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DEPARTMENT OF THE INTERIOR
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SUPPLEMENT TO PREDICTIVE MODELING OF EFFECTS OF THE PLANNED KINDRED LAKE ON GROUND-WATER LEVELS AND DISCHARGE, SOUTHEASTERN NORTH DAKOTA

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CONTENTS

ILLUSTRATIONS

SELECTED FACTORS FOR CONVERTING INCH-POUND UNITS TO THE INTERNATIONAL SYSTEM (SI) OF METRIC UNITS

A dual system of measurements--inch-pound units and the International System (SI) of metric units--is given in this report. SI is an organized system of units adopted by the 11th General Conference of Weights and Measures in 1960. Selected factors for converting inch-pound units to SI units are given below.

Multiply inch-pound unit	By	To obtain SI unit
Cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
Foot (ft)	0.3048	meter (m)
Inch (in)	25.40	millimeters (mm)
	2.540	centimeters (cm)
Mile (mi)	1.609	kilometer (km)
Square mile (mi^2)	2.590	square kilometer (km^2)

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ABSTRACT

A digital model was used to describe a ground-water system in glacial deltaic deposits near Kindred, North Dakota, and to predict the effects on ground-water levels of a planned lake at the 950-, 960-, 970-, 984-, and 995-foot (290-, 293-, 296-, 300-, and 303-meter) stages. This model is a supplement to an earlier model of the ground-water system for a planned lake at the 984-foot (300-meter) level.

The model analysis indicates that only the area within about 2 miles (3.2 kilometers) of the present Sheyenne River would be affected by rising water levels as a result of a lake stage at 995 feet (303 meters). The rise of water levels depends on time and hydraulic properties of the aquifer. The maximum projected rise in water levels is expected to occur in about 50 to 100 years. Evapotranspiration and existing drains will be effective in limiting the extent of water-level rise. Consequently, the area affected by rising water levels at each lake stage will be much smaller than that shown by the earlier model at the 984-foot (300-meter) stage.

INTRODUCTION

Construction plans by the U.S. Army Corps of Engineers (House Document No. 91-330) call for a dam to be built on the lower reaches of the Sheyenne River about 5 mi (8 km) southeast of Kindred in southeastern North Dakota (fig. 1). The original plan assumed a lake at a 984-ft (300-m) stage, which was modeled by Downey and Paulson (1974). As the result of recent analyses of alternative plans for flood control and water management in the lower Sheyenne River valley, the Corps of Engineers has requested additional study and analysis of the effects of the planned Kindred Lake on ground-water levels in surrounding areas. This study was then initiated as a supplement to the original study by Downey and Paulson (1974).

