PROJECTED GROUND-WATER DEVELOPMENT, GROUND-WATER LEVELS, AND STREAM-AQUIFER LEAKAGE IN THE SOUTH FORK SOLOMON RIVER VALLEY BETWEEN WEBSTER RESERVOIR AND WACONDA LAKE, NORTH-CENTRAL KANSAS, 1979-2020

By Jack Kume, R. J. Lindgren, and L. E. Stullken

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Inch-pound units of measurement in this report may be converted to the International System of Units (SI) using the following conversion factors:

Multiply inch-pound unit	By	To obtain SI unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	0.4047	hectare
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot per acre (ft/acre)	0.75	meter per hectare

DEFINITION OF TERMS

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 or springs (Lohman and others, 1972, p. 2).

Base flow - Leakage from the aquifer to a stream.

Evapotranspiration - Volume of water that is lost to the atmosphere by transpiration from vegetative growth and by evaporation from the soil or from the aquifer in shallow water-table areas.

Hydraulic conductivity - Volume of water at the existing kinematic viscosity that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Lohman and others, 1972, p. 4).

Hydraulic head - Height above a standard datum of the surface of a column of water that can be supported by a static pressure at a given point (Lohman and others, 1972, p. 7).

Leakage - Flow of water passing across a boundary or bed.

Leakance - Ratio of the vertical hydraulic conductivity of a bed to its thickness. It is a measure of the ability of a bed to allow vertical leakage.

Potentiometric surface - A surface which represents the static head. It is defined by the levels to which water will rise in tightly cased wells (Lohman and others, 1972, p. 11).

Specific yield - Ratio of the volume of water that the saturated material will yield by gravity drainage to the volume of the material (Lohman and others, 1972, p. 12).

Stream depletion - A decrease in streamflow due to a decrease of ground-water flow to the stream or increase in flow from the stream to the aquifer.

Storage coefficient - Volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head (Lohman and others, 1972, p. 13).

Transmissivity - Rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient (Lohman and others, 1972, p. 13).

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ABSTRACT

A two-dimensional finite-difference computer model was used to project changes in the potentiometric surface, saturated thickness, and stream-aquifer leakage in an alluvial aquifer resulting from four instances of projected ground-water development. The alluvial aquifer occurs in the South Fork Solomon River valley between Webster Reservoir and Waconda Lake in north-central Kansas.

In the first two projections, pumpage for irrigation was held constant at 1978 rates throughout the projection period (1979-2020). In the second two projections, the 1978 pumpage was progressively increased each year through 2020. In the second and fourth projections, surface-water diversions in the Osborne Irrigation Canal were decreased by 50 percent. For the third and fourth projections, each grid-block in the modeled area was classified initially as one of six types according to whether it represented irrigable or nonirrigable land, to its saturated thickness, to its location in or outside the canal-river area, and to its pumping rate. Grid blocks were classified to distribute increased pumpage to irrigable blocks on a priority basis.

The projected base-flow rates (leakage from the aquifer to the river) were lower during the irrigation season (June, July, and August) than during the other months of the year because of the decline in hydraulic head produced by ground-water pumpage. Stream depletion, calculated as a decrease below the average (1970-78) estimated winter base-flow rate of 16.5 cubic feet per second, varied inversely with base flow. For the first two projections, a constant annual cycle of well pumpage and recharge was used throughout the projection period. Aquifer leakage to the river was nearly constant by the mid- to late-1990's, implying that flow conditions had attained a stabilized annual cycle.

The third and fourth projections never attained an annual stabilized cycle because the irrigation pumpage rate was increased each year. The potentiometric surface was lower during the summer irrigation season than for the first two projections because the irrigation pumpage was greater. By the early 1980's, the hydraulic head had fallen below river stage, reversing the hydraulic gradient at the stream-aquifer interface and resulting in net leakage from the river to the aquifer during the summer months. By the early 1990's, the projected potentiometric surface of the aquifer was lower than the river stage even during the winter and spring months.

INTRODUCTION

Irrigation is practiced in the South Fork Solomon River valley between Webster Reservoir and Waconda Lake in north-central Kansas (fig. 1). Releases from Webster Reservoir make up a large part of the water supplies for irrigation. Ground water from irrigation wells supplements these surface-water releases. Water shortages occurred during 1972, 1978, 1981, and 1982, and no water was released from Webster Reservoir during those years. Water shortages have been a major factor contributing to the increase in ground-water development. Burnett and Reed (1986) reported that the number of irrigation wells increased substantially, from 12 to 93 wells, during 1970 to 1978. The conjunctive use of surface and ground water has proved very beneficial to the irrigators. However, there is a growing concern over whether the continued increase in ground-water withdrawals can be sustained. Because canal and lateral leakage of surface water is an important source of recharge to the alluvial aquifer, the saturated thickness in the aquifer could decrease markedly if this recharge is not available. This could cause the ground-water-withdrawal rates to ultimately decline because of lower well yields due to less saturated thickness.

A previous study by the U.S. Geological Survey in cooperation with the U.S. Bureau of Reclamation and the Kansas Geological Survey developed a digital computer model to simulate two-dimensional ground-water flow in the alluvial aquifer from 1970 through 1978 in the flood plain of the South Fork Solomon River between Webster Reservoir and Waconda Lake (Burnett and Reed, 1985; 1986). The alluvial aquifer is about 2-miles wide, and the modeled reach is 50-miles long.

Purpose and Scope

The model constructed by Burnett and Reed (1986) was for a period when the South Fork Solomon River valley was being developed (1970-78). Year-to-year recharge changed very little, but discharge from the alluvial aquifer was increasing. The purpose of this report is to present the results of four model projections (1A, 1B, 2A, 2B) of water levels in and discharge from the alluvial aquifer at monthly intervals from 1979 through the year 2020. In projection 1A and 1B, recharge and discharge were projected as constants through each annual cycle. In projections 2A and 2B, recharge was constant, and pumpage was increased each year.

This report describes the hydrologic responses simulated by the model. Further information on the model, including assumptions, interpretation of data, and comparison with measured values is available in Burnett and Reed (1985; 1986).

Computer Model Background

The digital model of the South Fork Solomon River valley stream-aquifer system uses a computer program written by Trescott and others (1976). This two-dimensional numerical model was prepared and used to simulate and evaluate the stream-aquifer system from 1970 through 1978 (Burnett and Reed, 1985; 1986). The model used 19 pumping periods (1970-79) representing a 3-month irrigation season (June through August) and a 9-month nonirrigation season (September through May) (Burnett and Reed, 1986). For this report, the duration of the pumping periods was changed. The simulated pumping periods were modified to provide results on a monthly basis. A total of 610 monthly pumping periods was used to simulate the stream-aquifer system, March 1970 to December 2020.

An additional program code was added to the digital model to convert the 3-month and the 9-month pumping-period data to appropriate monthly pumping-period data. Results of the digital-model simulations were used to calculate and to print monthly and yearly tables of the difference between the simulated base flow and the average (1970-78) estimated winter base flow and of net leakage between the river and aquifer. Another program code was added to the digital model to calculate the annual increase (270 acre-ft) in the total irrigation pumpage in projections 2A and 2B.

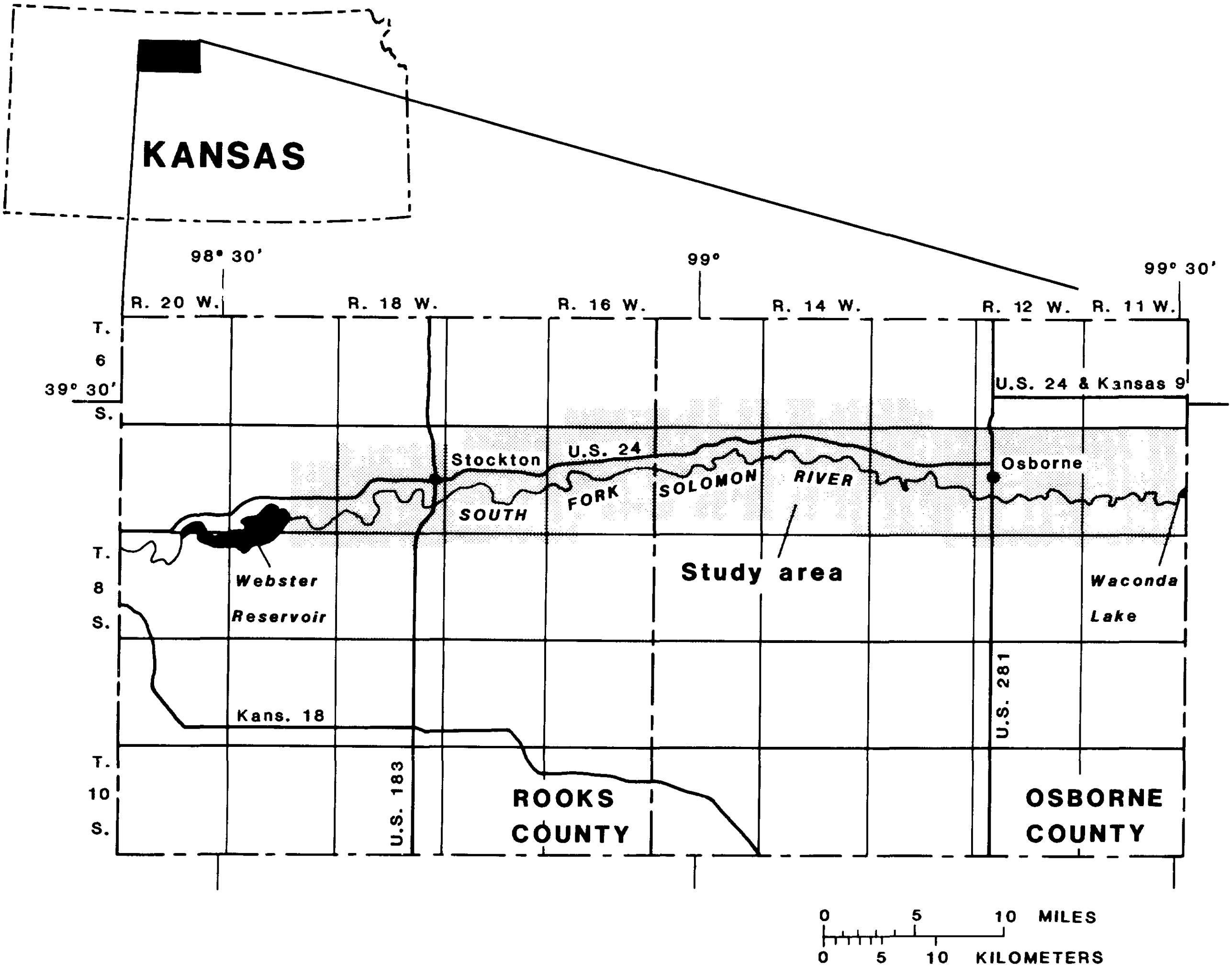

Figure 1.--Location of study area.

Accuracy Considerations

Development of the computer model as a predictive tool is based on the premise that, if historic hydrologic phenomena can be satisfactorily approximated by the model, then so can future conditions, within those same limits. Simulations of the relationship between historic stresses in the stream-aquifer flow system and of the system's response to those stresses are described in a previous report by Burnett and Reed (1986). This report assumes that this relationship did not change significantly in the projected system from 1979 to 2020. However, the hydrologic system in the South Fork Solomon River valley is dynamic. Large changes in streamflow, precipitation, and pumpage influence water levels in the alluvial aquifer. Although it may be possible to estimate future pumpage based on management control, it is very speculative to forecast changes in streamflow and precipitation. The characteristics of various streamflow and pumpage patterns that were chosen for this study were meant to illustrate possible future hydrologic conditions, thereby allowing management decisions to be based on results of a range of projections.

