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# HYDROLOGIC RESPONSE OF AQUIFERS TO DROUGHTS IN THE GREAT PLAINS, U.S.A.

By M. S. Bedinger

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CONTENTS


| | Page |
|---|---|
| Abstract | 1 |
| Introduction | 2 |
| The drought | 2 |
| South Platte River valley of Colorado | 4 |
| Ogallala aquifer of western Kansas | 7 |
| Sand Hills of Nebraska | 9 |
| Pleistocene aquifer of northeastern Nebraska | 11 |
| Conclusions | 14 |
| Acknowledgments | 15 |
| References cited | 16 |

ILLUSTRATIONS

Page

Figure 1. Map showing areas of study ----------------------- 3

## TABLES

Page

Table 1. Annual precipitation, in millimeters, at stations in the Great Plains, 1966 through 1977 ------------ 5

2. Average depths to water, in meters, in wells in the alluvial aquifer of South Platte River, 1968-1978 ------------------------------------- 7

3. Mean annual flows, in cubic meters per second, of streams in the Sand Hills of Nebraska ---------- 10

4. Average water levels in wells in the Sand Hills and Pleistocene aquifers, 1968-1978 -------------- 12

5. Mean annual flows, in cubic meters per second, of streams in the Elkhorn River basin of Nebraska ------------------------------------ 14

# HYDROLOGIC RESPONSE OF AQUIFERS TO DROUGHTS IN THE GREAT PLAINS, U.S.A.

By M. S. Bedinger


## Abstract

The hydrologic response of the aquifers to the drought of the mid-1970's varied significantly. The response depended upon the aquifer systems natural physical and hydraulic characteristics and stresses imposed by man. The variable response is illustrated by study of four northeastern aquifer systems in the region (1) Ogallala aquifer of Kansas, (2) Sand Hills aquifer of western Nebraska, (3) Pleistocene aquifer of northeastern Nebraska, and (4) The alluvial aquifer of the South Platte River valley, Colorado. The Ogallala aquifer is an areally extensive water table aquifer heavily tapped for irrigation supplies. In western Kansas declines increased averaging 1 cubic meter in 1976 compared to an average decline of between 0.3 to 0.6 m during the preceding 11 years. Water levels in the Sand Hills aquifer of Nebraska declined because of reduced recharge, but base flow from the areally extensive aquifer was not greatly reduced. The alluvial aquifer of the South Platte River valley contains a relatively small amount of water in storage. Water levels declined in response to increased withdrawals

from wells and decreased return flow from irrigation. Recharge to the Pleistocene aquifer of eastern Nebraska is local and discharge is to nearby streams. The storage is relatively small for a water table aquifer and the transmissivity is low. Water levels in the Pleistocene aquifer declined in response to the drought and the base flow to streams decreased to 50 to 80 percent of normal.

## Introduction

The effects of droughts upon ground-water reservoirs varies with the natural characteristics of the aquifers and the degree of man-induced stress on the aquifer system. Thus meteorologic trends in precipitation, solar radiation, wind, and temperature are reflected quite differently in aquifers having different natural characteristics and different man-induced stresses. This report is a general discussion of the effect of the drought of the mid-1970's as a recorded meteorological phenomenon and as the integrated effects of natural and man-induced stress observed in four aquifer systems in the Great Plains of the U.S.A.

The aquifer systems studied here include (1) the Ogallala aquifer of western Kansas, (2) the alluvial aquifer of the South Platte River valley of Colorado, (3) the Sand Hills aquifer of western Nebraska, and (4) the Pleistocene aquifer of northeastern Nebraska (fig. 1).