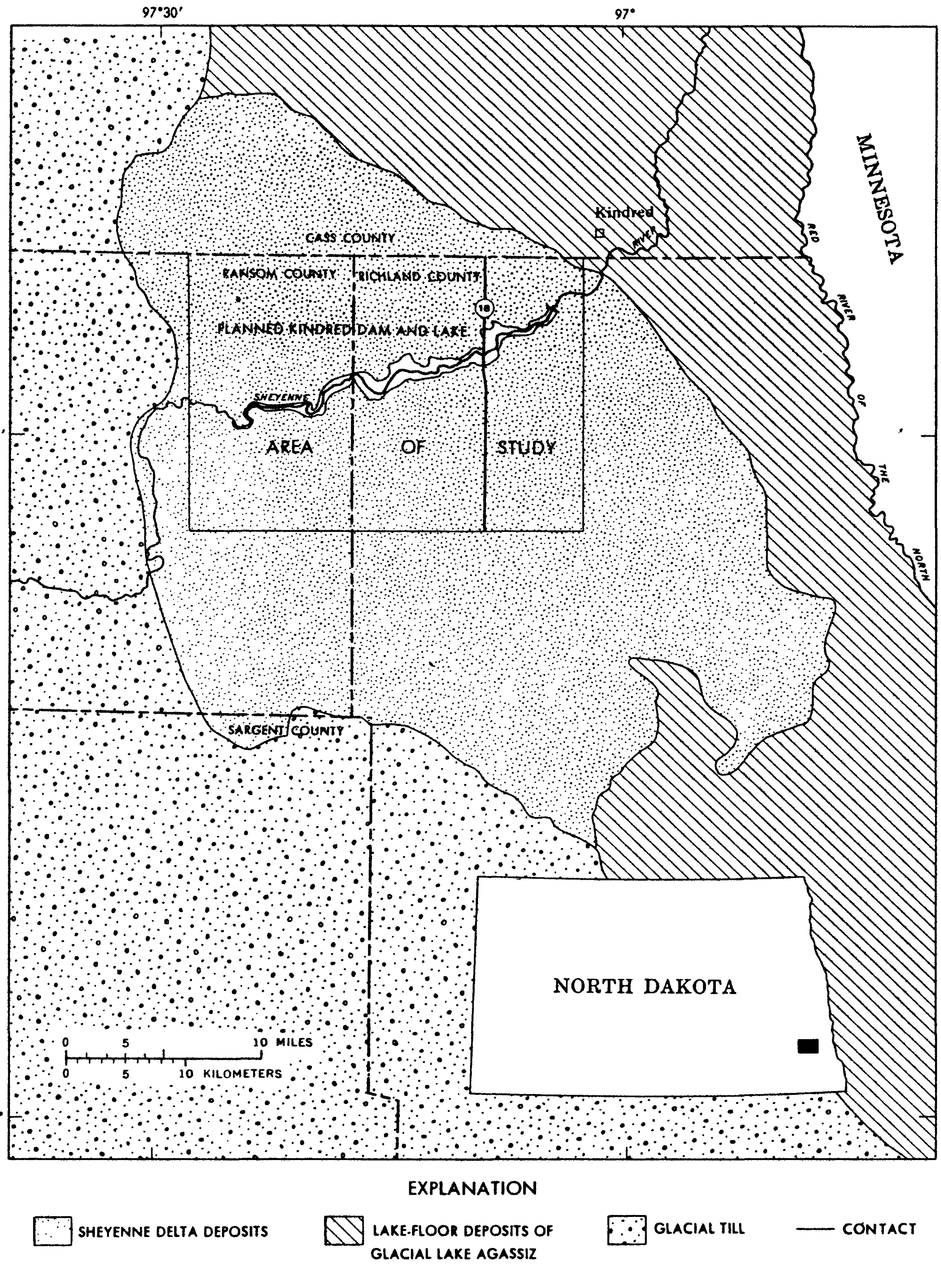

FIGURE 1.— Location of study area and major geologic features.

The reader is referred to the report of Downey and Paulson (1974) for: (1) A brief history of previous studies made in the Sheyenne delta area; (2) the methods used in collecting data; (3) the geologic units and their hydrologic properties; (4) ground-water levels and fluctuations; (5) the relationship to the Sheyenne River and its tributaries; and (6) a description of the digital model and theory behind it. The model used in this study is that of Downey and Paulson (1974), with modifications as described in this report.

Objectives

The main objective of this study was an evaluation of the effects of five different permanent lake stages [950, 960, 970, 985, and 995 ft (290, 293, 296, 300, and 303 m)], on the ground-water flow system using the original data and model, including an evaluation of the effects of all major natural and artificial drains on the ground-water flow system.

Location and General Description

The study area includes the Sheyenne River valley and adjacent areas on both sides of the valley (fig. 1). It extends from about 7 mi (11 km) east of the proposed damsite in sec. 14, T. 136 N., R. 51 W., westward about 28 mi (45 km). The simulated area is somewhat smaller than the study area and is in Richland and Ransom Counties.

The study area is part of a large northeastward-sloping sand plain encompassing about 750 mi^2 (1,940 km^2) in southeastern North Dakota that is identified in the geologic literature as the Sheyenne delta of glacial Lake Agassiz. The surface of the delta is gently rolling a few miles back from either side of the river valley and steeply rolling and rather rugged adjacent to the valley, where wind action has formed dunes, some of which are 50 to 75 ft (15 to 23 m) high.

The delta is bordered on the east by the nearly flat lake floor of glacial Lake Agassiz and on the west by rolling till deposits (drift prairie). The northeastern edge of the delta is marked by an escarpment that rises about 50 ft (15 m) above the lake floor.

The Sheyenne River has eroded a valley through the delta deposits. The valley generally is about 100 ft (30 m) deep and ranges from about 0.25 mi (0.4 km) wide at the damsite to about 1 mi (1.6 km) wide at the Richland-Ransom County line. The river channel is sinuous and is incised about 15 to 25 ft (4 to 8 m) below the flood plain, which primarily is underlain by alluvial deposits.

Much of the surface, particularly west of State Highway 18, is covered with native grasses. Extensive growths of native trees, mainly oak and aspen, are interspersed with the grasslands. The flood plain of the Sheyenne River is forested with cottonwood, elm, ash, and basswood.