As presently constructed, it is possible for the digital model to compute aquifer hydraulic heads lower than those of the streambed confining layer, thereby simulating a loss of hydraulic connection between the aquifer and the river. The leakage between the river and the aquifer, for that case, would be calculated erroneously by the model as a function of river hydraulic head minus aquifer hydraulic head; whereas the driving head differential would need to be limited to the river depth above the confining layer. As used, the model could not detect and limit leakage in such a situation. In the projections that follow, close inspection by the hydrologist was required to assure that computed flow between stream and aquifer was based on realistic stream-aquifer head differentials. If the model is to be used, as it is presently set up, for different projections, this same close inspection would be required. The effects of present model errors depend greatly upon the magnitude and location of any additional stresses applied to the model. A large stress in one reach causing lower water levels in the aquifer and excessive river leakage translates into higher ground-water levels and less leakage in another reach. If the interest is in the overall effect on a large area, this error may be acceptable; if on a small area, it may not.

Acknowledgments

Darrell Ewing of the U.S. Bureau of Reclamation provided assistance and information in this study. Kelvin Kolb, Division of Water Resources, Kansas State Board of Agriculture, provided information on irrigation pumpage. Leland Stroup of the Webster Irrigation District provided surface-water distribution records.

SIMULATED HYDROLOGIC PROPERTIES

Model Boundary Conditions

No-flow boundary conditions were used to simulate the impermeable lateral boundaries along most of the north and south sides of the modeled area except in areas where tributaries intercept the model boundaries (plate 1). Inflow from the alluvium of tributary valleys was modeled by constant-head grid blocks, assuming no development or seasonal changes in the water levels of the tributary alluvium and assuming that the calibrated model reasonably simulated ground-water gradients at those locations. Constant-head grid blocks also were used to represent Webster Reservoir and Waconda Lake at the upstream and downstream ends of the modeled area. The model features and streamflow-measurement sites are shown on plate 1. The simulated water-level surface for January 31, 1979 (Burnett and Reed, 1986, plate 4), was used as the starting water-level surface for the 1979-2020 projections.

Streamflow Conditions

Flow between the aquifer and the South Fork Solomon River was simulated using the leak-option routine in the finite-difference model (Trescott and others, 1976). The stream-aquifer interface was treated as if the two units were separated by a permeable membrane 0.6- to 12-ft thick, with a hydraulic conductivity of 0.13×10^{-5} (0.0000013) ft/s. Water could flow either way through the interface depending on hydraulic-head values in the aquifer. The model assumed that the hydraulic head in the river remained constant through time (1970-2020) so that only fluctuations of the water table affected flow at this interface.

Aquifer Characteristics

Hydraulic conductivity, a measure of the aquifer's ability to transmit water, was used by the model, in combination with water-level-dependent saturated thickness, to compute the required transmissivity distribution during simulation. A constant hydraulic conductivity of 1.5×10^{-3} ft/s (130 ft/d) was used in the model for the South Fork Solomon River alluvium during both calibration (Burnett and Reed, 1986) and these projections.

The magnitude of water-level change that occurs in a water-table aquifer in response to recharge or discharge of ground water depends on the specific yield. The South Fork Solomon River model used a constant specific yield of 0.20 during both calibration (Burnett and Reed, 1986) and these projections.

Discharge From Aquifer

Discharge from the ground-water system occurs as evapotranspiration, pumpage, and leakage to the river. Ground water also leaves the modeled area as subsurface outflow. Water is discharged from the aquifer to the atmosphere by evaporation and by transpiration from plants in areas where the water table is at or near the land surface. The evapotranspiration rate used for the 1979-2020 projection period was the same as was used during the 1970-78 calibration period by Burnett and Reed (1986). During the months of June, July, and August (irrigation season) the evapotranspiration rate was 4.76 ft^3/s, and for the other 9 months it was 1.10 ft^3/s.

Pumpage from irrigation and municipal wells is a major source of discharge from the aquifer. Withdrawals of ground water by municipal wells were computed by Burnett and Reed (1986) from records of pumpage, rates of use, hours pumped, and population. Net withdrawals by municipal wells were applied at a uniform rate of 1.4 ft^3/s throughout the simulation period (1970-2020). Burnett and Reed (1986) also determined ground-water irrigation pumpage rates by using an application rate of 1.0 ft/acre per season for lands irrigated solely by ground water and 0.5 ft/acre per season for lands irrigated by both surface and ground waters. Withdrawals by irrigation wells were applied at a uniform rate through the irrigation season of June, July, and August. Burnett and Reed (1986) reported average simulated (1970-78) well-discharge rates of 24 ft^3/s for the irrigation season and 1.4 ft^3/s for the nonirrigation season. The study described in this report uses the same well-discharge data through 1970-78 as Burnett and Reed (1986) and applies the well-discharge rates for 1979-2020 as described in the selection on "Projected Ground-Water Development, 1979-2020."

The exchange of water between the South Fork Solomon River and the alluvium occurs through the streambed. Stream-aquifer leakage can be either a source of recharge to or discharge from the aquifer. Leakage for this study was calculated as in Burnett and Reed (1986) by using a constant streambed (silt and clay) hydraulic conductivity of 0.13×10^{-5} ft/s and a streambed thickness ranging from 0.6 to 12 ft. Burnett and Reed (1986) reported that while there are reaches where flow is from the river to the aquifer, the river generally gains in flow from the aquifer across the modeled area. They also reported that the 1970-78 winter leakage from the aquifer to the river from Webster Reservoir to east of Osborne was about 13.6 ft^3/s or 10,000 acre-ft/yr. The total simulated winter leakage for 1970-78 from the aquifer to the river averaged 18.2 ft^3/s.

Subsurface outflow for the 1979-2020 projection period was simulated as in the 1970-78 calibration period by Burnett and Reed (1986) using constant heads at the eastern boundary of the modeled area.

Recharge to Aquifer

Recharge to the ground-water system occurs as water infiltrates from the land surface through the soil zone to the aquifer. The sources of water that may infiltrate from the land surface are precipitation and irrigation water (return flow). The amount of deep percolation depends on the amount of precipitation and irrigation water applied to the land surface, the rate of consumptive-use demand by plants, and the ability of the soil to hold and store water. When precipitation exceeds storage capacity of the soil, it recharges the aquifer by deep percolation.

Recharge from precipitation was applied at a uniform rate throughout the modeled area during each pumping period; however, the application rate varied from 5 to 15 percent of the precipitation occurring during each pumping period of the calibration period (1970-78) (Burnett and Reed, 1986). Simulated recharge from precipitation (1970-78) averaged 2.0 in/yr or 14.3 ft^3/s for the irrigation season and 11.7 ft^3/s for the nonirrigation season. These average values were used for the projection period, 1979-2020.

A major source of recharge during the irrigation season was seepage of diverted surface water from Osborne Irrigation Canal and laterals, simulated using recharge wells in appropriate nodes. Burnett and Reed (1986) reported an average simulated rate (1970-78) of 26.5 ft^3/s. Irrigation return flows of water applied to the fields also contribute to recharge to the aquifer. Burnett and Reed (1986) used 10 percent of the ground- and surface-irrigation water applied as the return-flow rate or an average simulated rate (1970-78) of 5.71 ft^3/s for the irrigation season. In this study, recharge from canals, laterals, and field application was varied from season to season during the calibration period of 1970-78 using the same values as Burnett and Reed (1986). Recharge for the projection period of 1979-2020 was based on the proportionate quantities of canal and lateral water presumed available and the amount of ground-water pumpage for that pumping period.

Subsurface inflow from the western boundary of the model area and from several valley tributaries also provides recharge to the aquifer. Burnett and Reed (1986) reported an average simulated rate of subsurface inflow (1970-78) of 1.86 ft^3/s.

PROJECTED GROUND-WATER DEVELOPMENT, 1979-2020

Four projections of ground-water development (1A, 1B, 2A, 2B) were made for 1979 to 2020. The projections used different combinations of surface-water diversions into the Osborne Irrigation Canal and well-pumpage rates. In all four simulations, changes were made in the digital-model code to convert the 90- (summer) and 275- (winter) day pumping periods per year, used in the original digital model (Burnett and Reed, 1986), to monthly pumping periods. The number of days in each pumping period was 28, 29, 30, or 31 days depending on the month and the year. The summer irrigation season was changed to a 92-day period (June, July, and August). To arrive at a compatible starting point for the projections, each simulation was started in March 1970 and stepped through the calibration period with the same conditions and flux rates used in Burnett and Reed (1986).

Stream depletion was calculated for this report as the deviation from the average 1970-78 estimated winter leakage of 16.5 ft^3/s from the alluvial aquifer to the river. The average 1970-78 winter streamflow increased 13.6 ft^3/s from Webster Reservoir to the town of Osborne (Burnett and Reed, 1986). Proportioned to include the stream reach east of Osborne, the estimated winter leakage from the aquifer was 16.5 ft^3/s. The model simulated vertical leakage to or from the stream as a function of the vertical hydraulic conductivity of the streambed material, thickness of the streambed material, area of the streambed through which leakage occurred, and the difference in hydraulic head between stream stage and the aquifer.

In projection 1A, pumpage was held constant at 1978 rates for the duration of the projection period from 1979 through 2020, and recharge and surface-water diversions into the Osborne Irrigation Canal were held constant at average 1970-78 rates.

In projection 1B, pumpage conditions were the same as those in 1A. However, the length of time that surface water was diverted into the Osborne Irrigation Canal was decreased by 50 percent from 1979 through 2020 compared to projection 1A. Therefore, the canal was dry for 50 percent of the water-diversion time that was used in projection 1A. It was assumed that the effect of 50-percent less surface water in the Osborne Irrigation Canal would cause a 50-percent decrease in leakage by the canal to the aquifer. Therefore, a 50-percent decrease in surface-water diversions into the Osborne Irrigation Canal was effected by decreasing the average (1970-78) leakage through canal (aquifer recharge) grid blocks by 50 percent and holding the decreased leakage constant from 1979 through 2020.

In projection 2A, hydrologic conditions were the same as in projection 1A, except that pumpage was increased annually after 1978. The annual increase in pumpage was distributed among irrigable nodes according to a priority system based on node type.

In projection 2B, pumpage conditions were the same as those in projection 2A. However, a 50-percent decrease in surface-water diversions into the Osborne Irrigation Canal was effected by decreasing the rate of leakage through canal grid blocks by 50 percent.

GROUND-WATER LEVELS AND STREAM-AQUIFER LEAKAGE

Pumpage at 1978 Rate

Surface-Water Diversion at Average 1970-78 Rate

(Projection 1A)

The potentiometric surface for projection 1A during December 2020 is shown in figure 2. The altitude of the projected potentiometric surface ranges from about 1,830 ft near Webster Reservoir to about 1,460 ft near Waconda Lake, with hydraulic heads generally decreasing in the downstream direction from the western end of the study area to the eastern end. Water-level contours near the river generally are concave in the upstream direction, indicating a gaining stream and, therefore, ground-water flow to the river.