## The Drought

Above normal annual precipitation prevailed in the region during

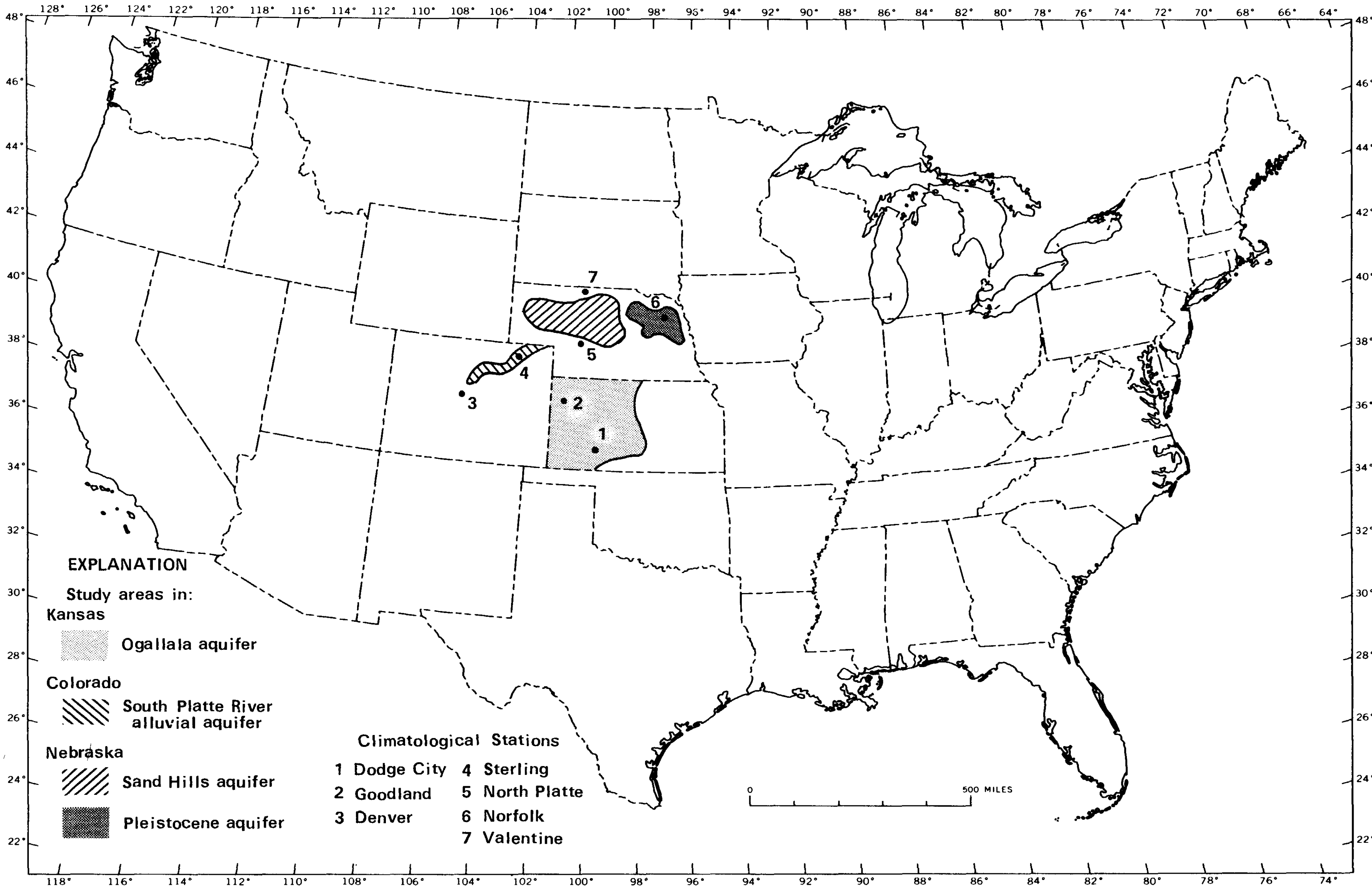


Figure 1.--Map showing areas of study.

1971, 1972, and 1973 (table 1). The drought was strongly evident in 1974 when precipitation was uniformly below normal and as much as 50 percent of normal in northeast Nebraska. The drought persisted through 1975 and 1976. The drought ended in 1977 as indicated by comparison of annual precipitation with normal annual precipitation.

The severity of the mid-1970's drought can be compared to the drought of the 1950's - one of the severest droughts of record for the southern Great Plains - by the use of the average accumulated deficiency of precipitation per year (AADP). The AADP for the area of study during 1952-56 (Nace and Pluhowski, 1965) ranged from 36 percent in southwestern Kansas, 27 percent in northwestern Kansas, 18 percent in northeastern Colorado and 20 percent in central and north-central Nebraska. The AADP for the study area during 1974-76 ranged from 10 percent in southwestern Kansas, 21 percent in northwestern Kansas, 17 percent in northeastern Colorado, 22 percent in central Nebraska, and 38 percent in north-central Nebraska. Thus, the mid-1970's drought was of shorter duration than the drought of the mid-1950's. Over most of the area the mid-1970's drought was less severe with the notable exception of north-central Nebraska.