Drainage on the delta surface is poorly developed, mainly because of the sandy texture and large permeability of the soils. Water tends to infiltrate into the soil rather than run off. However, east of State Highway 18 the area is underlain by deposits containing less sand and having less infiltration capacity than areas to the west, and several short spring-fed tributaries, generally less than 2 mi (3 km) long, have been eroded from the Sheyenne River back into the delta deposits. Three longer drainage canals, which connect to three shorter natural drains, have been constructed on the delta deposits.

The area receives about 20 in (510 mm) of precipitation annually (U.S. Environmental Data Service, 1972-77), of which about three-fourths generally occurs during the growing season May through October. Maps from the National Atlas (U.S. Geological Survey, 1970, p. 96) show that somewhat more than 82 percent of the annual evaporation of about 30 in (760 mm) also occurs during the same period. The climate is typical of the continental interior with cold dry winters.

Precipitation and temperature records (U.S. Environmental Data Service, 1972-77) and water-level records collected during this project and subsequently indicate that water levels throughout the project area rise during cool periods when evapotranspiration rates are small, and recharge (from precipitation and snowmelt) rates are considerably larger than the yearly average rate. These conditions generally occur every spring and apparently, on occasions when the weather is cooler than usual and precipitation is larger than normal, can extend into summer.

MODEL PARAMETERS

This study was made using a digital computer to solve the finite-difference equation for ground-water flow, as was done in the previous study by Downey and Paulson (1974).

The data collected during the previous study were used. However, because of the need for a more detailed evaluation of the effects of the drains, several model modifications were made.

Node Spacing

Node spacing in critical areas was changed from uniform nodes of 2,000 ft (610 m) on a side to either 500 by 500 ft (152 by 152 m) or 500 by 1,000 ft (152 by 305 m) on a side. Node spacing in less critical areas was changed to as much as 4,000 ft (1,220 m) wide and as much as 7,900 ft (2,100 m) long.

The change in node size necessitated expanding the size of the model. The lake stages of 950, 960, 970, 984, and 995 ft (290, 293, 296, 300, and 303 m) were simulated by using a 71 by 98 node model.

Model Boundaries

The model was terminated at a ground-water divide north of the Sheyenne River and in an area with an almost flat ground-water gradient south of the river. About one-half of the southern boundary is also along a ground-water divide. These boundaries are nearly the same as those used by Downey and Paulson (1974). The western boundary, however, was shortened to the node that includes the Sheyenne River at an altitude of 995 ft (303 m) above National Geodetic Vertical Datum of 1929.

Land Surface Altitudes

New land surface altitudes at each node were determined using 5-ft (1.5-m) contour maps. In some areas altitude variations of as much as 50 ft (15 m) exist within a node spacing, and an altitude near the mean was used.

Hydraulic Conductivities

The changes in node spacing also required new hydraulic conductivities at each node, but the changes that were made were within the values shown by Downey and Paulson (1974, pl. 3).

The tributary drains to the Sheyenne River were modeled as partially penetrating streams instead of constant-head nodes as in the original model.

Recharge and Evapotranspiration

The soil developed on the aquifer is porous and permeable. Thompson and Sweeney (1971) estimated vertical permeability equivalent to infiltration rates of 2 to 6.3 in (50 to 160 mm) per hour in soils similar to those in the report area. These rates are sufficiently high to preclude most runoff except when the ground is frozen, during extremely intense precipitation periods, or when the water table is very close to the land surface.

Flow through the unsaturated zone is complex and requires data collection beyond the limits of this study. However, through experimentation with a range of combinations of recharge and evapotranspiration rates, combinations were found that at least do not exceed empirical evaluations of the aquifer and soil characteristics. These combinations were used in calibrating the model. The range of values for areal recharge was between 20 and 40 percent of the total annual precipitation of 20 in (500 mm). The use of values of less than 20 percent provided insufficient recharge to compensate for flow to the Sheyenne River. Values in excess of 40 percent produced unrealistic simulated water levels.

Downey and Paulson (1974) considered evapotranspiration to be operating at near maximum potential rates in most of the area, and therefore, did not include a function for this process in their model. The present writer does not agree with this basic assumption because water levels under much of the area are too deep for maximum potential evapotranspiration to be effective.

The two-dimensional model used in this study allows input of only a linear evapotranspiration function with a maximum rate at land surface and a zero rate at a fixed depth. The average annual maximum potential evaporation rate in an area including the Sheyenne Delta aquifer is about 30 in (760 mm; Meyers, 1962).