The saturated thickness for projection 1A during December 2020 is shown in figure 3 and ranged from zero at several isolated locations to about 80 ft west of Stockton. For the eastern one-half of the study area (east of Alton, see plate 1), which had less saturated thickness than the western

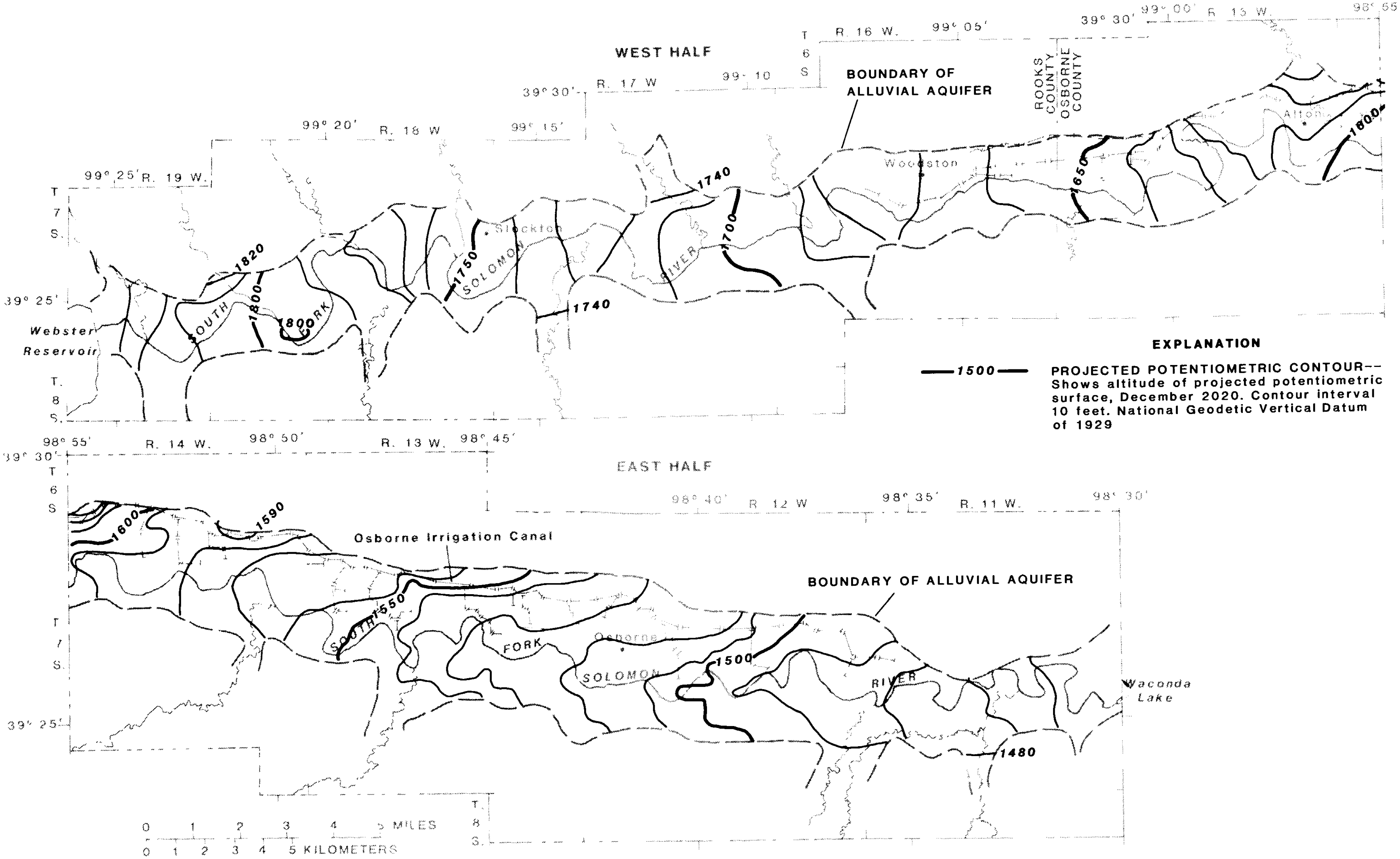

Figure 2.--Potentiometric surface, December 2020, projection 1A.

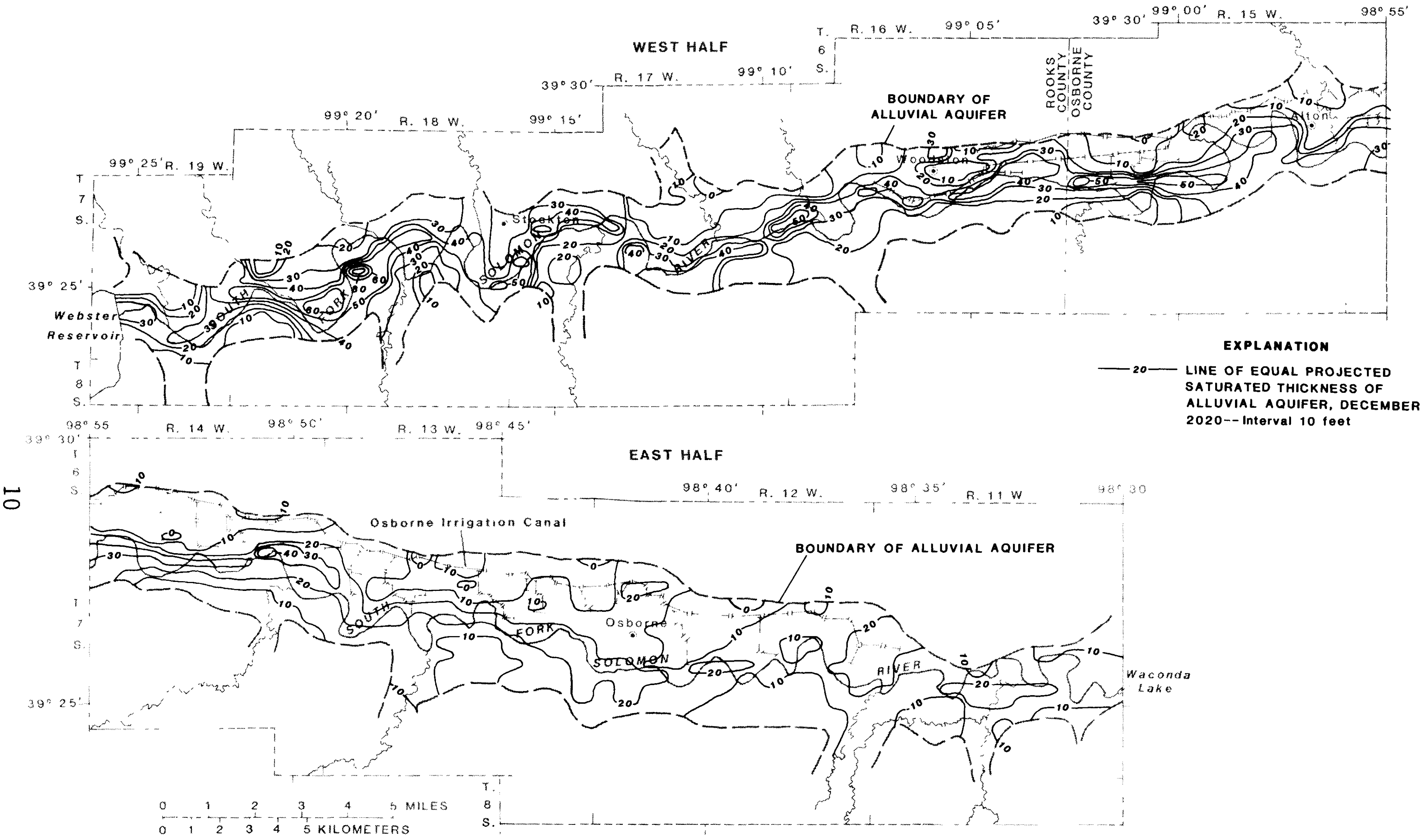

Figure 3.--Saturated thickness, December 2020, projection 1A.

one-half (west of Alton), the projected saturated thickness ranged from zero at several isolated locations to about 40 ft, 5.5 mi east of Alton. Most of the eastern area was in the 10-ft to 20-ft range. For the western one-half of the study area, the saturated thickness was greatest, with most of the area in the 20-ft to 50-ft range.

Simulated monthly and annual net leakage between the South Fork Solomon River and the alluvial aquifer for projection 1A (March 1970 through December 2020) are given in table 1. All of the values are negative, indicating movement of water from the alluvial aquifer to the river.

Table 1 shows that flow was from the alluvial aquifer to the river throughout the simulation period (all negative numbers). Leakage from the alluvial aquifer to the stream was least during the summer growing season (June, July, and August) when irrigation pumpage resulted in a generally lower hydraulic head in the aquifer. After the summer growing season, irrigation pumpage was minimal, and the aquifer hydraulic head began to rise, resulting in greater leakage from the alluvial aquifer to the river. Table 1, therefore, shows increasing leakage in the fall after the heavy irrigation pumpage season, with maximum leakage during the winter and spring when aquifer hydraulic heads are the highest. The net leakage was significantly higher during 1970-76, when there were fewer irrigation wells to withdraw ground water and more surface water to supply recharge to the aquifer.

As shown in table 1, monthly leakage reached a relatively constant value for each month by the mid-to-late 1990's, indicating the stream-aquifer system had reached a stabilized annual cycle. In this stabilized annual cycle, recharge and discharge have become balanced to the extent that there is no change from year to year for the same season. Therefore, there is no year-to-year change in hydraulic head and no annual change of water in storage. In a strict sense, a stabilized annual cycle does not occur in a large-scale stream-aquifer system due to year-to-year changes in climate and water use. However, since in projection 1A constant values of well pumpage and canal recharge were cycled from 1979 through 2020, a stabilized annual cycle was reached in the stream-aquifer system after a period of time. After the stream-aquifer system reached an equilibrium condition, the hydraulic head in the aquifer for the same season varied little, and year-to-year monthly leakage rates, therefore, remained relatively constant.

Simulated monthly and annual deviations from the average (1970-78) estimated winter base flow of 16.5 ft^3/s from the alluvial aquifer to the South Fork Solomon River between Webster Reservoir and Waconda Lake for projection 1A (March 1970 through December 2020) are given in table 2. The table gives an indication of stream depletion in comparison to an average (1970-78) estimated winter base-flow condition. Negative values occurred during 1970-76, indicating above-average base flow. Beginning in the summer of 1976, there was less than average base flow, and all the values were positive.

