. Payne & Yurtsever (1974) found an average decrease of 0.26‰ per 100 m for Oxygen-18 in Nicaragua.

2. Continental effect: deuterium and oxygen-18 decrease with increasing distance from the coast. The same explanation as for the altitude effect applies, only in this case the air masses move laterally from the coast inland. Every time cooler temperatures are encountered, the heavier isotopes are preferentially rained out, leaving an air mass continuously depleted in oxygen-18 and deuterium behind. An example is given by Rozanski et al. (1982). They found that the continental effect for deuterium in Europe varies from -3.3‰ per 1000 km in winter to -1.3 ‰ per 1000 km in summer, thus including a seasonal effect. Foerstel & Huetzen (1982) reported a continental effect of -3‰ per 1000 km for oxygen-18 in Germany.

3. Amount effect: A negative correlation between the amount of precipitation and the isotopic concentration of the rain fall is observed for continental stations. Dansgaard (1964) named this phenomenon "amount effect". The effect is assumed to be caused by the preferential rain-out of the heavy isotopes and by isotopic enrichment of the falling rain drops by evaporation. During longer or more frequent precipitation events, the rain becomes more depleted, whereas shorter or light rains are being enriched by evaporation (Dansgaard, 1964, Gat, 1971). Dansgaard (1964) also listed a possible isotopic exchange between the falling rain drops and the surrounding vapor as a reason for the isotopic enrichment of light rains. According to him, the vapor below the rain cloud has not been exposed to cooling processes, thus isotopic fractionation is not enhanced. Evidence for evaporation from falling rain drops has been published by Dansgaard (1953) and Ehhalt et al. (1963).

Gat & Gonfiantini (1981) mention an average depletion rate in oxygen-18 of about -1‰ per 100 mm precipitation as an amount effect.

4. Latitude effect: With increasing latitude the concentration of oxygen-18 and deuterium in precipitation decreases. Foerstel & Huetzen (1982) reported a decrease of 3‰ per 1000 km distance from the sea in oxygen-18 in Germany.

5. Seasonal effect: Winter precipitation is depleted in oxygen-18 and deuterium compared to summer precipitation. Fritz et al. (1974) observed a seasonal difference of 10‰ in oxygen-18 in a stream in the northern part of the U.S.. Foerstel & Huetzen (1982) reported a difference of 2‰ from winter to summer for deuterium concentration in precipitation in Europe.

In summary, at higher altitudes and latitudes, cooler temperatures, as well as with increasing distance from the coast, rainfall is depleted in oxygen-18 and deuterium. Recurrent evaporation and condensation processes have the same effect on the water vapor phase. Ferronsky et al. (1983) mention that the temperature gradient for variations in the isotopic composition of precipitation is about 3‰ per 1 °C.

Dansgaard (1964) demonstrated a linear correlation between mean annual oxygen-18 concentrations in precipitation and the average annual surface air temperature in degrees Celsius. However, his equation $^{18}O=(0.69)T - 13.6‰$ applies only for northern Atlantic coastal stations with surface air temperatures below 10 °C. A linear relation between average monthly oxygen-18 concentrations in precipitation and the mean monthly surface temperatures was established by Yurtsever (1975) for four stations in Europe and Greenland. The resulting equation is $\delta\,^{18}O = (0.521 +/- 0.014)T - 14.96 +/- 0.21‰$. Foerstel et al. (1975) used the IAEA world statistics for stable isotopes and found $\delta\,^{18}O = (0.38)\,T - 11.79‰$, where T represents the mean annual air temperature. This equation was used to calculate the mean annual air temperature at the time of recharge for the samples collected for this study. The above mentioned temperature/oxygen-18 relationships establish the fact, that the isotopic concentration of precipitation decreases with decreasing temperature. It should be noted, that on a worldwide basis, the relationship of surface air temperature and isotopic content of precipitation is far from linear (Gat, 1980).

Collecting water samples at different latitudes Craig (1961b) showed that the δ oxygen-18 and the δ deuterium values are linearly related according to $\delta\ O^{18}=8\ \delta\ D+d$, where δ equals 10 on a worldwide basis. Excluded from this relationship are waters from closed basins, where evaporation is a dominant factor. The above equation defines the so-called meteoric water line. The slope of 8 is interpreted as the fractionational separation being eight times larger for deuterium than for oxygen-18 (Ehhalt et al., 1963).

The parameter d is called the deuterium excess parameter and was defined by Dansgaard (1964) as $d=\delta\ D-\ 8\ \delta\ {}^{18}O$, to facilitate the correlation of any water sample with the meteoric water line. The d value of any sample can be interpreted as the intercept with the deuterium axis of a line with a slope of 8 ($\delta\ D/\delta\ {}^{18}O=8$) that passes through that intercept (Gat, 1980). All waters derived from the same air mass as the particular sample would presumably plot on that line. According to this view the deuterium ~~ac~~excess parameter is a function of the vapor forming process. Thus d may vary from location to location. Generally, the lower the humidity the larger is the isotopic fractionation and thus the deuterium excess parameter (Gat, 1983).

The slope of the meteoric water line may also vary, particularly in arid and semiarid areas. A slope of less than 8 characterizes non-equilibrium evaporation processes. Gat & Gonfiantini (1981) give a general range of 3.5 to 6 for the slope of the meteoric water line, and Gat (1980) reports a slope of 5 to 6 for arid regions.

The isotopic composition of an aquifer varies locally and as a function of depth, especially under unconfined conditions (Moser & Stichler, 1972).

Although seasonal changes can usually only be detected in very shallow aquifers, climatic changes may be preserved in deeper aquifers. Large isotopic changes in the composition of water are for example associated with the glacial stages of the Pleistocene. However, without further dating methods such as Carbon-14 and sufficient data regarding the origin and history of the air masses producing the precipitation that recharges the aquifer, much caution has to be used in interpreting stable isotope data in ground water.

Freon

Freon (Trichlorofluoromethane, CCl_3F), trade name Freon-11, is an entirely human-made component and was first commercially produced in 1931 (Hamilton, 1963). Mainly it was used then by the refrigeration and air conditioning industries. By 1943 the aerosol industry began to use it as a propellant in spray cans until the ban in 1978. In addition freon-11 is now used widely as a foaming agent and a solvent.

Consequently, it is present in significant amounts in the atmosphere and will be picked up by precipitation in proportional amounts. Lovelock (1974) measured Freon-11 contents in the atmosphere over southwest Ireland and over the North Atlantic and found the concentrations to be 79.8 ppt (10^{-12} v/v) and 86.6 ppt (10^{-12} v/v), respectively. Hester et al. (1975) reported a fluorocarbon-11 content of 60 ppt (10^{-12} v/v) at 6.4 km altitude and 80 ppt (10^{-12} v/v) at 18.3 km altitude over New Mexico.

Under the assumption that the industrial output of Freon-11 remains at 2×10^5 tons per year, the average lifetime of Freon-11 in the atmosphere would be about 1 year (Lovelock, 1971).

Freon-11 is more soluble in waters at lower temperatures (Hayes & Thompson, 1977). Generally, the solubility of Freon-11 is very low: 0.11 weight % at 25 °C (Davis et al., 1985).

Laboratory column studies by Ciccioli et al. (1980) showed that Freon-11 is generally not strongly sorbed on silicates or inorganic materials. If sorption occurs, it seems to be reversible. No permanent sorption has been observed on silicates. However, organic materials seem to absorb Freon-11 to a greater extent and permanently (Thompson & Hayes, 1979).

A study in the unsaturated zone of the Southern High Plains of Texas (Weeks et al., 1982) showed detectable amounts of Freon-11 at depths as great as 43.9 m.

Generally, the occurrence of Freon-11 is said to be parallel to that of tritium.

Atrazine

Atrazine is one of the most widely used herbicides in the midcontinent region of the U.S. (including Kansas) and belongs to the group of the triazines. It was first introduced in the early 1960's.

From 1964 to 1984 agricultural use of pesticides tripled (Nielsen & Lee, 1987) with 82% of this increase being caused by the increased use of herbicides, including atrazine.

Land use and agricultural practices, soil properties, recharge rates, and depth to the aquifer influence the vertical distribution of atrazine and its concentration in ground water.

The movement of atrazine in the unsaturated zone is related to the pH of the soil, the amount of organic matter and clay present, hydraulic conductivity, and soil moisture content (Helling & Gish, 1986, Bailey & White, 1964, 1970, Yaron et al., 1985). Soil pH and organic matter content seem to be the most important factors influencing the breakdown rate of atrazine. According to Hiltbold & Buchanan (1977) each unit increase in pH increases the persistence by 9 to 29 days, depending on soil type. An inverse relation exists between the mobility of atrazine and organic matter and clay content, cation exchange capacity and soil moisture content (Helling, 1971).

Microbial degradation is probably a more important breakdown mechanism for atrazine than chemical hydrolysis (Saltzman & Yarob, 1986).

The persistence of triazine herbicides varies among soils (Sheets & Shaw, 1963). Maier-Bode & Haertel (1981) mention a persistence of greater than 60 weeks but do not give a specific number. The persistence of atrazine in ground water is more or less unknown. Wehtje et al. (1981, 1983) and Junk et al. (1980) assume a slow rate of degradation once atrazine enters the aquifer. It is inferred that atrazine may persist for a long period of time in ground water.

Nitrate

Each year 10.6 Mio tons of nitrogen fertilizer are used in the Unites States (Hurlburt, 1988), and the use of inorganic nitrogen fertilizer increased fourfold from 1960 to 1980 (Nielsen & Lee).

Extensive use of fertilizer in northwest Kansas began in the mid 1950's/ early 1960's (Kansas State Board of Agriculture, 1989), parallel to the use of pesticides.

By the process of nitrification fertilizer nitrogen and organic nitrogen, i.e. nitrogen incorporated in organic substances such as manure, in the form of ammonia (NH_4^+) are converted to nitrate (NO_3^-) and nitrite (NO_2^{2-}). This oxidation process generally takes place in the unsaturated zone above the water table and requires sufficient oxygen and organic matter present in the soil. Aerobic bacteria such as Nitrosomas and Nitrobacter support the process of nitrification.

Nitrite is very unstable and is converted to either nitrate by oxidation or to nitrogen (N_2) by reduction.

Denitrification is a process by which nitrate is reduced to nitrite, nitrous oxide (N_2O) or nitrogen (N_2). This process takes place when the redox potential declines, i.e. the oxygen content of the environment declines and anaerobic conditions can result. Sufficient amounts of nitrate, organic matter and denitrifying bacteria are a prerequisite for denitrification processes to occur. Just like nitrification the process of denitrification generally takes place in the unsaturated zone. Hardly anything is known regarding denitrification in ground water (Freeze & Cherry, 1979).

Dissolved nitrogen occurs in several forms in ground water: ammonium (NH_4^+), ammonia (NH_3), nitrite (NO_2^{2-}), nitrate (NO_3^-), nitrous oxide (N_2O), nitrogen (N_2), and organic nitrogen. Nitrate, however, is the most abundant form of nitrogen.

Nitrate is very stable over a wide range of conditions and thus readily transported in water (Hem, 1983). The anionic form of nitrate prevents its adsorption onto clays and nitrate is also not absorbed by organic matter. Thus Nitrate moves with hardly any retardation with the ground water (Freeze & Cherry, 1979). Under aerobic conditions nitrate can be considered a conservative tracer.

A complication regarding the interpretation of nitrate data may be caused by the presence of geologic nitrogen. Boyce et al. (1976) found significant quantities of nitrate in thick loess deposits underlying upland surfaces in southwest and central Nebraska. Concentrations of 106 mg/l to 199 mg/l nitrate (as NO_3) were encountered in general, but maximum values of 385 mg/l nitrate were detected also. The primary drinking water standard for nitrate (as NO_3) is 45 mg/l. The high nitrate concentrations occur from 7 m depth to more than 30 m depth. However, in this case the depth is a function of irrigation. Irrigation waters leached the nitrate and transported it downward.

No studies have been conducted in Kansas to measure the nitrate concentrations in the unsaturated loess deposits.

The presence of significant amounts of nitrates may support evidence of recharge indicated by tritium, atrazine, freon or stable isotopes.

Chapter 8

Results

Ground Water

For this study a total of 15 wells was sampled for standard inorganic chemistry analyses, tritium, stable isotopes, freon and atrazine during the time period from November 1987 to November 1989. Fig. 41 depicts the location of the wells.

Wells at site 1 to 9 were sampled during the first phase of the study in November 1987. Two of these 9 wells were installed as monitoring wells by the Kansas Geological Survey. The other 7 wells were already existing wells, on which information was available and permission to sample was granted.

During the second phase of the study 6 new wells were installed by the Kansas Geological Survey, two more wells were installed at site 6 and at two additional sites, sites 10 and 11, well nests of 2 wells each were installed.

Table 7 lists the total depths, screened depths and the purpose of the different wells used for this study.

Table 7. Total Depth, Screened Depth, Water-level, and Use of Sampled Wells.

Site	Total Depth (m)	Screened Depth(m)	Water Level(m)*	Use
1	90.8	51.2–90.8	51.5	monitor
2	60.1	44.8-60.0	43.0	monitor
3	46.3	37.2-46.3	31.8	monitor
4	82.3	no data	50.0	irrigation
5	61.0	47.2-59.4	43.0	monitor
6a	37.2	33.5-36.6	32.9	monitor
6b	59.4	42.7-45.7	32.8	monitor
6c	57.9	51.8-57.9	32.9	monitor
7	9.7	6.4-9.4	7.2	monitor
8	27.4	24.4-27.4	18.3	domestic
9	54.9	38.4-53.6	36.0	dairy
10a	7.0	4.0-7.0	3.6	monitor
10b	32.3	27.7-32.3	3.6	monitor
11a	61.5	53.3-59.4	52.1	monitor
11b	73.1	68.6-73.1	52.1	monitor

*Depth below land surface

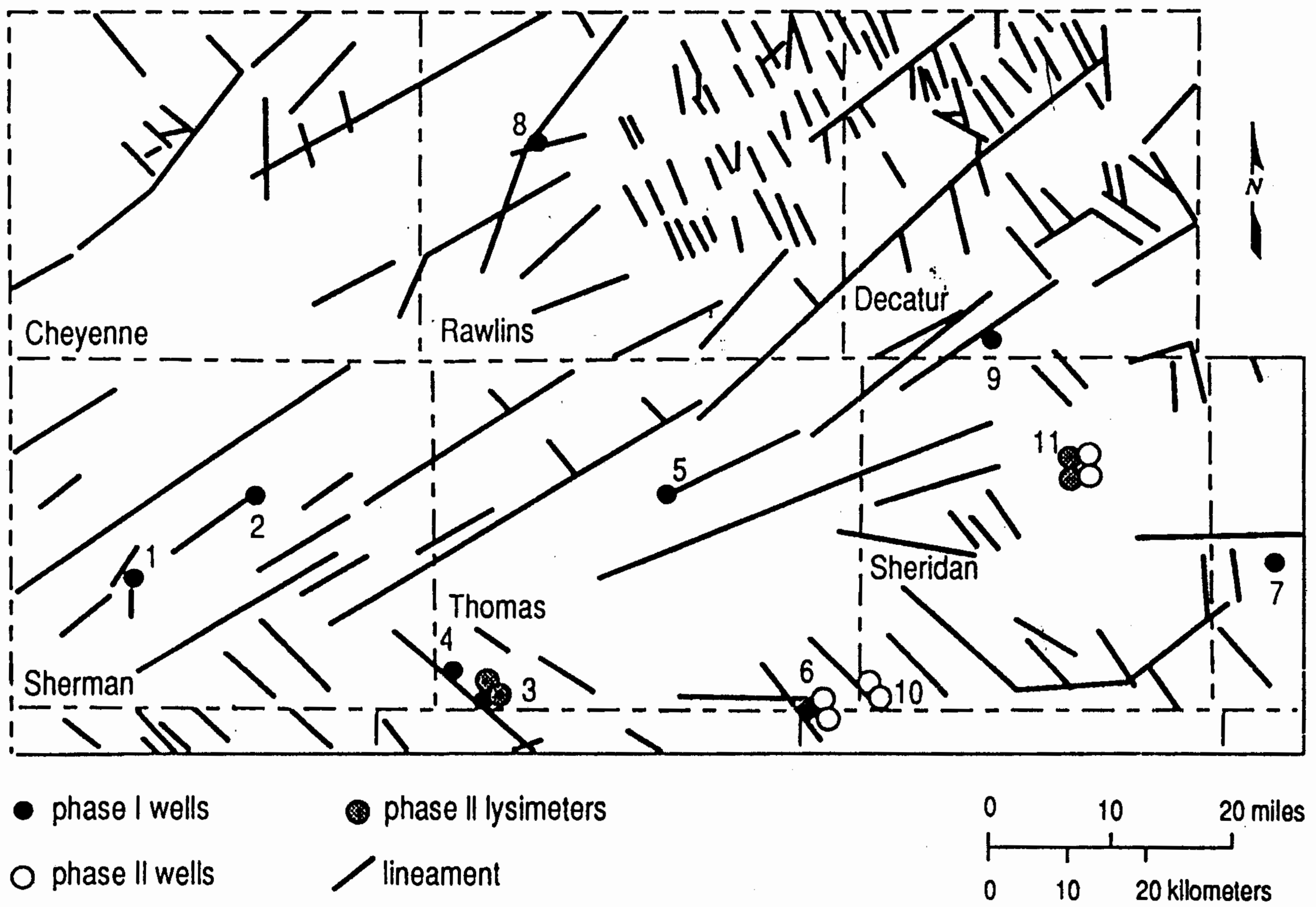


Figure 41: Well, lysimeter, and lineament locations in the study area (lineaments from McCauley, 1988).

Fig. 42 shows a lithologic cross section through selected well sites. The lithology was derived from drill cuttings obtained during installation of the monitoring wells at these particular sites. It should be noted, that the lithology of the Ogallala formation and the depth to water vary considerably from site to site. In response to these variations the water chemistry may differ, and may further be altered by anthropogenic influences. The screened intervals of the installed wells are also depicted. The wells are screened in different parts of the aquifer, which may result in a difference in water chemistry as well, if ground water stratification is present in the aquifer.

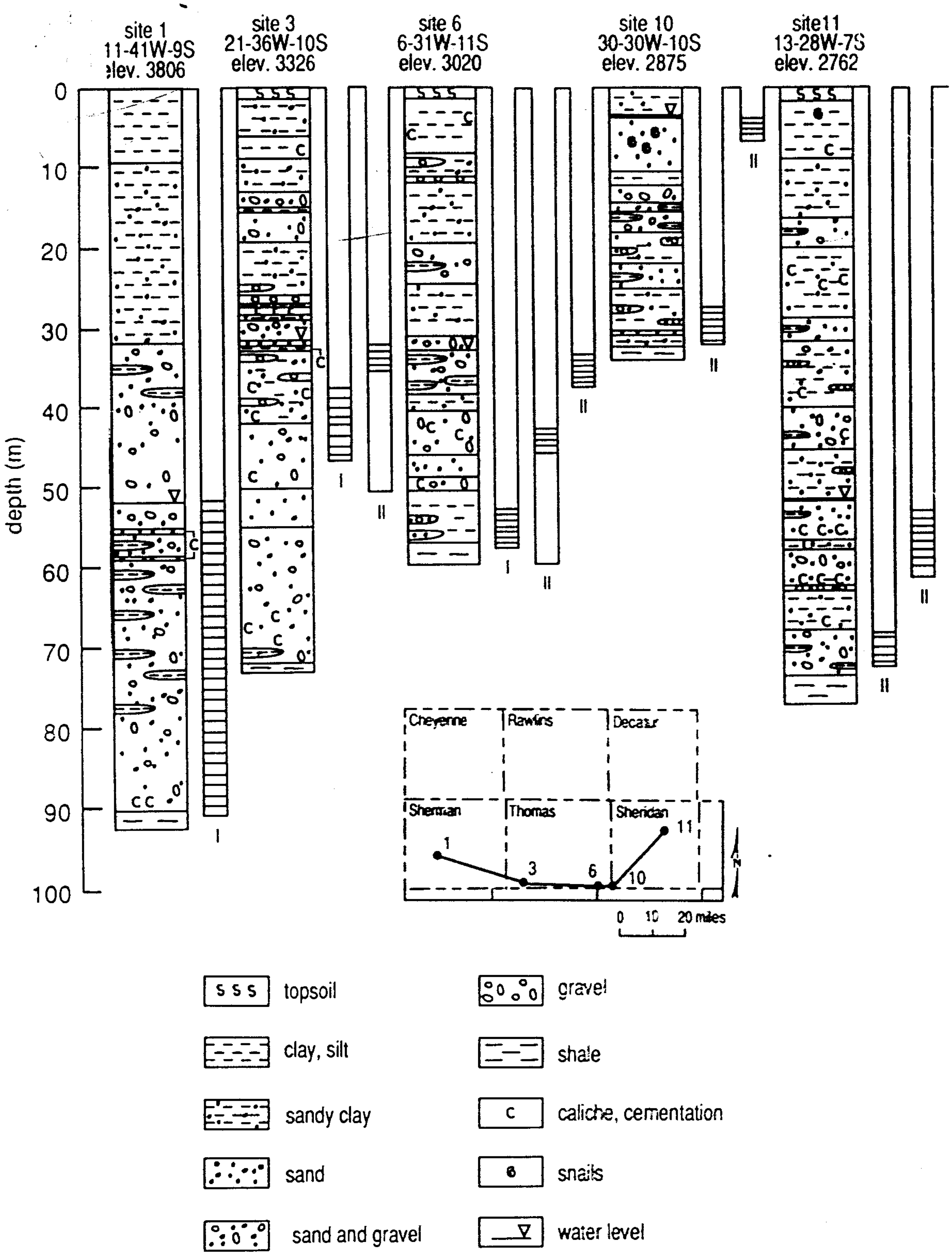
In the following the findings of the standard inorganic chemistry, tritium, freon and atrazine analyses are described. The results from the stable isotope analyses and the carbon-14 analysis are discussed separately.

Table 8 lists the results of the standard inorganic chemical analyses for all groundwaters sampled. Fig. 43 and 44 show the results of Ogallala ground waters analyzed for this study plotted in form of a trilinear Piper diagram. In addition to the well samples, a sample taken from the Saline River in March of 1989 is plotted. The surface water sample plots very close to the ground waters, thus indicating baseflow in the Saline River at the time of sample collection.

With two exceptions all waters plotted can be characterized as calcium-magnesium-bicarbonate or calcium-bicarbonate type waters.

Ground water tested at site 1 was more a calcium-sulfate-calcium-bicarbonate type water in 1987 and had changed to a calcium-magnesium-chloride-bicarbonate type water by August 1989. The change in water chemistry at this site can be attributed to irrigation and the proximity of the well to an old tail water trail feeding into a tail water pit used to catch excess waters from flood irrigation.

The ground water at site 7 is a calcium-sodium-chloride type water, possibly reflecting the presence of oil field disposal wells located just about 1.6 km to the southwest of the site.



approximate vertical scale, 1 cm = 12 m

Figure 42: Cross section through selected well sites in the study area

Table 8. Inorganic Chemistry Data.

Site # Date	Field Sp. Cond.	Lab Sp. Cond.	Field pH	Lab pH	SiO2 ppm	Ca ppm	Mg ppm	Na ppm	K ppm	Sr ppm	HCO3 ppm	SO4 ppm	Cl ppm	F ppm	NO3 ppm	NO2 ppm	Fe ppb	Mn ppb	B ppb	Ba ppb
1																				
11-87	745	705	7.15	7.8	47	81	27	30	6.1	1.2	226	99	14	0.8	60	2.85	51	42	163	96
8-89*				7.7		89	30	19	3		170	29.1	68		124.5					
2																				
9-87*						130	44.5	57	12.5		516	66	40	0.45	39.2		0.00			
11-87	1160	1150	6.7	7.6	70	134	47	63	12	2.1	608	69	30	0.4	37	0.023	<22	<4	277	191
9-88*						137	46	81	13.0		523	45	43	0.57	15.68		0.11			
10-89*						134	52	70	12		640.5	70	28		31.4		0.0			
3																				
11-87	615	570	7.4	7.9	32	70	18	26	12	0.8	276	28	15	0.8	28	0.14	<22	<4	96	168
5-89	600	590	7.5	6.8	30	75	20	14	11	0.9	298	19	16	0.6	35				98	190
8-89	600	600	7.5	6.8	30	75	20	13	12	1.0	302	19	16	0.6	33/34					
4																				
11-87	410	410	7.1	8.0	33	41	19	20	6.6	0.8	232	15	4.6	0.8	8.9	0.02	251	8	70	119
8-89	440	418		7.85	33	40	19	17	6.0	0.9	238	14	4.6	0.8	14					
5																				
9-87						51	16.5	17	7.2		187	24	12		18.7					
11-87	465	435	7.45	8.0	55	47	17	19	7.1	0.7	214	21	8.8	1.6	16	0.01	<22	<4	79	99
9-88						49	15.7	17.4	8		217	21.7	32	1.55	15.3		0.06			
10-89						34	19	21	7		222	20	7		21.3					
6a																				
11-88	560	570	6.7	7.8	33	59	26	16	6.7	1.3	234	37	29	0.6	22		65	<9	70	180
8-89	640	573		7.7	34	59	27	15	6.3	1.3	242	36	32	0.6	23					
6b																				
11-88	598	610	6.7	7.8	34	66	31	12	6.8	1.4	272	30	27	0.6	28		<29	<9	65	187
8-89	685	635		7.7	34	67	31	12	6.1	1.6	295	29	28	0.6	31					
6c																				
11-87	510	480	7.6	8.1	36	42	19	33	7.5	1.0	226	28	16	0.9	13	0.01	<22	<4	126	76
7																				
11-87	1900	1850	7.15	8.2	55	166	31	166	11	1.2	260	77	359	0.5	74	0.01	2170	938	86	361
8																				
11-87	555	485	7.55	8.1	73	36	20	37	12	0.8	225	37	7.4	1.8	18	0.01	<22	<4	127	53

*Analyzed at commercial laboratories.

Table 8. Inorganic Chemistry Data (con't.)

Site # Date	Field Sp. Cond.	Lab Sp. Cond.	Field pH	Lab pH	SiO2 ppm	Ca ppm	Mg ppm	Na ppm	K ppm	Sr ppm	HCO3 ppm	SO4 ppm	Cl ppm	F ppm	NO3 ppm	NO2 ppm	Fe ppb	Mn ppb	B ppb	Ba ppb
9																				
11-87	445	420	7.5	8.2	60	47	18	14	8.9	0.7	237	15	5.1	0.8	7.5	0.01	43	<4	63	125
10a																				
11-88	482	475	7.05	7.7	39	56	16	18	7.2	0.8	239	28	9.5	0.8	9.7		554	<9	75	173
8-89	580	555		7.6	37	67	19	19	7.0	1.0	253	57	10	0.7	16					
10b																				
11-88	672	455	6.95	7.7	33	46	17	31	6.1	0.8	227	22	11	0.8	10		<29	<9	120	86
8-89	470	450		8.15	32	44	13	30	5.1	0.8	235	21	11	0.8	11					
11a																				
11-88	450	455	6.95	7.8	59	47	18	21	6.8	0.6	221	26	10	1.3	15		165	<9	86	108
8-89	470	440		7.7	60	46	17	18	6.4	0.7	227	21	9.0	1.2	14					
11b																				
11-88	422	430	6.55	7.7	58	45	16	19	7.0	0.6	225	20	5.6	1.3	11		256	<9	89	110
8-89	450	420		7.7	57	43	15	19	6.4	0.6	228	20	5.5	1.3	11					
Saline River																				
3-89		775		8.1	36	93	28	31	12.0	1.1	386	55	29.0	1.1	0.6				105	

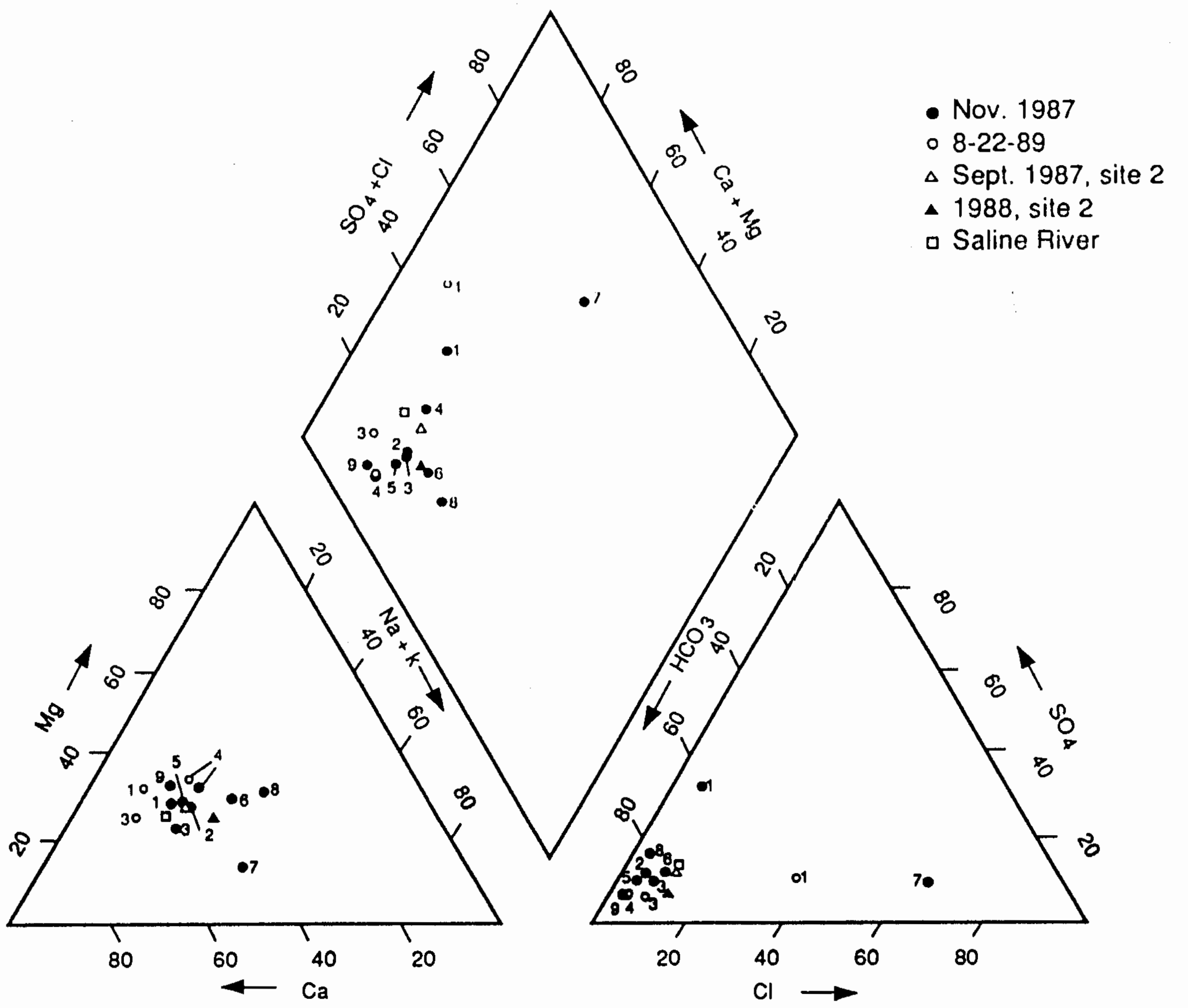


Figure 43: Standard inorganic chemistry analyses in % mq/l for groundwater samples from phase 1 wells

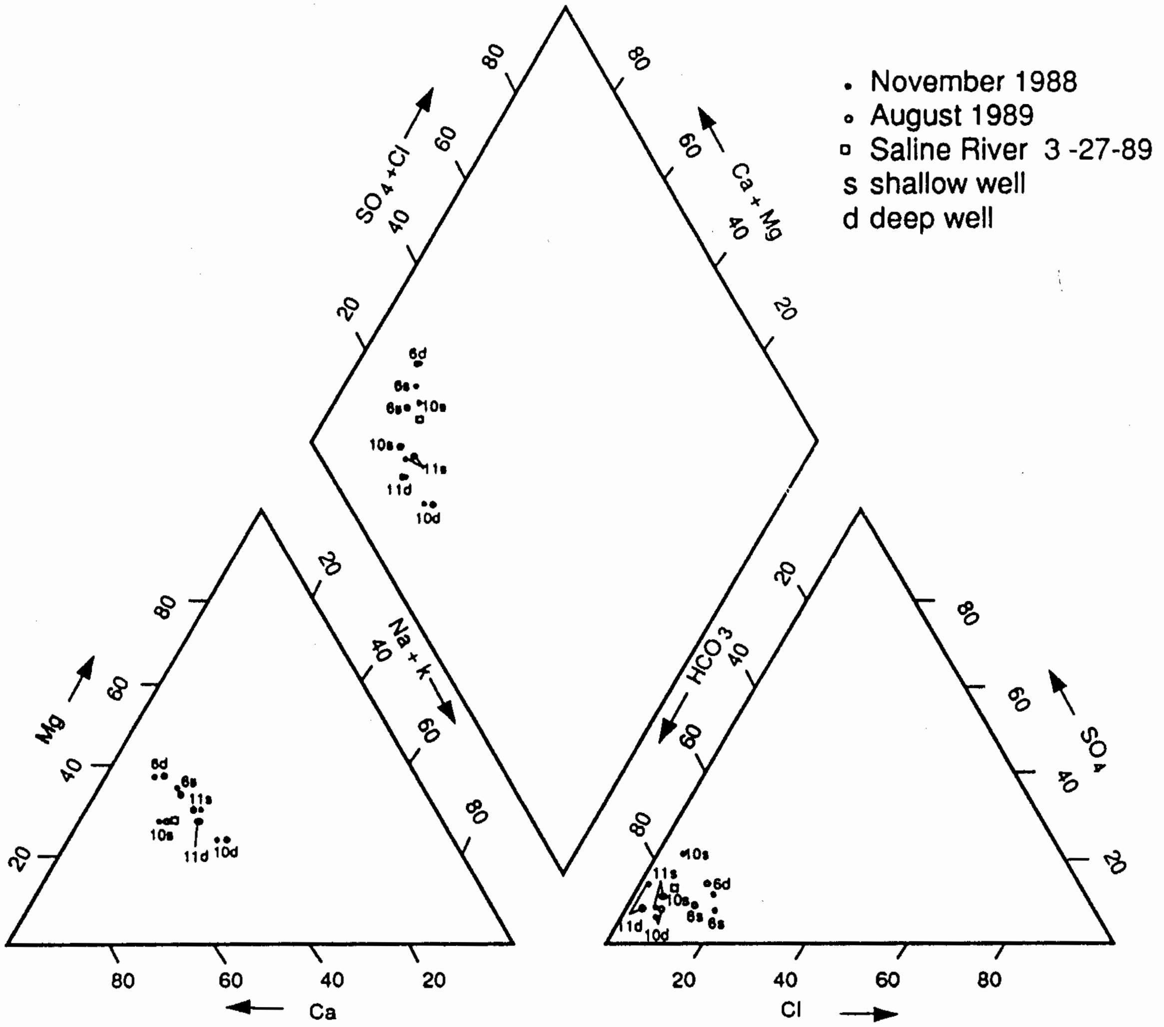


Figure 44: Standard inorganic chemistry analyses in % mq/l for ground water sampled at sites 6, 10, and 11 (phase 2 wells), and one surface water sample

Sampling procedures and analytical methods are described in Appendix A.