Ripple, Rubin, and van Hylckama (1972) describe a technique by which homogeneous soil types such as those in the Sheyenne delta may be evaluated for rates of evaporation. Calculations based on this technique show that evaporation can occur at rates close to the potential rate for depths to the water table of as much as 7.2 ft (2.2 m) depending on soil permeabilities. The potential rates and depths are in part meteorologically controlled and the maximum potential rates and depths occur only during the hotter summer months. It was necessary to vary rates and depths of effective evapotranspiration using various recharge rates to arrive at a balance between the two rates that simulated measured steady-state values.

A range of values for maximum evapotranspiration from 25 to 35 in (635 to 890 mm) per year was found to be in balance with the range of recharge rates described above. Maximum depths of 6 to 10 ft (1.8 to 3.0 m) for the effects of evapotranspiration proved to fit best with observed steady-state conditions. R. B. Shaver (North Dakota State Water Commission, unpublished data, 1981), while calibrating a digital model of the Oakes aquifer, which is similar to and about 40 mi (64 km) southwest of the Kindred area, found that a similar set of values for recharge and effective depth could be used. However, he found that he could most closely reproduce several years of hydrographs by using recharge rates between 7 and 8.25 in (178 and 210 mm) per year (varied with monthly precipitation) and an effective evapotranspiration depth limit of 8 ft (2.4 m). D. P. Ripley (North Dakota State Water Commission, written commun., 1980), while calibrating a digital model of the Edgeley aquifer, which is about 75 mi (120 km) west of the Kindred area, found that an average recharge rate of 7.70 in (196 mm) per year with an evapotranspiration rate of 0 at 8 ft (2.4 m), gave the best results.

ASSUMPTIONS, LIMITATIONS, AND CALIBRATION OF MODELS

The digital model used for this study is based on the following assumptions:

1. The Sheyenne Delta aquifer is an extensive ground-water body, and its boundaries generally are beyond the effects of the planned lake at any of the five proposed stages.

2. The geologic materials underlying the aquifer form a relatively impervious barrier to the flow of water.

3. Perennial streams, springs, and drains are in hydraulic connection with the ground-water system.

4. Recharge and discharge from the ground-water system are equal.

5. At any given point within the aquifer the vertical flow component is very small in comparison to the horizontal component.

6. The average effective depth limit of evapotranspiration is 8 ft (2.4 m).

7. Recharge to the aquifer is 7.4 in (180 mm) per year. This gave the best fit of simulated to measured water levels during calibration, using the assumed values of evapotranspiration.

8. The Sheyenne River in Ransom County in areas of elongated node spacing was assumed to be straight segments in order to

limit the represented width of the river to near that of the actual river.

9. The shoreline of the lake will form an aquifer boundary along which the change in head is equal to the difference between the present water table and the planned lake surface.

The accuracy of the projected rises in water levels is dependent upon how well the above assumptions represent actual field conditions. At the 970-ft (296-m) stage, except for a few local areas near the dam, and at lower stages the proposed lake will not exceed the boundaries of the flood plain. At the 984-and 995-ft (300- and 303-m) stages the proposed lake will encroach upon the valley walls and fill the downstream ends of the small tributary valleys within a few miles of the dam. At these latter two stages the lake will cover a part of the area where land-surface altitudes vary greatly, and some error in the simulated slope of the water table could result; however, the spacing of the natural drains will largely compensate for any such errors.

Digital-model calibration was obtained by Downey and Paulson (1974) by comparing the output from various simulations with the mean ground-water levels for September 1972 through August 1973. Recharge to the model system was adjusted so that the calculated water levels from the simulation were approximately the same as the mean water levels. Calculated discharge of about 30 ft^3/s (0.85 m^3/s) from the aquifer to the Sheyenne River corresponded well with the low-flow measurements for that part of the Sheyenne River included in the modeled area. Present model calibration was directed towards having the models reproduce, as closely as possible, the altitudes of the mean water levels shown on Downey and Paulson's (1974) plate 4.

After calibration, each of the various lake levels was superimposed, in turn, as constant-head nodes on the calibrated model. The resulting changes in head were then plotted on maps to make plates 1, 2, 3, 4, and 5 (in pocket).

RESULTS AND CONCLUSIONS

1. Water-level and streamflow data indicate that the Sheyenne River in the reaches of the planned Kindred Lake is in hydraulic connection with aquifers in the Sheyenne delta deposits and alluvial deposits in the Sheyenne River valley.