Since leakage from the aquifer to the river (base flow) was lowest during the summer irrigation season, the greatest depletion from the average

Table 1.--*Net leakage between river and alluvial aquifer, projection 1A, March 1970 through December 2020*

[Values given in acre-feet. Negative numbers indicate leakage from the aquifer to the river]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1970			-1,689	-1,572	-1,563	-1,694	-1,775	-1,791	-1,512	-1,501	-1,410	-1,415	-15,922
1971	-1,375	-1,210	-1,306	-1,231	-1,241	-1,196	-1,203	-1,185	-1,110	-1,142	-1,093	-1,112	-14,405
1972	-1,094	-1,007	-1,059	-1,008	-1,024	-839	-821	-790	-1,118	-1,242	-1,242	-1,316	-12,560
1973	-1,341	-1,230	-1,379	-1,350	-1,408	-1,375	-1,449	-1,493	-1,555	-1,657	-1,629	-1,703	-17,568
1974	-1,719	-1,565	-1,745	-1,699	-1,766	-1,434	-1,421	-1,409	-1,330	-1,338	-1,258	-1,263	-17,947
1975	-1,229	-1,083	-1,172	-1,109	-1,121	-1,034	-1,049	-1,061	-1,070	-1,119	-1,074	-1,094	-13,215
1976	-1,076	-991	-1,043	-993	-1,010	-730	-688	-674	-844	-911	-881	-901	-10,742
1977	-889	-792	-864	-823	-837	-688	-674	-671	-760	-815	-789	-808	-9,409
1978	-797	-710	-775	-739	-753	-357	-234	-155	-481	-575	-582	-616	-6,777
1979	-624	-567	-630	-610	-630	-390	-322	-290	-525	-622	-634	-675	-6,520
1980	-688	-653	-705	-688	-715	-429	-351	-315	-546	-641	-651	-690	-7,071
1981	-702	-642	-716	-698	-725	-438	-360	-323	-554	-649	-658	-697	-7,161
1982	-709	-647	-722	-703	-730	-442	-364	-328	-558	-653	-662	-701	-7,219
1983	-712	-650	-725	-706	-732	-445	-367	-330	-561	-656	-664	-703	-7,250
1984	-714	-675	-727	-707	-733	-445	-368	-331	-561	-656	-664	-703	-7,283
1985	-714	-651	-726	-706	-733	-445	-367	-330	-561	-656	-663	-703	-7,254
1986	-714	-651	-726	-706	-732	-444	-367	-330	-561	-655	-663	-702	-7,251
1987	-713	-650	-725	-705	-732	-444	-366	-330	-560	-655	-663	-702	-7,245
1988	-713	-674	-725	-705	-731	-444	-366	-330	-560	-655	-663	-702	-7,267
1989	-713	-650	-725	-705	-731	-443	-366	-329	-560	-655	-662	-701	-7,240
1990	-712	-650	-724	-704	-731	-443	-365	-329	-560	-655	-662	-702	-7,237
1991	-712	-650	-724	-704	-731	-443	-365	-329	-560	-654	-662	-701	-7,236
1992	-712	-673	-724	-704	-730	-443	-365	-329	-559	-654	-662	-701	-7,257
1993	-712	-649	-724	-704	-730	-442	-365	-329	-560	-654	-662	-701	-7,231
1994	-712	-649	-723	-704	-730	-442	-364	-328	-559	-654	-662	-701	-7,227
1995	-712	-649	-723	-703	-730	-442	-365	-328	-559	-654	-662	-701	-7,227
1996	-712	-672	-724	-704	-730	-442	-364	-328	-559	-654	-661	-701	-7,251
1997	-712	-649	-724	-704	-730	-442	-365	-329	-560	-654	-662	-701	-7,230
1998	-711	-649	-723	-703	-729	-442	-364	-328	-559	-654	-661	-701	-7,224
1999	-712	-649	-723	-704	-730	-442	-365	-329	-560	-654	-662	-701	-7,228
2000	-711	-672	-723	-703	-729	-442	-364	-328	-559	-654	-661	-700	-7,247
2001	-711	-649	-723	-703	-729	-442	-364	-328	-559	-653	-661	-700	-7,223
2002	-711	-648	-723	-703	-729	-441	-364	-328	-559	-653	-661	-700	-7,219
2003	-711	-648	-722	-703	-729	-441	-364	-328	-559	-653	-661	-700	-7,217
2004	-711	-671	-723	-703	-729	-441	-364	-328	-558	-653	-661	-700	-7,240
2005	-711	-648	-723	-703	-729	-441	-364	-328	-559	-653	-661	-700	-7,220
2006	-711	-648	-723	-703	-729	-441	-364	-328	-559	-653	-661	-700	-7,220
2007	-711	-649	-723	-703	-729	-442	-364	-329	-559	-654	-661	-700	-7,225
2008	-711	-672	-723	-703	-729	-441	-364	-328	-559	-653	-661	-700	-7,243
2009	-711	-648	-723	-703	-729	-441	-364	-328	-559	-653	-661	-700	-7,219
2010	-711	-648	-723	-703	-729	-441	-364	-328	-559	-653	-661	-700	-7,219
2011	-711	-648	-723	-703	-729	-441	-364	-328	-559	-653	-661	-700	-7,222
2012	-711	-672	-723	-703	-729	-441	-364	-328	-558	-653	-661	-700	-7,241
2013	-711	-648	-723	-703	-729	-442	-364	-328	-559	-654	-661	-700	-7,223
2014	-711	-648	-722	-703	-729	-441	-363	-327	-558	-653	-661	-700	-7,216
2015	-711	-648	-723	-703	-729	-441	-364	-328	-559	-654	-661	-700	-7,222
2016	-711	-671	-723	-703	-729	-441	-364	-328	-558	-653	-661	-700	-7,240
2017	-711	-648	-722	-703	-729	-441	-363	-328	-559	-653	-661	-700	-7,217
2018	-711	-648	-723	-703	-729	-441	-364	-328	-559	-653	-661	-700	-7,219
2019	-710	-648	-722	-702	-728	-441	-363	-327	-558	-652	-660	-699	-7,212
2020	-710	-671	-722	-703	-729	-441	-364	-328	-559	-653	-661	-700	-7,239

Table 2.--*Deviations from average (1970-78) estimated winter base flow, projection 1A, March 1970 through December 2020*

[Values given in acre-feet. Base flow is leakage from the aquifer to the river. The average estimated winter (1970-78) base flow was 16.5 cubic feet per second. Positive numbers are the amount of flow below average, and negative numbers are the amount of flow above average]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1970			-677	-592	-551	-714	-763	-779	-532	-489	-430	-403	-5,929
1971	-363	-296	-293	-251	-229	-216	-191	-173	-130	-130	-113	-100	-2,485
1972	-82	-60	-47	-28	-12	141	191	222	-138	-229	-262	-303	-608
1973	-329	-315	-367	-370	-396	-395	-437	-481	-575	-644	-649	-690	-5,648
1974	-707	-650	-732	-719	-754	-454	-408	-397	-350	-326	-278	-251	-6,028
1975	-217	-169	-160	-129	-109	-54	-37	-49	-90	-107	-94	-82	-1,295
1976	-64	-44	-30	-13	2	250	325	338	136	101	90	111	1,211
1977	123	123	149	157	175	292	338	341	220	197	191	205	2,510
1978	215	204	237	241	259	623	778	857	499	437	398	396	5,143
1979	388	347	382	370	382	590	690	722	455	390	346	337	5,400
1980	324	294	307	292	297	551	661	698	434	371	329	322	4,881
1981	310	273	296	282	288	542	653	689	426	363	322	315	4,759
1982	303	267	290	277	283	538	648	685	422	359	318	311	4,700
1983	300	264	287	274	280	535	645	682	419	357	316	309	4,670
1984	298	272	286	273	279	535	645	681	419	356	316	309	4,669
1985	299	263	286	274	280	535	645	682	419	357	317	310	4,666
1986	299	263	287	274	280	536	646	682	419	357	317	310	4,669
1987	299	264	287	275	281	536	646	682	420	357	317	310	4,674
1988	299	273	287	275	281	536	646	683	420	357	317	310	4,685
1989	299	264	288	275	281	537	646	683	420	358	318	311	4,679
1990	300	265	288	276	282	537	647	683	420	358	318	311	4,682
1991	300	265	288	276	282	537	647	683	420	358	318	311	4,684
1992	300	274	288	276	282	537	647	683	421	358	318	311	4,696
1993	300	265	289	276	282	538	647	683	420	358	318	311	4,688
1994	301	265	289	276	283	538	648	684	421	358	318	312	4,693
1995	301	265	289	277	283	538	648	684	421	358	318	311	4,692
1996	300	275	288	276	283	538	648	684	421	358	319	312	4,702
1997	301	265	289	276	282	538	647	683	420	358	318	312	4,690
1998	301	266	289	277	283	538	648	684	421	359	319	312	4,696
1999	301	265	289	276	283	538	648	683	420	358	318	312	4,691
2000	301	275	289	277	283	538	648	684	421	359	319	312	4,705
2001	301	266	289	277	283	538	648	684	421	359	319	312	4,697
2002	301	266	289	277	283	539	648	684	421	359	319	312	4,701
2003	302	266	290	277	284	539	648	684	421	359	319	312	4,703
2004	302	276	290	277	284	539	649	685	422	359	319	312	4,713
2005	302	266	290	277	283	539	648	684	421	359	319	312	4,700
2006	301	266	289	277	283	539	648	684	421	359	319	312	4,699
2007	301	266	289	277	283	538	648	684	421	358	319	312	4,694
2008	301	275	289	277	283	539	648	684	421	359	319	312	4,709
2009	301	266	290	277	283	539	649	684	421	359	319	312	4,701
2010	301	266	290	277	283	539	649	684	421	359	319	312	4,701
2011	301	266	289	277	283	539	648	684	421	359	319	312	4,698
2012	301	275	289	277	283	539	649	685	422	359	319	312	4,711
2013	301	266	289	277	283	538	648	684	421	359	319	312	4,697
2014	301	266	290	277	284	539	649	685	422	359	319	312	4,704
2015	301	266	289	277	283	539	648	684	421	359	319	312	4,698
2016	301	276	290	277	283	539	648	685	422	359	319	313	4,712
2017	302	266	290	277	284	539	649	684	421	359	319	312	4,702
2018	301	266	289	277	283	539	648	684	421	359	319	313	4,701
2019	302	266	290	278	284	539	649	685	422	360	320	313	4,707
2020	302	276	290	277	284	539	649	684	421	359	319	312	4,713

(1970-78) estimated winter base flow occurred at that time. As the hydraulic head in the aquifer rose during the winter and spring months, leakage to the river increased, the deviations became smaller, and conditions reached a stabilized annual cycle about 1985. In the stabilized annual cycle, monthly base flows are less than the average (1970-78) estimated winter base flow even during the winter months due to the generally lower hydraulic head in the aquifer as compared to the hydraulic heads during 1970-78.

Surface-Water Diversion at 50 Percent of Average 1970-78 Rate

(Projection 1B)

In projection 1B, hydrologic conditions were the same as for projection 1A, except that surface-water diversions into the Osborne Irrigation Canal were decreased by 50 percent after 1979. The decrease in surface-water diversions was simulated by decreasing the recharge for the Osborne Irrigation Canal nodes by 50 percent.

The potentiometric surface for projection 1B during December 2020 is shown in figure 4. The altitude of the projected potentiometric surface ranged from about 1,830 ft near Webster Reservoir to about 1,450 ft near Waconda Lake. The generally lower potentiometric surface in the alluvial aquifer, as compared to the potentiometric surface for projection 1A, especially in the western part of the study area, was caused by the decreased recharge to the aquifer in projection 1B.

The saturated thickness for projection 1B during December 2020 is shown in figure 5. Thickness ranged from zero at several isolated locations to about 80 ft at an isolated site west of Stockton. The projected saturated thickness was greatest in the western one-half of the area, with most of the area in the 20-ft to 40-ft range. Several areas were in the 50-ft to 60-ft range. The eastern one-half of the area had the least projected saturated thickness, with most of the area in the 10-ft to 20-ft range. Saturated thicknesses were somewhat less than those for projection 1A because of the lower hydraulic head resulting from less recharge to the aquifer.