Site 1

Site 1 is located in an upland area in Sherman County. The land around the site is farmed and it is known that the Ogallala aquifer underlying this area shows elevated nitrate concentrations.

The field adjacent to the site is presently under center pivot irrigation which was installed in 1985. Before the conversion to a center pivot irrigation system the area was under flood irrigation from 1960 onward. The monitoring well installed at this site in October 1987 is situated at the end of the former flood rows and near the former tail water trail that fed excess irrigation water to a tail water pit.

Currently, corn grown on the field receives an average nitrogen fertilizer application of about 150 lbs/acre. From 1960 until about 1982 sugar beets were grown here with an average nitrogen application of 200 lbs/acre.

The monitoring well is drilled to bedrock at 90.8 m and is screened up from this depth to 51.2 m below land surface. The water level below land surface at this site is 51.5m.

The well was sampled in November 1987 and the ground water can be described as a calcium-sulfate-bicarbonate type water (fig. 43). Table 8 lists the results of the standard inorganic analyses. High nitrate and sulfate concentrations of 60 mg/l and 99 mg/l respectively, reflect the high input of fertilizer and the fact that the this area is under irrigation since 1960. The nitrite concentration, determined on site, was 2.58 mg/l as nitrite.

Elevated calcium, magnesium, sulfate and boron values could be interpreted as evidence for recycled waters and/or the initial leaching of solutes, both caused by irrigation.

When land in a semiarid climate with high evaporation rates is reclaimed by irrigation the accumulated solutes tend to be leached away by the increased water supply

(Hem, 1985). They appear in drainage water and return flow, and will eventually show up in the ground water.

Caliche horizons in the unsaturated as well as in the saturated zone also represent a source of calcium, magnesium, sulfate, and bicarbonate.

In August 1989 the monitoring well was resampled by the Groundwater Management District and the water was subsequently analyzed by a commercial laboratory. The ground water had changed to a calcium-magnesium-chloride-bicarbonate type water (fig.43). The nitrate content had more than doubled from November 1987 to August 1989, from 60 mg/l to 124.5 mg/l. The chloride concentration increased nearly five-fold from 14 mg/l to 68 mg/l. Only the sulfate content decreased considerably from 99 mg/l to 29 mg/l. The cation concentration remained more or less the same.

The most likely explanation for this change in water chemistry over a nearly two year period is the following: During the 27 years of flood irrigation vertical leakage of accumulated solutes and fertilizer components occurred and these constituents are now showing up in the ground water. Vertical movement probably takes place in a piston-type flow manner enforced by the combined effects of the former flood irrigation system and the present center pivot irrigation system. The amount of naturally occurring recharge can be neglected compared to the induced recharge by irrigation return flow. The monitoring well is situated just barely out of reach of the center pivot irrigation system, but enough moisture is provided to accelerate the vertical flow.

Assuming piston type flow, the analysis of November 1987 possibly shows an initial slug reaching the ground water, with lower nitrates and higher amounts of solutes (caused by the onset of flood irrigation) than in 1989. The high nitrates and low sulfates in the 1989 analysis may reflect a later slug. High nitrogen fertilizer application to support the growth of sugar beets was well established and the initial solution of solutes had decreased, reflected by the lower sulfate content.

Sulfate and chloride are also used as byproducts in fertilizer and it is possible that a switch in fertilizer brands caused a lowering of the sulfate and an increase in chloride concentration.

The decrease of the bicarbonate content from 226 mg/l in 1987 to 170 mg/l in 1989 may have been caused by the flood irrigation practice. Increased temperatures of the waters in the flood rows as well as in the tail water trail and -pit induce a loss of dissolved carbon dioxide gas, and this allows the conversion of some bicarbonate to carbonate (CO_3), which precipitates (Hathaway et al., 1979). As a result, the moisture infiltrating the soil would be depleted in bicarbonate. The bicarbonate concentration in the 1987 sample of 226 mg/l would thus represent a more or less natural background level, not much influenced by irrigation effects. Natural bicarbonate contents in other ground waters analyzed for this study range between 214 mg/l and 302 mg/l. By 1989 another front of constituents, characterized by a lower bicarbonate content and thus a greater influence of irrigation on the water chemistry, had reached the ground water.

According to Hathaway et al. (1979) who described this effect of flood irrigation on the bicarbonate content based on the analyses of waters from eight tail water pits and their associated irrigation wells, no marked increase in the concentrations of calcium, magnesium, sodium, sulfate or chloride occurs in the tail water. This is also true at site 1, where the cations hardly changes at all from 1987 to 1989. However, as mentioned above, the chloride content increased nearly five-fold in the same time frame. This would support the assumption that the high chloride concentration is caused by fertilizer application. No natural source for chloride, such as salt beds, is known in the unsaturated zone or in the Ogallala formation itself.

It can not be excluded that some of the chloride, calcium and magnesium concentration may have been influenced by enrichment due to evaporation processes enhanced by irrigation practices.

Chloride is a very conservative ion, i.e. it does not react readily with other ions or compounds. If it would have been present in the tail water or in the unsaturated zone to begin with it would have moved down to the ground water with the other constituents, possibly at an even faster rate.

The irrigation well that feeds the center pivot system is located about 0.4 km to the west of the monitoring well at site 1. Samples taken by the Groundwater Management District and analyzed by commercial laboratories show that the water quality changed in exactly the same way here as at the monitoring well site from 1987 to 1989 (table 9), although not quite as dramatically. The initial concentrations in 1987 were all lower for the irrigation well compared to the monitoring well. A possible reason for this behavior is the center pivot system itself. The irrigation well is surrounded by irrigated soil, whereas the monitoring well is located out of the range of the center pivot. Thus the downward movement of soil moisture and its constituents at site 1 lags behind the vertical movement in the surrounding of the irrigation well.

The tritium content of the water sample taken at site 1 in November 1987 showed 2.8+/-0.5 TU. Calculating with a half-life of 12.3 years, the tritium content of this ground water in 1960 would have been 12.7 TU. This value is too low to indicate bomb related tritium.

Table 9: Standard inorganic chemistry results in mg/l from ground waters sampled at site 1

Date sampled	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3
Monitor well								
Nov. '87 *	81	27	30	6.1	226	99	14	60
Aug. '89	89	30	19	3	170	29.1	68	124.5
Irrigation well								
July '87 *	52	17	22	4.2	194	38	18	43
Aug. '89	62	20	19	2	186	28	15	68.7

* Analyzed at the Kansas Geological Survey

Three possibilities may be considered to explain the tritium content observed: 1. the tritium was derived from precipitation before the bomb tritium was released, i.e. before the mid 1950's, 2. the tritium stems from precipitation in the late 1970's, when the natural background level of tritium was reached again, and 3. the tritium is in fact bomb tritium, but was diluted by non-tritiated irrigation waters.

If the assumption is correct that piston type flow occurs at this site and that the 1987 inorganic chemistry analysis reflects a more or less initial slug of constituents triggered by the onset of irrigation in 1960, the first possibility can be ruled out. Additionally, dry land farming practices from 1953 to 1960 combined with the small amounts of precipitation and the so resulting low recharge rates in western Kansas would require farming on this site since the 18th century and an amount of manure or commercial fertilizer applied to the soil by far exceeding plant uptake for such a high nitrate concentration still to be present in the ground water in 1987.

In order to explain the low tritium content at this site by assuming precipitation in the 1970's as a cause one would have to consider the vertical movement of moisture to be about 4 m per year for the tritium to reach the water table by 1987. Even considering the fact that this site is located not directly under but very close to a center pivot system it is hard to imagine such a great recharge rate. In view of the results from site 11 (see pp. 186-188) it seems impossible.

Seismic shotholes, put in in 1981, are present in the area (fig. 45) and if they were unplugged or poorly plugged they possibly could serve as conduits to the ground water and thus accelerate downward movement. However, this would fail to explain the changes in water chemistry, especially the change in the bicarbonate content.

The most likely explanation seems to be that the constituents of the ground water sample taken in 1987 are influenced by the effects of flood irrigation as described earlier and that the tritium detected in this sample is thus bomb related tritium. However, due to low precipitation in western Kansas, the dilution effect of the non-tritiated ground water

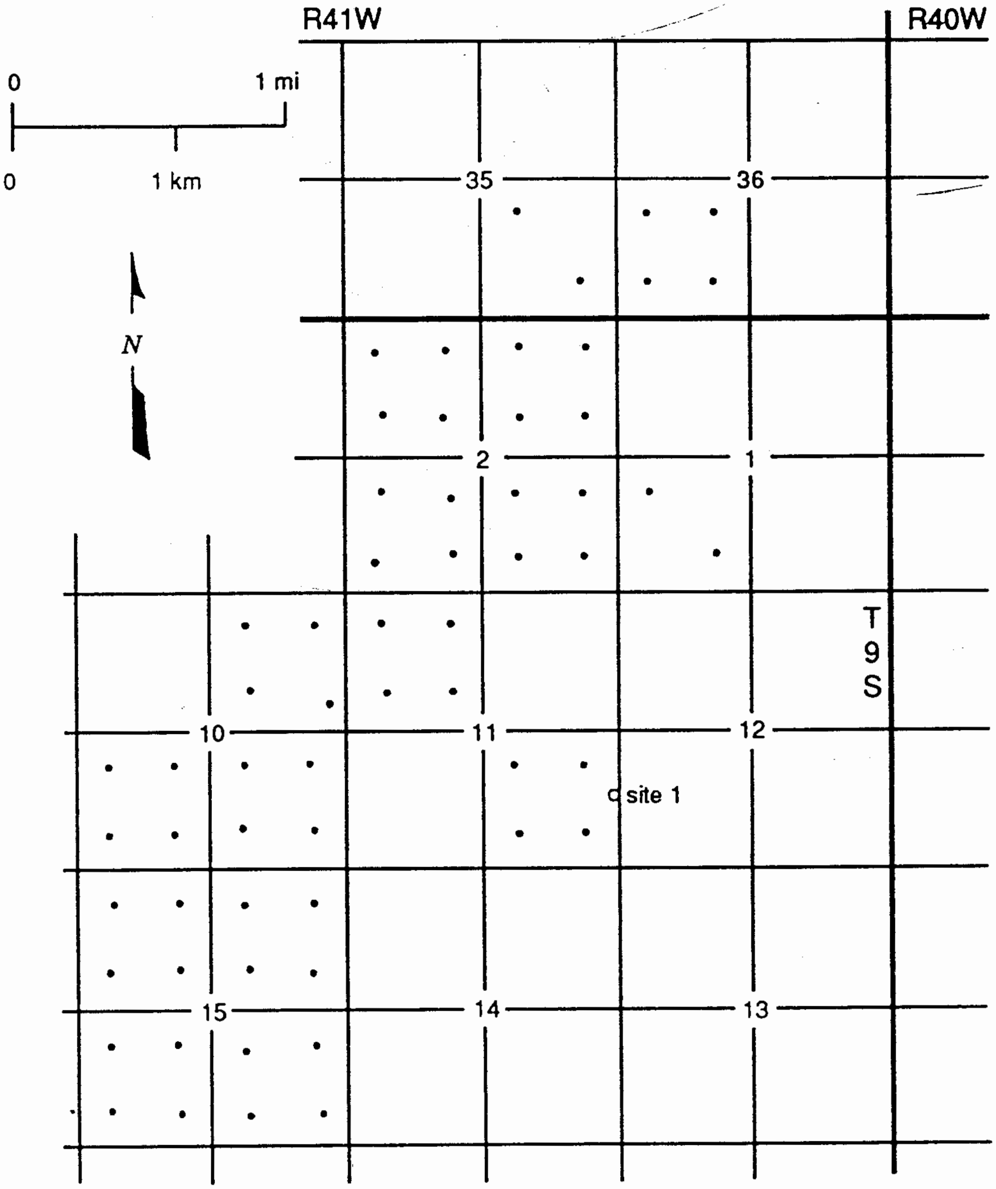


Figure 45: Seismic shotholes in the surroundings of site 1

used for flood irrigation, and radioactive decay of the tritium itself it is not recognizable as such anymore.

The assumption of the ground water from the irrigation well not being tritiated is not based on an actual analysis performed in the 1960's. But it can be considered impossible for any precipitation of the mid to late 1950's, when bomb tritium first was released, to reach the ground water table by 1960, especially not under dry land farming practices. That would mean a vertical rate of movement through the unsaturated zone of more than 5 m. Another irrigation well in a similar geographic setting was sampled in Thomas County in November 1987 (site 4) during the course of this study and here the tritium content was below the detection limit.

The possibility of the tritium being diluted bomb tritium is the only way to explain the inorganic chemistry to a satisfactory degree. The rate of downward movement in this case would be about 1.8 m per year, which is about three times as much as the vertical movement at site 11 (see pp. 186-188). The faster vertical movement of soil moisture at site 1 can be attributed to irrigation. Site 11 is located on non-irrigated land.

Freon and atrazine concentrations were below the detection limit at this site 1.

Site 2

The county of Sherman had this well (well 2) installed in May of 1987 as part of a monitoring system for the county landfill. The well is located on the north side of the old part of the landfill, other monitoring wells are situated to the east and west of the landfill complex (fig. 46).

The water level is 43 m below land surface and the well is screened from 44.8 m to 60 m below land surface.

All wells are sampled on a yearly basis by the Groundwater Management District to monitor for possible leakage from the landfill.

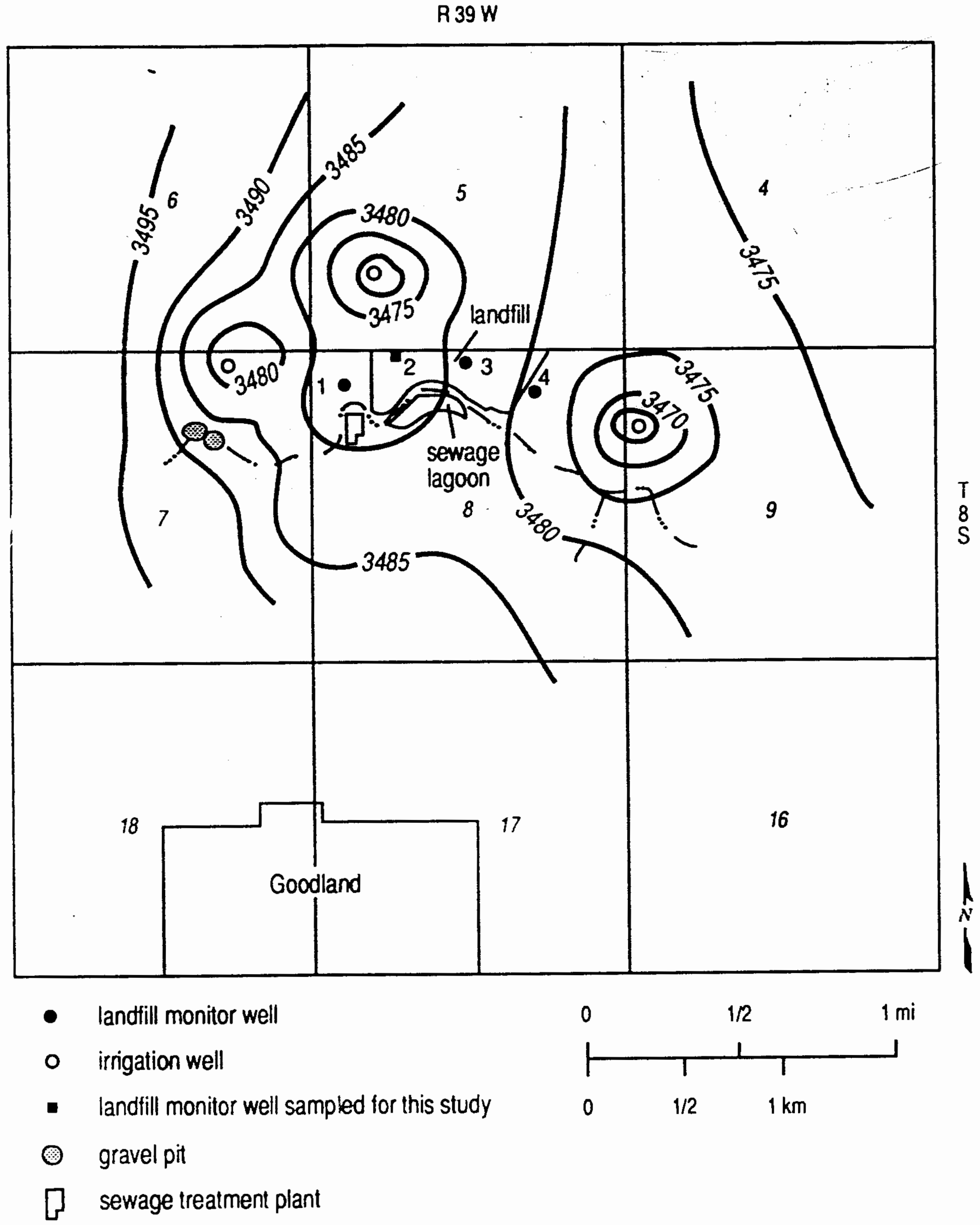


Figure 46: Water level contours in feet above sea level as effected by irrigation pumpage, site 2

Table 10 lists the results of standard inorganic analyses performed on samples from the monitoring wells taken in the years 1987 to 1989. Except for the monitoring well sampled particularly for this study in November 1987 (well 2) all wells were sampled by the Groundwater Management District and subsequently analyzed by commercial laboratories. For the 1987 and 1988 analyses the Groundwater Management District used the same laboratory, however, in 1989 they switched to a different one. Because results of the same water sample may vary from laboratory to laboratory, the results from the 1989 samples should not be compared to the other samples as far as absolute numbers are concerned. Analyses for the years 1987 and 1988 may not be totally accurate either. There were instances when results had to be rejected by the Management District because of obvious inconsistencies.

For this study the results are only intended to show the general trend of ground water chemistry and possible movement of ground water around and underneath the landfill area.

As can be seen in fig. 46 the monitoring well on the west side of the landfill (well 1) is located upgradient. This fact is also reflected in the water chemistry. In all three years concentrations of the respective components are lower in this well than in all the other monitoring wells.

This particular well was installed in 1986 by the city of Goodland to serve as a drinking water supply well. It is not used year-around but is pumped only infrequently. The fact that the 1987 analysis for this well does not show any sodium is based on an analytical error. The water is not treated in any way directly at the well but is pumped to a treatment plant.

Table 10 also shows a water analysis from an irrigation well about 3.2 km to the south of the landfill, sampled in July 1978. The water chemistry of this well can be interpreted as background chemistry for this area, the sulfate, nitrate and chloride concentrations here are very likely due to agricultural practices. Except for those constituents, the analyses of the waters from the irrigation well and the western monitoring well are very similar.Water from both these wells can be classified as calcium-bicarbonate type water.

Table 10: Standard inorganic chemistry results in mg/l of ground water collected from the Sherman County landfill monitoring wells, site 2, and an irrigation well to the south

Date sampled	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3
<u>Well 1</u>								
Sept. '87	42	12.5	0.0(?)	4.75	163	13	11	23.5
Sept. '88	31	11.3	26	6	330	9	12	16.1
Oct. '89	25	15	32	4	200.1	18	7	17.7
<u>Well 2</u>								
Sept. '87	130	44.5	57	12.5	516	66	40	39.2
Nov. '87 *	134	47	63	12	608	69	30	37
Sept. '88	137	46	81	13	523	45	43	15.7
Oct. '89	134	52	70	12	640.5	70	28	31.4
<u>Well 3</u>								
Sept. '87	110	36.5	65	10.5	385	31	98	46.4
Sept. '88	102	35	45	10	426	7.3 (?)	88	25.3
Oct. '88	104	44	70	8	425.8	31	102	38.5
<u>Well 4</u>								
Sept. '87	86	25	122	24	406	27	117	24.1
Sept. '88	108	34	131	8.4	412	29.6	127	20.1
Oct. '89	85	28	160	9	499	40	116	15.1
<u>Irrigation well</u>								
July '87 *	51	18	39	4.7	179	49	31	57

* Analyzed at the Kansas Geological Survey

The concentrations in the ground water of the well particularly sampled for this study (well 2) compared to the analyses of wells 3 and 4 are generally higher with the exception of chloride and sodium. This indicates a source of sodium and chloride present in the landfill area probably in the vicinity of wells 3 and 4. Natural regional ground water flow is from west to east in this area.

The Piper diagram (fig. 43) shows the waters of wells 2 and 3 as a calcium-bicarbonate type, whereas well 4 yields a calcium-sodium-chloride-bicarbonate type water.

A ground water model was run by the Groundwater Management District before the installation of the landfill monitoring wells in order to find the most suitable well locations. The landfill is surrounded by three irrigation wells, and two public water supply wells are located to the east and southeast. Using a modified version of a water table aquifer simulation program (WASP), these wells were pumped artificially at their maximum appropriated rate to determine ground water flow during the pumping season. Well 1 was not included in the model, because of its infrequent use. Fig. 46 shows the resulting static water level contours from sea level at this site as effected by irrigation pumpage.

It is obvious that the irrigation well to the north exerts the most influence on the ground water flow. The cone of depression includes the sewage treatment plant, 3/4 of the sewage lagoon to the south of the inactive part of the landfill, the intermittent stream, part of the landfill itself and monitoring well 2. The sewage lagoon is only lined with bentonite, thus there is a potential for leakage. In addition the lagoon overflows into the intermittent stream, which results in permanent flow in the stream from that point onward.

According to the model results (fig. 46) flow from the lagoon to well 2 would occur whenever the irrigation well to the north is pumped. Elevated concentrations of calcium, magnesium, potassium, bicarbonate, sulfate and boron (table 10) in the water of well 2 may be interpreted as evidence for recycled waters, strongly indicating flow from the lagoon to the well. Evaporation from the open surface of the lagoon would cause a general enrichment of water constituents.

Chloride and sodium concentrations in well 2 are higher than in well 1 but lower than in wells 3 and 4. However, this phenomenon is very likely caused by the afore mentioned source of sodium and chloride influencing only wells 3 and 4. Without the masking effect of that source sodium and chloride values in well 2 would probably exceed those in wells 3 and 4 due to enrichment in the lagoon.

The nitrate concentration in the ground water of well 2 was 37 mg/l in November 1987 (table 10), representing one of the higher concentrations encountered in ground water during this study.

Of all the wells sampled for this study, well 2 is the one with the highest amount of tritium in the ground water (23+/-1.7 TU), and the only well that showed detectable concentrations of freon (10.5 ppb). No water sample was taken from the sewage lagoon and analyzed for tritium, but it is very likely that the lagoon represents the source of the tritium.

Precipitation samples taken in November 1987 and October 1988 indicate an average tritium content of about 20 TU. Additional enrichment could occur by evaporation from the open surface of the lagoon.

The freon in the well water could originate either in the landfill itself by release from products containing fluorocarbons, or from precipitation caught in the lagoon and subsequently transported to the well by ground water flow.

It is concluded that the tritium at this site combined with the inorganic analyses and the flow model indicates artificially induced recharge, i.e. underground flow from the lagoon to well 2 caused by pumpage of the irrigation well to the north.

It would be interesting to obtain a water sample from the irrigation well to see how far the water from the lagoon has migrated.

No atrazine was detected in the ground water at this site.

Site 3

The monitoring well at this site was installed in September 1987 by the Kansas Geological Survey close to the center of a playa-like structure. The north/south extension of the depression is about 1.6 km and the east/west extension amounts to roughly 2.4 km.

The land within the depression is farmed without the use of irrigation.

The water level at this site is about 31.8 m below land surface and the well is screened from 37.2 m to 46.3 m below land surface. Fig. 33 in chapter 6 depicts a hydrograph of this particular well.

When the well was first sampled in November 1987 doubts remained as to the degree of development of the well due to equipment problems. Thus in May 1989 the well was re-sampled for tritium, stable isotopes and standard inorganic chemistry. In August 1989 another sample was taken exclusively for general inorganic chemistry analysis alone.

In May and August of 1989 the inorganic chemistry of the ground water sampled at this site was close to identical, so only the results of one of the analyses was plotted in the Piper diagram.

The November 1987 sample as well as both the 1989 samples show a calcium-bicarbonate type water (fig. 43).

The analytical results from November 1987 compared to the ones from May/August 1989 do not indicate a badly developed well in November 1987 (table 8). With the exception of sodium, sulfate, and nitrate the concentrations of constituents are more or less the same. The decrease in sodium and sulfate of 12 mg/l and 9 mg/l respectively, and the increase in nitrate of 7 mg/l can best be explained by vertical flow from the unsaturated zone to the ground water, the change in the afore mentioned concentrations possibly related to the farming of the land surface.

Although the geometry of a depression as such is likely to act as a collector for precipitation and surface run-off and evaporation processes from an open surface may take place, no such effect can be deduced from the inorganic chemistry data collected at this site.

It is likely that the occurrence of standing water in the depression is very rare. The landowner reported about 30 cm of standing water in the playa in June of 1987 and about 1 m occasionally when he was growing up about 40 years ago. In July of 1989 the western part of the playa, separated by a road from the monitoring well site, was flooded.

However, in general these events seem to occur too infrequently to exert an influence on the water chemistry.

The tritium content in the November 1987 sample was 1.6+/-0.6 TU. By May 1989 it had slightly increased to 3.1+/-0.7 TU. These results, combined with the changes in sodium, sulfate, and nitrate over the same time period seem to support the assumption of vertical moisture movement to the aquifer.

However, if the range of analytical error is considered, the two tritium analyses could be essentially the same: 2.4 TU and 2.4 TU, respectively.

The amounts of tritium are too low to indicate any bomb related tritium. Applying a halflife of 12.3 years, the 1989 tritium content at this site would have been around 15 TU in 1951/52 or around 20 TU in 1940. According to the precipitation samples analyzed for tritium for this study, these values for tritium in precipitation are acceptable.

The water level at this site is 31.8 m below land surface. Assuming uniform piston type flow in the unsaturated zone it took the moisture approximately 37 years to reach the water table as recharge, and it traveled at an average rate of about 0.7 m per year.

This figure represents only a very rough estimate. Possible mixing between "layers" of moisture in the piston type flow model are not taken into account and a perfectly smooth flow pattern is assumed, i.e. the stratigraphy of the unsaturated zone has been neglected. Enrichment processes due to evaporation of accumulated water in the playa and the subsequent infiltration into the unsaturated zone has also been neglected in calculating the above mentioned vertical rate of flow as well as infiltration of enriched late spring/early summer precipitation.