2. The data on plates 1 through 5 show projected water-level rises of 1 ft (0.3 m) or more at steady-state conditions for all proposed lake stages. The areas affected by water-level rises of 1 ft (0.3 m) or more are larger at each succeeding higher lake stage. However, even at the 995-ft (303-m) lake stage, the area

affected by a rise of 1 ft (0.3 m) is smaller than the area shown to be affected at the 984-ft (300-m) stage by Downey and Paulson (1974) in the earlier model. The difference in the modeled results is due primarily to the effects of evapotranspiration and, to a lesser extent, to the the greater control in the model of the natural drains due to smaller node spacing.

3. Where the lake will innundate only the Sheyenne River flood plain, ground-water levels will rise 1 ft (0.3 m) or more in the Sheyenne Delta aquifer only in those areas near the lake and beneath the steeply sloping valley sides. Where the lake encroaches upon the steeper sides of the valley, water-level rises of more than 1 ft (0.3 m) will be restricted to areas where present water levels are more than 5 ft (1.5 m) below land surface. By comparing projected water-level rises at the 995-ft (303-m) stage (pl. 5) with the present depth to water (Downey and Paulson, 1974, pl. 5), and using an effective evapotranspiration depth of 6 ft (1.8 m), water-level rises of more than 1 ft (0.3 m) generally would be restricted to areas where present water levels are more than 10 ft (3 m) below land surface. This is a somewhat larger area than is shown on plates 1 through 5. By using an effective evapotranspiration depth limit of 8 ft (2.4 m) in the model, water-level rises will be approximately as shown by the lines on plates 1 through 5. There may be some error in the calculated water levels immediately adjacent to the proposed lake because of the irregular shape of the lake and the model method of representing data at the center of each node. If effective evapotranspiration depth of 10 ft (3 m) is used, the model shows that the area affected by a 1-ft (0.3-m) rise in water levels will be somewhat smaller than is shown on plates 1 through 5.

4. If the actual effective depth of evapotranspiration is between 6 and 10 ft (1.8 and 3 m) and recharge is not more than 8.25 in (210 mm), water levels will not change appreciably more than 2 mi (3.2 km) from the present river at lake stages of 995 ft (303 m) or lower.

5. The tributaries and manmade drains as well as evapotranspiration will limit the extent of water-level rise.

6. Considerable time will be required for the maximum rise in water levels to occur. Within the area between the lake shore and the 1-ft- (0.3-m-) rise line, the water-level rise will be progressively larger toward the lake. Based on available data, the maximum projected rise in ground-water levels at each lake stage will occur several decades after filling of Kindred Lake. Various computer simulations indicate that the maximum projected rise in ground-water levels should occur in about 50 to 100 years. The model assumes a steady-state condition has been reached when there is less than a 0.02-ft (0.01-m) rise in 30 years.

DEFINITIONS OF TECHNICAL TERMS
(From Langbein and Iseri, 1960, and Lohman and others, 1972)

Aquifer--A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Confining bed--A body of "impermeable" material stratigraphically adjacent to one or more aquifers.

Evapotranspiration--Water withdrawn from a land area by evaporation from water surfaces and moist soil and plant transpiration.

Ground water, confined--Ground water under pressure significantly greater than atmospheric.

Ground water, unconfined--Water in an aquifer that has a water table.

Head--Height above a standard datum of the surface of a column of water (or other liquid) that can be supported by a static pressure at a given point.

Hydraulic conductivity--Volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic gradient--The change in head per unit of distance in a given direction.

Infiltration--The flow of a fluid into a substance through pores or small openings. It connotes flow into a substance in contradistinction to the word percolation, which connotes flow through a porous substance.

National Geodetic Vertical Datum of 1929 (NGVD of 1929)--A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level."

Percolation--Movement, under hydrostatic pressure, of water through the interstices of a rock, or soil, except through large openings such as caves.

Potentiometric surface--As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells.

Saturated zone--That part of the water-bearing material in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric.

Specific yield--The ratio of volume of water which a rock or soil, after being saturated, will yield by gravity to the volume of the rock or soil. Generally expressed as a percentage or decimal fraction.

Stage--The height of a water surface above an established datum plane.

Storage coefficient--The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Surface runoff--That part of the runoff that travels over the soil surface to the nearest stream channel.

Transmissivity--The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths.

Water table--Surface in an unconfined water body at which the pressure is atmospheric. Defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water.

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