Simulated monthly and annual leakage between the South Fork Solomon River and the alluvial aquifer for projection 1B (March 1970 through December 2020) are given in table 3. All of the values were negative, indicating movement of water from the alluvial aquifer to the river. As was the case for projection 1A, leakage from the aquifer to the stream was least during the summer irrigation season and greatest during the winter and spring months. Also, as was the case for projection 1A, the stream-aquifer system reached a stabilized annual cycle after a period of time. It occurred about 1990.

Comparing table 3 with table 1 shows that leakage from the aquifer to the stream was much less for projection 1B than for 1A. The reason for the smaller leakage was the 50-percent decrease in recharge through the

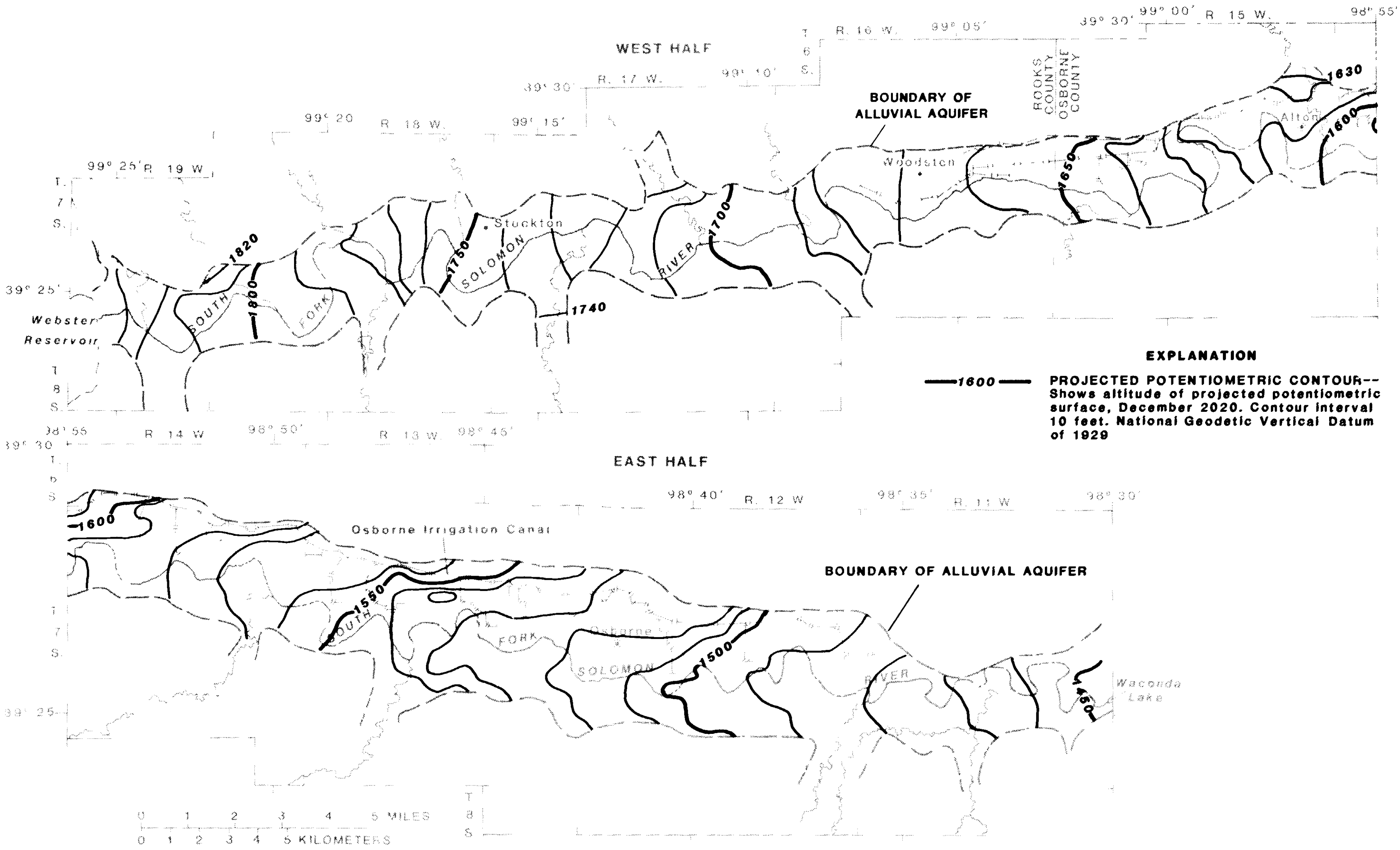

Figure 4.--Potentiometric surface, December 2020, projection 1B.

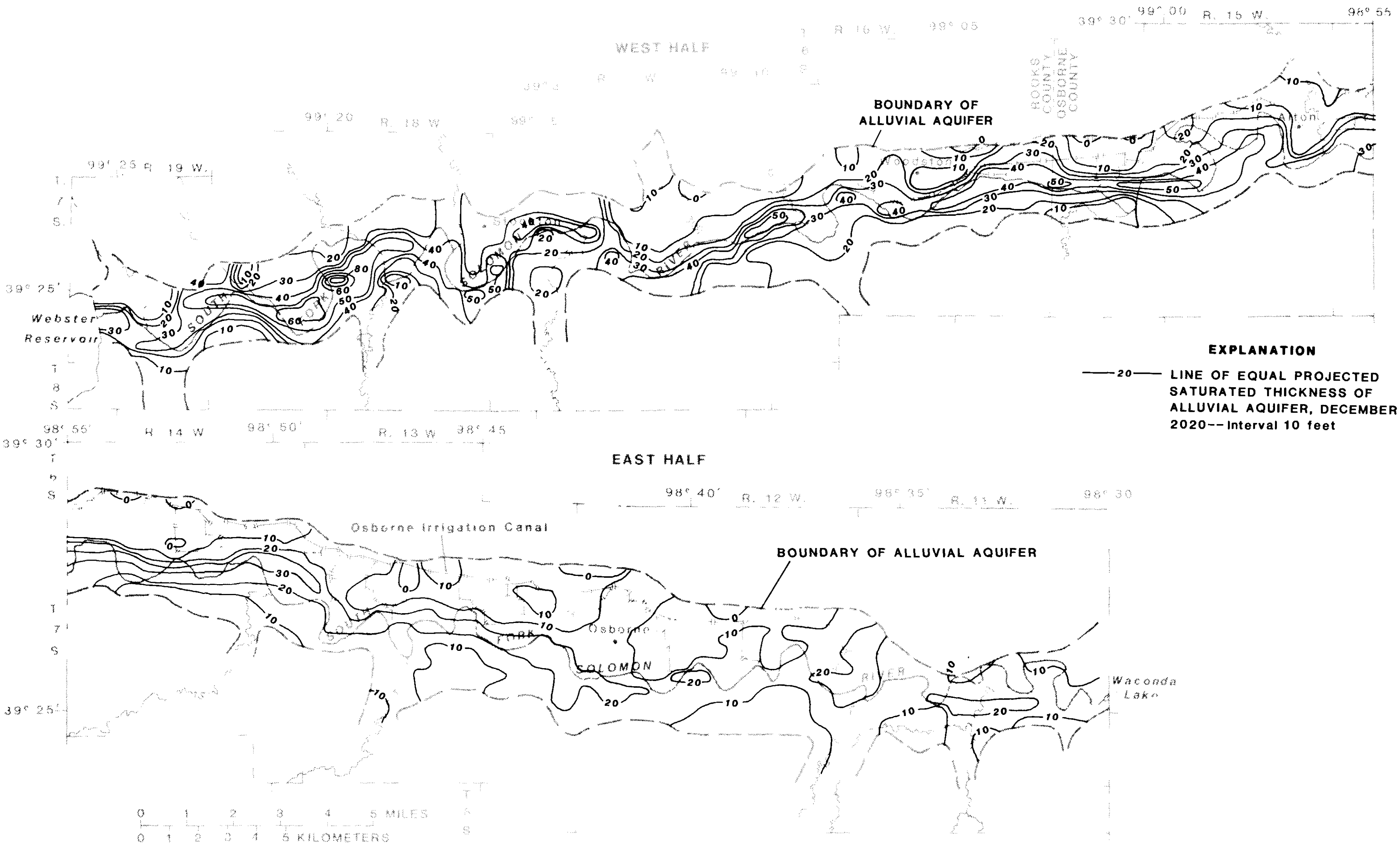

Figure 5.--Saturated thickness, December 2020, projection 1B.

Table 3.--*Net leakage between river and alluvial aquifer, projection 1B, March 1970 through December 2020*