It is known that stratification of tritium in an undisturbed aquifer may occur and that the highest concentrations are present in the top zone of the aquifer (Dincer & Davis, 1968, Job, 1970, Verhagen, et al., 1970, Airey et al., 1970). Fig. 47 shows water levels and screened depths of the wells sampled for the first phase of the study. Only the lower 9.1 m of the monitoring well at site 3 are screened, about 5.4 m of standing water are present

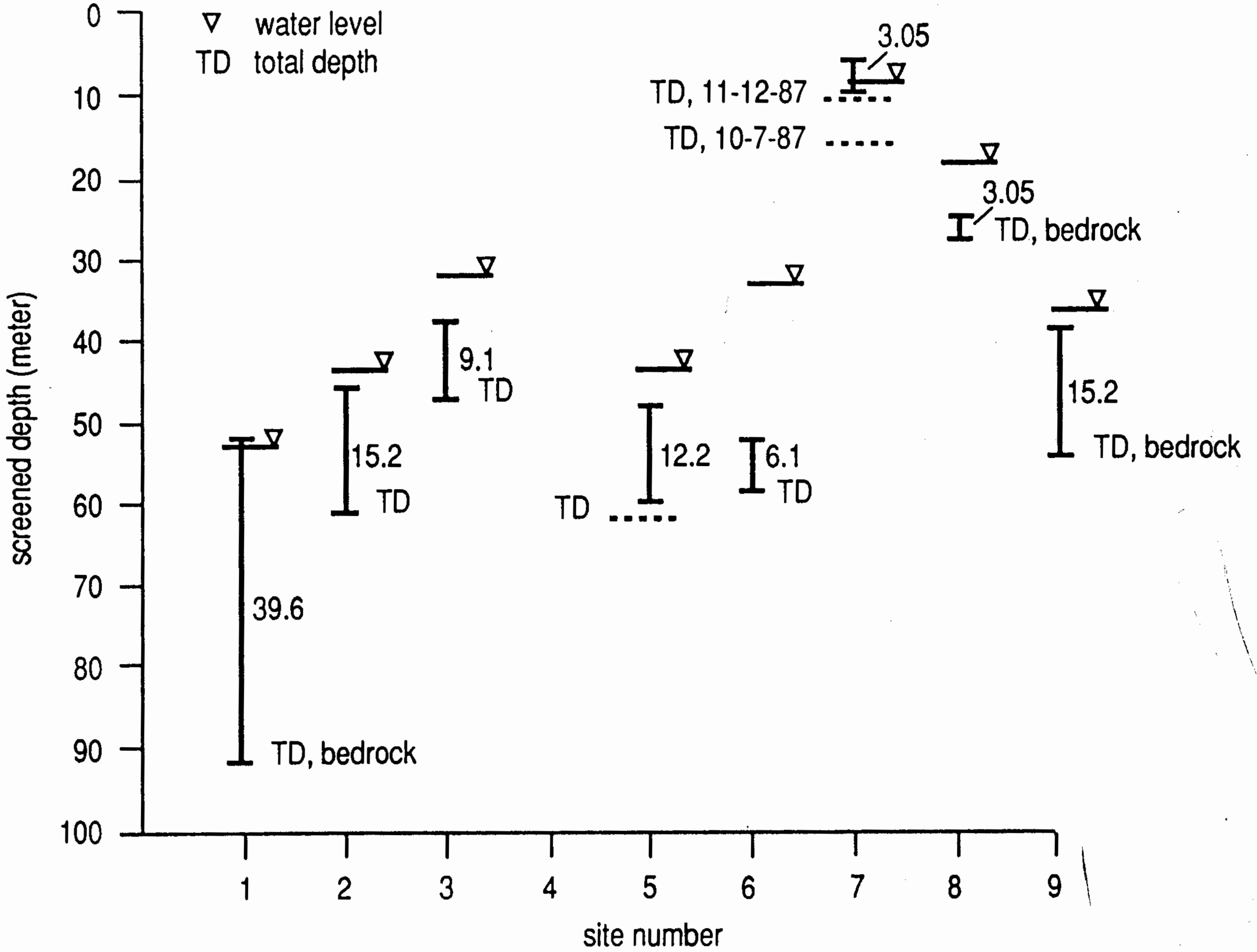


Figure 47: Total depth, screened depth, and water levels of phase 1 wells

above the screened area. Because the well was only pumped at a maximum rate of 0.04 m^3/sec it is very likely that no water from the upper part of the aquifer was drawn to the well and subsequently sampled.

Thus it is possible that the assumed rate of movement in the unsaturated zone at this site is underestimated, because the time needed for movement from the land surface down to the water table was calculated based on a tritium content about 5.4 m below the water table.

Atrazine and freon in the ground water sampled at this site were below the detection limit.

Site 4

At this site an irrigation well was sampled in November 1987. The exact construction of the well is unknown, no official record was filed. A copy of a log taken from a test hole drilled in the vicinity of the irrigation well was provided by the landowner (see appendix).

However, irrigation wells are generally screened over the total saturated thickness of the aquifer to ensure sufficient water quantity at all times. It is fairly safe to assume that this applies in this case as well.

The well is located in upland area, the land around it is farmed.

Two samples were taken from this well, in November 1987 and in August 1989. Both analyses indicate a calcium-magnesium-bicarbonate type water (fig. 43), the samples are nearly identical. The constituent that changed the most is nitrate, it increased by 5.1 mg/l (table 8).

Only in November 1987 the water was analyzed for tritium. The level was below the detection limit of 0.8+/-0.5 TU.

Depth to water at this site is about 50 m. It is impossible that tritium derived from precipitation in the late 1970's or later had reached the aquifer and then decayed to levels below the detection limit. The tritium content in precipitation being roughly 20 TU, moisture recharged from precipitation in the late 1970's should still contain about 5 TU.

Thus it can be safely assumed that the bomb related tritium is still in transit in the unsaturated zone at this site and did not yet reach the ground water.

No atrazine and/or freon were present in the ground water at this site.

Site 5

One of the monitoring wells for the Thomas County landfill was sampled at this site. The well was installed in 1987 and is sampled on a yearly basis by the Groundwater Management District. The location of the well is upgradient, on the west side of the landfill.

Depth to water at this site is 43 m, the well is screened from 47.2 m to 59.4 m below land surface.

Table 11 shows a summary of standard inorganic chemistry analyses performed on samples from the landfill monitoring wells. For comparison purposes, an analysis performed in 1978 on ground water from an irrigation well located about 2.4 km to the east of the landfill is included.

Table 11: Standard inorganic chemistry results in mg/l of ground waters collected from the Thomas County landfill monitoring wells, site 5, and an irrigation well to the east.

Date sampled	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3
Colby West								
Sept. '87	51	16.5	17	7.2	187	24	12	18.7
Nov. '87 *	47	17	19	7.1	214	21	8.8	16
Sept. '88	49	15.7	17.4	8	217	21.7	32	15.3
Oct. '89	34	19	21	7	222	20	7	21.3
Colby East								
Sept. 87	53	17.7	14.4	7.6	187	26	11	14.1
Sept. '88	45	16.6	14.9	8	217	32.8	5	9.5
Oct. '89	30	20	18	7	213.5	25	5	9.3
Colby South								
Sept. '87	58	18.5	17.6	7.2	188	27	11	21
Sept. '88	43	15.6	17.6	7	185	20.7	28	15.8
Oct. '89	35	21	21	6	219.6	25	6	22.15
Irrigation well								
July '87 *	40	17	24	5.6	221	21	7.6	13

* Analyzed at the Kansas Geological Survey

Except for the November 1987 analysis on water from the western monitoring well all samples were collected by the Groundwater Management District and subsequently analyzed by commercial laboratories. In 1987 and 1988 the same laboratory was used but in 1989 the Management District switched to a different one.

The water quality does not change very much over the years and is more or less the same in all the three monitoring wells. It seems to reflect the general ground water quality in the area, the analyses are nearly identical with the one performed on ground water from the irrigation well in 1978. The ground water can be characterized as a calcium-bicarbonate type water (fig. 43).

No tritium, atrazine or freon was detected in the sample taken in November 1987 from the westernmost monitoring well.

Based on the combined results of all analyses performed the bomb related tritium is still in transit in the unsaturated zone.

Depth to water at this site is 43 m. The rate of vertical movement of soil moisture would have to be about 3.5 m per year in order for post-bomb tritium to reach the ground water, and with an average tritium content of 20 TU in precipitation one would expect to be able to identify tritium in the ground water.

Site 6

Three wells were sampled at this site, located in a pasture. A pre-existing, currently unused well, installed as an oil field supply well (well 6c) was sampled in November 1987. The well was never used as such, because no oil was ever found here. Two more wells (wells 6a and 6b) were installed by the Kansas Geological Survey in September 1988 in a well nest about 3 m away from the existing well, in order to obtain information about possible stratification of tritium in the ground water at this site.

Similar to site 3, the water table is relatively shallow compared to most other sites investigated during this study: 32.9 m below land surface. Fig. 33 in chapter 6 depicts hydrographs for all the three wells.

Overall, the ground water samples from all three wells do not show any unusual water chemistry (table 8). The oil field supply well (well 6c), screened from 51.8 m to 57.9 m, yields a calcium-bicarbonate type water (fig. 44). The ground water tapped in the two wells in the well nest (wells 6a and 6b) can be classified as a calcium-magnesium-bicarbonate type water in both cases (fig. 44). The water sample taken from the oil field supply well shows lower concentrations for nearly all the analyzed constituents.

One possible explanation for this difference is the location of the screened intervals in the wells. The wells in the well nest are screened from 33.5 m to 36.6 m (well 6a) and 42.7 m to 45.7 m (well 6b), respectively. Thus the possibility of tritium stratification may be reflected in the inorganic chemistry as well.

The possibility that the ground water quality changed from 1987 to 1989 does not seem to be very likely. However, the oil field supply well was not re-sampled in 1989 and a change in water quality over a 2 year period can not totally be excluded.

When the oil field supply well at this site tested negative for tritium in November 1987 it was thought possible that the aquifer was sampled at too great a depth to detect the tritium, if there was stratification occurring in the ground water. The difference between the top of the screen and the water table is 19 m in this particular well (fig. 47).

Thus 2 more wells were installed in 1988 with screened intervals as mentioned above. The samples taken in November 1988 indicated 1.9+/-0.7 TU for the shallow well and 0.9+/-0.7 TU -with a repeat run of 2.6+/-0.6 TU- for the deeper screened well. Due to budgetary constraints the oil field supply well could not be re-sampled for tritium in 1988.

It seems possible that there is indeed a stratification of tritium occurring in the ground water at this site. However, the differences between tritium concentrations in the wells are too small to represent absolute proof. If the two values for the deeper screened well are interpolated, a tritium content of 1.75 TU results, which is less than the 1.9 TU in the shallower well. But taken the error range of the analyses into account the tritium concentration could also be identical. The same reasoning can be applied comparing the tritium concentration of the oil field supply well with the concentration in the other two wells.

However, the nitrate content of the three ground waters sampled at this site seems to reflect the trend of the tritium concentrations. The water collected from the oil field supply well contained 13 mg/l nitrate, whereas the ground water from the shallow well and the deep well showed nitrate levels of 22 mg/l to 23 mg/l and 31 mg/l, respectively.

Thus an indication for stratification is present at this site but the data can not be interpreted as absolute evidence.

The fact that there is a minor amount of tritium present in the ground water probably indicates recharge from precipitation prior to the release of bomb tritium. Under the assumption that this is true, the maximum rate of vertical movement in the unsaturated zone would be about 1 m per year. One would expect a higher tritium content if post-bomb tritium were to be assumed.

No atrazine or freon were detected in the ground water at this site.

Site 7

At this site a shallow well situated on the eastern recharge boundary of the Ogallala aquifer was sampled. The water level here is 7.18 m below land surface and the well is screened from 6.4 m to 9.4 m below land surface.

The well was installed by the Kansas Department of Health and Environment in July 1987 as a monitoring well for oil fields located around the well site.

A sample from this well had to be obtained by using a bailer, because the filters of the pump kept clogging up due to the amount of sediment in the well. When the well was installed in July 1987 the total depth was 15.8 m, however, when the well was sampled for this study in November 1987, the total depth had decreased to 9.8 m. An accumulation of 6 m of sediment took place over a period of only 4 months. It has to be assumed that the well casing broke during well installation.

Incorrect and/or careless salt water disposal practices caused a change in ground water chemistry in this area, as reflected by the standard inorganic chemistry of the well water. Of all the ground waters sampled during this study, the ground water at this particular site shows the highest specific conductivity values and high calcium, magnesium, sodium, sulfate, chloride and nitrate concentrations (table 8). But only the chloride content exceeds the United States Environmental Protection Agency's recommended limit of 250 mg/l (U.S.E.P.A., 1976).

When the well was sampled for chloride in July 1987 by the Kansas Department of Health and Environment the chloride content was even higher: 500 mg/l.

The primary sources for the high sodium and chloride concentrations is a salt water disposal well about 0.8 km to the southwest of the monitoring well. The disposal well was either screened in such a way that the Ogallala aquifer was influenced by the disposed salt water or the steel casing of the well may be broken or corroded.

Surface water in a creek located about 200 m east of the site showed a specific conductivity of over 40.000 μmhos/cm when tested by the Groundwater Management District. No water sample was taken, however. Several springs, which feed into the creek exhibit high conductivity values as well.

In the Piper diagram (fig. 43) the water plots as a calcium-sodium-chloride type water.

The high amount of trace elements in this ground water may be due to the adsorption of these constituents onto clay surfaces. The sample contained a large amount of sediment and was left to settle out rather than filtered prior to analysis. However, in water contaminated by brines one would expect a higher amount of trace elements.

The elevated nitrate and sulfate concentrations are probably caused by farming practices in the area. However, sulfate as well as calcium and magnesium concentrations may also be associated with the water chemistry of the disposed brine.

The tritium content at this site was 5.6+/-0.7 TU in November 1987. It can be attributed to the shallow depth of ground water.

Based on the thickness of the unsaturated zone one could expect to see some bomb related tritium at this site. The lack of a high tritium concentration in the ground water may be caused by the dilution effect of the non-tritiated salt water introduced by the disposal well. The brine is derived from a Pennsylvanian age formation.

But it is most likely that any bomb related tritium has been flushed out of the system already, and the 5 TU are caused by precipitation since the mid 1970's, again possibly diluted by the salt water. In this case the vertical movement of moisture would be averaging about 0.6 m per year. In view of the results from site 11 (see pp. 186-188), this rate of movement seems very reasonable.

Without further data it is not possible to identify the exact source of the tritium.

Site 8

A domestic well, constructed in 1979 was sampled at this site. The water level is 18.3 m below land surface, and the well is screened from 24.4 m to 27.4 m below land surface. Depth to the underlying Pierre Shale is 26.5 m, the unsaturated zone is thus only 8.2 m thick.

When sampled in November 1987 the ground water was a calcium-magnesium-bicarbonate type water and of drinking water quality (fig. 43).

The well owner reported a change in water quality occurring in spring, which can probably be attributed to the existence of an unplugged, abandoned well, which is installed in a pit. This old well is located on a slope just about 50 m away from the well sampled. These old wells could serve as conduits to the ground water. Bank infiltration due to the proximity of the well to North Beaver Creek, a perennial stream, seems unlikely. The well is probably not pumped at a high enough rate to extend a cone of depression to the stream.

Nothing unusual is showing up in the inorganic water chemistry (table 8). Compared to most of the ground waters analyzed for this study - with the exception of sites 1,2, and 7, where the ground water chemistry is influenced by other factors- the sulfate content is slightly elevated. This phenomenon can be attributed to the shallow depth of the underlying Pierre Shale in this area.

The tritium in this ground water was below the detection limit of 0.8+/-0.5 TU, which seems to contradict the occurrence of seasonal changes in the ground water quality.

With a background tritium value of about 20 TU in precipitation one would expect to see evidence of tritium in the well water, if seasonal changes do indeed occur.

The well was sampled in November. It is very possible that any ground water that may have been influenced by downward moving moisture during the spring was pumped out of the well at this point.

This explanation is only valid under the assumption that the ground water is not tritiated in this area.

Without further analyses it is impossible to give the exact reason for the fact that a seasonal change is observed by the well owner but no tritium is found in the ground water at this site.

Based on the results at site 11 (see pp. 186-188) one would not expect to find tritium recharged under natural conditions in the ground water at this site. Assuming a vertical moisture movement of 0.5 m it would take 36.6 years for the peak of the bomb-related tritium to reach the water table at this site, provided the conditions in the unsaturated zone at the two sites are similar.

No freon or atrazine were found in the ground water at this site.

Site 9

At this site, located in Decatur County, a well supplying a dairy operation was sampled. The well was installed in 1987 and has a screened interval from 38.4 m to 53.6 m below land surface. The water level is at 36 m below land surface. Pierre shale was encountered at a depth of 53 m.

When the water samples were taken in November 1987 the well was pumping at a rate of 9.46 l/sec.

According to the Piper diagram (fig. 43) a calcium-magnesium- bicarbonate type water is present here. The inorganic chemistry analysis shows nothing unusual (table 8). The water quality is very good, the water is suitable for drinking water purposes.

Tritium in this particular ground water was below the detection limit of 0.8+/-0.7 TU. Thus it can be assumed that the bomb related tritium is still in transit in the unsaturated zone. The rate of movement through the unsaturated zone would be too great to assume post-bomb tritium.

No atrazine and/or freon were detected in the water yielded by this well.

Site 10

Two wells were installed at this site in September 1988 by the Kansas Geological Survey. The wells are located in a pasture, about 150 m away from an intermittent stream.

The water level at this site is about 3.6 m below land surface, fig. 23 in chapter 6 shows a hydrograph for both the wells.

According to the landowner the stream hardly ever carries water since irrigation started in this area. Several springs that used to feed into the stream went dry, because the water level was lowered by irrigation.

The wells are screened from 4 m to 7 m and 27.7 m to 32.3 m respectively.

Samples were taken in November 1988 and in August 1989. In both years the water was of a calcium-bicarbonate type in both wells (fig. 44). The inorganic chemistry data are listed in table 8.

Comparing the analyses from the deeper screened well with the ones from the shallow well at this site, it is obvious that the ground water tapped by the shallow well has a slightly higher content of dissolved solids in 1988. The difference becomes more pronounced in the 1989 analyses.

The ground water tapped by the deeper screened well did hardly change at all from November 1988 to August 1989, the results of the analyses are nearly identical.

Compared to November 1988, the shallower well shows elevated concentrations of mainly calcium, bicarbonate, sulfate, and nitrate in August 1989, reflecting the shallow water table of 3.6 m below land surface and the short distance between the top of the screen and the water table.

Use of the land as a pasture probably influences the sulfate and nitrate concentrations in the shallow ground water. The nitrate concentrations are nearly identical in both wells. Ground water collected from the shallow well contained 9.4 mg/l to 10 mg/l nitrate and water from the deep well showed a nitrate concentration of 11 mg/l (table 8).

The two analyses seem to indicate seasonal changes in water quality in the shallow ground water, however two samples are not conclusive enough to establish that as a fact.

In November 1988 ground water from the shallow well had a tritium content of 1.2+/-0.8 TU, the deeper ground water at the other well showed a tritium concentration below the detection limit of 0.8+/-0.6 TU. Thus the difference in inorganic chemistry is also reflected by the tritium content.

Given the shallow water table one would not expect to see any bomb related tritium at this site anymore. However, with a background level of about 20 TU in precipitation, a tritium concentration of 1.2 TU is surprisingly small.

The assumption could be made that tritium is lost somewhere in the unsaturated zone. One possibility is tritium uptake by plants, which in this case would be the grasses growing on the pasture. Another possibility is exchange with hydroxyl groups on clay surfaces present in the unsaturated zone. The rate and the amount at which tritium is lost to both, vegetation and clays, is very small.

If a seasonal change in water quality in the shallow well, as indicated by the inorganic water chemistry, would be taken for granted then moisture in the unsaturated zone would move at a very fast rate, and the tritium would move more or less accordingly.

It seems possible that a period without much precipitation and thus recharge is reflected by the tritium content of the November 1988 water sample. Recharge in western Kansas takes place in winter, when the ground is not frozen, and in spring, provided enough moisture from precipitation is available.

This explanation of the low tritium content seems to be very likely, especially in view of the tritium content of a core taken from 2.47 m to 3.1 m below land surface at this site (see pp. 186-188). The tritium concentration in this 63 cm long core was 7.6+/-0.8 TU, a little more indicative of recent precipitation. The core was taken May 30, 1989, after the recharge period. A more detailed description of the unsaturated zone is given lateron.

It seems that the rate of recharge at this site could be very fast and that any tritium related to the emissions in the 1960's could have been flushed out of the ground water system at this site. But without more information regarding the water quality throughout the year and the tritium distribution in the unsaturated zone it is not possible to make a more precise statement.

Site 11

Two wells were installed in a well nest at this site in September 1988 by the Kansas Geological Survey.

The water level here is about 52.1 m below land surface. Fig. 33 in chapter 6 depicts hydrographs for both the wells. The shallower well is screened from 53.3 m to 59.4 m and the deeper well has a screened interval from 68.6 m to 73.1m.

The ground water at this site was sampled in November 1988 and August 1989 in both wells.

Water collected from the shallow well plots as a calcium-magnesium-bicarbonate type water in the Piper diagram (fig. 44) in 1988 and 1989. The magnesium characterization of this particular ground water is not very pronounced: the magnesium content was barely above 30 % meq/l in both years (30.16 % meq/l and 30.15 % meq/l).

Ground water tapped by the deeper screened well is a calcium-bicarbonate type water.

The nitrate concentrations in the shallow well ranged from 14 mg/l to 15 mg/l, ground water collected from the deep well at this site had a nitrate content of 11 mg/l (table 8).

The tritium content of the ground water in the shallower screened well at site 11 was 0.9+/-0.6 TU when sampled in November 1988. The water tapped by the deeper well contained 1.1+/-0.6 TU. These results are too similar to indicate stratification of tritium in the ground water.

Based on the depth to water at this site, the tritium has to be pre-bomb tritium. A closer investigation of the unsaturated zone at this site more than supports this statement. The results of that investigation are discussed in detail under the subheading "Unsaturated zone", p. 155.

Summary

In summary, the ground waters analyzed during this study can generally be characterized as calcium-bicarbonate or calcium-magnesium-bicarbonate type waters. Only at sites 1, 2, and 7 is this characterization not valid, ground water collected at these particular sites showed anthropogenic influences such as fertilizer application, and influence of salt water intrusion.

At sites 3 and 4, which are located about 2.4 km apart along the same lineament (fig. 41), different ground water types were encountered. The ground water site 3 is a calcium-bicarbonate type water, whereas the ground water site 4 is a calcium-magnesium-bicarbonate type water. In general, concentrations of all analyzed ground water constituents are higher at site 3 compared to site 4, which may be due to enrichment caused by evaporation of water accumulated at the playa surface. Besides being dependent on the surface morphology, the difference in water chemistry may be due to different materials present in the unsaturated zone and different farming practices. Based on the standard inorganic chemistry data it is impossible to say, if the lineament does or does not exert influence on the ground water chemistry and if it represents a preferential recharge area.

Tritium was detected in only 9 of the 15 wells sampled. All ground waters that contained elevated tritium concentrations also showed higher nitrate concentrations than ground waters with no detectable amounts of tritium. However, this correlation between tritium and nitrate is most likely to occur in agricultural areas where nitrogen fertilizer is applied. No evidence for the presence of geologic nitrogen was found.Table 12 lists the tritium and nitrate concentrations for the various ground waters sampled. At sites 1, 2, 3, 6, and 7 the correlation between tritium and nitrate is especially evident.

For sites 1, 3, 6, and 7 it was possible to deduce rates of vertical soil moisture movement based on the tritium concentration of the ground water. The rates are 1.5 m/year, 0.7 m/year, a maximum of 1 m/year, and 0.6 m/year for sites 1, 3, 6, and 7, respectively. Site 1 is located on the edge of the sphere of influence of a center pivot irrigation system, which explains the rapid rate of moisture movement from land surface to the ground water. All other sites are located on non-irrigated land.

Table 12: Tritium and nitrate concentrations in ground water in the study area

Location	Tritium content (TU)	Nitrate content (as nitrate, in mg/l)
Site 1	2.8+/-0.5	60.0
Site 2	23+/-1.7	37.0
Site 3	1.6+/-0.6	28.0
	3.1+/-0.7	35.0
Site 4	<0.8+/-0.5	8.9
Site 5	<0.8+/-0.5	16.0
Site 6a	1.9+/-0.7	22.0
Site 6b	1.75+/-0.6	28.0
Site 6c	<0.8+/-0.5	13.0
Site 7	5.6+/-0.7	74.0
Site 8	<0.8+/-0.5	18.0
Site 9	<0.8+/-0.7	7.5
Site 10a	1.2+/-0.6	9.4
Site 10b	<0.8+/-0.6	10.0
Site 11a	0.9+/-0.6	15.0
Site 11b	1.1+/-0.6	11.0

The above mentioned rates of vertical moisture movement should be considered rough estimates only. Unless the sedimentology and the tritium/depth distribution of the unsaturated zone is known, no precise statement regarding vertical flow rates can be made.

All encountered tritium concentrations in the ground water were well below the calculated amount of tritium derived from the emissions in the early 1960's of 409 TU that should, according to the tritium input function (see chapter 7), still be present in the unsaturated or the saturated zone. It is possible, however, that ground water containing bomb related tritium was diluted at site 1 and 7, so that it is not recognizable as such anymore. But without further information regarding the tritium concentration in the unsaturated zone at these sites, this remains an assumption.

Freon was detected in only one ground water sample, the monitoring well at site 2. The freon here can probably be attributed to the influence of artificial recharge at this site.

Atrazine tested negative in all the ground waters analyzed.

Surface Water

One intermittent stream sample was collected for standard inorganic chemistry and stable isotope analyses: the Saline River in Sheridan County was sampled in March 1989. The results of the standard inorganic analyses are listed in table 8. The water can be described as a calcium-bicarbonate type water (fig. 44), indicating baseflow at the time of sample collection. The stable isotope analysis supports this statement.

The tritium content was 8.6+/-0.9 TU, the nitrate concentration was, however, only 0.6 mg/l. Thus no correlation between tritium and nitrate is present in this case.

Some of the tritium was possibly contributed by precipitation.

Stable isotopes and carbon-14

Fig. 48 shows the stable isotope composition of all waters sampled during this study, including ground-, surface-, and soil waters as well as precipitation. Table 13 lists the results of the analyses and the calculated deuterium access parameters. The mean annual air temperature at the time of precipitation for these meteoric waters was calculated according to $T = \frac{\delta O^{18} + 11.79‰}{0.38}$ (Foerstel et al., 1975) and is listed in table 13 as well.

All water samples plot close to the meteoric line as established by Craig (1961), confirming that precipitation was the origin of all waters analyzed. The meteoric water line for the study area based on the results of the stable isotope analyses of the collected water samples is depicted in fig. 48 as well. With the exception of ground waters collected at sites 3 and 4, all ground waters plot relatively close together along the meteoric line.

The temperature dependency of deuterium and oxygen-18 is very obvious in table 13. The more depleted in oxygen-18 and deuterium the water samples are, the lower the mean annual air temperature at the time of precipitation was.

The ground waters sampled at sites 3 and 4 show the coolest and the warmest air temperature, respectively, also documented by their opposite position along the meteoric water line. These two sites are located about 2.4 km apart and the same lineament transects

Table 13: Stable isotope concentrations in ground water, surface water, soil moisture and precipitation in the study area. Deuterium access parameters and the average annual air temperature at the time of precipitation are listed as well

Location	Date sampled	O^{18}	D	D ~~ac~~excess parameter	Average annual air T (°C)
Site 1	Nov. '87	-11.6	-86	6.8	0.5
Site 2	Nov. '87	-11	-81.5	6.5	2.1
Site 3	Nov. '87	-7.7	-57.5	4.1	10.8
	May '89	-6.5	-49.07	2.93	13.9
Site 4	Nov. '87	-12.6	-92	8.8	-2.1
Site 5	Nov. '87	-11	-79	10	2.1
Site 6a	Nov. '88	-10.4	-79.64	3.58	3.6
Site 6b	Nov. '88	-9.9	-78.1	1.1	5.0
Site 6c	Nov. '87	-9.6	-69	7.8	5.8
Site 7	Nov. '87	-10.9	-79.5	7.7	2.3
Site 8	Nov. '87	-11.6	-86	6.8	0.5
Site 9	Nov. '87	-10.8	-77	9.4	2.6
Site 10a	Nov. '88	-10.3	-78.59	3.81	3.9
Site 10b	Nov. '88	-10.1	-76.90	3.90	4.4
Site 11a	Nov. '88	-10.4	-76.74	6.46	3.6
Site 10b	Nov '88	-10.5	-81.48	2.52	3.4
Site 3					
shallow lysimeter (10.8 m)	March '89	-7	-49.46	6.54	12.6
deep lysimeter (19.7 m)	March '89	-6.3	-48.94	1.46	14.4
Site 11					
deep lysimeter (19.8 m)	March '89	-11.5	-80.44	11.56	0.8
Saline River	March '89	-9.8	-75.55	2.85	5.2
Precipitation	Nov. '87	-8.6	-61.5	7.3	8.4

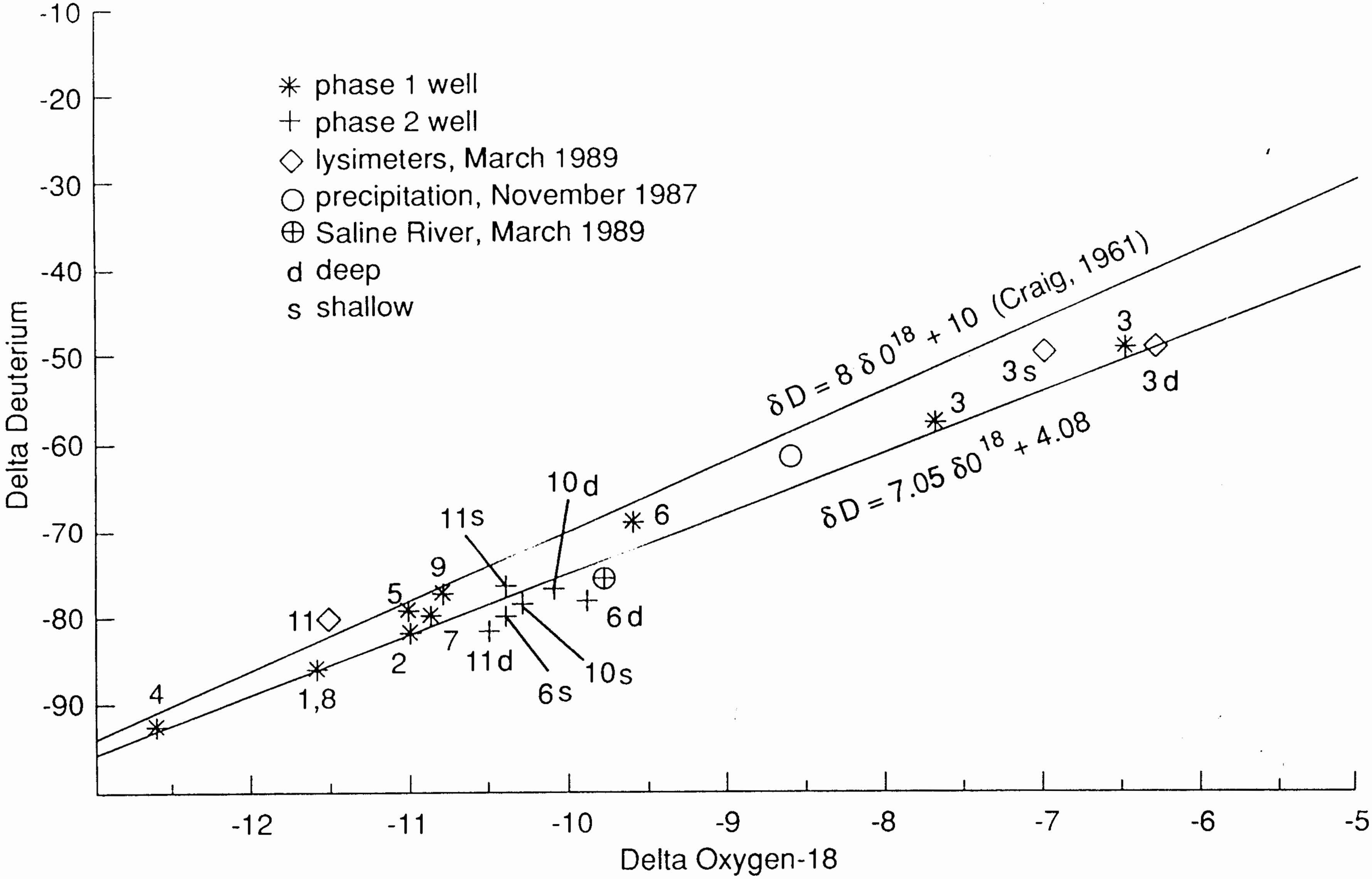


Figure 48: Stable Isotopes

both sites (fig. 41). If lineaments indeed have an influence on the recharge process to the Ogallala aquifer, this large difference in stable isotope concentrations of the two ground water samples should not be present. Thus it is concluded that there is no preferential recharge at least along this particular lineament. The difference in stable isotope concentrations in ground water at the two sites located close to this lineament is attributed to the morphological difference of the site locations, i.e. site 4 is located in an upland area with a depth to water of about 50 m and the site 3 is located in a playa-like structure, where the depth to water is about 18 m less than at site 1.