## South Platte River Valley of Colorado

The segment of the South Platte River valley of Colorado studied extends 322 km from near Denver, Colo., to the Colorado-Nebraska State line (fig. 1). The valley underlain by the alluvial aquifer occupies 2,460 $km^2$, a little more than half of which is irrigated. An excellent description of the hydrology of the stream-aquifer system is given in

Table 1.--Annual precipitation, in millimeters, at stations in the Great Plains, 1966 through 1977

[Locations of climatological stations are shown in figure 1. Values in parentheses are the 1941 to 1970 normal annual precipitation; underlined values are less than the 1941 to 1970 normal annual precipitation]

| | Kansas | | Colorado | | Nebraska | | |
|---|---|---|---|---|---|---|---|
| Calendar Year | Dodge City (523) | Goodland (423) | Denver (400) | Sterling (380) | North Platte (505) | Norfolk (618) | Valentine (452) |
| 1966 | 359 | 290 | 275 | 341 | 446 | 534 | 478 |
| 1967 | 541 | 399 | 592 | 522 | 443 | 566 | 379 |
| 1968 | 706 | 348 | 308 | 399 | 433 | 584 | 520 |
| 1969 | 477 | 474 | 547 | 479 | 386 | 693 | 293 |
| 1970 | 311 | 335 | 349 | 291 | 412 | 643 | 351 |
| 1971 | 642 | 444 | 278 | 389 | 616 | 590 | 451 |
| 1972 | 787 | 535 | 428 | 426 | 416 | 657 | 452 |
| 1973 | 823 | 532 | 583 | | 552 | 743 | 591 |
| 1974 | 504 | 334 | 356 | 217 | 309 | 309 | 268 |
| 1975 | 478 | 432 | 394 | 346 | 411 | 501 | 284 |
| 1976 | 427 | 234 | 341 | 291 | 466 | 472 | 285 |
| 1977 | 562 | 510 | 263 | 507 | 632 | 919 | 830 |

Hurr and Schneider (1975), from which the following is largely taken. Irrigation water during the period 1947-70 averaged 1,210 x $10^6$ $m^3$ annually from surface water and 518 x $10^6$ $m^3$ annually from ground water. About 50 percent of the applied irrigation water recharges the ground-water system; a large part of which ultimately seeps into the river. In the South Platte River valley, surface water and ground water are two components of one hydraulic system, and analyses of stresses on the system, be they natural or man induced, must consider the interrelation between them.

The surface-water supply in the area is augmented by transmountain diversions from the Colorado and Laramie River basins. Since 1954, transbasin diversions have increased the flow of the South Platte River by an average of about 179 x $10^6$ $m^3$ per year.

Wells have been used to obtain water for irrigation since 1900, although significant installation of wells did not begin until 1934. By 1970 there were over 3,000 large capacity irrigation wells (greater than 0.0063 $m^3/s$) within the study area.

Average annual water levels in wells in the alluvial aquifer measured in the spring are shown in table 2.

Table 2.--Average depths to water, in meters, in wells in the alluvial aquifer of South Platte River, 1968-1978

| | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Average | 8.31 | 8.43 | 8.38 | 8.11 | 8.35 | 8.21 | 7.67 | 7.82 | 7.77 | 8.01 | 8.21 |
| Annual Change | -- | -.12 | +.05 | +.27 | -.24 | +.14 | +.54 | -.15 | +.05 | -.24 | -.20 |

The effect of drought on water levels in the alluvial aquifer is thus the combined effect of decrease in natural recharge, increased withdrawal of ground water for irrigation, and changes in recharge from applied surface and ground water. Because, a large part of the irrigation water is surface water from upstream parts of the basin and from transbasin diversions, drought conditions in the local area have a minor direct effect on ground-water levels.

## Ogallala Aquifer of Western Kansas

The Ogallala aquifer underlies an area of 404,000 km$^2$ in the Great Plains from Texas to South Dakota. In western Kansas (fig. 1) the Ogallala Formation of late Tertiary age is from 30 to 120 m in thickness and is composed largely of sand and gravel. The lower part of the

Ogallala is saturated with water and is a major source of water for irrigation. In western Kansas, the Ogallala was tapped by over 11,000 large capacity wells by 1974. Withdrawal of water for irrigation is in excess of ground-water recharge and a classical case of ground-water mining exists. Historically water levels have declined since development began because the aquifer is being progressively depleted. Droughts are reflected as increased water level declines in the Ogallala aquifer primarily through increased withdrawal for irrigation.