[Values are given in acre-feet. Negative numbers indicate leakage from the aquifer to the river]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1970			-1,689	-1,572	-1,563	-1,694	-1,775	-1,791	-1,512	-1,501	-1,410	-1,415	-15,922
1971	-1,375	-1,210	-1,306	-1,231	-1,241	-1,196	-1,203	-1,185	-1,110	-1,142	-1,093	-1,112	-14,405
1972	-1,094	-1,007	-1,059	-1,008	-1,024	-839	-821	-790	-1,118	-1,242	-1,242	-1,316	-12,560
1973	-1,341	-1,230	-1,379	-1,350	-1,408	-1,375	-1,449	-1,493	-1,555	-1,657	-1,629	-1,703	-17,568
1974	-1,719	-1,565	-1,745	-1,699	-1,766	-1,434	-1,421	-1,409	-1,330	-1,338	-1,258	-1,263	-17,947
1975	-1,229	-1,083	-1,172	-1,109	-1,121	-1,034	-1,049	-1,061	-1,070	-1,119	-1,074	-1,094	-13,215
1976	-1,076	-991	-1,043	-993	-1,010	-730	-688	-674	-844	-911	-881	-901	-10,742
1977	-889	-792	-864	-823	-837	-688	-674	-671	-760	-815	-789	-808	-9,409
1978	-797	-710	-775	-739	-753	-357	-234	-155	-481	-575	-582	-616	-6,777
1979	-624	-567	-630	-610	-630	-309	-213	-161	-464	-568	-585	-628	-5,989
1980	-644	-613	-664	-650	-677	-312	-206	-151	-453	-554	-571	-612	-6,108
1981	-628	-577	-647	-633	-660	-295	-189	-134	-437	-538	-556	-597	-5,891
1982	-613	-563	-633	-619	-646	-282	-177	-123	-426	-528	-545	-586	-5,742
1983	-602	-554	-623	-610	-636	-273	-167	-114	-418	-519	-537	-578	-5,631
1984	-594	-567	-615	-603	-629	-266	-161	-107	-412	-513	-532	-572	-5,572
1985	-589	-542	-609	-597	-624	-261	-156	-103	-408	-509	-527	-568	-5,493
1986	-584	-538	-605	-593	-620	-258	-152	-99	-405	-506	-525	-565	-5,450
1987	-582	-536	-602	-591	-617	-255	-149	-97	-402	-503	-522	-563	-5,418
1988	-579	-553	-600	-589	-615	-253	-148	-95	-401	-502	-521	-561	-5,417
1989	-578	-532	-599	-587	-613	-251	-146	-93	-399	-500	-519	-559	-5,377
1990	-576	-531	-597	-585	-611	-250	-145	-92	-398	-499	-518	-559	-5,361
1991	-575	-530	-596	-584	-610	-249	-144	-92	-398	-498	-517	-558	-5,351
1992	-574	-548	-596	-584	-610	-248	-143	-91	-397	-498	-517	-558	-5,365
1993	-574	-529	-595	-583	-609	-248	-143	-91	-397	-498	-517	-557	-5,342
1994	-574	-529	-595	-583	-609	-247	-142	-91	-397	-497	-517	-557	-5,337
1995	-574	-529	-595	-583	-609	-248	-143	-91	-397	-497	-517	-557	-5,338
1996	-573	-547	-595	-583	-609	-247	-142	-90	-396	-497	-516	-557	-5,353
1997	-573	-528	-594	-583	-609	-247	-142	-90	-396	-497	-516	-556	-5,332
1998	-573	-528	-594	-582	-608	-247	-142	-90	-396	-496	-516	-556	-5,327
1999	-573	-528	-594	-582	-608	-247	-142	-90	-396	-497	-516	-556	-5,329
2000	-573	-547	-594	-583	-608	-247	-142	-90	-396	-497	-516	-556	-5,350
2001	-573	-528	-594	-582	-608	-247	-141	-89	-396	-496	-515	-556	-5,324
2002	-572	-527	-593	-582	-607	-246	-141	-89	-396	-496	-515	-556	-5,320
2003	-572	-527	-593	-582	-608	-246	-141	-89	-396	-496	-515	-556	-5,322
2004	-572	-547	-594	-582	-608	-246	-142	-90	-396	-497	-516	-556	-5,344
2005	-573	-528	-594	-582	-608	-246	-141	-90	-396	-496	-515	-556	-5,324
2006	-572	-528	-593	-582	-608	-246	-141	-89	-396	-496	-515	-556	-5,323
2007	-572	-527	-593	-582	-607	-246	-141	-89	-395	-496	-515	-556	-5,321
2008	-572	-546	-594	-582	-608	-246	-142	-90	-396	-496	-516	-556	-5,344
2009	-572	-527	-593	-582	-607	-246	-141	-89	-395	-496	-515	-556	-5,321
2010	-572	-527	-593	-582	-608	-246	-141	-89	-396	-496	-515	-556	-5,322
2011	-572	-527	-593	-581	-607	-246	-141	-89	-395	-496	-515	-556	-5,319
2012	-572	-546	-593	-582	-608	-246	-141	-89	-396	-496	-515	-556	-5,340
2013	-572	-527	-593	-581	-607	-246	-141	-89	-395	-496	-515	-555	-5,317
2014	-571	-527	-592	-581	-607	-245	-141	-89	-395	-496	-515	-555	-5,314
2015	-572	-527	-593	-581	-607	-246	-141	-89	-396	-496	-515	-556	-5,320
2016	-572	-546	-593	-582	-608	-246	-141	-89	-396	-496	-515	-556	-5,341
2017	-572	-527	-593	-582	-608	-246	-141	-89	-396	-496	-515	-556	-5,323
2018	-572	-527	-593	-581	-607	-246	-141	-89	-395	-496	-515	-556	-5,319
2019	-572	-527	-593	-582	-607	-246	-141	-89	-396	-496	-515	-556	-5,321
2020	-572	-546	-593	-582	-607	-246	-141	-89	-395	-496	-515	-555	-5,338

Osborne Irrigation Canal recharge grid blocks in projection 1B that resulted in a generally lower hydraulic head. The lower hydraulic head in the alluvial aquifer resulted in less leakage to the stream.

Simulated monthly and annual base-flow deviations from the average (1970-78) estimated winter base flow from the alluvial aquifer to the South Fork Solomon River between Webster Reservoir and Waconda Lake for projection 1B (March 1970 through December 2020) are given in table 4. Comparing table 4 with table 2 indicates that the deviations from the average 1970-78 estimated winter base flow were greater for projection 1B than for 1A after May 1979. Less recharge to the aquifer in projection 1B resulted in a generally lower hydraulic head and less leakage from the aquifer to the river (less base flow).

A mass balance for the last 12 months of projection 1B is shown in table 5. The volume of water moving into and out of the aquifer during this period of the projection represents flow rates during a stabilized annual cycle.

Pumpage Increased Annually

In projections 2A and 2B, irrigation pumpage was increased each year, beginning in 1979. The average number of acres irrigated by the 184 approved wells in the study as of 1981 was 60 acres per well (Kelvin Kolb, Kansas State Board of Agriculture, oral commun., 1982). An assumed application rate during one irrigation season of 1.5 ft/acre of water gives a volume of 90 acre-ft per well per year. An examination of recent new well development indicates a reasonable estimate of future well development to be three wells per year (270 acre-ft/yr). The programming code used to distribute the new pumpage each year resulted in an average annual increase in pumpage of about twice the estimated new development.

The simulation of streamflow depletion was a major item in this study. Increased ground-water pumpage results in decreasing ground-water levels, decreased leakage from the aquifer to the river, and a reduction of flow in the river. The simulations were considered terminated when the stream was estimated to be dry. In the simulations, the river was considered dry when the annual leakage from the river to the aquifer was greater than that from the aquifer to the river.

As mentioned earlier in "Accuracy Considerations," this model, as presently setup, requires close inspection to ensure that the leakage calculation from stream to aquifer was not affected unduly by declining water levels in the aquifer. At the end of the simulations, water levels in the aquifer were below the river level in the corresponding node by more than 2 ft in only 4 of the 201 nodes in which leakage was computed.

In order to distribute the annual increase in pumpage, each grid block in the modeled area was classified as one of six grid-block types (fig. 6) as follows:

Type 0 - nonirrigable blocks or blocks outside the model boundary;

Table 4.--*Deviations from average (1970-78) estimated winter base flow, projection 1B, March 1970 through December 2020*

[Values given in acre-feet. Base flow is leakage from the aquifer to the river. The average winter (1970-78) estimated base flow was 16.5 cubic feet per second. Positive numbers are the amount of flow below average, and negative numbers are the amount of flow above average]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1970			-677	-592	-551	-714	-763	-779	-532	-489	-430	-403	-5,929
1971	-363	-296	-293	-251	-229	-216	-191	-173	-130	-130	-113	-100	-2,485
1972	-82	-60	-47	-28	-12	141	191	222	-138	-229	-262	-303	-608
1973	-329	-315	-367	-370	-396	-395	-437	-481	-575	-644	-649	-690	-5,648
1974	-707	-650	-732	-719	-754	-454	-408	-397	-350	-326	-278	-251	-6,028
1975	-217	-169	-160	-129	-109	-54	-37	-49	-90	-107	-94	-82	-1,295
1976	-64	-44	-30	-13	2	250	325	338	136	101	99	111	1,211
1977	123	123	149	157	175	292	338	341	220	197	191	205	2,510
1978	215	204	237	241	259	623	778	857	499	437	398	396	5,143
1979	388	347	382	370	382	671	799	851	516	444	395	384	5,930
1980	368	334	348	330	335	668	806	862	527	458	409	400	5,845
1981	385	338	365	347	352	685	823	878	543	474	424	415	6,029
1982	400	351	379	361	366	698	835	890	554	485	435	426	6,178
1983	410	360	390	370	376	707	845	898	562	493	443	434	6,288
1984	418	380	397	377	383	714	851	905	568	499	448	440	6,381
1985	423	372	403	383	389	719	856	909	572	504	453	444	6,427
1986	428	376	407	387	393	722	860	913	575	506	455	447	6,470
1987	431	379	410	389	395	725	863	915	578	509	458	450	6,502
1988	433	394	412	391	397	727	864	917	579	510	459	451	6,535
1989	434	382	413	393	399	729	866	919	581	512	461	453	6,542
1990	436	384	415	395	401	730	868	920	582	513	462	454	6,559
1991	437	384	416	396	402	731	868	921	582	514	463	454	6,568
1992	438	399	417	396	402	732	869	921	583	514	463	455	6,587
1993	438	385	417	397	403	732	869	921	583	515	463	455	6,578
1994	439	386	418	397	403	733	870	922	583	515	463	455	6,583
1995	438	386	417	397	403	732	870	922	583	515	463	455	6,582
1996	439	400	418	397	403	733	870	922	584	515	464	456	6,599
1997	439	386	418	397	404	733	870	922	584	515	464	456	6,588
1998	439	386	418	398	404	733	871	923	584	516	464	456	6,593
1999	439	386	418	398	404	733	870	922	584	516	464	456	6,590
2000	439	400	418	397	404	733	870	922	584	515	464	456	6,603
2001	439	386	419	398	404	733	871	923	584	516	465	457	6,595
2002	440	387	419	398	405	734	871	923	584	516	465	457	6,599
2003	440	387	419	398	405	734	871	923	584	516	465	456	6,598
2004	440	400	419	398	404	734	871	923	584	516	464	456	6,608
2005	440	387	419	398	404	734	871	923	584	516	465	456	6,595
2006	440	387	419	398	405	734	871	923	584	516	465	456	6,596
2007	440	387	419	398	405	734	871	923	585	516	465	457	6,599
2008	440	401	419	398	404	734	871	923	584	516	464	456	6,609
2009	440	387	419	398	405	734	871	923	585	516	465	457	6,599
2010	440	387	419	398	405	734	871	923	584	516	465	456	6,598
2011	440	387	419	399	405	734	871	923	585	516	465	457	6,600
2012	440	401	419	398	405	734	871	923	584	517	465	457	6,612
2013	440	387	419	399	405	734	871	923	585	517	465	457	6,603
2014	441	388	420	399	405	735	872	924	585	516	465	457	6,606
2015	440	387	419	399	405	734	871	923	584	516	465	457	6,599
2016	440	401	419	398	405	734	871	923	584	516	465	457	6,612
2017	440	387	419	398	405	734	871	923	584	516	465	457	6,597
2018	440	387	419	399	405	734	871	923	585	516	465	457	6,600
2019	440	387	419	398	405	734	871	923	584	516	465	457	6,599
2020	440	401	419	398	405	734	871	923	585	516	465	457	6,614