The ground water collected from the irrigation well at site 4 is the most depleted water of all waters analyzed. The calculated mean annual air temperature at the time of recharge was -2.1 °C. This means, that the this particular ground water was recharged either during the winter or in a generally cooler climate. To obtain an estimate regarding the age of the ground water stored in the Ogallala aquifer, this specific water sample was analyzed for carbon-14. The resulting age is 72.3 +/-0.6 % modern or 801 years B.C., the latter representing the age calibrated against the tree ring curve. Thus the ground water sampled at site 4 could be Holocene in age, however, without a carbon-13 correction this can not be stated as a fact. As mentioned above, site 4 is located in an upland area, the depth to water is about 50 m below land surface. It seems possible that all ground waters of the Ogallala aquifer at that depth may be Holocene (?) in age, if no apparent recharge features are present and no artificial recharge occurs. However, more samples need to be analyzed for carbon-14 and carbon-13 before a conclusive statement can be made.

Without a carbon-14 analysis it is impossible to deduce the age of ground water from stable isotope analyses. A good example for this is the result of the oxygen-18 and deuterium analyses of soil water collected from the deep lysimeter at site 11, located 19.8 m below the land surface. The soil water is depleted with respect to stable isotopes compared to the precipitation sample and most other water samples analyzed. It plots close to the ground water sample collected from site 4, which was determined to be Holocene (?) in age. But with a tritium content of 46 TU on the average the soil water in the unsaturated zone at site 1f is certainly not Holocene in age, but of very recent origin. The precipitation and the subsequent recharge of this particular soil water very likely occurred during the winter as indicated by the calculated mean annual air temperature of 0.8 °C. In this case, there is no connection between the stable isotope composition and the tritium content or the age of the sample.

The waters with the highest stable isotope concentrations were collected at site 3, which is located in a playa-like structure. Both ground water samples taken in November 1987 and in May 1989 and the soil water samples show high calculated mean annual air temperatures at the time of precipitation, ranging from 10.8 °C to 14.4 °C. The ground and soil waters sampled at site 3 were recharged under warmer temperatures than the rest of all the analyzed waters, probably in the time period from spring to fall. Evaporation processes may have caused additional enrichment of the waters infiltrating the ground.

The difference in stable isotope composition between the two lysimeters at site 3, located at 10.8 m and 19.7 m, respectively, is also reflected by the standard inorganic analyses and the tritium content. The soil water collected from the shallow lysimeter is more depleted in stable isotopes than the soil water collected from the deep lysimeter and also plots a little further away from the meteoric water line, which indicates a higher degree of evaporation. Thus the two soil waters seem to have been recharged under different conditions, possibly in different seasons. The differences in soil water chemistry are discussed in greater detail lateron.

The precipitation sample collected in November 1987 in Colby is more depleted in oxygen-18 and deuterium than the samples collected at site 3, which is also documented by the calculated surface temperature for the precipitation sample: 8.4 °C.

The stream sample of the Saline River collected in March 1989 plots in the vicinity of most of the groundwater samples in fig. 44, thus indicating base flow at the time of sample collection. This coincides well with the standard inorganic water chemistry results.

The deuterium access parameters calculated for all samples analyzed (table 13) range from 1.46 to 7.3, indicating different vapor forming processes of the respective precipitation the samples were derived from.

Summary

In summary, stable isotopes are not useful for differentiating between older and younger waters, unless other dating methods such as carbon-14 and tritium are employed as well. Without knowledge regarding the origin of the precipitating air mass much caution is needed in the interpretation of stable isotope analyses.

One of the intents of analyzing for stable isotopes in this study was to investigate a possible connection between tritium content and stable isotope composition of Ogallala ground waters. Apparently, no connection does exist.

Based on the stable isotope analyses of the ground waters encountered at site 3 and 4, located only about 2.4 km apart along the same lineament, these structures do not exert any influence on the recharge process to the Ogallala aquifer. At least in this case, the depth to ground water combined with the difference in morphology between the two sites is the relevant factor as far as recharge is concerned. Most ground waters of the Ogallala aquifer analyzed for stable isotopes have a similar isotopic composition as indicated by fig. 48 and table 13.

Unsaturated zone

At three sites in the study area lysimeters were installed and/or soil cores were taken. Fig. 41 shows the location of these sites.

Two types of pressure/vacuum lysimeters were installed, depending on the depth of placement in the unsaturated zone. For depth up to 15 m the model 1920 lysimeter from Soil moisture Equipment Corp. was used, whereas for greater depth the model 1940 from the same company was installed. The difference between these two models is the presence of check valves in the 1940 model to prevent over pressurization of the lysimeter.

The lysimeters were installed using an auger rig. After the lysimeters were set, the holes were back filled with natural material with intermediate layers of bentonite to prevent the development of conduits for moisture percolating from the land surface down to the lysimeter.

The lysimeters were set in about 15 pounds of silica flour, which surround the ceramic cup at the bottom of each lysimeter. The silica flour acts as a dessicant and enhances moisture extraction from the soil. Vacuum was applied to the lysimeters in order to create a pressure gradient from the soil to the lysimeter. The soil water collected in the ceramic cup was sampled by pressurizing the lysimeter.

The lysimeters were sampled for standard inorganic chemistry, tritium, and stable isotopes. The samples intended for isotope analyses were extracted by using nitrogen gas to pressurize the lysimeter. Samples for the analyses of standard inorganic components were retrieved by pressurizing the lysimeter with air oxygen.

Specific conductivity and pH were measured in the field and in the laboratory, whenever enough sample water could be extracted for these measurements.

Because of the soil moisture conditions in the unsaturated zone, it took about 3 months before the lysimeters could be sampled after installation.

Generally, the lysimeters were left under vacuum conditions for about 2 weeks to ensure a sufficient quantity of soil water collectable for analyses.

Yields in the lysimeters ranged from about 60 ml to nearly 600 ml.

Soil cores were taken with a trailer mounted Giddings rig pushing a 1.2 m long core barrel into the ground, and with a truck mounted auger rig, using a 0.6 m long and 5 cm in diameter split spoon sampler. The split spoon sampler was drilled into the ground inside the auger flights.

Particle size distribution was determined according to the method described by Day (1965) and Gee & Bauder (1986), the calcium carbonate content was determined according to Dreimanis (1962), and the moisture content was determined using the gravimetric method described by Gardner (1986). Nitrate and tritium concentrations were analyzed as well as porosity. However, it was not possible to analyze all cores consistently for these parameters.

At the final depth installation of the lysimeters soil samples were collected for the analyses of atrazine. None of the samples tested positive for atrazine.

Site 3

This site is located in a playa-like structure. A well was installed here in 1987 and subsequently sampled for standard inorganic chemistry, isotopes, freon, and atrazine. Based on the results it was assumed that tritium stratification may occur in the ground water at this site. Thus a second well was installed in September 1988, which was screened higher in the aquifer than the well previously sampled. However, it was not possible to develop the new well sufficiently and no formation water sample could be collected. Thus it was decided to obtain information about the unsaturated zone instead.

Two lysimeters were installed at this site in September 1988. One lysimeter was placed at a depth of 10.8 m, referred to as the shallow lysimeter in the following text, and another lysimeter was installed at 19.7 m depth below land surface, lateron referred to as the deep lysimeter.

In April and July of 1989 a complete set of standard inorganic chemistry analyses was performed on water collected from both the lysimeters. In December 1988, and June, August and September 1989 the soil water samples were only analyzed for sulfate, chloride and nitrate concentrations. In November 1989 only the nitrate content was determined.

The shallow lysimeter yielded a calcium-sulfate-bicarbonate type water, whereas the soil water collected in the deep lysimeter can be characterized as a calcium-bicarbonate type water (Fig. 49). This characterization is valid for the months of April and July 1989, when complete analyses were performed.

As indicated by the different soil water types encountered the soil water chemistry at a depth of 10.8 m differs considerably from the one at 19.7 m depth. Table 14 shows the inorganic chemistry data for both lysimeters.

Generally, the water yielded by the deep lysimeter has higher concentrations of nearly all analyzed constituents, except for sodium and sulfate.

Sulfate concentrations are about twice as high in the shallow lysimeter as compared to the deep one, with the exception of December 1988, when the water collected in the deep lysimeter had a sulfate concentration of 230 mg/l and was thus 32 mg/l higher than soil water yielded by the shallow lysimeter.

Chloride concentrations are three to seven times higher in the deep lysimeter as compared to the shallow lysimeter.

A more or less fourfold increase in nitrate concentrations can be observed from 10.8 m to 19.7 m depth at this site. The nitrate concentration in soil water collected from the shallow lysimeter was 39 mg/l on the average, whereas the average concentration in water from the deep lysimeter was 156 mg/l nitrate.

The differences in the anion content between soil waters collected from the shallow and deep lysimeters are not quite so dramatic (see table 14).

The analyses on water yielded by the shallow lysimeter indicate a general decrease in sulfate and chloride from March to September. Nitrates remain more or less at a constant concentration. The complete analyses performed in April and July are nearly identical for the anions and nitrate, chloride and sulfate. However,the sulfate concentration went up from April to June and declined subsequently from June to July to nearly the same concentration as in April.

The soil water collected in the deep lysimeter (19.7 m depth) shows a similar behavior as the water sampled from the shallow lysimeter over the same period of time.

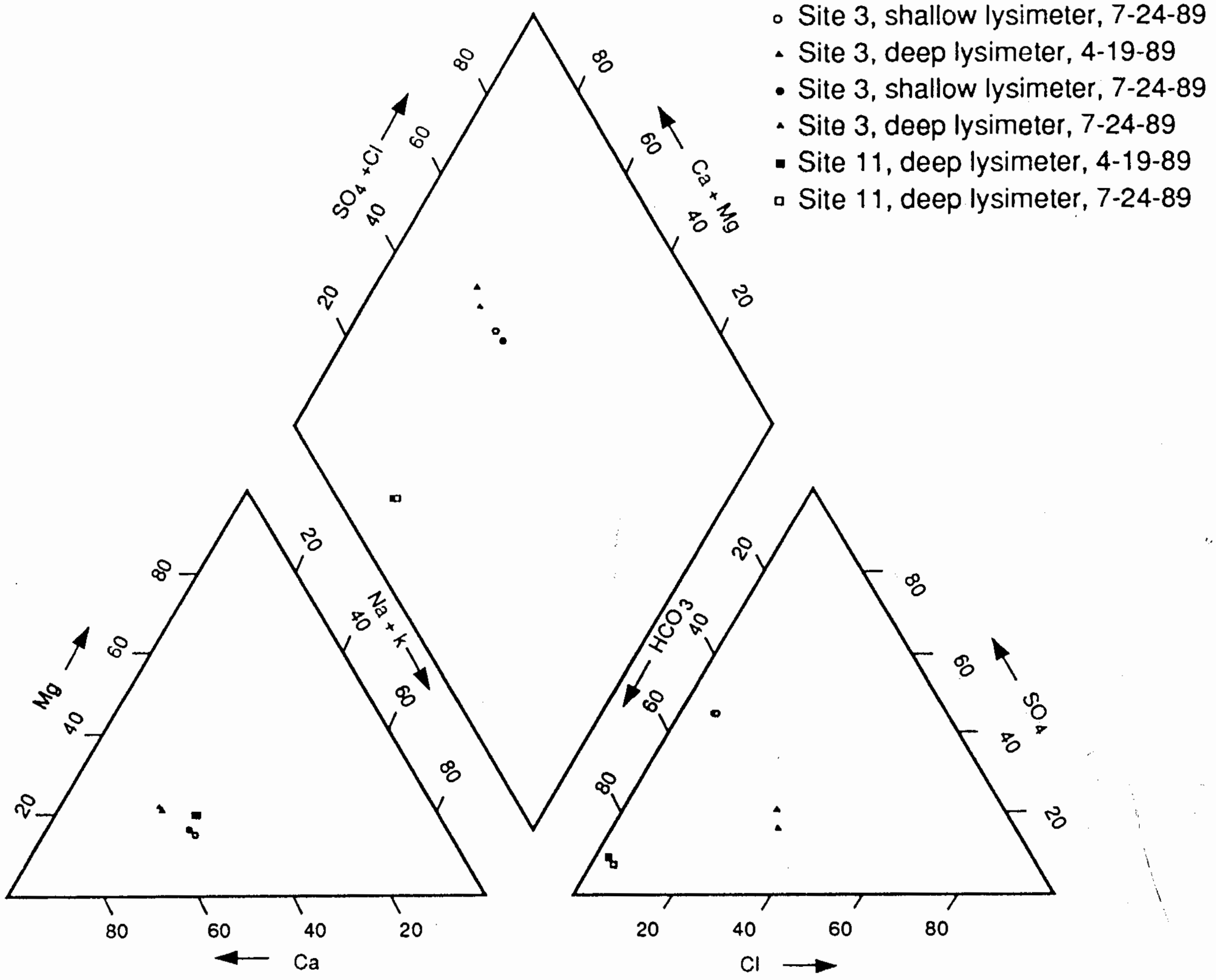


Figure 49: Standard inorganic chemistry analyses of soil water collected in lysimeters at sites 3 and 11

Table 14 : Standard inorganic chemistry results in mg/l from soil water collecetd in the lysimeters at site 3

Date sampled	field pH	lab pH	field spec. cond.	lab spec. cond.	SiO_2	Ca	Mg	Na	K	Sr	HCO_3	SO_4	Cl	F	NO_3
						Shallow lysimeter (10.8 m)									
12-1-88						107	17	48	16	0.8	198	23			
3-27-89	6.75			920							217	30			
4-19-89		7.85		1210	87	92	16	50	18	0.8	233	163	19	0.7	40
6-19-89	7.35		1000									182	20		39
7-24-89		7.65		818	90	95	17	50	19	0.8	235	165	18		39
8-22-89	6.65		815	798								151	16		38
9-26-89	6.85		775									148	13		39
						Deep lysimeter (19.7 m)									
12-1-88												230	167		
4-19-89		7.85		1210	85	138	31	42	29	1.4	269	91	103	0.7	164
6-19-89	7.15			1230								83	100		156
7-24-89		7.5		1150	88	135	31	40	30	1.3	266	68	104		162
8-2289				1130								69	99		152
9-26-89		7.15	1040									70	92		151
11-1-89															153

Concentrations of sulfate and chloride generally decrease and the anions remain more or less constant from April to July. Nitrate concentrations in the soil moisture at this depth show a slight decrease, whereas the concentrations at the depth of the shallow lysimter (10.8 m depth) seemed to be more constant. At the depth of 19.7 m the sulfate and chloride concentrations in the December 1988 sample are higher than in all the consecutive samples taken from the deep lysimeter, possibly indicating the movement of a slug caused by fertilizer application through the unsaturated zone. Unfortunately, no nitrate analysis could be performed on the December 1988 sample, because of the insufficient water quantity yielded by the deep lysimeter at that particular time. However, if the high chloride and sulfate concentrations would have been caused by leaching of minerals in the unsaturated zone, this would have been documented in all consecutive samples as well. This not being the case, the December 1988 analysis represents an anthropogenic factor in the water chemistry. Fertilizer application on the surface of the playa structure or in the surrounding area would be a possible cause. Based on the fact that chloride, sulfate and more or less nitrate concentrations as well display a decreasing trend from December 1988 to September 1989, it is fairly safe to assume that this trend represents the tail end of a slug, which was probably at or close to its maximum in December 1988. The lack of February and March data prevents a more conclusive statement.

The difference in soil water chemistry between the moisture from the depth of 10.8 m and 19.7 m is also reflected in the tritium concentrations. Water from the shallow lysimeter shows a tritium concentration below the detection limit of 0.8+/-0.6 TU, whereas moisture from the deep lysimeter is characterized by a tritium content of 4.8+/-0.7 TU. Both the samples were taken in March 1989.

The stable isotope analyses reflect the above mentioned differences as well. Soil water taken from the shallow lysimeter is more depleted in oxygen-18 and deuterium than soil water collected from the deep lysimeter. The deuterium access parameters of 1.46 at 10.7 m depth and 6.54 at 19.8 m depth (table 13) emphasize the difference and indicate a different vapor forming process for the precipitating air masses and thus a different origin of the respective air masses. Fig. 48 depicts the location of the two samples relative to the meteoric water line. The water sample taken from the deep lysimeter plots farther away from the meteoric line, indicating that the precipitation from which the sample originated was probably subject to a greater amount of evaporation than the precipitation that contributed to the sample collected from the shallow lysimeter. The difference in position to the meteoric line of the two lysimeter samples can be interpreted as a seasonal effect. Water collected from the shallow lysimeter could have been derived from fall, winter or spring precipitation, which would result in depletion of stable isotopes due to the cooler air temperature and less influence of evaporation. The water sampled from the deep lysimeter could have been derived from late spring/early summer precipitation, thus exhibiting enrichment in the stable isotope component compared to the soil water collected in the shallow lysimeter and a greater influence of evaporation.

The difference in nitrate concentrations between 10.8 m depth and 19.7 m depth in the soil profile at this site could support this theory. Fertilizer is usually applied in late spring for the summer crops and in August/September for the winter wheat.

However, this does not explain the absence of tritium in the water sample collected from the shallow lysimeter.

Soil cores were taken at different depths at this site and subsequently analyzed for particle size distribution and calcium carbonate content. Cores from the upper 3 m of the unsaturated zone were analyzed for nitrate and soil moisture content as well. The following intervals were cored: from 0 m to 3 m a continuous core was taken, the next interval was cored from 6.2 m to 10.8 m, and lastly a core was obtained from 18.4 m to 21.5 m. Except for the upper 3 m the cores were originally obtained to check the unsaturated zone for the most suitable locations for the installation of the lysimeters. This explains the depth distribution of the cores.

Appendix C lists the results of the particle size and the calcium carbonate content analyses as well as the moisture content in the upper 3 m of the profile. Fig. 50 depicts the obtained data in form of graphs.

The particle size distribution in the unsaturated zone at this site may explain the absence of tritium in the shallow lysimeter and the differences in general water chemistry and stable isotope concentration between samples from the shallow and the deep lysimeter. The sediment at 10.8 m depth where the shallow lysimeter is located is characterized by a higher clay and silt content and a lower sand content than the sediment at 19.7 m depth, the location of the deep lysimeter. The sand, silt and clay contents at 10.8 m depth are 12.4%, 62%, and 25% respectively. At 19.7 m depth the sand component makes up 27% and the silt and clay contents are 54% and 15%, respectively. Also, the clay content in the section above the shallow lysimeter up to 2.6 m below land surface is fairly high: 34% on the average. The clay content in the zone between the two lysimeters shows a generally increasing trend. There are no data available from about 10.8 m to 19.3 m depth. Thus only general trends can be deduced from this interval.

It seems possible that the clay content in the sediments above the shallow lysimeter and in the zone between the two lysimeters restricts or slows down the vertical movement of soil moisture. At a depth of 3 m the sediment was so clayey and compact that it was impossible to obtain further soil cores by using the Giddings rig. Incidentally, the calcium carbonate content at this depth shows a marked increase (fig. 50). To a depth of 7.4 m the calcium carbonate content remains fairly high at around 12 %. From 7.4 m to 9.3 m depth the calcium carbonate content decreases and stays at an average level of about 2.8 %. This behavior may also influence the permeability of the sediment.

It is possible that any moisture that infiltrates the unsaturated zone at the surface will be slowed down considerably around 2.6 m depth. The clays could potentially more or less inhibit vertical flow and thus act as a semipermeable boundary. If this is true the tritium

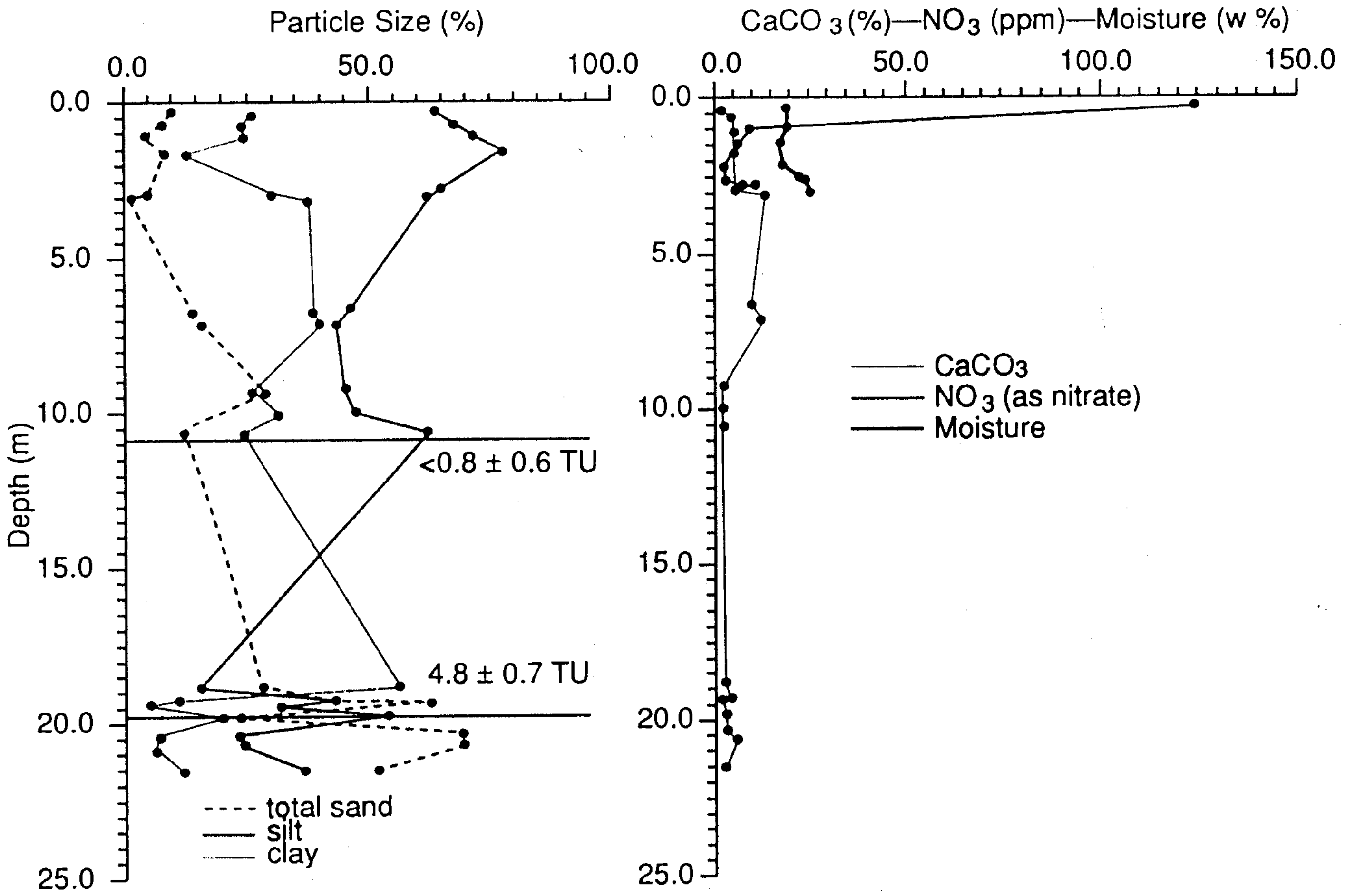


Figure 50: Particle size distribution, calcium carbonate, nitrate, and moisture content in the unsaturated zone at site 3

peak from the 1961/62 emissions could still be above 10.8 m, the depth of the shallow lysimeter.

The particle size distribution (fig. 50) indicates a generally increasing trend regarding the clay content in the zone between the two lysimeters, i.e. between 10.79 m and 19.29 m depth, suggesting low permeabilities. Thus it is also possible, that the tritium peak may be present between 10.79 m and 19.29 m depth.

The adsorption of tritium by clay minerals seem to have only a minimal effect on the tritium concentration in the unsaturated zone. Stewart (1965, 1967) found that tritium fractionation occurs by diffusion of the tritiated water through the soil. The tritium is slowly interacting with the clays, i.e. exchange with hydroxyl groups takes place, preferentially with fractured edge and surface exposed hydroxyls. In general, the rate of exchange is dependent on the clay type, the moisture availability, i.e. the concentration of available tritiated hydrogen atoms and the time of exposure (Rabinowitz, 1969, Stewart, 1965). Isotopic exchange between tritiated water and hydroxyl groups of clay minerals is more important in kaolinite clays (Gvirtzman & Magaritz, 1986). Here the available hydroxyl groups are readily accessible at the surface, whereas for illite and montmorillonite available hydroxyl groups are mainly present on the edges of the clay plates. Halevy (1964) found the percent exchange of tritiated water with surface hydroxyls in kaolinite to be less than 1 %. If this is true, the percent exchange in illite and montmorillonite should be even smaller, because of the lower accessibility of hydroxyl groups.

Thus it is possible, that some of the tritium in the soil profile at this site may have been adsorbed onto clays, if the rate of vertical movement was sufficiently slow and thus enough time was given for exchange of tritiated water with the clays. But any bomb related tritium present in the unsaturated zone would certainly still be recognizable as such, even if tritium adsorption by clay minerals occured.

Thus with the data available for this site at this point in time, the most likely explanation for the difference in water chemistry, tritium and stable isotope concentration between the shallow and the deep lysimeter, would be lateral flow at the depth of the deep lysimeter, possibly enhanced by the geometry of the playa and of course by the sandier sediment. If the tritium and the high nitrate concentrations in the soil water collected at the deep lysimeter moved vertically, the enrichment of the moisture in these two components must have happened between 10.8 m and 19.7 m depth, which seem to be very unlikely in view of the nitrate profile in the upper 3 m of the unsaturated zone. At a depth of about 30 cm the nitrate concentration is 124 mg/l, caused by fertilizer application. It then decreases very abruptly to 9.7 mg/l at 90 cm depth and decreases from thereon downward. At a depth of 2.9 m a slight increase in nitrate occurs to 11.5 mg/l. However, it seems very unlikely that the increase would result in a value as high as 160 mg/l, as detected at the depth of the deep lysimeter. Assuming the same behavior for every application of fertilizer, i.e. a marked decrease in concentration from the surface downward as described above, the nitrate concentrations at the depth of the deep lysimeter can not result from vertical movement of fertilizer nitrate at this site. The field farmed within the playa was never placed under irrigation, wheat is grown under dryland conditions. Thus the vertical movement of soil water constituents is solely dependent on the amount of precipitation infiltrating the unsaturated zone.

The presence of a high amount of geologic nitrogen at a depth of 19.7 m can probably be excluded, because the chloride concentration at this depth is high as well. The parallel occurence of high nitrates and chlorides indicate an anthropogenic source, i.e. fertilizer, especially because no sources for chloride are naturally present in the unsaturated zone.

Without further data regarding the tritium distribution with depth at this site it is not possible to calculate the rate of vertical soil moisture movement or the rate of recharge. No tritium peak resulting from the thermonuclear explosions in the years 1961/62 was found at the depths sampled in the unsaturated zone at this site (10.8 m and 19.7 m below land surface). The ground water at this site displays a lower tritium content than the soil water collected at the deep lysimeter. Taking all the data available into account it is concluded that the tritium peak is still in transit in the unsaturated zone, possibly above a depth of 19.7 m and maybe even above 10.8 m depth.

Site 10

This site is located in the vicinity of an intermittent stream in a pasture. The depth to ground water is only 3.6 m below land surface, the shallowest water level of all the different research sites that were investigated during this study.

The ground water at this site did not show appreciable amounts of tritium, 1.2+/-0.6 TU and <0.8+/-0.6 TU. A lysimeter was installed here in September 1988 at a depth of 3.2 m below land surface, but it was never possible to retrieve a sample. It is very likely that the ceramic cup of the lysimeter cracked during installation so that the lysimeter never held vacuum.

Because it was impossible to use the lysimeter, a soil core for tritium analysis was taken instead. Using a Giddings rig, a 63 cm long core was collected at the end of May 1989 at a depth from 2.47 m to 3.1 m. The tritium concentration in this core was analyzed to be 7.6+/-0.8 TU. This value is higher than the tritium encountered in the ground water of the shallow well (1.2+/-0.6 TU), which is screened from 4 m to 7 m below land surface. However, the tritium concentration in the sampled interval in the unsaturated zone is too low to indicate bomb related tritium.

A clearly defined soil profile is present at this site. The A-horizon, characterized by a dark, silty, structureless soil ranges from 0 m to about 80 cm depth. A more clayey B-horizon, displaying a prismatic structure, is present from 80 cm to 1.28 m depth, followed by a silty, calcareous C-horizon. Sand laminations within the sediment document the alluvial character of the unsaturated zone.

Fig. 51 shows the particle size distribution, calcium carbonate and nitrate content from 30 cm to 3.3 m depth. Samples for moisture content were taken at the same depth the core for tritium analysis was collected from.

The silt content remains more or less constant throughout the sampled section at an average of 62.5 %, whereas sand and clay contents vary from 1.69 % to 41.35 % and 5.19 % to 34.57 %, respectively. From 1.2 m to 1.8 m depth the material is very sandy (41.35 %) and from 2.2 m to 2.7 m the clay component is the dominant particle size. Except for these two peaks, the profile is fairly uniform in regard to the particle size distribution.

The calcium carbonate content increases from 2.52 % at 30 cm depth to 9.33 % at a depth of 2.4 m. It then decreases abruptly to 2.85 % at 2.4 m depth and increases again to 5.92 % at 3.1 m depth.

The nitrate concentration is low and more or less constant with depth, it ranges from 1.33 mg/l to 2.21 mg/l.

The moisture content is very high in the interval sampled, the average value is 29.3 w %. This is caused undoubtedly by the shallow water table at this site.

Based on the results of the ground water analyses at this site and the tritium content of the core, it is very likely that the tritium peak from the 1961/62 emissions is no longer present in either the unsaturated or the saturated zone. Because of the shallow depth to water, the bomb related tritium travelled through the unsaturate zone, reached the ground water and was subsequently flushed out of the system.