The effect of the drought of the mid-1970's on water levels is documented in the report by Pabst (1978). Measurements of depth to water are made in midwinter, mostly January, in about 1,100 wells. The measurements show that the water table in northwestern Kansas declined an average of about 0.7 m during 1977, 0.7 m during 1976, and 0.7 m in 1975, and an average annual decline of less than 0.3 m during the 12-year period; the water table in west-central Kansas declined an average of about 0.7 m in 1977, 1 m in 1976, 1 m in 1975 and an average annual decline of 0.5 m during the 12-year period prior to 1975; in southwestern Kansas the water table declined an average of 1.3 m in 1977, 1.5 m in 1976, and 1.3 m in 1975. The average annual decline for the 12-year period prior to 1975 was 0.7 m.

The greater declines in 1975 and 1976 are attributed primarily to the drought causing an increase in withdrawal of ground water. Declines were less during 1977 in west-central and southwest Kansas following the drought. Average annual declines lessened further in 1978 with less than 0.5 m decline in northwest and west-central Kansas and 0.75 m decline in southwest Kansas.

## Sand Hills of Nebraska

In central Nebraska, north of the Platte River, the principal aquifer consists of the Ogallala Formation, Pleistocene fluvial deposits, and an overlying thick section of wind blown sand. This region of about 50,000 $km^2$ is called the Sand Hills (fig. 1). The permeable nature of the sands on the surface permits rapid infiltration of precipitation. As a result, there is little or no direct surface runoff. It has been estimated that as much as 25 percent of the precipitation is recharged to the water table (Lohman, 1953). The water table is near the land surface, and streams draining the Sand Hills are fed by ground water. The area is not heavily developed for ground-water withdrawal for irrigation. Mean annual flows of streams in the Sand Hills are remarkably uniform from year to year as shown in table 3. Streams were not greatly affected by the drought of the mid-1970's.

Table 3.--Mean annual flows, in cubic meters per second, of streams in the Sand Hills of Nebraska

| Stream | Calendar Year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 |
| Middle Loup River at Dunning *11.3 | 11.3 | 11.3 | 11.9 | 11.7 | 11.2 | 11.1 | 11.7 | 11.6 |
| Snake River above Merritt Dam *5.78 | 5.66 | 5.55 | 5.81 | 5.78 | 5.83 | 5.75 | 5.78 | 5.78 |
| Calamas River near Burwell *8.47 | 8.16 | 7.87 | 8.75 | 8.44 | 8.01 | 8.24 | 8.69 | 9.06 |
| Dismal River near Thedford *5.41 | 5.44 | 5.44 | 5.44 | 5.35 | 5.35 | 5.41 | 5.47 | 5.47 |

* Mean for period of record.

Base flow of a stream is that part of streamflow derived from ground-water discharge. Base flow declines gradually during fair weather as ground-water storage is depleted. The recession curve can be synthesized from a streamflow record by graphical procedures (Horton, 1933). Rorabaugh (1964) found that once sufficient time has elapsed after a recharge event, the recession curve can be represented by a straight line on a semilogarithmic plot. The decline of base flow from a ground-water basin over a period of time is related to the ground-water basin time constant. Expressing this as the time in days ( t/cycle) for base flow to recede through one log cycle of flow,

$$\Delta t/\text{cycle} = \frac{0.933a^2S}{T}$$

The time constant is a function of the transmissivity, T, and storage coefficient, S, of the aquifer and the mean distance from the stream to the ground-water divide, a, obtained by dividing the area of the drainage basin by the perennial stream length, Rorabaugh, 1963, and Trainer and Watkins, 1974. Thus, the uniformity of base flow component is a function of geomorphic, hydrologic, and geologic characteristics of the basin.

Time constants determined from 1974 records of three streams in the Sand Hills (Middle Loup River at Dunning, Calamus river near Burwell, and Snake River above Merritt) are each about 115 days/cycle. The uniformity of streamflow is thus attributed to the large time constant. Physically the large time constant is related to the typically large storage coefficient of the water table aquifer, and the relatively small perennial stream lengths in relation to the size of the stream basins.

Average annual water levels in seven wells in the Sand Hills measured in the fall are shown in table 4. There is a marked decline during the drought years (1974-76) and recovery in 1977-78.