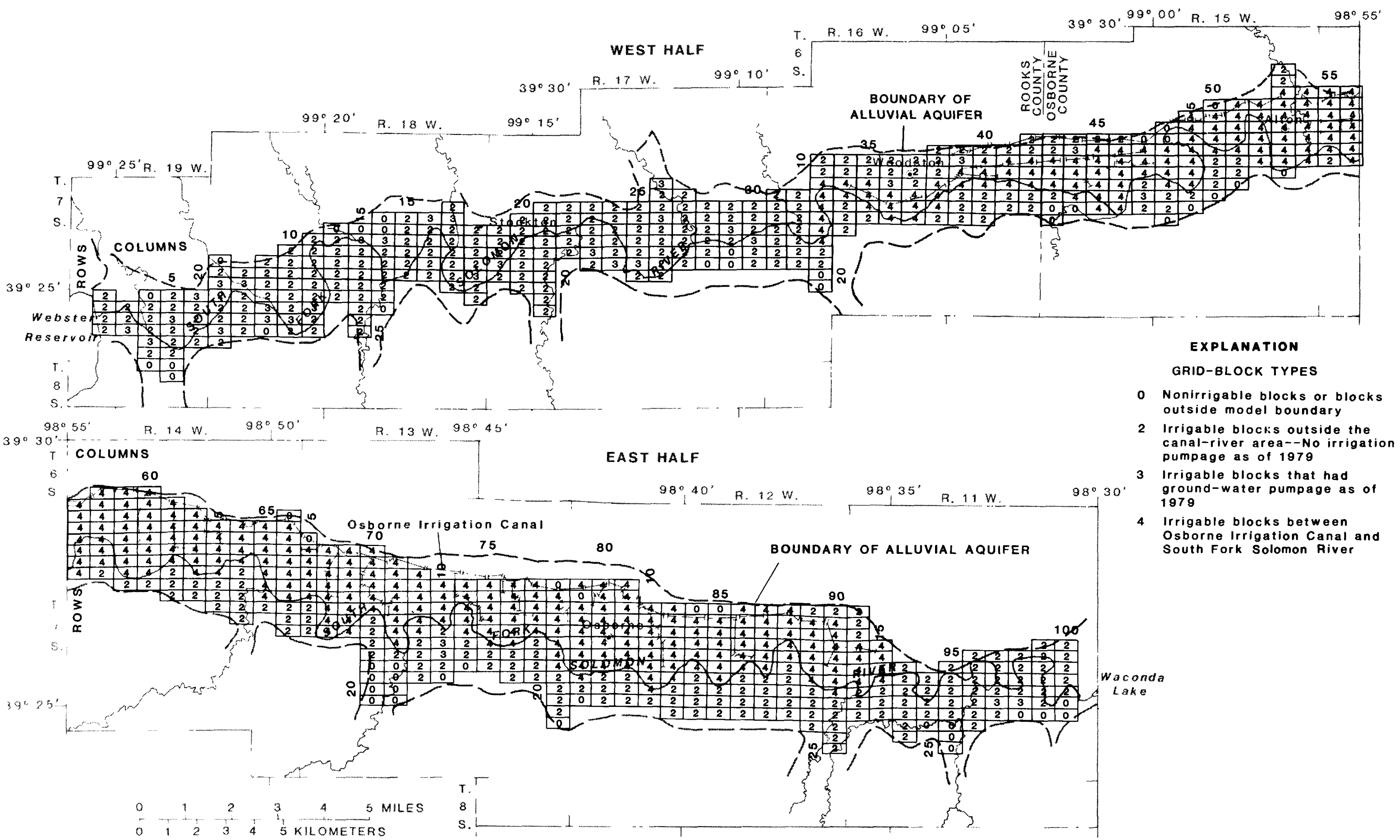

Figure 6.--Starting grid-block types, May 1979.

Type 1 - irrigable blocks in which the saturated thickness falls below 13 ft during the projection;

Type 2 - irrigable blocks outside the canal-river area that had no irrigation pumpage as of 1979;

Type 3 - irrigable blocks that had ground-water pumpage as of 1979;

Type 4 - irrigable blocks located between Osborne Irrigation Canal and South Fork Solomon River; and

Type 5 - irrigable blocks in which pumpage is at a maximum value based on the saturated thickness in the block.

The assumption was made that additional development would occur first in the type-4 grid blocks, proceed to the type-3 blocks, and occur lastly in the type-2 blocks. Grid blocks were classified as irrigable if they contained 50 percent or more of the soils classified by the U.S. Soil Conservation Service as capability classes I-IV (Fleming, 1977; Palmer, 1982). Soils in capability classes I-IV are considered arable by the U.S. Soil Conservation Service and, on that basis, were considered irrigable for purposes of distributing future pumpage increases. Blocks containing less than 50 percent of soils classified as capability classes I-IV were considered to be nonirrigable.

Table 5.--*Mass balance for the last 12 months of projection 1B*

	Average annual flow (cubic feet per second)
Recharge to aquifer	
Precipitation	12.36
Canal leakage	2.73
Boundary inflow	2.41
Leakage from river	8.72
Total recharge	26.22
Discharge from aquifer	
Storage	0.01
Evapotranspiration	.24
Pumpage	9.67
Boundary outflow	.20
Leakage to river	16.09
Total discharge	26.21
Percent of imbalance = 0.00	

The starting grid-block types are shown in figure 6 and include types 0, 2, 3, and 4. Nearly all the blocks are type 2 or 4 and include irrigable land both outside (type 2) and within (type 4) the area between the Osborne Irrigation Canal and the South Fork Solomon River. Irrigable blocks that were already pumping ground water as of 1979 are shown as type-3 blocks in figure 6.

Code changes were made in the digital-computer model in order to calculate a maximum well-discharge rate for each grid block as a function of the saturated thickness in the grid block. A maximum well-discharge rate was calculated during each pumping period for specified grid blocks using the equation:

$$Q = 0.005413\ (SAT)^{1.44}\ , \tag{1}$$

where Q = well discharge, in cubic feet per second; and

SAT = saturated thickness at start of pumping period, in feet.

Equation 1 is derived from a curve depicting the relationship between saturated thickness and the maximum well-discharge rate resulting in an 80-percent drawdown at the center of an 80-acre field (one-half the area of a grid block in the model grid) in 90 days. The curve is shown in figure 7.

The maximum well-discharge rate necessary to produce an 80-percent drawdown at the center of a grid block after pumping 90 days was determined using digital-modeling procedures. A digital model of an area one-half the size of a grid block in the projection-model grid, using the same values for hydraulic conductivity and specific yield used in this report and subdivided into a 21-row x 21-column grid, was used. Model computations were made for starting saturated thicknesses of 20, 50, and 100 ft at various well-discharge rates. Plotting the well-discharge rates and drawdowns at the end of a 90-day pumping period gave a curve from which the discharge producing an 80-percent drawdown in 90 days was determined for each saturated thickness. Saturated thickness then was plotted against the well-discharge rate, yielding the relationship between saturated thickness and maximum well discharge.

The annual pumpage increase was distributed throughout the modeled area on a priority basis dependent on grid-block type. The annual increase was divided evenly among the blocks of a given type during the 92-day summer irrigation season (June, July, and August). The order of priority for types was: (1) type 4, (2) type 3, and (3) type 2. The annual pumpage increase was distributed first among irrigable grid blocks located between irrigation canals and the river. After all these type-4 blocks had a pumpage rate equal to the maximum well-discharge rate calculated for each block, the annual pumpage increase then was distributed among irrigable blocks that were already pumping ground water as of 1979 (type-3). Similarly, after all the type-3 blocks had a pumpage rate equal to the maximum well-discharge rate calculated for each block, the annual pumpage increase then was distributed among irrigable blocks outside the canal-river area that had no irrigation pumpage as of 1979 (type-2).

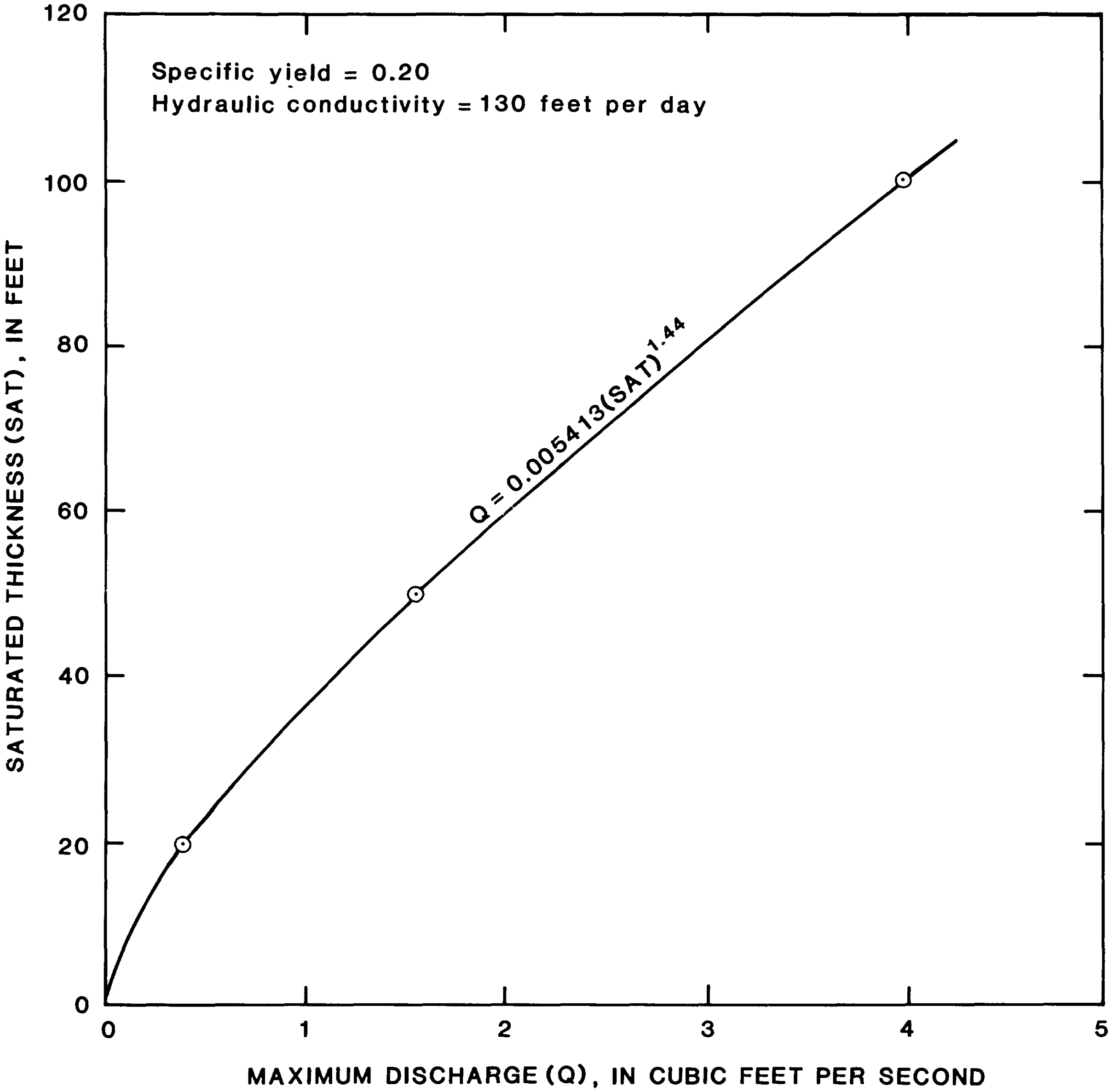

Figure 7.--Relationship between saturated thickness and maximum well discharge.

The saturated thickness and maximum well-discharge rate were calculated for appropriate grid blocks (dependent on type) at the beginning of each pumping period. When the saturated thickness in a block fell below 13 ft (a yield of approximately 50 gal/min by each of two wells), well discharge in that block was set to zero, and the type changed to 1. Changing the type to 1 had the effect of excluding that block from subsequent pumpage-increase calculations. When the well discharge in a block reached the maximum discharge rate allowed based on saturated thickness, the grid-type designation was changed to 5, and well discharge thereafter remained at the calculated maximum value unless the saturated thickness fell below 13 ft.

In projections 1A and 1B, the net annual (June 1 to May 31) leakage was negative for every year, indicating a net annual leakage from the alluvial aquifer to the river. During the summer irrigation season, the monthly net leakage was less than that for nonirrigation months, indicating the potentiometric surface was depressed due to irrigation pumping. However, during the nonirrigation months, the potentiometric surface of the alluvial aquifer rebounded, resulting in a general increase in net monthly leakage from the aquifer to the river through the following months.