If the vertical rate of soil moisture movement of 0.5 m/year calculated for site 11 is applied here, this behavior has to be expected. Considering a vertical rate of movement of 0.5 m /year, the tritium would have reached the ground water 7.2 years after it first entered the unsaturated zone. Taking the particle size distribution of these two site (sites 10 and 11) into account, the moisture at site 10 may have moved a little slower than 0.5 m /year. The sediment at this site (site 10) is characterized by an average sand content of 16.7 % and an

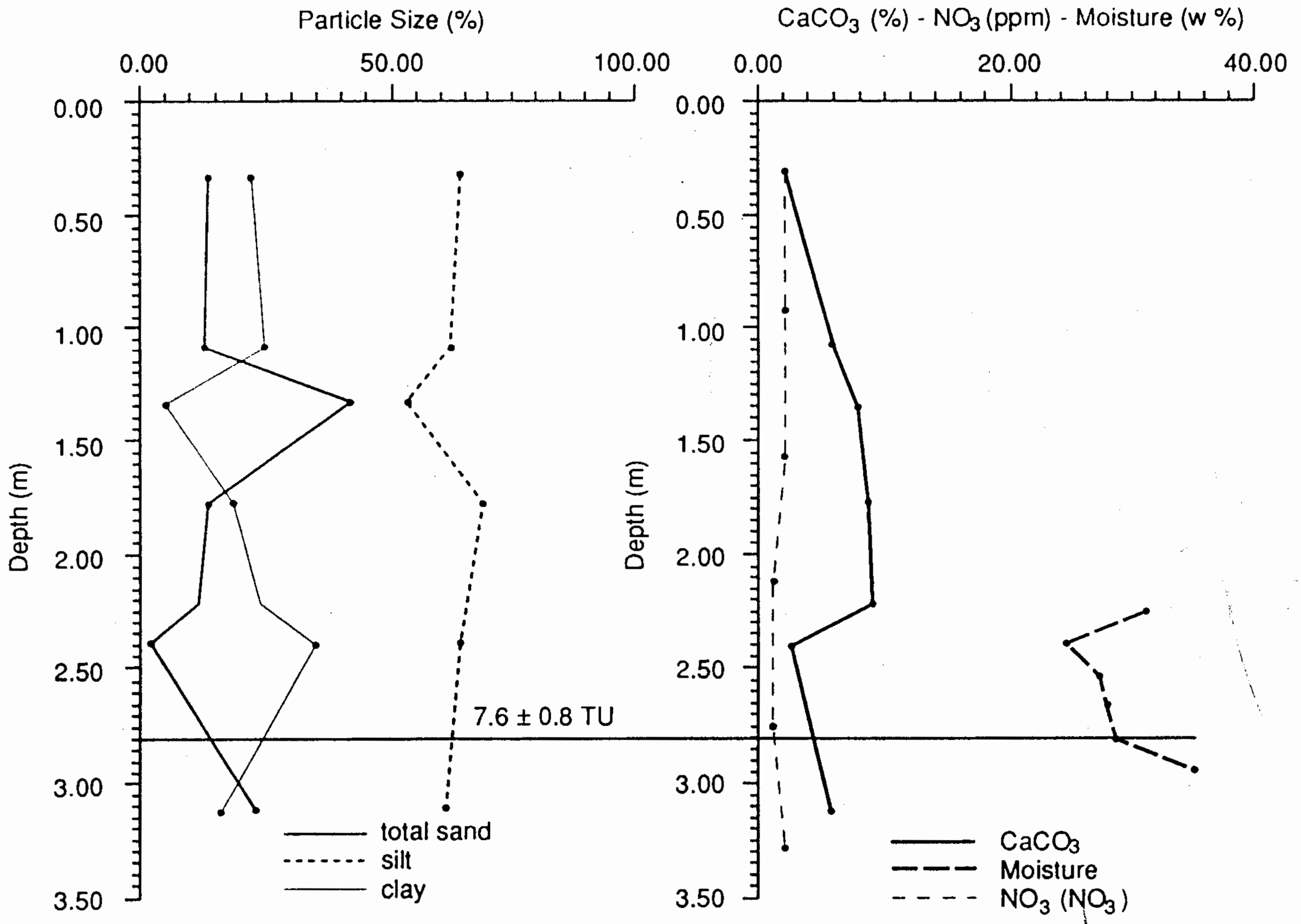


Figure 51: Particle size distribution, calcium carbonate-, nitrate- and moisture content in the unsaturated zone at site 10

average clay content of 20.7 % to a depth of 3.1 m, the depth that marks the end of the soil core taken for tritium analysis. The unsaturated zone of site 11, for which the vertical soil moisture movement could be calculated, is made up of an average sand content of 19 % and an average clay content of 19.2 % to the depth at which the tritium peak was found. Thus at site 10 there is less sand and a little more clay present in the unsaturated zone. However, the difference is probably not enough to account for a major difference in the rate of vertical soil moisture movement.

The tritium content of 7.6+/-0.8 TU of the core has to be caused by more recent precipitation. Even if the rate of vertical movement is cut into one half to 0.25 m/year, which is probably too low, the precipitation that caused the tritium content of the core would have been derived from the years 1977/78. Under this assumption the bomb tritium would have reached the water table after about 14 years, in 1977.

It seems thus fairly safe to assume that the tritium produced by the bomb explosions in 1961/62 is no longer present at this site, neither in the unsaturated zone nor in the ground water.

Site 11

This site, located in an upland area with no apparent recharge features such as lineaments, intermittent streams and playa-like structures close to it. During the time period from the beginning of the investigations at this site in September 1988 to September 1989 the field the site is located in was not farmed.

The loess cover at this site is about 13 m thick.

Originally, two lysimeters were installed at this site in September 1988, one at a depth of 12.2 m and another one at 19.8 m depth. The shallow lysimeter never yielded any water. It was retrieved in November 1989. The ceramic cup and the lysimeter in general were intact, which was expected, because the lysimeter did hold vacuum. However, rests of the 15 pounds of silica flour the lysimeter was embedded in that were still attached to the ceramic cup after the lysimeter was pulled, were completely dry. Based on this fact it has to be assumed that macropore flow takes place at this particular depth in the profile. The lysimeter did not yield any water, because there simply was no moisture available at that depth. The soil moisture apparently circumvented the location of the lysimeter.

The lysimeter at 19.8 m depth could be sampled and the results of the standard inorganic chemistry analyses are listed in table 8. Samples were taken in December 1988 and in March, April, June, July, August, September and November 1989.

Two complete sets of standard inorganic analyses were performed on the April and July samples. According to the results of these analyses the soil water at 19.8 m depth can be characterized as a calcium-bicarbonate type water. The analyses performed on the April and July samples are nearly identical.

Throughout the time period mentioned above, the lysimeter was sampled for sulfate, chloride and nitrate. The chemistry of the soil water did not change much in regard to these constituents. The sulfate content decreased from December 1988 to November 1989 from 35 mg/l to 26 mg/l. The chloride concentrations remained more or less constant, but show minor fluctuations. The lowest chloride contents occured in April and September, the values are 1.9 mg/l and 1.8 mg/l, respectively. The highest chloride content occured in July with 4.1 mg/l. Nitrate concentrations remained nearly constant from April to November 1989, they range from 26 mg/l to 28 mg/l. Thus, based on the standard inorganic chemistry results no evidence for vertical movement of a slug as observed at site 3 is present at this site during the time monitored.

The stable isotope content of the soil water collected in the lysimeter at 19.8 m depth is depicted in fig. 48 and listed in table 13. There is a marked difference between the soil water at site 3 and this site as far as the stable isotope content is concerned. The samples plot on opposite ends of the meteoric water line (fig.48). Soil water sampled at this site (site 11) is much more depleted in oxygen-18 and deuterium compared to the soil water at site 3. The deuterium access parameters emphasize this difference. The soil water collected at site 11 shows a deuterium access parameter of 11.56, which is considerably more than the deuterium access parameters of the soil water samples collected at site 3. Although the deep lysimeter at site 3 and the lysimeter at site 11 are located at nearly the same depth, 19.7 m and 19.8 m respectively, the difference between the samples retrieved from these lysimeters is great.

According to the equation by Foerstel et al. (1975) the mean annual air temperature at the time of recharge was 0.76 °C for the soil water sample collected at site 11, whereas the mean annual air temperature at the time of recharge for the sample retrieved from the deep lysimeter at site 3 was 14.4 °C. The soil water at site 11 was recharged under cooler temperatures, which is also documented in the higher rate of depletion of the stable isotopes. The soil water at site 11 is thus recharged in a different season, possibly from snow melt.

It is impossible to use the stable isotope data of these two lysimeter samples to deduce a difference in vertical soil moisture movement at the two sites. The difference in the season of recharge could be within the same year, or the soil water at site 3 could have been recharged in late spring/early summer of a given year and the soil water at site 11 was recharged several years earlier or later.

This is a good example of the limitations of stable isotope analysis for age determinations. Without other types of analyses such as Carbon-14 or tritium, the only fact that can be determined with certainty by stable isotope analysis is that there is a difference in age. But it is impossible to determine just how great this age difference is.

The tritium concentration at 19.8 m depth at site 11 was 43+/-2.9 TU in March 1989, 48+/-3.1 TU in June of 1989 and 47+/-8 TU in November 1989. Taking the error range into account, the tritium content was essentially constant from March to June. The tritium here is definitely derived from bomb explosions. The background tritium concentration in precipitation is about 20 TU in the study area, thus it seems impossible that recharge from recent precipitation resulted in a tritium of more than 40 TU. The tritium concentration at site 3 at about the same depth was only 4.8+/-0.7 TU. Thus the soil water at site 3 is either older or younger than the soil water at site 11.

Calculating with a halflife of 12.3 years, the tritium content at site 11 at 19.8 m depth would have been about 198 TU in 1963, which is a little low according to the tritium input function (fig. 38 and fig. 39). Thus the recharge must have taken place either before or after 1963. According to fig. 38 precipitation derived from the years 1955, 1956, 1960, and 1961 as well as 1972 to 1982 that infiltrated the ground as recharge could have a tritium content around 40 TU in 1989. However, the tritium input function in fig. 38 does not take evaporation rates into account, but represents average annual tritium concentration in precipitation. Considering recharge to take place only from October to March, the tritium concentrations available to infiltrate the unsaturated zone via precipitation will be considerably less.

Table 6 lists the tritium concentrations in precipitation from 1953 to 1984 considering only the potential recharge period from October to March. The tritium concentrations left in 1989 after radioactive decay took place are listed as well. Loss of tritium caused by plant uptake and/or adsorption onto clays or soil organic matter is not considered.

According to table only the precipitation in 1970 and during the time period from 1962 to 1966 can be excluded with certainty as a cause for the tritium concentration in the soil water at 19.8 m depth at this site.

In the beginning of November 1989 an additional lysimeter was installed at this site at a depth of 13.1 m. At the end of November a sample was collected for the analyses of sulfate, chloride and nitrate. Chloride and sulfate concentrations were considerably higher compared to the soil water collected in the lysimeter at 19.8 m depth: 47 mg/l and 124 mg/l, respectively (table 15). Nitrate concentrations were about the same at 13.1 m depth and a depth of 19.8 m. Sulfate and chloride are hardly adsorbed in the unsaturated zone, they can be considered as fairly conservative constituents. Both sulfate and chloride can be

Table 15: Standard inorganic chemistry results in mg/l of soil water collected in lysimeters at site 11

Date sampled	field pH	lab pH	field spec. cond.	lab spec. cond.	SiO_2	Ca	Mg	Na	K	Sr	HCO_3	SO_4	Cl	F	NO_3
Deep lysimeter (19.8 m)															
12-1-88												35	3.9		
3-27-89	6.85											32	2.4		
4-19-89		7.65		625	84	67	16	37	11	0.6	340	29	1.9	0.7	28
6-1-89												28	3.2		28
6-19-89	7.25			620								27	3.3		28
7-24-89		7.6		620	86	70	17	39	11	0.7	346	27	4.1		26
8-21-89	6.9		630	618								27	2.7		26
9-25-89	7.2		615									27	1.8		26
11-2-89	7.3		610									26	3.4		28
Shallow lysimeter (13.1 m)															
12-4-89				1040								129	47		31

incorporated into the soil profile as by-products of nitrogen fertilizer. The reason, the nitrate concentration is not higher at 13.1 m depth compared to 19.8 m depth can be twofold: 1) nitrate is not a conservative constituent, and 2) nitrate is being used to a higher degree by growing crops.

The tritium content in the soil water collected at the shallow lysimeter at a depth of 13.1 m was 172.9+/-11.4 TU in December 1989. As confirmed by the soil cores collected at this site, this amount of tritium represents the tritium peak in the soil profile.

This result implies that the tritium concentration of about 48 TU in the soil water collected in the deep lysimeter at a depth of 19.8 m has to be older than 27 years, i.e. precipitation contributing to the soil moisture at this depth had to infiltrate the unsaturated zone before 1962.

At the end of September 1989 the upper 8 m of the unsaturated zone were cored at this site. A core from 9.3 m to 9.91 m was collected in the beginning of June 1989, and the cores from 10.9 m to 21.34 m were taken at the end of October/beginning of November 1989. The different times the cores were taken were caused by problems in scheduling the use of equipment.

Fig. 52 shows the particle size distribution, calcium carbonate and moisture content in the unsaturated zone at this site. Silt is the main component in the upper 13 m of the profile with an average of 61.8 %. Average sand and clay contents are 19 % and 19.2 %, respectively. The interval from about 6 m to 10 m depth is characterized by a wildly fluctuating particle size distribution. As indicated by the high calcium carbonate content as well, this interval may represent an old erosional surface, possibly the boundary between the Peoria loess and the overlying Loveland loess. From about 13 m depth on downward the sediments become more sandy and grade into sediments characteristic for the Tertiary Ogallala formation.

Fig. 52 depicts the moisture content and the porosity from land surface to a depth of 21.3 m. Samples for moisture content were taken in June, September and November 1989.

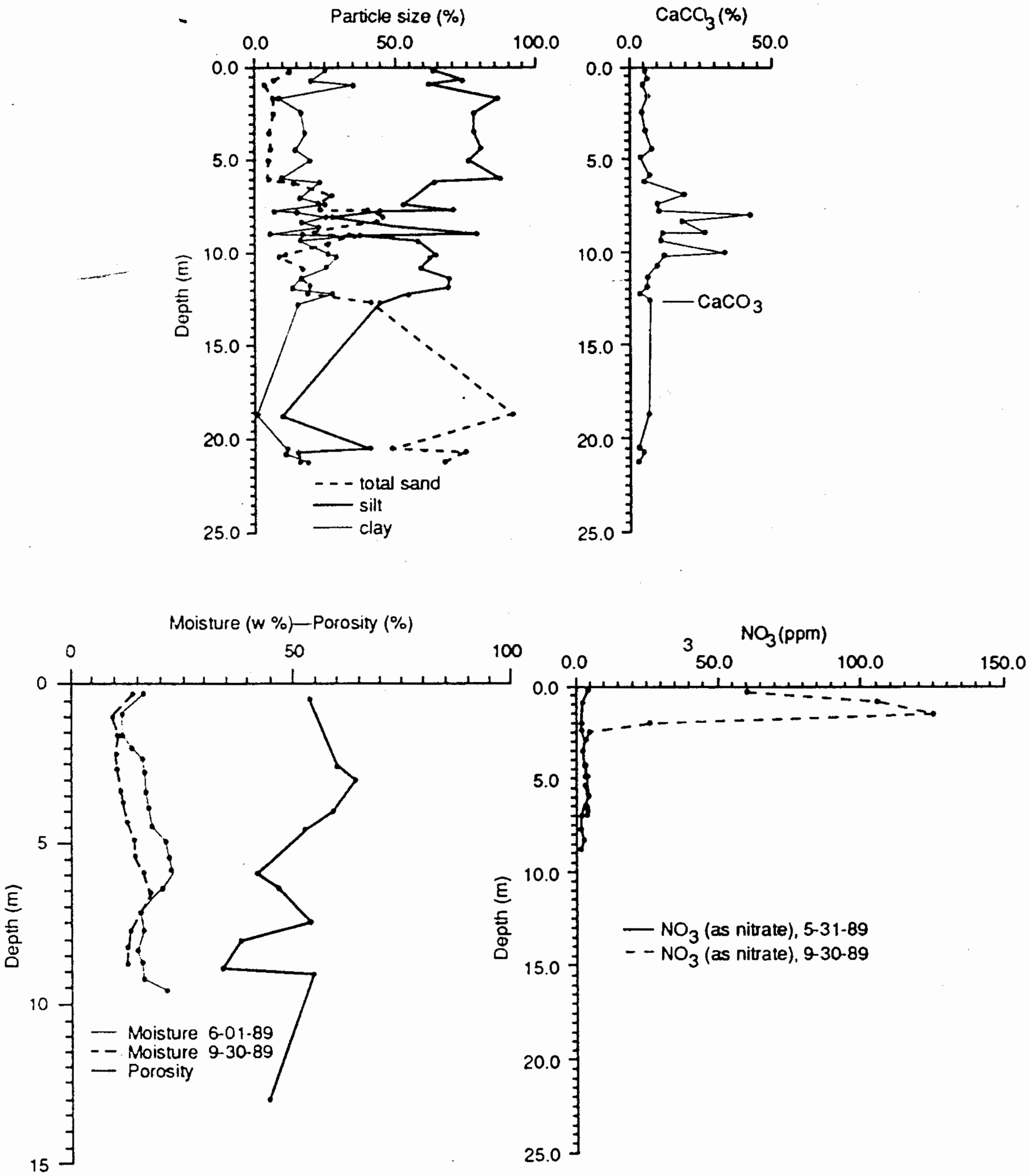


Figure 52: Particle size distribution, calcium-carbonate, nitrate and moisture content as well as porosity of the unsaturated zone at site 11

The samples were collected from the same cores the tritium analyses were performed on. Approximately the same depth was cored in June and September 1989, however the samples were generally not taken from exactly the same depth intervals. Also, the actual location wherethe core was taken at the site varies by about 5 m.

The general trend of the moisture curve shows a decrease in moisture content from June to September. The average moisture concentration in the profile from land surface to 9.9 m depth in June was 17.08 w%. In September a total depth of 9.1 m was cored, and the average moisture content over this interval of the unsaturated zone was 13.12 w%.

In November 1989 only cores from a depth of 10.9 m to 21.3 m were collected and subsequently analyzed for moisture. The average moisture content in this interval was 13.5 w%. The very low moisture concentrations in the interval from 16.4 m depth to 18.6 m can be attributed to the very sandy character of the sediment at this depth.

Porosity values were obtained for certain depth of the profile from some of the cores collected for moisture and tritium analyses. Porosity data from 0.5 m, 1.8 m, 3.0 m, 4.2 m, 5.3 m, 6.5 m, 7.5 m, and 9.1 m were obtained in June 1989. In September 1989 porosity data were obtained from depths of 2.5 m, 4.6 m, 6.1 m, 7.9 m, and 9.0 m. In November 1989 only the porosity for a depth of 13.04 m was determined. The porosity results are depicted in fig. 52. Average porosity in June was 55.9 % from 0.47 m to 9.2 m depth. In September the average porosity from 2.5 m to 9 m depth was 45.8 %. Besides being dependent on the particle size distribution the difference in porosity throughout the sampled section of the profile may also be due to different degrees of compaction of the sediment while obtaining the cores.

Table 16 lists the results of the tritium analyses performed on the collected soil cores and the water retrieved from the lysimeters, and fig. 53 depicts the results in the form of a graph. The tritium concentrations of the 60 cm long core intervals are plotted in the graph as a value in the middle of the cored depth, i.e. if a core was taken for example from 0 cm to 60 cm depth, the tritium content is plotted at a depth of 30 cm in the diagram. If not

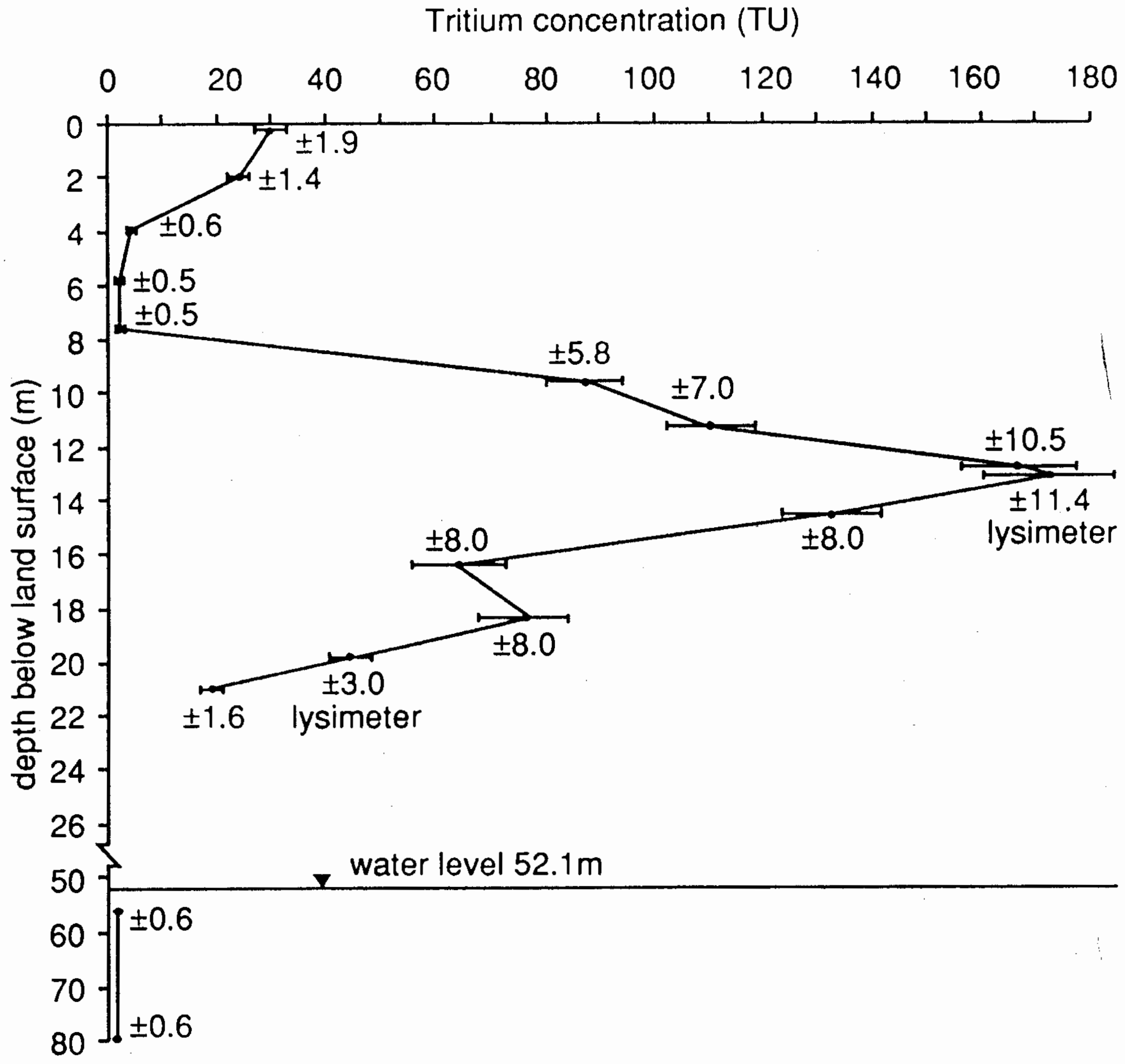


Figure 53: Tritium concentrations in the unsaturated zone at site 11

stated otherwise, the depth distribution of respective tritium concentrations in the following text is derived from such interpolation.

The tritium concentration of 29.6+/-1.9 TU from 0 cm to 60 cm depth and of 23.5+/-1.4 TU from 1.83 m to 2.44 m depth in the profile can probably be attributed to enrichment due to infiltration of isotopically heavier summer precipitation and enrichment by evaporation. The latter factor however may not amount to much. Foster & Smith (1980) mention a maximum enrichment of soil water by evaporation of 2 %. No fractionation and thus enrichment of tritium occurs during transpiration through plants (Zimmermann et al., 1966).

Table 16: Tritium concentrations at different depth in the unsaturated zone at site 11.

Depth interval	Date sampled	Tritium (TU) concentration
0.00-0.60	9-30-89	29.0+/-1.9
1.83-2.44	9-30-89	23.5+/-1.4
3.66-4.27	9-30-89	3.9+/-0.6
5.49-6.10	9-30-89	1.7+/-0.5
7.31-7.92	9-30-89	1.5+/-0.5
9.30-9.91	6-1-89	87.8+/-5.8
10.9-11.45	11-1-89	109.6+/-7
12.5-13.08	11-1-89	167+/-10.5
13.12	12-4-89	172.9+/-11.4
14.32-14.93	11-1-89	133.1+/-8
16.13-16.74	11-1-89	64.0+/-8
17.98-18.59	11-1-89	78.0+/-8
19.84	Average of 3, 6 and11-89	46
20.73-21.43	11-1-89	18.5+/-1.6

As mentioned above, the upper 8 m of the unsaturated zone were cored at the end of September 1989. In August and September 1989 45 mm and 42 mm of precipitation, respectively, were recorded at the Colby weather station.Thus it is possible that a) some of this precipitation infiltrated the unsaturated zone and was subsequently sampled or b) that the precipitation pushed other moisture present in the soil which was also derived from enriched summer rain (seasonal tritium effect) downward in a piston-type flow manner. However, the amount of precipitation mentioned above was recorded at the Colby weather station and not at the Hoxie weather station, the latter being located about 9.5 km to the south of the site. Precipitation in Kansas is known to be sporadic, thus it could be possible that it rained in Colby while no precipitation occurred in Hoxie. The more likely scenario is, however, that the amount of precipitation at site 11 was larger than the precipitation recorded at Colby as implied by the nitrate distribution in the unsaturated zone.

The nitrate concentrations in the profile at this site at the end of September support the assumption that the elevated tritium concentrations to 2.44 m depth are caused by recent precipitation. Fig. 52 depicts the nitrate concentrations in the soil profile down to a depth of about 9 m. Nitrate analyses were performed on cores collected at the end of May and on cores taken at the end of September, when the cores were also analyzed for tritium.

There is a marked difference between the two nitrate curves in fig. 52. The results from the May analyses show hardly any nitrate in the profile, the values range from 2.2 mg/l to 5.3 mg/l, whereas the September analyses indicate nitrate concentrations as high as 120 mg/l.

This can be attributed to the fact that the field was not farmed for at least one year and thus no fertilizer was applied. According to the landowner nitrogen fertilizer was applied in August of 1989 prior to the planting of wheat, and this is reflected in the September analyses of the nitrate concentrations. A clearly defined peak occurs at a depth of about 1.5 m. The maximum amount of time that could have passed between the application of fertilizer and the collecting of the cores is two months. The only means by which the nitrate could have reached a depth of 1.5 m in the soil profile is by movement of soil moisture provided by precipitation.

Thus the nitrate concentrations at the end of September support the assumption of recent rainfall possibly combined with evaporation as a cause for the elevated tritium concentrations in the upper 2.44 m of the unsaturated zone.

The vertical movement of moisture up to a depth of about 2.5 m, the depth where the nitrate content does not show any influence of fertilizer application any more, would be about 2.5 m per 2 months or 1.25 m /month. However, this represents a conservative estimate. The rate of movement could in fact be higher than that. The landowner could not remember when exactly the fertilizer was applied in August, thus the two months represent the largest time interval possible between the application of the fertilizer and the collection of the cores.

The rate of infiltration and the rate of downward movement of any moisture in the unsaturated zone is highly dependent on the amount of precipitation. The combined precipitation of August and September 1989 recorded at the Colby weather station of 87 mm is not enough to result in this high a rate of vertical soil moisture movement, especially not when the rate of evaporation is taken into account. Only vertical flow of moisture through pores explains the observed rapid movement of nitrate of 1.25 m/month to a satisfactory degree. Average porosity to a depth of 2.5 m is 58 % at this site, thus a transmission of soil moisture through pores rather than the soil material itself is possible.

Thus it is concluded, that the rate of precipitation at site 11 was either very much higher than the amount of rain recorded at the Colby weather station, or that the soil moisture in the upper part of the unsaturated zone at this site is conducted by porous flow only.

Unfortunately, the weather data from the Hoxie weather station were not available when this report was written. The weather station is automated and the results are collected at the Climatic Data Center in South Carolina. Data from 1989 will be released earliest at the end of March of 1990.

The rate of 1.25 m/month as an average vertical movement of soil moisture in the upper 2.5 m of the unsaturated zone at this site should be used with caution. Without a raingauge on site and a daily recording of the rainfall and the rate of evaporation directly at the site no precise statement of the vertical rate of moisture movement in the upper 2.5 m in the soil profile is possible.

Several factors may influence the abrupt decline in tritium content by about 19.6 TU, from 23.5+/-1.4 TU in the interval from 1.83 m to 2.44 m depth to 3.9+/-0.6 TU from 3.66 m to 4.27 m depth and the low tritium concentrations of 1.7+/-0.5 TU and 1.5+/-0.5 TU from 5.49 m to 7.92 m depth. Soil moisture uptake by plants may have caused a decrease in tritium concentration once the tritium was incorporated in the soil. Adsorption by clay minerals and organic soil matter can be excluded as a diminishing factor for the tritium content in the cored intervals analyzed, because the method of tritium analysis from soil cores included toluene extraction of the soil moisture, which requires heating of the soil sample to a temperature of 250 °C (see Appendix B for methods). At this temperature the lattice water of the clay minerals will be removed as well as the adsorbed water on the clay surfaces. Thus any tritium adsorbed onto or incorporated into clay minerals will be accounted for. However, adsorption may have occurred from 2.44 m to 3.66 m depth.

But even all the above mentioned factors together would probably not account for a decline of 19.6 TU and the very low tritium concentrations in the subsequently sampled intervals. It could thus be possible that precipitation depleted in tritium might have infiltrated the ground and caused the low tritium concentration observed.

The tritium input function (fig. 38 and table 6) does not show any correlation between the low tritium concentrations encountered in this interval of the soil profile and the tritium content in precipitation that could potentially have infiltrated the unsaturated zone. According to fig. 38 tritium values corrected for radioactive decay below 20 TU only exist in 1953 and 1955. The tritium concentrations left in 1989 calculated from recharge months only, listed in table 6, would be 5.2 TU in 1955 and 5.4 TU in 1953. However, the data for 1953 could only be based on the months from October to December, because no tritium data in precipitation are available prior to September 1953. Average tritium input over the last 10 years is too young to have decayed to levels of 3.9 TU and lower as detected in the soil profile at this site. Thus the low tritium concentrations from about 3.66

m to 7.92 m depth can not be explained simply by a low tritium input into the unsaturated zone. Possibly fast preferential flow along pores combined with soil moisture uptake by plants, and adsorption onto clays may explain the low tritium values encountered.

At 7.6 m depth the tritium peak in the profile starts to develop: the tritium content increases to 87.8+/-5.8 TU. A small break in the tritium/depth distribution curve is present from 9.6 m to 11.2 m depth, when the increase in tritium is only about 21.8 TU compared to a 86.3 TU increase above and a 57.4 TU increase below this particular sampling depth. From the very clearly defined peak at 13.1 m depth downward the tritium concentration decreases abruptly. At 16.4 m depth the tritium content has diminished to 64+/-8 TU and may remain at that concentration to a depth of 18.3 m, if the error range of the samples is taken into account. The average tritium concentration of soil water collected in the deep lysimeter at 19.8 m depth in March, June and November 1989 is 46 TU. The last core was taken from 20.73 m to 21.43 m depth. The tritium concentration of soil moisture in this interval is 18.5+/-1.6 TU. Thus from 18.3 m depth to 21.34 m depth the tritium content shows a very gradual decline (fig. 53).

No correlation between particle size distribution and tritium concentration in the unsaturated zone is apparent at this site. This can possibly be attributed to the high porosity of around 50 % on the average. It is very likely that preferential flow occurs along the pores. Plate 1 shows photographs of cores taken at different depths. The pores are clearly recognizable without any optical aids.