## Pleistocene Aquifer of Northeastern Nebraska

The Elkhorn River Basin occupies an area of 18,000 $km^2$ in northeastern Nebraska (fig. 1). The upper or western three fifths of the basin is underlain by silts and clayey sand which overlie the Ogallala

Table 4.--Average water levels in wells in the Sand Hills and Pleistocene aquifers, 1968-1978

SAND HILLS AQUIFER OF NEBRASKA
DEPTH TO WATER IN METERS, IN SELECTED WELLS

| | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Average | 8.54 | 8.81 | 8.78 | 8.75 | 8.78 | 8.50 | 8.75 | 9.20 | 9.24 | 8.87 | 8.81 |
| Annual change | - | -.27 | +.03 | +.03 | -.03 | +.28 | -.25 | -.45 | -.04 | +.37 | +.06 |
| Cumulative change 1974-78 | - | - | - | - | - | - | -.25 | -.70 | -.74 | -.37 | -.31 |

PLEISTOCENE AQUIFER OF NORTHEASTERN NEBRASKA
DEPTH TO WATER LEVEL, IN METERS, IN SELECTED WELLS

| | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Average | 13.20 | 13.01 | 13.23 | 13.32 | 13.26 | 12.89 | 13.11 | 13.32 | 13.93 | 13.99 | 13.75 |
| Annual change | - | +.19 | -.22 | -.09 | +.06 | +.37 | -.22 | -.21 | -.61 | -.06 | +.24 |
| Cumulative change 1974-78 | - | - | | - | - | - | -.22 | -.43 | -1.04 | -1.10 | -.86 |

Formation. The surface materials in the extreme western part of the basin are similar in character to the Sand Hills. The lower two-fifths of the basin is underlain at the surface by loess mantled Pleistocene till and an underlying fluvial sand and gravel composing an aquifer. Cretaceous formations underlie the sand and gravel. The till is composed generally of poorly sorted silt, clay, sand, and gravel with local well-sorted outwash deposits. The Cretaceous bedrock is composed of shale, limestone, marl, and sandstone. The permeability of the Cretaceous and Pleistocene deposits is markedly less than the deposits underlying the Sand Hills. The major stream valleys are underlain by sand and gravel deposits which together with the fluvial sand and gravel deposits which underlie the till yield water to irrigation wells.

The average annual streamflows at four sites in the Elkhorn River Basin are shown in table 5. The effect of the mid-1970's drought is evident in the deficient flows during the drought years at all four stations. Variability of annual flows is much greater than streams of the Sand Hills as shown by the two stations on Logan Creek whose drainage basins are wholly within the lower two thirds of the basin. The time constant of Logan Creek at Euling is about 80 days/log cycle. The lower time constant compared to those in the Sand Hills reflects the greater stream length per drainage area (smaller a), less recharge, and less base runoff from the basin.

Table 5.--Mean annual flows, in cubic meters per second, of streams in the Elkhorn River Basin of Nebraska

| Stream | Calendar year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 |
| Elkhorn River at Ewing *4.81 | 3.62 | 4.30 | 5.64 | 2.95 | 1.59 | 2.04 | 3.12 | 4.93 |
| Elkhorn River at Norfolk *14.1 | 12.9 | 13.7 | 15.7 | 10.0 | 8.13 | 8.13 | 10.2 | 13.5 |
| Logan Creek at Pender *3.79 | 8.67 | 3.40 | 4.11 | 2.19 | 2.29 | 1.62 | 1.50 | 3.17 |
| Logan Creek near Euling *5.10 | 10.5 | 4.36 | 7.73 | 4.13 | 3.62 | 1.93 | 2.02 | 5.10 |

*Mean for period of record.

Average annual water levels in ten wells in the Pleistocene aquifer measured in the fall are shown in table 4. There is a marked decline during the drought years (1974-76) and a continued decline in 1977. Cumulative decline in the Pleistocene aquifer is greater than in the Sand Hills aquifer.

## Conclusions

The effect of drought upon ground-water reservoirs varies with the natural characteristics of the aquifers and the degree of man-induced stress on the aquifer. The alluvial aquifer of the South Platte River valley is dominated by return flow (recharge) from diversions and application of surface water. Fluctuations of water level largely reflect the amount of surface water applied for irrigation and ground water withdrawn for irrigation. Natural recharge from precipitation in the valley is a minor influence on water level fluctuations. Water level fluctuations in the Ogallala aquifer are dominated by withdrawals of water for irrigation. Recharge is relatively small; storage in the aquifer is large. Decline of water level during the drought reflects increased withdrawal as demand for water is increased. Water levels in the Sand Hills of Nebraska largely reflect the natural response of the aquifer to changes in climate. The aquifer is areally extensive, recharge is high, and a uniform base flow from the aquifer is sustained. Water levels respond rapidly to recharge and water levels decline markedly but not greatly during drought. The lower Elkhorn River Basin of northeastern Nebraska, underlain by Pleistocene deposits are generally less permeable and receive less recharge than the Sand Hills. Base flow is less well sustained and water levels decline markedly during drought.

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