The downward movement of tritiated water in soil was found to occur in a piston-type flow manner (Zimmermann et al., 1966, 1967, Smith et al., 1970). The pulse of tritium introduced into the unsaturated zone will form a tagged layer, which moves down as a distingiushable boundary between older rain water below and younger meteoric water above the layer. Diffusion effects tend to broaden the peak tritium pulse.

Based on the tritium content and moisture distribution a tritium inventory was established for the unsaturatd zone at this site. The amount of tritium in the profile is calculated as the product of soil water content in meters water column and the measured tritium concentration in TU.

Table 17 lists the water content in meters water column from land surface to a depth of 21.3 m.

Table 17: Water content in meters water column at site 11

	Depth (m)	Water content (m)
	0.00-0.60	0.0172
	0.60-1.20	0.0155
	1.20-1.80	0.0153
	1.80-2.00	0.0162
	2.00-2.65	0.0172
	2.65-3.10	0.0171
	3.10-3.70	0.0174
	3.70-4.13	0.0176
	4.13-4.74	0.0176
	4.74-5.13	0.0185
	5.13-5.74	0.0186
	5.74-6.14	0.0188
	6.14-6.84	0.0181
	6.84-7.45	0.0167
	7.45-8.05	0.0170
	8.05-8.66	0.0176
	8.66-9.11	0.0170
	9.11-9.30	0.0173
	9.30-9.91	0.0184
	10.90-11.45	0.0173
	12.50-13.10	0.0168
	14.30-14.90	0.0166
	16.40-16.70	0.0118
	18.00-18.60	0.0092
	20.70-21.30	0.0157
total		0.3645

In table 18 the potential amount of tritium input into the unsaturated zone via precipitation from 1953 to 1989 is listed and in fig. 54 the data are depicted in graph form. The precipitation recorded at the weather station in Hoxie, which is located fairly close to site 11, for the potential recharge months, i.e. from January to March and from October to December, was multiplied by the tritium concentration (TU) recorded at the monitoring station in Ottawa. The value calculated for 1983 was also applied to the years from 1984 to

1989, based on the assumption that the mean tritium concentration in precipitation did not change significantly over this period of time.

Table 18: Tritium inventory (TU m) in precipitation from 1953 to 1989, for the period from January to March and October to December of each year

Year	TU m	TU m corrected for decay to 1989
1953	3.8	0.6
1954	17.5	3.0
1955	1.7	0.3
1956	5.2	0.9
1957	13.8	2.6
1958	48.6	9.3
1959	94.5	18.7
1960	22.9	4.7
1961	30.3	6.4
1962	112.5	24.7
1963	131.6	30.0
1964	116.4	27.5
1965	130.0	32.0
1966	23.9	6.1
1967	4.8	1.3
1968	10.0	2.8
1969	31.7	9.3
1970	12.3	3.8
1971	21.2	6.9
1972	4.0	1.4
1973	14.2	5.2
1974	7.5	2.9
1975	5.6	2.3
1976	2.5	1.1
1977	4.3	2.0
1978	4.3	2.2
1979	8.6	4.8
1980	8.7	5.3
1981	9.5	6.6
1982	5.1	3.9
1983	4.6	4.0
1984	4.6	4.0
1985	4.6	4.0
1986	4.6	4.0
1987	4.6	4.0
1988	4.6	4.0
1989	4.6	4.0

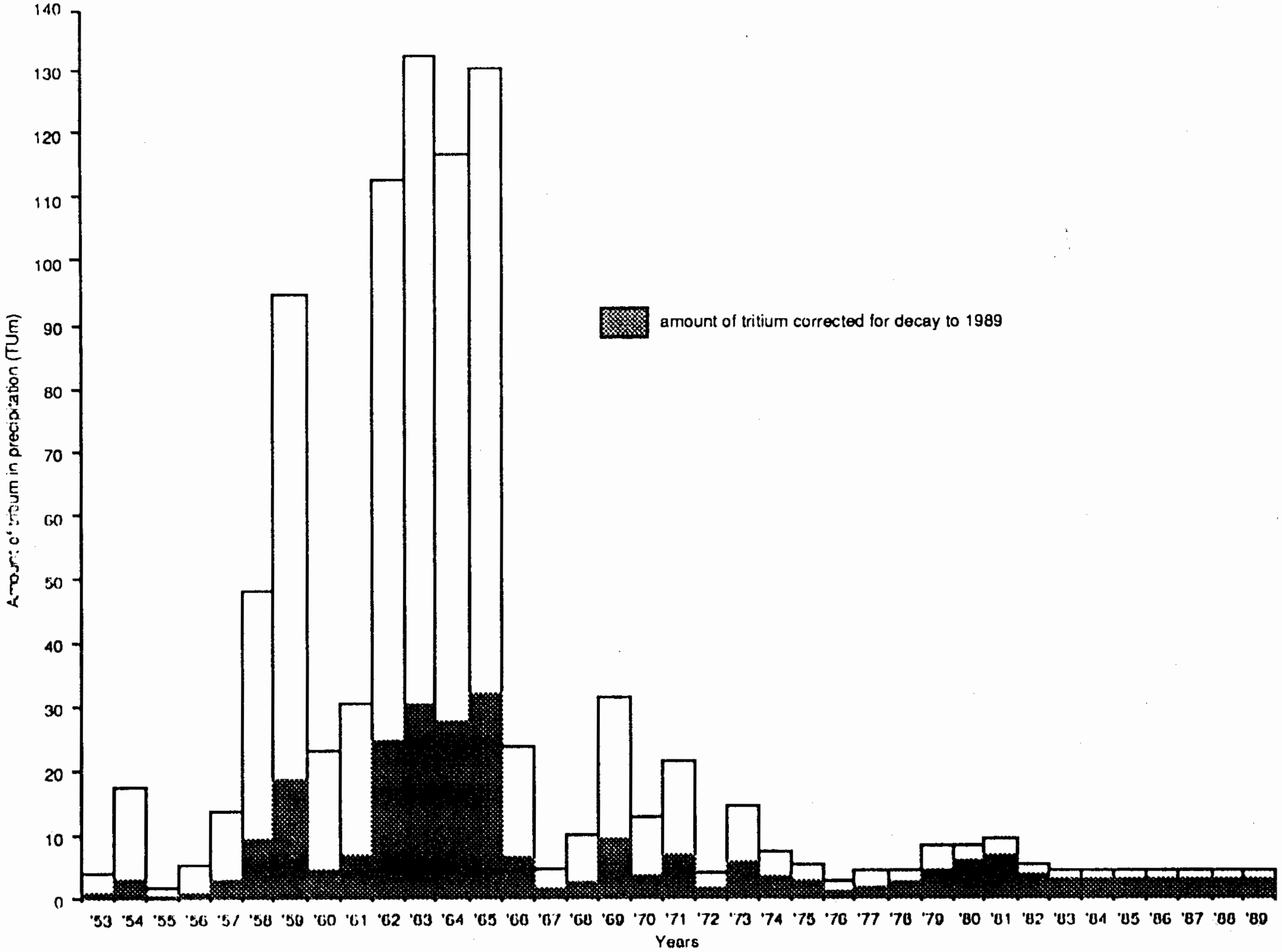


Figure 54: Amount of tritium in precipitation, January to March and October to December, 1953-1989 and amounts corrected for decay to 1989

a. From 4 m to 4.5 m below land surface

b. From 7 m to 8.2 m below land surface

Plate 1: Selected cores from the unsaturated zone at site 11

The time period from 1962 to 1965 represents the years with the highest amount of tritium in precipitation. The amount of tritium in precipitation increased as of 1958 and generally decreased after 1965.

With the data listed in tables 17 and 18 and precipitation data from the weather station in Hoxie regarding the months where moisture is most likely to infiltrate the ground and subsequently move to greater depth, i.e. from January to March and from October to December, it was possible to calculate the amount of precipitation that infiltrated the unsaturated zone over a certain period of time. The following equation is applied:

$$\text{Infiltration}\ \ (\text{mm/ year}) = \left(\frac{\dfrac{\sum_{x_1}^{x_2} \text{TUm}\ \ \text{soil}}{\#\,\text{samples}}}{\dfrac{\sum_{t_1}^{t_2} \text{TUm}\ \ \text{precip.}}{\Delta t}} \right) \times \sum_{t_1}^{t_2} \text{precip.}$$

where: x_1, x_2 = depth in unsaturated zone,

t_1, t_2 = time in years,

precip. = precipitation (mm)

Assuming possible years of infiltration, based on the tritium/depth distribution (fig. 53), five different infiltration rates were calculated for five different intervals in the unsaturated zone.

1. The profile from land surface to a depth of 21.43 m is considered, i.e. the total profile sampled. It is assumed that the amount of tritium present from 20.73 m to 21.43 m stems from precipitation around the year 1958, the initial year of higher amounts of tritium being recorded in precipitation. Accordingly, the years from 1958 to 1989 are considered to have contributed the moisture present in the profile. Thus:

   average amount of tritium in the unsaturated zone = 1.02 TU m average amount of tritium in precipitation, 1958-1989 = 7.79 TU m

average amount of precipitation, 1958-1989 = 128 mm

The average infiltration rate into the unsaturated zone over the period from 1958 to 1989 is thus 17 mm/year.

2. Considering the peak tritium input from the years 1962 to1965 to be located from 9.3 m to 14.93 m depth in the unsaturated zone, the following parameters are valid:

average amount of tritium in the unsaturated zone = 0.58 TU m

average amount of tritium in precipitation, 1962-1965 = 28.55 TU m

average amount of precipitation, 1962-1965 = 116 mm

Thus an average infiltration rate of 2 mm/year results for the period from 1962 to 1965.

3. If the tritium peak is located as assumed under 2., the moisture above this depth should be younger and should have infiltrated from 1966 to 1989, assuming piston-type flow. For the interval from land surface to a depth of 7.92 m, the following data are valid:

average amount of tritium in the unsaturated zone = 0.158 TU m

average amount of tritium in precipitation, 1966-1989 = 4 TU m

average amount of precipitation, 1966-1989 = 110 mm

An average infiltration rate of 4 mm/year results for the period from 1966 to 1989.

4. The peak tritium input from 1962 to 1965 is asssumed to be located from 12.5 m to 14.39 m depth in the unsaturatd zone. Thus:

average amount of tritium in the unsaturated zone = 1.97 TU m

average amount of tritium in precipitation, 1962-1965 = 28.55TU m average amount of precipitation, 1962-1965 = 116 mm

An average infiltration rate of 8 mm/year results for the period from 1962 to 1965.

5. If the assumption regarding the location of the tritium peak under 4. is valid, then moisture infiltrated from 1966 to 1989 is located from land surface to a depth of 11.45 m. The following parameters result:

   average amount of tritium in the unsaturated zone = 0.63 TU m
   average amount of tritium in precipitation, 1966-1989 = 4 TU m
   average amount of precipitation, 1966-1989 = 110 mm

   The resulting infiltration rate is 17 mm/year.

Thus depending on what locations are assumed for the tritium peak in the unsaturated zone at this site, average infiltration rates from 2 mm/year to 17 mm/year result. the average overall infiltration rate calculated from the complete profile sampled is 17 mm/year. The calculated infiltration rates in mm/year are to be considered rough estimates. Precipitation in Kansas can vary considerably from year to year and so can the respective infiltration rates.

Compared to the assumed recharge rates to the Ogallala aquifer in western Kansas from 4 mm/year to 14 mm/year, the deduced infiltration rates for the unsaturated zone at this site are quite reasonable.

The rate of vertical moisture movement in the insaturated zone at site 11 varies from 0.4 m/year to 0.5 m/year, depending on the assumed location of the tritium peak in the unsaturated zone. If the complete profile down to a depth to 21.43 m is considered and the amount of tritium at that depth is assumed to be derived from precipitation of the year 1958, then the rate of vertical movement is 0.8 m/year.

Summary

The analytical results from samples collected in the unsaturated zone at sites 3, 10, and 11 indicate large differences in the movement of soil moisture, thus reflecting the morphologic setting of the different sites.

Site 3 is located in a playa-like structure, the water table is about 32 m below land surface. The upper part of the cored unsaturated zone at this site is less permeable than the lower, sandier part of the profile. It is assumed, that the vertical flow rate, at least down to a depth of 10.8 m, is very slow. A lateral flow component in the lower, more permeable part of the unsaturated zone, possibly enhanced by the geometric form of the playa, is indicated by the analyses. No bomb related tritium was detected at this site. Insufficient tritium data from the unsaturated zone prohibited the calculation of flow rates for the vertical movement of soil moisture.

Site 10 is located in the vicinity of an intermittent stream, depth to water is only 3.6 m. No high tritium concentrations were detected at the depth from 2.47 m to 3.1 m in the unsaturated zone. It is assumed that the bomb tritium moved through the unsaturated zone, reached the ground water and was subsequently flushed out of the system.

Site 11 is located in an upland area. The loess cover at this site is about 13 m thick, depth to water is about 52 m below land surface. The peak of the tritium emission in the early 1960's was detected at around a depth of 13.1 m. Volume and rate of recharge to the unsaturated zone were calculated for various depth intervals.

The location, materials composing the unsaturated zone, depth to water and the amount of precipitation at the respective sites all influence the movement and the amount of soil moisture in the unsaturated zone, as documented by the difference in soil water chemistry between the lysimeters at sites 3 and 11. The deep lysimeter at site 3 is located at more or less the same depth as the deep lysimeter at site 11, 19.7 m and 19.8 m, respectively. However, the soil waters collected differ greatly in tritium and stable isotope composition.

Table 19 shows tritium and nitrate concentrations in the soil water collected in the lysimeters and in the soil moisture extracted from cores, where data were available. A correlation between nitrate and tritium concentration could be established for soil waters collected at the lysimeters at site 3, where nitrate and tritium concentrations were higher at 19.7 m depth than at 10.7 m depth. No correlation of these two components was evident in the soil waters collected from the lysimeters at site 11. Site 3 was farmed during the duration of this study, whereas site 11 was left in fallow. Only at the very end of the study, in September 1989 wheat was planted at this site. Thus the correlation between tritum and nitrate in the unsaturated zone will only be present if there is a source for the nitrate available.

Table 19: Tritium and nitrate concentration in soil water collected in lysimeters

Site 3		
Shallow lysimeter (10.8 m)	0.8+/-0.6	39.5
Deep lysimeter (19.7 m)	4.8+/-0.7	156
Site 11		
Shallow lysimeter (13.1 m)	172+/-11.4	27
Deep lysimter (19.8 m)	46	31

The high nitrate concentrations in the upper 2.44 m of the unsaturated zone of site 11 are due to the application of nitrogen fertilizer in August 1989. Down to a depth of 7.29 m, where nitrate data are available, there seems to be no correlation between nitrate and tritium concentrations in the moisture extracted from soil cores. Unfortunately, not enough samples for nitrate analyses were available to match all the tritium analyses.

Chapter 9

Summary

A total of 15 wells was sampled for standard inorganic chemistry, tritium, stable isotopes, freon, and atrazine during the time period from November 1987 to November 1989. Three lysimeters were sampled for standard inorganic chemistry, tritium, and stable isotopes from December 1988 to November 1989. Soil cores were utilized for the determination of tritium, nitrate, atrazine, calcium carbonate, particle size, porosity, and moisture content.

In addition one stream sample was collected for the analyses of tritium, stable isotopes and standard inorganic chemistry. A precipitation sample was analysed for tritium, stable isotopes, and freon, and on an additional precipitation sample, collected one year later, only the tritium content was determined.

Of all the different analytical methods tested during phase 1 of the study to differentiate between older and younger waters, tritium combined with standard inorganic chemistry analyses, especially nitrates clearly worked best.

Atrazine tested negative in all wells sampled and was not detected in the unsaturated zone at the final depth of installation of the lysimeters.

Freon was only detected in one ground water sample.

Stable isotopes did not prove to be very useful, because they do not yield a specific age determination. To avoid misinterpretation of data, they should only be used in conjunction with other methods when age determinations are attempted. If the tritium peak from the 1961/1962 emissions would have been detected in the ground water and at more than one site in the unsaturated zone, stable isotope data could have been used for correlation purposes. However, as an implication regarding the stable isotope content of the Ogallala aquifer in general, the collected Oxygen-18 and Deuterium data may be helpful for future research projects. The Oxygen-18 concentrations encountered in the ground water ranged from -12.6 ‰ to -6.5 ‰, the deuterium concentrations ranged from --86 ‰ to -

49.07 ‰. The stable isotope concentration in the unsaturated zone varied from -6.3 ‰ to -11.5 ‰ for oxygen-18, and from -80.44 ‰ to -48.94 ‰ for deuterium.

One carbon-14 sample was taken of ground water at site 4. The age of this particular ground water of the Ogallala aquifer is probably Holocene.

Tritium was detected in only 9 of the 15 wells sampled for this study. The tritium concentrations encopuntered in the ground water ranged from less than 0.8 TU, i.e. below the detection limit, up to 23+/-1.7 TU. In the unsaturated zone the concentrations ranged from less than 0.8 TU up to 172.9+/-11.4 TU. Fig. 55 depicts the sampling sites and the respective tritium concentrations detected.

A good correlation between nitrate and tritium could be established. All ground waters containing elevated tritium levels also showed higher nitrate concentration. However, this correlation is only relevant if there is a source for the nitrate present. In the unsaturated zone, the correlation between tritium and nitrate was only present at one site.

At four sites rates of vertical moisture movement could be calculated based on the tritium concentration of the ground water. The rates vary from 0.6 m/year to a maximum of 1 m/year under non-irrigated land, under irrigated land a rate of 1.8 m/year was deduced.

At site 11 the vertical rate of soil moisture movement could be determined for three different depth intervals in the unsaturated zone:

1.25 m/month from land surface to a depth of 2.5 m

0.4 m/year from land surface to a depth between 9.3 m and 14.93 m

0.5 m/year from land surface to a depth between 12.5 m and 14.39 m

0.8 m/year from land surface to a 21.43 m depth

The rate of movement in the upper zone of the profile from land surface down to a depth of 2.5 m is highly dependent on the amount of precipitation available for infiltration and the vegetative cover. Thus this rate of movement may only be valid for the particular time when the samples were taken.

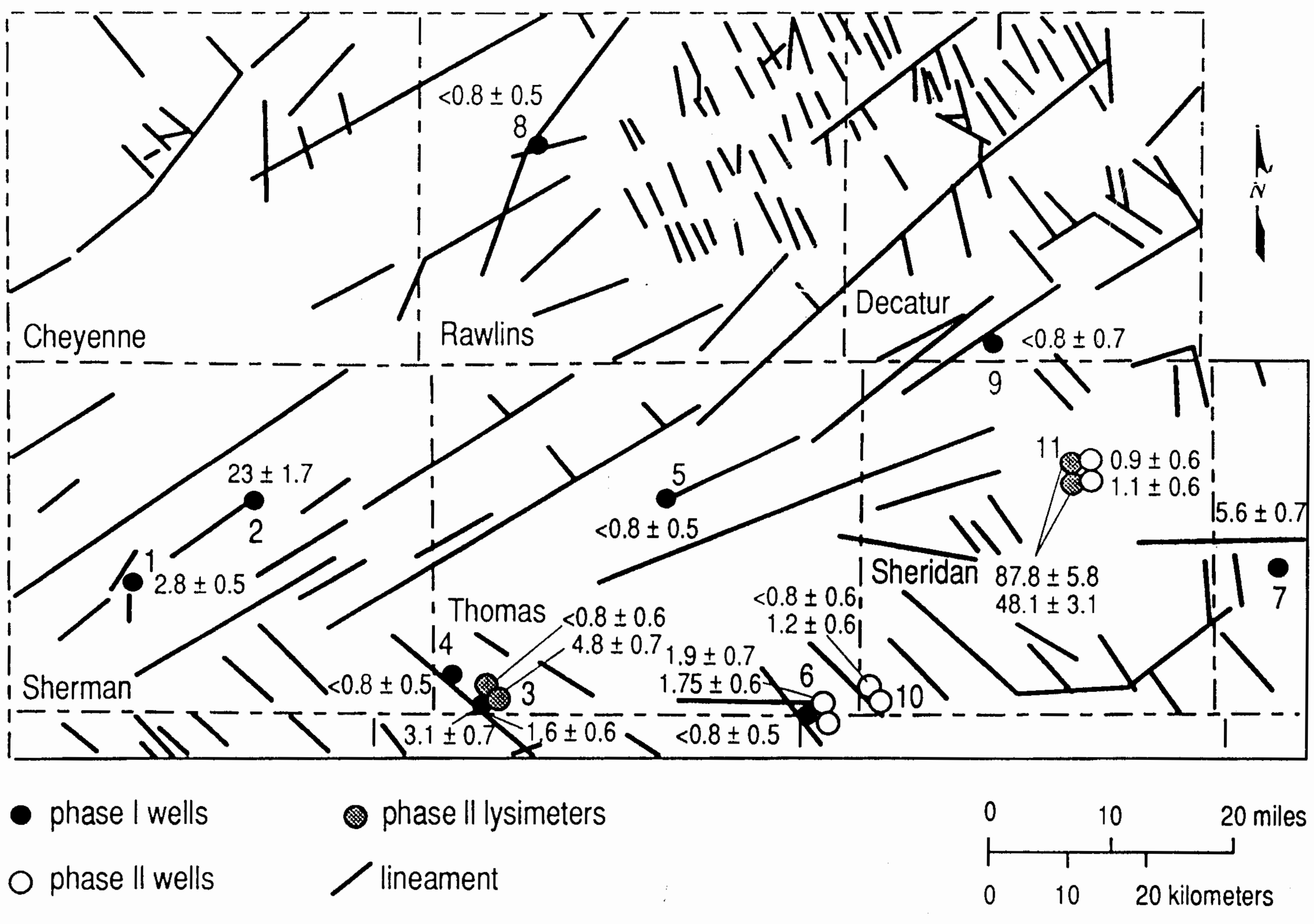


Figure 55: Well, lysimeter, and lineament locations in the study area (lineaments from McCauley, 1988).

No good correlation between the tritium/depth distribution and the particle size distribution in the unsaturated zone could be established. This is probably due to preferential flow through pores, the average porosity in the unsaturated zone at site 11 down to a depth of 13.1 m is around 50 %. However, it can not be excluded that tritium adsorption by clays also represents an important factor.

Based on the moisture content and tritium/depth distribution, the amount of precipitation that infiltrated the unsaturated zone varies from 2 mm/year to 17 mm/year. These numbers coincide very well with the estimated recharge rates to the Ogallala aquifer in western Kansas.

Lineaments do not seem to influence the recharge process to the Ogallala aquifer as indicated by the large difference in water chemistry between ground water sampled at sites 3 and 4. These sites are located along the same lineament about 2.4 km apart.

Although a recent study (Nativ & Riggio, 1989) indicated that recharge to the Ogallala aquifer in Texas is mainly by leakage through undrained depressions, this does not seem to be the case here. Site 3 is located in an undrained depression or playa, but no bomb tritium was detected in the ground water or in the unsaturated zone at depth of 10.7 m and 19.8 m. More data from the unsaturated zone have to be available to determine flow directions and rates at this particular site. It seems that a lateral flow component is present in the lower part of the profile.

Intermittent streams themselves only exert influence on recharge to the Ogallala aquifer when they are losing water to it. Data collected from the three research sites located close to intermittent streams do not show any influence of the location on the tritium concentration. However, the depth to water is usually shallower in the vicinity of intermittent streams and that fact does influence the rate and the amount of recharge.

The depth to water, morphology of the area, sediments in the unsaturated zone, climate and farming practices all influence the rate and the amount of recharge to a very great degree.

Based on the results of this study the Ogallala aquifer has not been recharged in areas with a great depth to ground water since at least the early 1960's. Unless the water table is shallow, the tritium peak from the emissions in the early 1960's is still in transit in the unsaturated zone. The amounts of tritium detected in the ground water samples do not indicate bomb related tritium, with the possible exception of site 1. At this particular site irrigation waters may have diluted the tritium in the ground water, so that the peak may not be obvious anymore. However, without data from the unsaturated zone this remains an assumption.

For future research it is recommended to concentrate on the unsaturated zone to detect the tritium peak from the emissions of the years 1961/1962 and thus being able to calculate vertical rates of moisture movement. Particle size distribution, porosity, moisture content, and hydraulic conductivities of the unsaturated zone should be determined simultaneously with the analyses for tritium. It would benefit the interpretation of the tritium data, if soil cores could be obtained from land surface to the water table. At site 3 of this study, a tritium/depth profile would also prove very helpful in expalining the unexpected tritium concentrations of soil water collected in the lysimeters.

Recharge to the Ogallala aquifer seems to be very site specific, depending on the morphology, the amount of water available for infiltration, crop type, soil type, and the material and characteristics of the unsaturated zone. A comparison of recharge under irrigated sites versus dryland farmed sites and rane land versus dryland farmed land would be interesting. A wide variety of sites has to be researched to obtain a general, area wide recharge figure for the Ogallala aquifer in western Kansas.

References

Angell, R.C., Tricks, B.D., Barker, W.L., and Hamilton, V.L., 1984: Soil survey of Sheridan County, Kansas, U.S. Dept. of Agr., Soil Conservation Service, p. 82

Alvarez, L.W., and Cornog, R., 1939: Helium and hydrogen of mass 3, Phys. Review, vol. 56, no. 6, pp. 613-613.

Athavale, R.N., Murti, C.S., and Chand, R., 1980: Estimation of recharge to the phreatic aquifers of the Lower Maner Basin, India, by using the tritium injection method, Jour. Hydrol., 45, pp. 185-202.

Bailey, G.W., and White, J.L., 1964: Review of adsorption and desorption of organic pesticides by soil coloids, with implications concerning pesticide bioactivity, Agric. and Food Chem., vol.12, no. 4, pp. 324-332.

Bailey, G.W., and White, J.L., 1970: Factors influencing the adsorption, desorption, and movement of pesticides in soil, in: Residue Reviews, F.A. Gunther, J.D. Gunther (eds.), vol. 32, pp. 29-92.

Bavel, C.H.M., van, 1956: Estimating soil moisture conditions and time for irrigation with the evapotranspiration method, U.S. Agr. Res. Serv. Paper ARS 41-111.

Bayne, C.K., 1956: Geology and ground-water resources of Sheridan County, Kansas, Kansas State Geol. Surv., Bull. 116, p. 94.

Bayne, C.K., 1969: Evidence of multiple stades in the Lower Pleistocene of northeastern Kansas, Trans. Kansas Acad. Sci., 71. pp. 340-349.

Bayne, C.K., and O'Connor, H.G., 1968: Quaternary system, in: The startigraphic succession in Kansas, D.E. Zeller (ed.), Kansas State Geol. Surv., Bull. 189, pp. 59-67.

Begemann, F., 1956: Distribution of artificially produced tritium in nature, in: Nuclear processes in geologic settings, Nuclear Sci. Ser., report no. 19, p. 204.

Begemann, F., 1959: Neubestimmung der natuerlichen irdischen Tritiumzerfallsrate und die Frage der Herkunft des "natuerlichen" Tritiums, Zeitschr. fuer Naturforschung, 14a, Heft 4, pp. 334-342.

Begemann, F., 1962: Der natuerliche Tritiumhaushalt der Erde und die Frage seiner zeitlichen Variation, Chimia, vol. 16, pp. 1-28.

Begemann, F., and Libby, W.F., 1957: Continental water balance, ground water inventory and storage times, surface ocean mixing rates and world-wide water circulation patterns from cosmic-ray and bomb tritium, Geochim. et Cosmochim. Acta, vol. 12, pp. 277-296.

Bortolami, G.C., Ricci, B., Susella, G.F., and Zuppi, G.M., 1979: Isotope hydrology of the Val Corsaglia, Maritime Alps, Piedmont, Italy, Isotope Hydrology 1978, vol. 1, IAEA, Vienna, pp. 327-349.

Boyce, J.S., Muir, A.P., Edwards, A.P., Seim, E.C., and Olson, R.A., 1976: Geologic nitrogen in Pleistocene loess in Nebraska, Jour. of Environ. Qual., vol. 5, no. 1, pp. 93-96.

Brown, R.M., 1961: Hydrology of tritium in the Ottawa valley, Geochim. et Cosmochim., Acta, vol. 21, pp. 199-216.

Brown, R.M., and Grummitt, W.E., 1956: The determination of tritium in natural waters, Canadian Jour. of Chem., vol. 34, pp. 220-226.

Camp Dresser & McGee, Inc., Black and Veatch, and Arthur D. Little, Inc., 1982: Six-state High Plains Ogallala regional resources study, Report to U.S. Dept. Comm. and High Plains Study Council, p. 231.

Ciccioli, P., Cooper, W.T., Hammer, P.M., and Hayes, J.M., 1980: Organic solute-mineral interactions; a new method for the determination of groundwater velocities, Water Resources Res., 16, pp. 217-223.

Craig, H., 1961a: Standard for reporting concentrations of deuterium and oxygen-18 in natural waters, Science, vol. 133, pp. 1833-1834.

Craig, H., 1961b: Isotopic variations in meteoric waters, Science, vol. 133, pp. 1702-1703.

Craig, H., Gordon, L.I., and Horibe, Y., 1963: Isotopic exchange effects in the evaporation of water, 1. Low temperature experimental results, Jour. Geophys. Res., 68, pp. 5079-5087.

Craig, H., and Gordon, L.I., 1965: Deuterium and oxygen-18 variations in the ocean and the marine atmosphere, in: Stable isotopes in oceanographic studies and palaeotemperatures, E. Tongiorgi (ed.), pp. 9-130.

Craig. H., and Lal, D., 1961: The production rate of natural tritium, Tellus, vol. 13, no. 1, pp. 85-105.

Daniels, R.B., Handy, R.L., and Simonson, G.H., 1960: Dark-colored bands in the thick loess of western Iowa, Jour. Geol., 68, pp. 450-458.

Dansgaard, W., 1953: The abundance of O18 in atmospheric water and water vapour, Tellus, vol. 5, pp. 461-469.

Dansgaard, W., 1964: Stable isotopes in precipitation, Tellus, vol. 16., no. 4, pp. 436-468.

Darton, N.H., 1899: Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian, U.S. Geol. Surv., 19th annual report, part 4, 1897-1898, pp. 719-785.

Darton. N.H., 1920: Description of the Syracuse and Lakin quadrangles, U.S. Geol. Surv., Syracuse-Lakin folio, no. 212. p. 10.

Day, P.R., 1965: Particle fractionation and particle size analysis, in: Methods of soil analysis, part 1: Physical and mineralogical properties, including: Statistics of measurement and sampling, C.A. Black (ed.), Americ. Soc. Agronomy, Madison, Wisconsin, pp. 545-567.

Davis, S.N., Campbell, D.J., Bentley, H.W., and Flynn, T.J., 1985: Ground water tracers, National Water Well Assoc., Worthington, Ohio, p. 200.

Davis, S.N., and DeWiest, R.J.M., 1966: Hydrogeology, John Wiley and Sons, Inc., New York, London, Sydney, p. 463.

Diffendal, R.F., Jr., 1984: Comments on the geological history of the Ogallala formation in the southern panhandle of Nebraska, Proc. Ogallala Aquifer Symp. 2, Lubbock, Texas, G.A. Whetstone (ed.), pp. 194-216.

Dincer, T., and Davis, G.H., 1968: Some considerations on tritium dating and the estimates of tritium input function, Internat. Assoc. Hydrogeol., memoires, vol. 8, pp. 276-286.

Dort, W. Jr., 1965: Nearby and distant origins of glacier ice entering Kansas, Americ. Jour. Sci., 263, pp. 598-605.

Dort, W., Jr., 1966a: Multiple early Pleistocene glacial stades, northeastern Kansas, Geol. Soc. Americ., special paper, 87, p. 47.

Dort, W., Jr., 1966b: Nebraskan and Kansan stades: complexity and importance, Science, 154, pp. 771-772.

Dort, W., Jr., 1985: Field evidence for more than two early Pleistocene glaciations of the Central Plains, Inst. Tertiary-Quaternary Studies, Ter-Qua, symp. series, 1, pp. 41-51.

Dreeszen, V.H., 1970: The stratigraphic framework of Pleistocene glacial and periglacial deposits in the Central Plains, in: Pleistocene and recent enviroments of the Central Great Plains, W. Dort, Jr., J.K. Jones, Jr. (eds.), Dept. Geol., Univ. Kansas, spec. publ., no. 3, The Univ. of Kansas Press, Lawrence, Kansas, pp. 9-22.

Dreimanis, A., 1962: Quantitative gasometric determination of calcite and dolomite by using chittick apparatus, Jour. Sed. Petrol., 32, pp. 520-529.

Eardley, A.J., 1949: Paleotectonic and paleogeologic maps of central and western North America, Americ. Assoc. Petrol. Geologists Bull., vol. 33, pp. 655-682.

Ehhalt, D., Israel, G., Roether, W., and Stich, W., 1963: Tritium and deuterium content of atmospheric hydrogen, Jour. Geophys. Res., vol. 68, no. 13. pp. 3747-3751.

Ehhalt, D., and Knott, K., 1965: Kinetische Isotopentrennung bei der Verdampfung von Wasser, Tellus, 17, pp. 389-397.

Ehhalt, D., Knott, K., Nagel, J.F., and Vogel, J.C., 1963: Deuterium and oxygen-18 in rain water, Jour. Geophys. Res., vol. 68, no. 13, pp. 3775-3780.

Eichler, R., 1966: Deuterium-Isotopengeochemie des Grund-und Oberflaechenwassers, Geol. Rundschau, Bd. 55, H. 1, pp. 144-159.

Elias, M.K., 1931: The geology of Wallace County, Kansas, Kansas State Geol. Surv., Bull. 18, p. 254.

Faltings, V., and Harteck, P., 1950: Der Tritiumgehalt der Atmosphaere, Zeitschr. fuer Naturforsch., 5a, H. 8, pp. 438-439.

Faure, G., 1986: Principles of isotope geology, John Wiley and Sons, New York, 2nd edition, p. 589.

Fenneman, N.M., 1931: Physiography of the western United States, McGraw-Hill Book Co., New York, 1st edition, p. 534.

Fergusson, G.F., 1965: Radiocarbon and tritium in the upper troposphere, proc. 6th internat .conf. on radiocarbon and tritium dating, Pullman, Washinton, pp. 525-540.

Ferronsky, V.I., and Polyakov, V.A., 1982: Environmental isotopes in the hydrosphere, John Wiley and Sons, New York, p. 466.

Ferronsky, V.I., Vlasova, L.S., and Esikov, A.D., 1983: Relationships between climatic changes and variations in isotopic compostion of groundwater, precipitation and organic soil matter in the Quaternary period, in: Palaeoclimates and palaeowaters: a collection of environmental isotope studies, proc., IAEA, Vienna, pp. 13-35.

Fireman, E.L., 1953: Measurement of the (n, H^3) cross section in nitrogen and its relationship to the tritium production in the atmosphere, Phys. Review, vol. 91, no. 4, pp. 922-926.

Foerstel, H., Putral, A., Schleser, G., and Lieth, H., 1975: The world pattern of oxygen-18 in rainwater and its importance in understanding the biogeochemical oxygen cycle, in: Isotope ratios as pollutant and behaviour indicators, proc., IAEA, Vienna, pp. 3-.

Foerstel, H., and Huetzen, H., 1982: 18O/16O-ratio of groundwater at the Federal Republic of Germany, in: Stable isotopes, proc. 4th internat. conf., Analytical Chemistry Symp. Ser., vol. 11, H.-L. Schmidt, H. Foerstel, K. Heinzinger (eds.), Elsevier, pp. 173-178.

Fontes, J. Ch., 1980: Environmental isotopes in groundwater hydrology, in: Handbook of environmental isotope geochemistry, P. Fritz, J.Ch. Fontes (eds.), vol. 1: The Terrestrial Environment , A, Elsevier, pp. 75-140 .

Foster, S.S.D., and Smith-Carrington, A., 1980: The interpretation of tritium in the Chalk unsaturated zone, Jour. Hydrol., 46, pp. 343-364.

Frankel, L., 1957: Relative rates of loess deposition in Nebraska, Jour. Geol., 65, pp. 649-652.

Frazee, C.J., Fehrenbacher, J.B., and Krumbein, W.C., 1970: Loess distribution from a source, Soil Sci. Soc. Americ., proc., vol. 34, pp. 296-301.

Freeze, R.A., and Cherry, J.A., 1979: Groundwater, Prentice Hall, Inc., New Jersey, p. 604.

Fritz, P., Drimmie, R., and Render, F.W., 1974: Stable isotope contents of a major praerie aquifer in central Manitoba, Canada, in: Isotope techniques in groundwater hydrology, vol. 1, proc., IAEA, Vienna, pp. 379-398.

Frye, J.C., 1945: Geology and ground-water resources of Thomas County, Kansas, Kansas State Geol. Surv., Bull. 59, p. 110.

Frye, J.C., 1970: The Ogallala formation - a review, proc. Ogallala aquifer symp., Lubbock, Texas, R.B. Mattox, W.D. Miller (eds.), Internat. Center for Arid and Semi-arid Land Studies, spec. report 39, pp. 5-14.

Frye, J.C., and Swineford, A., 1946: Silicified rock in the Ogallala formation, Kansas State Geol. Surv., Bull. 64, part 2, pp. 33-76.

Frye, J.C., and Leonard, A.B., 1951: Stratigraphy of the late Pleistocene loesses in Kansas, Jour. Geol., vol. 59, no. 4, pp. 287-305.

Frye, J.C., and Leonard, A.B., 1952: Pleistocene geology of Kansas, Kansas State Geol. Surv., Bull. 99, p. 230.

Frye, J.C., Leonard, A.B., 1954: Significant new exposures of Pleistocene deposits, at Kirwin, Phillips County, Kansas, Kansas State Geol. Surv., Bull. 109, part 3, pp. 29-48.

Frye, J.C., Leonard, A.B., and Swineford, A., 1956: Stratigraphy of the Ogallala formation (Neogene) of northern Kansas, Kansas State Geol. Surv., Bull. 118, p. 92.

Frye, J. C., and Leonard, A.B., 1957: Ecological interpretations of Pliocene and Pleistocene stratigraphy in the Great Plains region, Americ. Jour. Sci., 255, pp. 1-11.

Frye. J.C., and Willman, H.B., 1963: Development of Wisconsinan classification in Illinios related to radiocarbon chronology, Bull. Geol. Soc. Americ., 74, pp. 501-506.

Frye, J.C., Willman, H.B., and Glass, H.D., 1968: Correlation of midwestern loesses with the glacial succession, in: Loess related eolian deposits of the world, vol. 12, proc. 7th congr., Intern. Assoc. for Quat. Res., C.B. Schultz, J.C. Frye (eds.), Univ. of Nebraska Press, Lincoln, Nebraska, pp. 3-21.

Gat, J.R., 1970: Environmental isotope balance of Lake Tiberias, Isotope Hydrology, IAEA, Vienna, pp. 109-127.

Gat, J.R., 1971: Comments on the stable isotope method in regional groundwater investigations, Water Resour. Res., vol. 7, no. 4, pp. 980-993.

Gat, J.R., 1980: The isotopes of hydrogen and oxygen in precipitation, in: Handbook of environmental isotope geochemistry, P. Fritz, J.Ch. Fontes (eds.), vol. 1, The terrestrial environment, A, Elsevier, pp. 2-47.

Gat, J.R., 1983: Precipitation, groundwater and surface water control of climate parameters on their isotopic composition and their utilization as palaeoclimatological tools, in: Palaeoclimates and palaeowaters: a collection of environmental isotope studies, proc., IAEA, Vienna, pp. 3-12.

Gat, J.R., Karfunkel, U., and Nir, A., 1962: Tritium content of rainwater from the eastern mediterranean area, in: Tritium in the physical and biological sciences, vol. 1, proc., IAEA, Vienna, pp. 41-54.

Gat, J.R., and Gonfiantini, R., 1981: Stable isotope hydrology, deuterium and oxygen-18 in the water cycle, Technical Reports Ser., no. 210, IAEA, Vienna, p. 335.

Gee, G.W., and Bauder, J.W., 1986: Particle-size analysis, in: Methods of soil analysis, part 1: Physical and mineralogical methods, A. Klute (ed.), Americ. Soc. Agron., Soil Sci. Soc. Americ., pp. 383-411.

Geiger, C.O., Lacock, D.L., Merry, C.E., and Schneider, D.R., 1988: Water resources data, Kansas, water year 1988, U.S. Geol. Surv., water data report, KS-88-1, p. 490.

Giauque, W.F., and Johnston, H.L., 1929: An isotope of oxygen, mass 18, Jour. Americ. Chem. Soc., 51, pp. 1436-1441.

Gilbert, G.K., 1896: The underground water of the Arkansas valley in eastern Colorado, U.S. Geol. Surv., 17th annual report, part 2, pp. 551-601.

Grant-Taylor, T.L., and Taylor, C.B., 1967: Tritium hydrology of New Zealand, Isotopes in Hydrology, IAEA, Vienna, pp. 381-400.

Grosse, A., von, Johnston, W.M., Wolfgang, R.L., and Libby, W.F., 1951: Tritium in nature, Science, 113, pp. 1-2.

Gutentag, E.D., and Weeks, J.B., 1980: Water table in the High Plains aquifer in 1978 in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, U.S. Geol. Surv. Hydrol. Invest. Atlas 642, scale 1:2.500.000.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984: Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, U.S. Geol. Surv., Prof. Paper 1400-B, p. 63.

Gvirtzman, H., and Magaritz, M., 1986: Investigation of water movement in the unsaturated zone under an irrigated area using environmental tritium, Water Resour. Res., vol. 22, no.5, pp. 635-642.

Halevy, E., 1964: The exchangeability of hydroxyl groups in kaolinite, Geochim. et Cosmochim. Acta, vol. 28, pp. 1139-1145.

Hamilton, J.M., Jr., 1963: The organic fluorcchemicals industry, in: Advances in fluorine chemistry, M. Stacy, J.C. Tatlow, A.G. Sharpe (eds.), Butterworths, London, pp. 117-180.

Hathaway, L.R., Waugh, T.C., Galle, O.K., and Dickey, H.P., 1979: Chemical quality of irrigation waters in northwestern Kansas, Kansas State Geol. Surv., Chemical Quality Series, no. 8, p.45.

Hathaway, L.R., Waugh, T.C., Gale, O.K., and Dickey, H.P., 1981: Chemical quality of irrigation waters in the Equus Beds area, south-central Kansas, Kansas State Geol. Surv., Chemical Quality Series, no. 10, p. 45.

Haworth, E., 1897: Physiography of western Kansas, Kansas State Geol. Surv., vol. 2, pp. 11-49.

Hay, R., 1890: A geological reconnaissance in southwestern Kansas, U.S. Geol. Surv., Bull. 57, p. 49.

Hayes, J.M., and Thompson, G.M., 1977: Trichlorofluoromethane in ground water - a possible indicator of ground-water age, Purdue Univ., Water Resour. Res. Center, Techn. Report no. 90, p. 25.

Helling, C.S., 1971: Pesticide mobility in soils, 3. Influence of soil properties, Soil Sci. Soc. Americ., proc., 35, pp. 743-748.

Helling, C.S., and Gish, T.J., 1986: Soil characteristics affecting pesticide movement into ground water, in: Evaluation of pesticides in ground water, Americ. Chem. Soc. Symp. Ser., 315, W.Y. Garner, R.C. Honeycutt, H.N. Nigg (eds.), pp. 14-38.

Helyar, T., 1988: Kansas statistical abstract, 1978-1988, Inst. Public Policy and Business Res., Univ. of Kansas, p.289.

Hem, J.P., 1983: Study and interpretation of the chemical characteristics of natural water, U.S. Geol. Surv., Water-Supply Paper 2254, 3rd ed., p. 263.

Hester, N.E., Stephens, E.R., and Taylor, O.C., 1975: Fluorcarbon air pollutants, measurements in lower stratosphere, Environ. Sci. and Techn., vol. 9. no. 9, pp. 875-876.

Hibbard, C.W., 1952: Vertebrate fossils from Late Cenozoic deposits of central Kansas, Kansas Univ. Paleontological Contributions, Vertebrata, Art. 2, pp. 1-14.

Hiltbold, A.E., and Buchanan, G.A., 1977: Influence of soil pH on persistence of atrazine in the field, Weed Science, vol. 25. no. 6, pp. 515-520.

Hodson, W.G., 1963: Geology and ground-water resources of Wallace County, Kansas, Kansas State Geol. Surv., Bull. 161, p. 108.

Hodson, W.G., 1969: Geology and ground-water resources of Decatur County, Kansas, Kansas State Geol. Surv., Bull. 196, p. 41.

Hodson, W.G., and Wahl, K.D., 1960: Geology and ground-water resources of Gove County, Kansas, Kansas State Geol. Surv., Bull. 145, p. 126.

Hurlburt, S., 1988: The problem with nitrates, Water Well Journal, vol. 22, no. 8, pp. 37-42.

International Atomic Energy Agency, 1967: Tritium and other environmental isotopes in the hydrologic cycle, Techn. Reports Ser. no. 73, IAEA, Vienna, p. 81.

International Atomic Energy Agency, 1969: Environmental isotope data no. 1: World survey of isotope concentration in precipitation (1953-1963), Techn. Reports Ser. no. 96, IAEA, Vienna, p. 421.

International Atomic Energy Agency, 1970: Environmental isotope data no. 2: World survey of isotope concentration in precipitation (1964-1965), Techn. Reports Ser. no. 117, IAEA, Vienna, p. 404.

International Atomic Energy Agency, 1971: Environmental isotope data no. 3: World survey of isotope concentration in precipitation (1966-1967), Techn. Reports Ser. no. 129, IAEA, Vienna, p. 402.

International Atomic Energy Agency, 1973: Environmental isotope data no. 4: World survey of isotope concentration in precipitation (1968-1969), Techn. Reports Ser. no. 147, IAEA, Vienna, p. 334.

International Atomic Energy Agency, 1975: Environmental isotope data no. 5: World Survey of isotope concentration in precipitation (1970-1971), Techn. Reports Ser. no. 165, IAEA, Vienna, p. 309.

International Atomic Energy Agency, 1979: Environmental isotope data no. 6: World survey of isotope concentration in precipitation (1972-1975), Techn. Reports Ser. no. 192, IAEA, Vienna, p. 187.

International Atomic Energy Agency, 1983: Environmental isotope data no. 7: World survey of isotope concentration in precipitation (1976-1979), Techn. Rports Ser. no. 226, IAEA, Vienna, p. 241.

International Atomic Energy Agency, 1986: Environmental isotope data no. 8: World survey of isotope concentration in precipitation (1980-1983), Techn. Reports Ser. no. 264, IAEA, Vienna, p. 184.

Israel, G., Roether, W., and Schumann, G., 1963: Seasonal variations of bomb-produced tritium in rain, Jour. Geophys. Res., vol. 68, no. 13., pp. 3771-3773.

Jenkins, E.D., and Pabst, M.E., 1975: Water development for irrigation in northwestern Kansas, U.S. Geol. Surv., open-file report 4-75, p. 39.

Job, C., 1970: Die Verwendung atmosphaerischen Tritiums und anderer Radionuklide zu hydrologischen Untersuchungen, Steirische Beitraege zur Hydrogeologie, 22, pp.

215-230.

Johnson, C.R., 1958: Geology and ground-water resources of Logan County, Kansas, Kansas State Geol. Surv., Bull. 129, p. 178.

Johnson, W.D., 1901: The High Plains and their utilization, U.S. Geol. Surv., 21st. annual report, part 4, pp. 601-741.

Junk, G.A., Spalding, R.F., and Richard, J.J., 1980: Areal, vertical and temporal differences in ground water chemistry: 2. organic constituents, Jour. Environm. Quality, vol. 9., no. 3, pp. 479-483.

Kansas State Board of Agriculture, 1989: Kansas fertilizer tonnage report, Topeka, Kansas, p. 7.

Kansas Geological Survey, 1989: Annual oil-and gas production report 1988, Data base no. 1, unpagenated

Kaufman, S., and Libby, W.F., 1954: The natural distribution of tritium, Physical Review, vol. 93. no. 6, pp. 1337-1344.

Kirshenbaum, I., 1951: Physical properties and analysis of heavy water, McGraw-Hill, New York.

Lal, D., and Peters, B., 1962: Cosmic-ray-produced isotopes and their application to problems in geophysics, Progr. Elem. Particle Cosmic Ray Phys., 6, pp. 1-74.

Larson, G.J., Delcore, M.R., and Offer, S., 1987: Application of the tritium interface method for determining recharge rates to unconfined drift aquifers, 1. homogeneous case, Jour. Hydrol., 91, pp. 59-72.

Lee, W., and Merriam, D.F., 1954: Preliminary study of the structure of western Kansas, Univ. of Kansas Publ., Kansas State Geol. Surv., Oil and Gas Investig. no.11, p. 23.

Leonard, A.B., 1951: Stratigraphic zonation of the Peoria loess in Kansas, Jour. Geol., vol. 59, no. 4, pp. 323-332.

Leverett, F., 1898: The Peorian soil and weathered zone (Toronto formation?), Jour. Geol.. vol. 6, pp. 244-249.

Libby, W.F., 1946: Atmospheric helium-3 and radiocarbon from cosmic radiation, Physical Review, 69, pp. 671-672.

Libby, W., 1956: Radioactice strontium fallout, Proc. National Acad. Sci. of the U.S., 42, pp. 365-390

Logan, W.N., 1897: The Upper Cretaceous of Kansas, Kansas State Geol. Surv., vol. 2, pp. 195-234.

Lovelock, J.E., 1971: Atmospheric fluorine compounds as indicators of air movement, Nature, vol. 230, pp. 379.

Lovelock, J.E., 1974: Atmospheric halocarbons and stratospheric ozone, Nature, vol. 252, pp. 292-294.

Luckey, R.R., 1984: The High Plains regional aquifer-flow system simulation of the central and northern High Plains, in: proc. Ogallala aquifer symp. 2, Lubbock, Texas, G.A. Whetstone (ed.), Texas Tech. Univ., pp. 48-66.

Luckey, R.R., Gutentag, E.D., and Weeks, J.B., 1981: Water-level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, U.S. Geol. Surv., Hydrologic Investigations Atlas HA-652.

Lugn, A.L., 1939: Classification of the Tertiary system in Nebraska, Geol. Soc. Americ. Bull., vol. 50, pp. 1245-1276.

Lugn, A.L., 1960: The origin and sources of loess in the Great Plains in North America, Int. Geol. Congress, 21st session, Norden, pp. 223-235.

Lutenegger, A.J., 1985: Desert loess in the midcontinent, U.S.A., program and abstracts, First Int. Conference on Geomorphology, Manchester, England, p. 378.

Maher, J.C., and Collins, J.B., 1948: The Hugoton Embayment of the Anadarko Basin in southwestern Kansas, southeastern Colorado, and the Oklahoma panhandle, Americ. Assoc. Petrol. Geol. Bull., vol. 32, no. 5, pp. 813-816 .

Maier-Bode, H., and Haertel, K., 1981: Linuron and monolinuron, Residue Reviews, vol. 77, p. 364.

Martell, E.A., 1963: On the inventory of artificial tritium and its occurence in atmospheric methane, Jour. Geophys. Res., vol. 68, no. 13, pp. 3759-3769.

May, D.W., 1989: Late-Quaternary landscape evolution in the Platte River basin, Nebraska, Assoc. Americ. Geographers, annual meeting, program and abstracts, p. 131.

McCauley, J.R., 1988: Landsat lineament map of western Kansas, Kansas State Geol. Surv., open file report 88-20.

McClain, T.J., Jenkins, E.D., Keene, K.M., and Pabst, M.E., 1975: Water resources of Gove, Logan, and Wallace counties, west-central Kansas, U.S. Geol. Surv., Hydrologic Investigations Atlas HA-521.

Meek, F.B., and Hayden, F.V., 1862: Descriptions of new Cretaceous fossils from Nebraska territory, Philadelphia Acad. Nat. Sci. Proc., vol. 13, pp. 21-28.

Merriam, D.F., 1963: The geologic history of Kansas, Kansas State Geol. Surv. , Bull. 162, p. 317.

Merriam, D.F., and Frye, J.C., 1954: Additional studies of the Cenozoic of western Kansas, Kansas State Geol. Surv., Bull. 109, part 4, p. 64.

Meyer, W.R., Groves, B.L., and Carlson, G.W., 1952: 1952 irrigation experiments, U.S. Dept. Agriculture Soil Conservation Service Research, p. 132.

Moser, H., and Stichler, W., 1970: Deuterium measurements on snow samples from the Alps, Isotope Hydrology 1970, IAEA, Vienna, pp. 43-57.

Moser, H., Stichler, W., and Zoetl, J., 1972: Altersgliederung von tiefliegenden artesischen Waessern, Naturwissenschaften, Jg. 59, H. 3, pp. 122-123.

Morrison, P., and Beard, D.B., 1949: H^3 and the origin of terrestrial helium, Phys. Review, vol. 75, pp. 1332-1333.

Nativ. R., and Riggio, R., 1989: Meteorologic and isotopic characteristics of precipitation events with implications for ground-water recharge, Southern High Plains, Atmospheric Res., vol. 23, pp. 51-82.

Nielsen, E.G., and Lee, L.K., 1987: The magnitude and costs of groundwater contamination from agricultural chemicals - a national perspective - , U.S. Dept. Agriculture and Natural Resource Economics Division, p. 53.

Nier, A.O., 1950: A redetermination of the relative abundance of the isotopes of carbon, nitrogen, oxygen, argon, and potassium, Phys. Review, 77, pp. 789-793.

O'Connor, H.G., and McClain, T.J., 1982: Ogallala aquifer study in Kansas, Geohydrology, Kansas Water Office, p. 99.

Ogrosky, H.O., and Mockus, V., 1964: Hydrology of agricultural lands, in: Handbook of applied hydrology, Ven Te Chow (ed.), sec.21, McGraw Hill, New York, pp. 21/1-21/95.

Payne, B.R., 1972: Isotope hydrology, Adv. Hydroscience, 8, pp. 95-138.

Payne, B.R., and Yurtsever, Y., 1974: Environmental isotopes as a hydrogeological tool in Nicaragua, in: Isotope techniques in groundwater hydrology, vol. 1, IAEA, Vienna, pp. 193-202.

Penman, H.L., 1956: Estimating evaporation, Trans. Americ. Geophys. Union, vol. 37, no. 1, pp. 43-50.

Prescott, G.C., Jr., 1952: Geology and ground-water resources of Cheyenne County, Kansas,

Kansas State Geol. Surv., Bull. 100. p. 106.

Prescott, G.C., Jr., 1953: Geology and ground-water resources of Sherman County, Kansas, Kansas State Geol. Surv., Bull. 105. p. 130.

Prescott, G.C., Jr., 1955: Geology and ground-water resources of Graham County, Kansas, Kansas State Geol. Surv., Bull. 110, p. 98.

Rabinowitz, D.D., 1969: Forced exchange of tritiated water with natural clays, Master's thesis, New Mexico Institute of Mining and Techn., Socorra, New Mexico, p.72.

Rauert, W., 1971: Ueber Messungen von Tritium und Kohlenstoff-14 bei hydrologischen Untersuchungen, Geologica Bavarica, 64, pp. 36-74.

Reed, E.C., and Dreeszen, V.H., 1965: Revision of the classification of the Pleistocene deposits of Nebraska, Nebraska Geol. Surv., Bull. 23, p. 65.

Reed, E.C., Dreeszen, V.H., Bayne, C.K., and Schultz, C.B., 1965: The Pleistocene in Nebraska and northern Kansas, in: The Quaternary of the United States, H.E. Wright, Jr., D.G. Frey (eds.), Princeton Univ. Press, Princeton, New Jersey, pp. 187-202.

Reed, E.C., Dreeszen, V.H., Drew, J.V., Souders, V.L., Elder, J.A., and Boellstorff, J.D., 1966: Evidence of multiple glaciation in the glacial-periglacial area of eastern Nebraska, in: Guidebook, 17th annual meeting, Midwestern section, Friends of the Pleistocene, Univ. of Nebraska, Lincoln, Nebraska, pp. 1-25.

Riesenfeld, E.H., and Chang. T.L., 1936: Ueber den Gehalt an HDO und H_2O^{18} in Regen und Schnee, Deutsch. Chem. Ges. Ber., 69, pp. 1305-1311.

Roether, W., 1967: Estimating the tritium input to groundwater from wine samples; groundwater and direct run-off contribution to Central European surface waters, in: Isotopes in Hydrologyy, IAEA, Vienna, pp.

Rozanski, K., Muennich, K.O., and Sonntag, C., 1982: Modelling of stable isotope composition of atmospheric water vapour and precipitation, in: Stable isotopes, proc. 4th int. conference, Analytical Chem. Symp. Ser., vol. 11, H.-L. Schmidt, H.Foerstel, K. Heinzinger (eds.), Elsevier, pp. 153-160.

Ruhe, R.V., 1983: Depositional environment of late Wisconsin loess in the midcontinental United States, in: Late-Quaternary environments of the United States, vol. 1: The late Pleistocene, H.E. Wright, Jr., S.C. Porter (eds.), Univ. of Minnesota Press. Minneapolis, Minnesota, pp. 130-137.

Ruhe, R.V., Miller, G.A., and Vreeken, W.J., 1971: Paleosols, loess sedimentation, and soil stratigraphy, in: Paleopedology: Origin, nature, and dating of paleosols, D.H. Yaalon (ed.), Hebrew Univ. Press, Jerusalem, Israel, pp. 41-60.

Schultz, C.B., and Stout, T.M., 1945: Pleistocene loess deposits of Nebraska, Americ. Jour. Sci., 243, pp. 241-244.

Self, H., 1978: Environment and man in Kansas, a geographical analysis, The Regents Press of Kansas, Lawrence, Kansas, p. 288.

Seni, S.J., 1980: Sand-body geometry and depositional systems, Ogallala formation, Texas, Bureau of Economic Geology, Univ. of Texas, Austin, Texas, report of investigations, no. 105, p. 36.

Sheets, T.J., and Shaw, W.L., 1963: Herbicide properties and persistence in soils of s-triazines, Weeds, 11, pp. 15-21.

Smith, H.T.U., 1940: Geologic studies in southwestern Kansas, Kansas State Geol. Surv., Bull. 34, p. 212.

Socolofsky, H.E., and Self, H., 1988: Historical atlas of Kansas, Univ. of Oklahoma Press, Norman, Oklahoma, 2nd ed., p. 74.

Steeples, D.W., and Buchanan, R., 1983: Kansas GeoMaps, Kansas State Geol. Surv., Educational Series, no.4, p. 30

Stewart, G.L., 1965: Experiences using tritium in scientific hydrology, proc. 6th int. conference on radiocarbon and tritium dating, Pullman, Washington, pp. 643-659.

Stewart, G.L., 1967: Fractionation of tritium and deuterium in soil water, in: Isotope techniques in the hydrologic cycle, Geophys. Monograph Ser., no. 11, Americ. Geophys. Union, G.E. Stout (ed.), pp. 159-167.

Stullken, L.E., Watts, K.R., and Lindgren, R.J., 1985: Geohydrology of the High Plains aquifer, western Kansas, U.S. Geol. Surv., Water Resour. Investigations Report 85-4198, p. 86.

Swineford, A. and Frye, J.C., 1951: Petrography of the Peoria loess in Kansas, Jour. Geol., 59, no. 4, pp. 306-322.

Swineford, A., Frye, J.C., and Leonard, A.B., 1955: Petrography of the late Tertiary volcanic ash falls in the central Great Plains, Jour. Sed. Petrol., vol. 25, pp. 243-261.

Suess, H.E., 1969: Tritium in geophysics as an international research project, Science, 163, pp. 1405-1410.

Teegarden, B.I., 1967: Cosmic-ray production of deuterium and tritium in the earth's atmosphere, Jour. Geophys. Res., vol. 72, no. 19, pp. 4863-4868.

Thatcher, L.L., and Payne, B.R., 1965: The distribution of tritium in precipitation over continents and its significance to ground-water dating, proc. 6th int. conference on radiocarbon and tritium dating, Pullman, Washington, pp. 604-629.

Thompson, G.M., and Hayes, J.M., 1979: Trichlorofluoromethane in groundwater - a possible tracer and indicator of groundwater age, Water Resour. Res., vol. 15, no. 3, pp. 546-554.

Theis, C.V., 1936: Possible effects of ground-water on the Ogallala formation of Llano Estacado, abstract, Washington Acad. Sci. Jour., vol. 26, pp. 390-392.

Townsend, M., Shaukat, N., Healy, J., and McClain, T., 1989: January 1989 Kansas water levels and data related to water-level changes, Kansas State Geol. Surv., Ground- Water Series, 10, p. 127.

Trewartha, G.T., Robinson, A.H., and Hammond, E.H., 1967: Physical elements of geography, McGraw Hill, New York, 5th ed., p. 660.

U.S. Atomic Energy Commission, 1960: Rules and Regulations, Title 10 - Atomic Energy, Federal Register, p. 11.

U.S. Environmental Protection Agency, 1976: National interim primary drinking water regulations, Office of Water Supply, EPA-509/9-76-003, p. 159

U.S. Environmental Protection Agency, 1977: National secondary drinking water regulations, Federal Register, vol. 42, no. 62, part 1, pp. 17143- 17147

U.S. Geological Survey, 1978: Water resources investigations in Kansas, U.S. Geol. Surv. Folder, 1 sheet

Vinogradov, A.P., Devirts, A.L., and Dobkina, E.I., 1968: The current tritium contents of natural waters, Geochim, Int., 5 (5), pp. 952-966, translated from : Geochimiya, 10, pp. 1147-1162.

Waggoner, P.E., and Bingham, C., 1961: Depth of loess and distance from source, Soil Sci. Soc. Americ., proc., vol. 92, pp. 396-401.

Walters, K.L., 1956: Geology and ground-water resources of Rawlins County, Kansas, Kansas State Geol.Surv., Bull. 117, p. 100

Weeks, J.B., 1986: High Plains regional aquifer-system study, in: Regional aquifer-system analysis program of the U.S. Geol. Surv., summary of projcets, 1978-1984, R.J. Sun (ed.), U.S. Geol. Surv., Circular 1002, pp. 30-49.

Weeks, E.P., Earp, D.E., and Thompson, G.M., 1982: Use of atmospheric fluorcarbons F-11 and F-12 to determine the diffusion parameters of the unsaturated zone in the Southern High Plains of Texas, Water Resour. Res., vol. 18. no. 5, pp. 1365-1378.

Weeks, J.B., and Gutentag, E.D., 1984: The High Plains regional aquifer - geohydrology, in: proc. of the Ogallala aquifer symp. 2, Lubbock, Texas, Texas Tech. Univ., G.A. Whetstone (ed.), pp. 6-25.

Weeks, J.B., Gutentag, E.D., Heimes, F.J., and Luckey, R.R., 1988: Summary of the High Plains regional aquifer-system analysis in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming, U.S. Geol. Surv. Prof. Paper 1400-A. p. 30.

Wehtje, G.R., Leavitt, J.R.C., Spalding, R.F., Mielke, L.N., and Schepers, J.S., 1981: Atrazine contamination of groundwater in the Platte River valley of Nebraska from non-point sources, The Science of the Total Environ., vol. 21, pp. 47-51

Wehtje, G.R., Spalding, R.F., Burnside, O.C. Lowry, S.R., and Leavitt, J.R.C., 1983: Biological significance and fate of atrazine under aquifer conditions, Weed Science, vol. 31, no. 5, pp. 610-618.

Welch, J.E., and Hale, J.M., 1987: Pleistocene loess in Kansas - status, present problems, and future considerations, in: Quaternary environments of Kansas, W.C. Johnson (ed.), Kansas State Geol. Surv., Guidebook Ser. 5, pp. 67-84.

Williams, C.C., and Lohman, S.W., 1949: Geology and ground-water resources of a part of south-central Kansas, Kansas State Geol. Surv., Bull. 79, pp. 1-455.

Williston, S.W., 1895: Semi-arid Kansas, Kansas Univ. Quart., vol. 3, pp. 209-216.

Williston, S.W., 1897: The Kansas Niobrara Cretaceous, Kansas State Geol. Surv., vol. 2, pp. 235-246.

Wilson, A.T., and Fergusson, G.J., 1960: Origin of terrestrial tritium, Geochim. et Cosmochim., vol.18, no, 3/4, pp. 273-277.

Yaron, B., Gerstl, Z., and Spencer, W.F., 1985: Behaviour of herbicides in irrigated soils, in: Advances in Soil Sci., vol. 3, B.A. Stewart (ed.), Springer Verlag, New York, pp. 122-190.

Yurtsever, Y., 1975: Worlwide survey of stable isotopes in precipitation, Rep. Sect. Isotope Hydrol., IAEA, Vienna, p. 40.

Zeller, D.E., 1968: The stratigraphic succession in Kansas, Kansas State Geol. Surv., Bull. 189, p. 81.

Zimmermann, U., Ehhalt, D., and Muennich, K.O., 1966: Soil-water movement and evapotranspiration: changes in the isotopic composition of the water, in: Isotopes in Hydrology, IAEA, Vienna, pp. 567-585.

Zimmermann, U., Muennich, K.O., and Roether, W., 1967: Downward movement of soil moisture traced by means of hydrogen isotopes, in: Isotope techniques in the hydrologic cycle, Geophys. Monograph Ser., no.11, G.E. Stout (ed.), Americ. Geophys. Union, pp. 28-36.

Appendix A

Drilling Logs

Site 1, well installed by the Kansas Geological Survey in 1987
total depth = 90.8 m, screened depth = 51.2 m - 90.8 m, water level = 51.5 m*

Depth (m)	Geology
0 - 9.1	clay
9.1 - 32.0	sandy clay
32.0 - 39.6	clayey sand and gravel
39.6 - 50.3	sandy gravel with clay lenses
50.3 - 54.4	sand and gravel
54.4 - 55.8	caliche, cementation zone
55.8 - 57.9	sand and gravel with clay lenses
57.9 - 58.5	caliche
58.5 - 64.0	sand and gravel with clay lenses
64.0 - 67.0	sand and gravel with clay lenses and caliche zones
67.0 - 77.7	sand and gravel with clay lenses
77.7 - 88.4	sand and gravel
88.4 - 89.9	sand and gravel with caliche zones
89.9 - 92.0	Pierre Shale

Site 2, well installed by commercial driller in 1987
total depth = 61 m, screened depth = 44.8 m - 60 m, water level = 43 m*

Depth (m)	Geology
0 - 4.6	topsoil
4.6 - 12.8	clay
12.8 - 14.6	medium sand
14.6 - 16.5	clay
16.5 - 20.1	medium sand and gravel
20.1 - 20.4	caliche
20.4 - 21.3	medium sand and coarse gravel
21.3 - 25.6	sandy clay
25.6 - 27.4	cemented sand
27.4 - 32.3	caliche
32.3 - 35.4	medium sand
35.4 - 37.2	caliche
37.2 - 38.4	medium sand
38.4 - 42.1	caliche
42.1 - 43.3	medium sand
43.3 - 46.0	caliche
46.0 - 46.3	medium sand
46.3 - 50.9	caliche
50.9 - 52.7	medium sand
52.7 - 55.8	caliche
55.8 - 56.4	medium sand
56.4 - 56.7	clay
56.7 - 58.5	medium sand
58.5 - 59.4	caliche
59.4 - 61.0	medium sand

61.0 - 62.5	caliche
62.5 - 63.1	medium sand
63.1 - 64.0	clay

Site 3, well installed by the Kansas Geological Survey in 1987
total depth = 46.3 m, screened depth = 37.2 m - 46.3 m, water level = 31.8 m

Depth (m)	Geology
0 - 9.5	clay
9.5 - 18.3	sand and gravel
18.3 - 18.6	clay and fine sand
18.6 - 19.2	sand and gravel
19.2 - 25.3	sand, silt, and clay
25.3 - 46.3	sand and gravel

Site 4, well installed by commercial driller, year unknown
no information regarding well construction available, water level = 50 m*

Depth (m)	Geology
0 - 44.2	"top"
44.2 - 47.2	fine sand and gravel
47.2 - 48.5	medium gravel
48.5 - 50.3	sandy clay and fine sand
50.3 - 52.1	sandy clay
52.1 - 56.4	sandy clay lenses and medium gravel
56.4 - 59.4	medium gravel
59.4 - 61.3	fine sand and medium gravel
61.3 - 62.5	fine sand
62.5 - 64.0	sandy clay lenses, fine sand, and medium gravel
64.0 - 67.4	sandy clay
67.4 - 68.6	medium gravel
68.6 - 70.4	no information
70.4 - 74.7	sandy clay lenses and medium gravel
74.7 - 77.1	sandy clay
77.1 - 86.9	no information
86.9 - 90.5	Pierre Shale

Site 5, well installed by commercial driller in 1987
total depth = 59.4 m, screened depth = 47.2 m - 59.4 m, water level = 43.0 m*

Depth (m)	Geology
0 - 0.6	top soil
0.6 - 13.7	clay
13.7 - 28.0	medium to coarse gravel
28.0 - 32.3	coarse gravel with clay lenses
32.3 - 35.1	fine to medium gravel with clay lenses
35.1 - 36.9	clay
36.9 - 39.6	clay with thin gravel lenses
39.6 - 42.4	clay with cementation zones, caliche (?)
42.4 - 42.7	caliche
42.7 - 44.2	fine gravel

44.2 - 46.0	caliche
46.0 - 48.8	caliche,clay lenses
48.8 - 52.4	caliche, thin gravel lenses
52.4 - 56.7	caliche, clay lenses
56.7 - 61.0	fine to medium gravel

Site 6, 2 wells (6a and 6b) were installed in a well nest by the Kansas Geological Survey in 1988, no log was available for well 6c, which was installed by a commercial driller
well 6a: total depth = 37.2 m, screened depth = 33.5 m - 36.6 m, water level = 32.9 m*
well 6b: total depth = 59.4 m, screened depth = 42.7 m - 45.7 m, water level = 32.9 m*
well 6c: total depth = 57.9 m , screened depth = 51.8 m - 57.9 m, water level = 32.9 m*

Depth (m)	Geology
0 - 0.9	top soil
0.9 - 8.4	grey silty clay, some caliche
8.4 - 8.8	light grey clay with sand and gravel lenses
8.8 - 11.3	light grey sandy clay
11.3 - 11.9	sand and gravel
11.9 - 15.5	white sandy clay
15.5 - 19.3	tan/pinkish and white clays, sand
19.3 - 24.4	sand and gravel with clay lenses
24.4 - 27.1	greenish/grey sandy clay
27.1 - 31.1	grey/pink clay with sand and gravel lenses
31.1 - 33.5	sand and gravel
33.5 - 33.8	clay
33.8 - 37.8	sand and gravel with clay lenses
37.8 - 39.9	tan and white clays with sand and gravel lenses
39.9 - 45.7	sand and gravel, some caliche
45.7 - 48.5	sand
48.5 - 48.8	hard zone, caliche (?)
48.8 - 50.0	sand and gravel
50.0 - 55.5	pinkish/tan sandy clay with sand and gravel lenses
55.5 - 55.8	sand
55.8 - 57.0	grey sandy clay
57.0 - 59.4	ocher, tan, and grey clays, more orange with depth, shale pieces

Site 7, well installed by the Kansas Department of Health and Environment in 1987
total depth = 9.8 m, screened depth = 6.4 m - 9.4 m, water level = 7.18 m*

Depth (m)	Geology
0 - 0.9	brown silty clay
0.9 - 1.8	red/brown sandy silt
1.8 - 2.4	white cemented sand, silt and gravel, mortar bed
2.4 - 5.5	fine sand
5.5 - 5.8	caliche and white clay
5.8 - 7.0	caliche, mortar bed
7.0 - 10.7	clay and sand
10.7 - 13.7	fine to medium sand
13.7 - 15.8	coarse sand and gravel

Site 8, well installed by a commercial driller in 1979
total depth = 27.4 m, screend depth = 24.4 m - 27.4 m, water level = 18.3 m*

Depth (m)	Geology
0 - 12.2	clay
12.2 - 18.3	clay and fine sand
18.3 - 26.5	sand and gravel
26.5 - 27.4	Pierre Shale

Site 9, well installed by a commercial driller in 1987
total depth = 53.6 m, screened depth = 38.4 m - 53.6 m, water level = 36 m*

Depth (m)	Geology
0 - 0.9	top soil
0.9 - 14.3	clay
14.3 - 25.0	caliche
25.0 - 28.6	fine sand
28.6 - 29.6	caliche
29.6 - 37.2	clay
37.2 - 40.5	caliche
44.4 - 46.3	medium sand
46.3 -55.6	Pierre Shale

Site 10, 2 wells were installed by the Kansas Geological Survey in 1988
well 10a: total depth = 7 m, screened depth = 4 m - 7 m, water level = 3.6 m*
well 10b: total depth = 132.3 m, screened depth = 27.7 m - 32.3 m, water level = 3.6 m*

Depth (m)	Geology
0 - 2.1	dark brown silty clay
2.1 - 4.0	greyish/brown silty clay
4.0 - 10.7	coarse sand with mollusk shells
10.7 - 12.5	tan clay and caliche, sandy at 39 ft
12.5 - 14.6	gravelly sand
14.6 - 16.1	fine and interbedded with clay and coarse sand
16.1 - 16.5	tan clay
16.5 - 18.0	sand and gravel interbedded with clay
18.0 - 21.9	tan clay interbedded with sand and gravel
21.9 - 25.3	fine sand interbedded with clay
25.3 - 26.5	tan clay
26.5 - 30.2	tan clay interbedded with sand and gravel
30.2 - 31.1	fine sand
31.1 - 31.7	sandy clay
31.7 - 32.3	sandy clay with gravel lenses
32.3 - 33.8	grey weathered shale

Site 11, 2 wells were installed in a well nest by the Kansas Geological Survey in 1988
well 11a: total depth = 61.5 m, screened depth = 53.3 m - 59.4 m, water level = 52.1 m*
well 11b: total depth = 73.1 m, screened depth = 68.6 m - 73.1 m, water level = 52.1 m*

Depth (m)	Geology
0 - 0.6	dark grey top soil
0.6 - 9.1	tan/brown silt, some caliche, mollusk shells
9.1 - 16.5	tan sandy silt

16.5 - 20.1	sand and gravel with clay lenses
20.1 - 25.6	pinkish/tan siltstone with sandy clay and sand lenses, some caliche
25.6 - 29.0	pinkish/tan sandy clay
29.0 - 31.7	medium sand with clay lenses
31.7 - 39.9	pinkish/tan clay with sand and gravel lenses
39.9 - 45.4	sand and gravel, some caliche
45.4 - 48.8	grey/tan sandy clay with sand and gravel lenses
48.8 - 51.5	white sandy clay
51.5 - 56.1	coarse sand
56.1 - 56.4	hard zone, caliche (?)
56.4 - 57.0	coarse sand
57.0 - 58.5	white and grey clays
58.5 - 61.3	sand and gravel
61.3 - 61.6	hard zone
61.6 - 62.8	white sandy clay
62.8 - 63.4	sand and gravel
63.4 - 66.7	white sandy clay
66.7 - 68.3	tan clay with sand lenses (hard)
68.3 - 73.9	sand and gravel with clay lenses
73.9 - 77.4	grey shale, Pierre Shale

* below landsurface

Appendix B

Sampling procedures

To avoid contamination the samples were taken using a Bennett sample pump, provided by the Groundwater Management District. Only at one site, site 7, the sample had to retrieved by using a PVC bailer.

The wells were pumped about 1 hour at a rate of 0.04 m^3/sec prior to sampling to ensure that fresh formation water was sampled.

Samples for the analysis of calcium, magnesium, sodium, potassium, strontium, bicarbonate, sulfate, chloride, fluoride, and silica were collected in a 500 ml unacidified plastic bottle. A sample of 200 ml was acidified with 2 ml 6 molar HCL was collected from each well for the analysis of nitrate and trace metals. However, trace metals were not analyzed consistently for all water samples.

Samples for tritium, stable isotopes, and freon were collected at the same time as the samples for standard inorganic analyses. However, these particular samples were collected in glass bottles with a teflon lined closure. No preservatives were used. For direct count tritium analyses, water samples were collected in 150 ml clear glass bottles. For enriched tritium analyses, 500 ml of sampling water were required, this amount was collected in 500 ml clear glass bottles.

Water samples for stable isotope analyses were collected in 150 ml clear glass bottles, although only 10 ml of water are necessary to perform the actual analyses. The analyses of freon from water samples required 500 ml of sample water, which was collected in 500 ml clear glass bottles.

Samples for atrazine were collected in 2 gallon glass jugs. All sample bottles were filled in such manner that no headspace was present in the bottle. From the time the samples were collected to the time they arrived at the Kansas Geological Survey, the samples were stored in ice chests filled with crushed ice. Upon arrival the samples were refrigerated. Standard inorganic chemistry analyses were performed at the

Kansas Geological Survey laboratories, whereas samples for all other above mentioned constituents were shipped to commercial laboratories.

Analytical procedures

Standard inorganic chemistry analyses were performed at the Kansas Geological Survey laboratories.

Analyses for calcium, magnesium, sodium, potassium, strontium, silica, and the trace metals were performed on a Jarrel-Ash inductivity-coupled plasma (ICP) unit. The bicarbonate concentration was measured by potentiometric titration using an autotitrimeter. Chloride, sulfate, and nitrate levels were determined employing a Technicon Auto-Analyzer 2 system. Fluoride analyses were by ion-selective electrode.

No duplicate sets of samples were taken. In table B.1 standard deviations based on hundreds of previous samples analyzed at the Kansas Geological Survey laboratories are listed (Hathaway et al., 1979,1981).

Table B.1: Standard deviations for inorganic analyses performed at the Kansas Geological Survey laboratories (Hathaway et al., 1979, 1981)

Constituent	$\pm\sigma$
SiO_2	1.35 ppm
Ca	1.3 ppm
Mg	0.6 ppm
Na	1.6 ppm
K	0.2 ppm
Sr	0.05 ppm
HCO_3	0.9 ppm
SO_4	1.95 ppm
Cl	1.7 ppm
F	0.04 ppm
NO_3	0.85 ppm
Fe	17 ppb
Mn	8.7 ppb
Spec. Cond.	15 µmhos/cm at 25 °C

All samples collected during phase 1 of the study were also field checked for nitrite. A portable Hach DR/1A colorimeter was used for this purpose.

Field measurements of water temperature, pH, and specific conductivity were taken at the time of sample collection. PH and specific conductivity measurements were repeated in the laboratory using a Labline meter calibrated at 25 °C for the specific conductivity determination and an autotitrimeter for the pH determination.

Atrazine

Atrazine was determined in soil extract solutions and ground water water samples at the Kansas State Board of Agriculture Pesticide Laboratory using a Hewlett Packard 5890A Gas Chromatograph with an HP5470 mass selective detector. Atrazine extraction efficiencies from soils were between 95 % and 100 %.

Determination of atrazine in ground water

Reference method: Method 507: Determination of nitrogen- and phosphorus-containing pesticides in ground water by gas chromatography with a nitrogen-phosporus detector, September 1986 supplement to: Methods for the determination of organic compounds in finished drinking water and raw source water, Physical and Chemical Methods Branch, Environmental Monitoring and Support Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Summary of method: A 1 liter volume of sample (or volume available diluted to 1 liter) is extracted with methylene chloride; the extract is dried through anhydrous sodium sulfate, concentrated to dryness, and the residue is taken up in 5.0 m l hexane. The extract is then scanned for atrazine using a Hewlett Packard 5710 gas chromatograph with a nitrogen/phosphorus detector. Any sample extracts positive for atrazine are confirmed and secondarily quantitated using a Hewlett Packard 5890A gas chromatograph with an HP 5970 mass selective detector in the "single ion monitoring mode" specifically for atrazine.

Determination of atrazine in soil

Reference method: Method 3550: Sonication extraction, in: Test methods for evaluating soil waste, vol. 1B, Laboratory manual physical/chemical methods, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C., November 1986, SW-846, 3rd. edition.

Summary of method: 50 g of sample are sonicated with 200 ml of 1:1 hexane:acetone. The extract is decanted, concentrated to dryness, and the residue is taken up in 10 ml of hexane. The extract is scanned and quantitated using a Hewlett Packard 5890A gas chromatograph with an HP 5970 mass selective detector in the "single ion monitoring mode" specifically for atrazine.

Determination of nitrate in soils

Nitrate was determined in soil extract solutions at the Kansas State University Soil Testing Laboratory using Technicon Auto Analyzer 2 system. The detection limit is 0.02 mg nitrate (N) / l.

Reference method: Method 487-77A, Armstrong, F.A.J., Sterns, C.R., and Strickland, J.D.H., 1967: The measurement of upwelling and subsequent biological processes by means of the Technicon Auto Analyzer and associated equipment, Deep-Sea Research, 14, pp. 381-389; Grasshoff, K., 1969: Technicon international congress.

Summary of method: The submitted amount of dry soil sample is ground up and 2 g of dry soil are weighed into an 50 ml Erlenmeyer flask and 20 ml 2 N KCl are added; the extract is shaken for 1 hour. The extract is filtered through Whatman #41 filter paper and subsequently run through the Technicon Auto Analyzer 2 system using a 1 ppm nitrate (N) standard prepared in 2 N KCl. The nitrate in the extract is reduced to nitrite by a copper-cadmium reductor column. The nitrite ion then reacts with sulfanilamide under acidic conditions to form a diazo compound. This compound then couples with N-1-naphthylethylenediamine dihydrochloride to form a reddish-purple azo dye.

Determination of tritium in ground water and in soils

Tritium was determined in ground water samples and in soil extract solutions. The analyses were performed at the Environmental Isotope Laboratory of the University of Waterloo, Ontario, Canada using a Packard 4530 or a Packard 1550 liquid scintillation counter. A laboratory standard, made by diluting NBS-4361 tritium reference material with background water, is used. The standard is calibrated to NBS-4926C which is run directly in the counter. The standard is corrected monthly for tritium half-life decay. The background water is from a well with a radiocarbon activity older than 3500 years and a conductivity of less than 2 sigma increase in cpm as compared to direct counting. The detection limit for enriched tritium is 0.8 TU with an error value of +/- 0.8 TU. The detection limit for direct count tritium is 6 TU with an error limit of +/-7 TU or +/- 8 TU.

Reference methods: Packard, 1986: Tri Carb liquid scintillation analyzer model 1500 operation manual, Rev. A. Publication no. 169-3059, Packard Instrument Co., Inc.; Raylor, C.B., 1977: Tritium enrichment of environmental waters by electrolysis: development of cathodes exhibiting high isotopic separation and precise measurement of tritium enrichment factors, proceedings of the International Conference of Low-Radioactivity Measurements and Applications, Slovenski Pedagogicke Nakladatelstvo, Bratislava, pp. 131-140.

Summary of method: 250 ml of sample water are vacuum distilled to about 15 ml; for enrichment 8 g of 30 dpm/g tritium standard is diluted up to 250 g with background water (dead water), the distilled water sample is added. One half of this mixture is poured into the anode of a 300 ml metall cell, designed by IAEA, 25 1 g aliquots of sodium peroxide are added. The so prepared cell is run through electrolysis together with 3 cells containing backgrounds and 1 cell deionized lab water. The sample is again vacuum distilled. For direct count tritium analyses, 10 ml of sample are required.The procedure starts with a vacuum distillation, which is identical with the last vacuum distillation of the enriched water samples. The actual counting procedure is the same for enriched and direct tritium analyses. A Canberra-Packard Pico-fluor low level tritium cocktail is added to the samples; 10 ml of the cocktail are added to samples for direct count tritium analyses, and 8 ml of the cocktail are added to samples for enriched tritium analyses. A Packard 4530 or a Packard 1550 liquid scintillation counter is used to count the tritium in the samples, the result is tritium in cpm (counts per minute). The laboratory reports the data in TU (tritium units).

Determination of tritium in soils

At least 500 g of soil at 1 % saturation with water or a minimum of 15 ml of soil water is required for analyses. The necessary amount of soil is is broken up into a 1000 ml Erlenmeyer flask (max. 1/3 full). Toluene is added until the soil is just covered. An azeotropic distillation is performed, the soil water is extracted. The rest toluene is removed from the distilled extract by adding a 2 mm layer of melted hydrocarbon wax (parafin) on top of the extract. When the wax solidifies, the water, now free of hydrocarbons, is separated.

The analytical procedures from there on are the same ones as described for tritium analyses from water in the above section.

Determination of deuterium in ground water

The analyses were performed at the Environmental Isotope Laboratory at the University of Waterloo, Ontario, Canada and the laboratories of Krueger Enterprises, Inc., Geochron Laboratory Division, Massachusetts, U.S.A.. Most of the analyses were performed, however, at the University of Waterloo. Thus in the following only the analytical procedures used by the University of Waterloo are described.

Reference method: Coleman, M.L., Shepherd, T.J., Durham, J.J., Rouse, J.E., and Moore, G.R., 1982: Reduction of water with zinc for hydrogen isotope analysis, Analytical Chemistry, pp. 993-995.

Summary of method: 70g to 75 g of the -30 to +60 mesh fraction of zinc are placed into an 125 ml Erlenmeyer flask, enough 25 % HNO_3 are added to cover the zinc and swirl the flask. Deionized water is added to stop the reaction, excess liquid is removed. This procedure is repeated twice. 10 % HNO_3 are added to cover the zinc and deionized water is added to stop the reaction, excess water is removed, the process is repeated. The zinc is then washed with acetone to remove all water traces. For 1 hour a vacuum is applied under 300 ^{0}C. To 400 mg of the so prepared zinc 10 micro l of sample are added, the solution is frozen down with a methanol/dry ice slush. Vacuum is applied and the solution is then heated at 460 ^{0}C for 45 minutes. After cooling to room temperature, the resulting hydrogen gas is analyzed on the mass spectrometer .

Determination of oxygen-18 in water

The analyses were performed at the Environmental Isotope Laboratory at the University of Waterloo, Ontario, Canada, and at the laboratories of Krueger Enterprises, Inc., Massachusetts, U.S.A.. Most of the analyses were performed at the University of Waterloo, so only these particular analytical procedures are described.

Reference methods: Epstein,S., and Mayeda, T.K., 1953: Variations of the $^{18}O/^{16}O$ ratio in natural waters, Geochim. et Cosmochim. Acta, vol. 4, p. 213; Fritz, P., Frape, S.K., Drimmie, R.J.. and Heemskerk, A.R., 1986: Reply to comments by Grabczak et al. on "Water-rock interaction and chemistry of groundwaters from the Canadian Shield", Geochi. et Cosmochim. Acta, vol. 50, pp. 1561-1563; Moser, H. (ed.), 1977: Jahresbericht 1977, Internal reports of the Institut fuer Radiohydrometrie, GSF Muenchen, 169, pp. 70-71; Gonfiantini, R., 1984: Report of the advisory group meeting on stable isotope reference samples for geochemical and hydrological investigations, IAEA, Internal Report, p. 77.

Summary of method: One drop of 85 % phosphoric acid is added to a 30 ml reaction vessel, 8 ml of sample are added subsequently. Slightly positive pressure of Coleman Instrument Grade carbon dioxide (99.999 % pure) is introduced to the samples.The phosphoric acid facilitates degassing and equilibration of the water with the CO_2. In a temperature controlled bath the samples are shaken continuously overnight. Carbon dioxide gas is then extracted through a methanol-dry ice trap (-76 ^{0}C removes water vapor) and introduced to a Micromass 903 triple collector SIRA mass spectrometer. The preparation and extraction of the CO2 is done on a fully automated system attached to a Micromass 903 mass spectrometer. Reference gas is Coleman CO2 calibrated versus V-SMOW. All results are reported with respect to V-SMOW.

Determinatuon of Freon in ground water

Freon samples were analyzed at Global Geochemistry Corporation laboratories in California.

Reference methods: U.S. Environmenmtal Protection Agency Method 8010: Guidelines establishing test procedures for the analysis of pollutants under the Clean Water Act; final rule and interim rule and proposed rule, part 136, October 26, 1984; Bellar, T.A., nd Lichtenberg, J.J., 1979: Semi-autimated headspace analysis of drinking waters and industrial waters for purgeable volatile organic compunds, in: Measurement of organic pollutants in water and wastewater,van Hall (ed.), ASTM STP 686, pp. 109-129.

Summary of method: 5 ml of sample are introduced into a gas chromatograph by using the Teckmar Dynamic Head Space concentrator. A temperature program is used in the gas chromatograph to separate the organic compounds. Detection is achieved by a halogen-specific detector (HSD).

Appendix C

Parameters of the unsaturated zone, sites 3 and 11.

Table C.1 : Particle size distribution and calcium carbonate content at site 11

Depth (m)	Sand (w%)	Silt (w%)	Clay (w%)	$CaCO_3$ (%)
0.09 – 0.14	12.46	62.56	24.98	2.51
0.6 – 0.73	6.78	73.76	19.46	6.06
0.87 – 0.93	3.97	60.77	35.26	5.18
1.57 – 1.65	5.83	86.28	7.89	6.45
2.29 – 2.44	6.64	77.22	16.14	4.68
3.50 – 3.57	5.08	77.57	17.34	5.88
4.39 – 4.45	5.21	80.08	14.70	8.21
4.95 – 5.01	4.79	75.63	19.58	3.73
5.96 – 6.02	4.54	86.79	8.66	7.58
6.11 – 6.17	13.31	63.61	23.07	5.24
6.90 – 6.96	27.53	56.99	15.48	20.54
7.30 – 7.39	22.58	52.36	25.06	10.37
7.66 – 7.73	23.01	70.74	6.25	10.59
7.77 – 7.80	40.33	45.02	14.65	10.78
8.02 – 8.08	46.15	25.61	28.24	42.88
8.32 – 8.40	44.23	38.95	16.82	19.09
8.53 – 8.59	28.41	48.90	22.68	22.61
8.93 – 9.00	16.59	78.79	4.62	28.21
9.08 – 9.12	38.93	28.59	32.47	11.99
9.20 – 9.50	27.06	57.80	15.14	11.15
10.02 –10.08	10.06	63.80	26.14	34.55
10.20 –10.23	8.01	62.80	29.20	13.04
10.78 –10.81	16.92	58.59	24.48	9.61
11.30 –11.36	16.10	68.30	15.60	6.28
11.82 –11.88	19.22	68.48	12.30	6.65
12.12 –12.18	18.61	53.87	27.52	4.50
12.62 –12.68	40.96	44.08	14.96	7.54
18.29 –19.08	90.98	9.02	0.00	6.69
20.48 –20.54	48.46	40.81	10.73	3.59
20.63 –20.73	74.48	14.96	10.56	4.78
20.85 –21.49	66.55	15.18	18.28	2.90

Table C.2 : Moisture content in the unsaturated zone at site 11. June 1989

Depth (m)	moisture (w%)	moisture (g)
0.0-0.6	16.30	5.06
0.6-1.2	11.55	3.75
1.2-1.8	11.36	3.58
1.8-2.0	13.33	4.27
2.0-2.65	16.18	5.10

2.65-3.10	16.53	4.96
3.10-3.70	16.66	5.23
3.70-4.13	17.56	5.47
4.13-4.74	18.29	5.45
4.74-5.13	21.24	6.32
5.13-5.74	21.89	6.45
5.74-6.14	22.90	6.60
6.14-6.84	19.97	5.95
6.84-7.45	15.27	4.68
7.45-8.05	16.23	4.93
8.05-8.66	15.05	5.43
8.66-9.11	16.12	4.90
9.11-9.30	16.76	5.23
9.30-9.91	21.53	6.20

Table C.3 : Moisture content in the unsaturated zone at site 11, September 1989

Depth (m)	moisture (w%)	moisture (g)
0.0-0.6	14.15	3.72
0.60-1.31	9.49	2.60
1.31-1.92	11.03	2.98
1.92-2.38	10.25	2.79
2.38-2.99	10.78	2.92
2.99-3.47	11.48	3.09
3.47-4.08	11.77	3.16
4.08-4.60	13.04	3.46
4.60-5.21	14.46	3.79
5.21-5.73	14.42	3.78
5.73-6.34	16.69	4.29
6.34-6.92	17.89	4.55
6.92-7.53	15.43	4.01
7.53-7.98	13.46	3.56
7.98-8.59	12.95	3.44
8.59-9.11	12.65	3.37

Table C.4 : Moisture content in the unsaturated zone at site 11, November 1989

Depth (m)	Moisture (w%)	Moisture (g)
10.9-11.45	21.01	5.21
12.5-13.1	18.81	4.76
14.3-14.9	17.86	4.55
16.4-16.7	5.73	1.63
18.0-18.6	2.66	0.78
20.7-21.3	14.96	3.91

Table C.5 : Particle size distribution and calcium carbonate content at site 3

Depth (m)	Sand (w%)	Silt (w%)	Clay (w%)	$CaCO_3$ (%)
0.33 - 0.40	9.93	64.01	26.06	1.97
0.61 - 0.67	8.37	67.20	24.43	5.20

1.07 – 1.13	4.54	71.19	24.26	5.02
1.57 – 1.66	9.67	77.92	12.41	5.03
.62 – 3.10	5.25	64.28	30.47	5.73
3.05 – 3.08	0.49	62.31	37.20	13.43
6.60 – 6.66	14.88	46.39	38.72	10.03
6.84 – 7.41	16.71	43.71	40.11	13.07
9.30 – 9.34	28.55	45.20	26.24	2.19
9.96 – 10.02	20.20	47.93	31.87	1.99
10.50 – 10.79	12.56	62.50	24.94	2.15
19.29 – 19.32	42.21	47.74	10.05	3.34
19.32 – 19.35	62.87	31.75	5.37	2.11
19.69 – 19.90	22.05	54.63	23.31	2.60
20.30 – 20.36	68.93	23.68	7.39	3.13
20.66 – 20.73	69.09	24.23	6.68	5.71
21.37 – 21.49	51.15	36.59	12.26	2.77