In projections 2A and 2B, the same seasonal pattern of leakage between the river and the alluvial aquifer was observed. However, the increasing pumpage after 1979 resulted in a lower potentiometric surface in the aquifer during the summer irrigation season than for projections 1A and 1B. By the early 1980's, the depressed hydraulic head fell below the altitude of river stage, reversing the river-aquifer hydraulic gradient and resulting in net leakage from the river to the aquifer during the summer irrigation season. As was the case in projections 1A and 1B, during the nonirrigation months the potentiometric surface also rebounded in projections 2A and 2B, resulting in net monthly leakage from the aquifer to the river. However, by the early 1990's, the total net leakage from the river to the aquifer during the irrigation season was greater than the total net leakage from the aquifer to the river during the nonirrigation season due to the increased irrigation pumpage. The net annual (June 1 to May 31) leakage was positive during 1992 (2A) and 1989 (2B), indicating a net movement of water for the year from the river to the aquifer.

Surface-Water Diversion at Average 1970-78 Rate (Projection 2A)

In projection 2A, recharge and surface-water diversions in Osborne Irrigation Canal were held constant at average (1970-78) summer and winter rates. Irrigation pumpage was increased annually. The potentiometric surface for projection 2A during February 1993 is shown in figure 8. The altitude of the projected surface ranged from about 1,830 ft near Webster Reservoir to 1,450 ft near Waconda Lake.

The saturated thickness for projection 2A during February 1993 is shown in figure 9. Thickness ranged from zero at several isolated sites to about 80 ft at an isolated site west of Stockton. Projected saturated thickness was generally greatest in the western one-half of the study area where most of the area was in the 20-ft to 50-ft range. It was least in the eastern one-half where most of the area was in the 10-ft to 20-ft range.

Simulated net monthly and annual leakage between the river and the alluvial aquifer for projection 2A (March 1970 through May 1993) are given in table 6. Leakage occurred from the aquifer to the river (negative values) and from the river to the aquifer (positive values). A seasonal pattern of net monthly leakage is evident. Irrigation pumpage during June, July, and August depressed the projected potentiometric surface of the aquifer, resulting in less leakage from the alluvial aquifer to the river in the early part of the projection period and greater leakage from the river to the aquifer after the early 1980's. During the nonirrigation season, the potentiometric surface rebounded, resulting in greater leakage from the aquifer to the river.

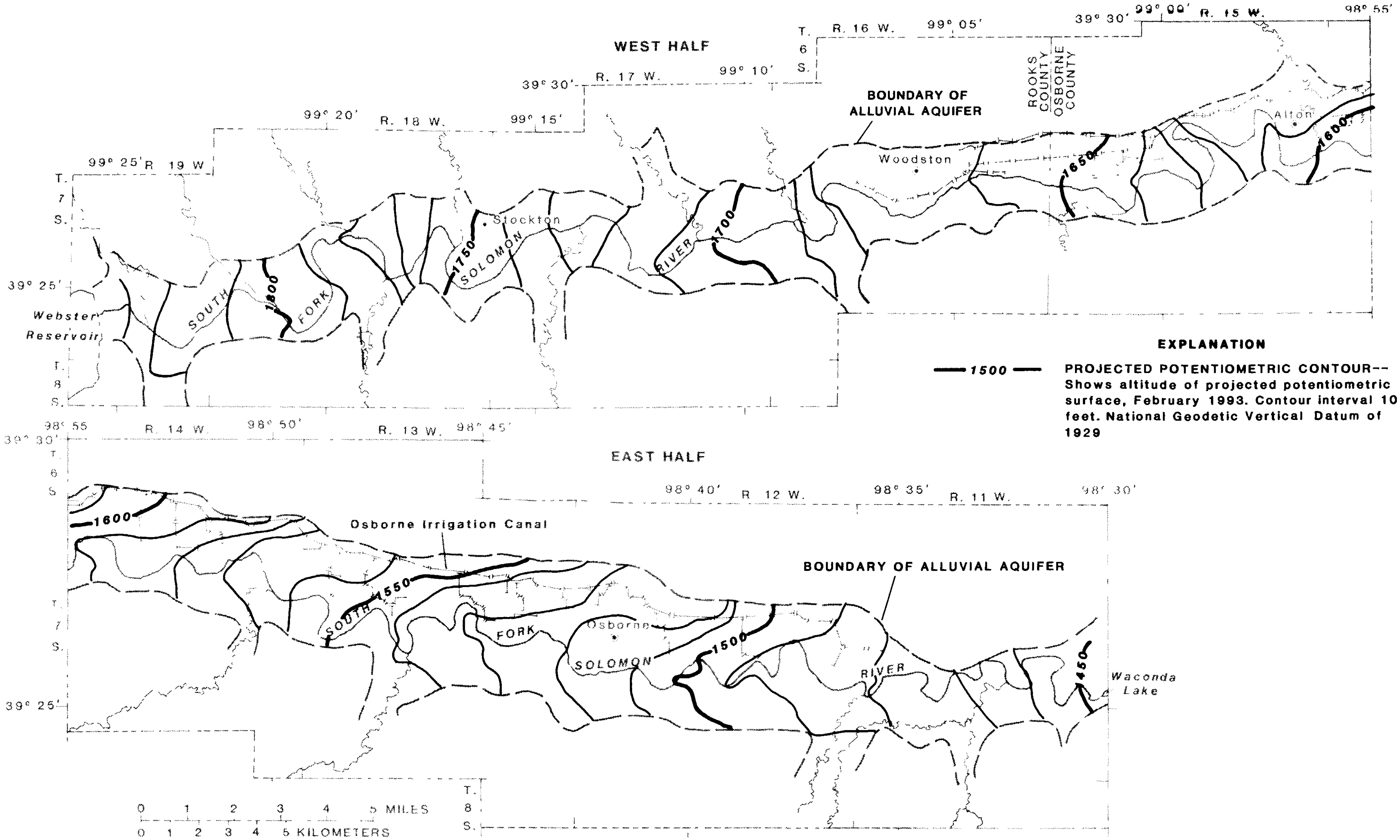

Figure 8.--Potentiometric surface, February 1993, projection 2A.

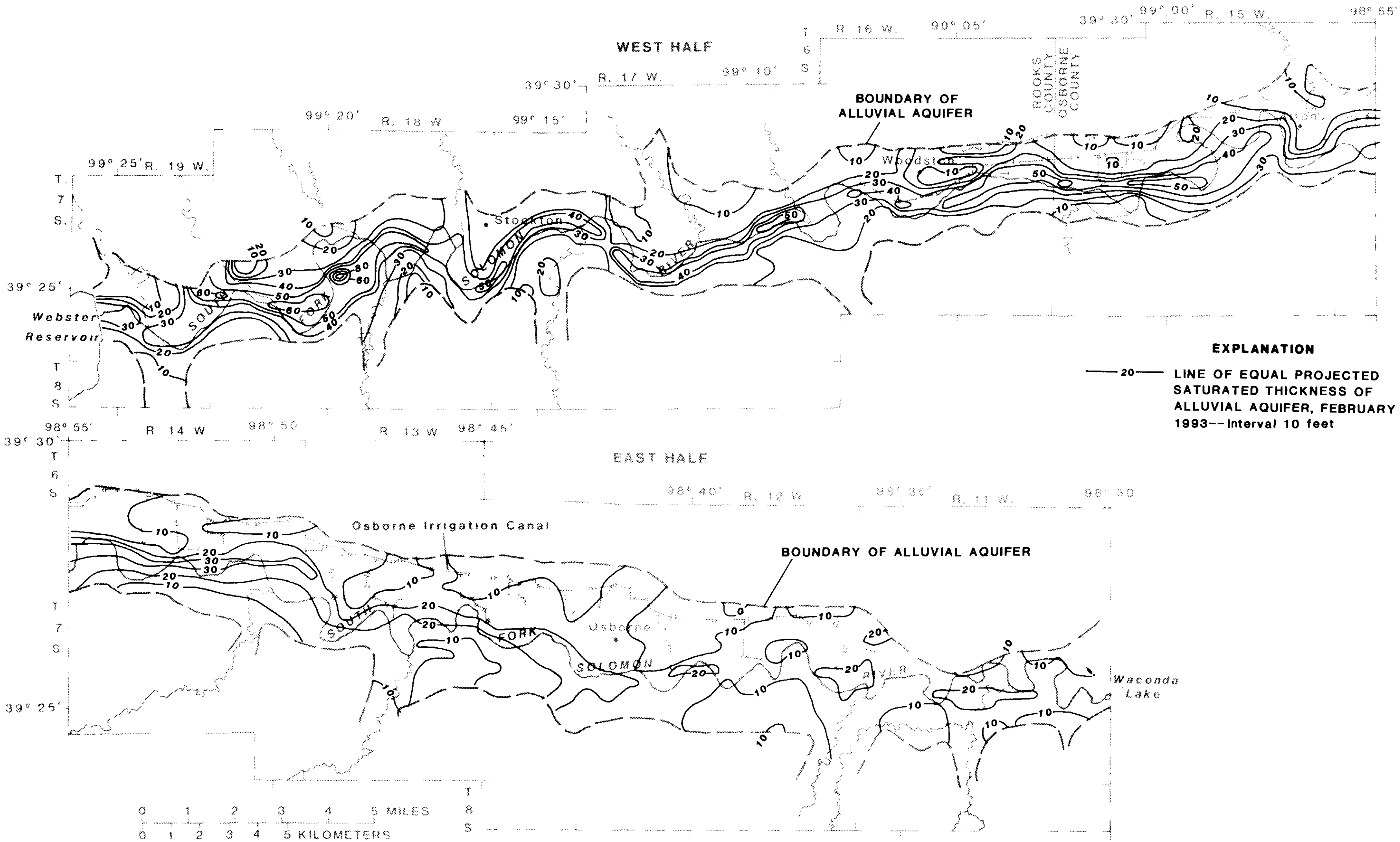

Figure 9.--Saturated thickness, February 1993, projection 2A.

Table 6.--*Net leakage between river and alluvial aquifer, projection 2A, March 1970 through May 1993*

[Values given in acre-feet. Positive numbers indicate leakage from the river to the aquifer. Negative numbers indicate leakage from the aquifer to the river]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1970			-1,689	-1,572	-1,563	-1,694	-1,775	-1,791	-1,512	-1,501	-1,410	-1,415	-15,922
1971	-1,375	-1,210	-1,306	-1,231	-1,241	-1,196	-1,203	-1,185	-1,110	-1,142	-1,093	-1,112	-14,405
1972	-1,094	-1,007	-1,059	-1,008	-1,024	-839	-821	-790	-1,118	-1,242	-1,242	-1,316	-12,560
1973	-1,341	-1,230	-1,379	-1,350	-1,408	-1,375	-1,449	-1,493	-1,555	-1,657	-1,629	-1,703	-17,568
1974	-1,719	-1,565	-1,745	-1,699	-1,766	-1,434	-1,421	-1,409	-1,330	-1,338	-1,258	-1,263	-17,947
1975	-1,229	-1,083	-1,172	-1,109	-1,121	-1,034	-1,049	-1,061	-1,070	-1,119	-1,074	-1,094	-13,215
1976	-1,076	-991	-1,043	-993	-1,010	-730	-688	-674	-844	-911	-881	-901	-10,742
1977	-889	-792	-864	-823	-837	-688	-674	-671	-760	-815	-789	-808	-9,409
1978	-797	-710	-775	-739	-753	-357	-234	-155	-481	-575	-582	-616	-6,777
1979	-624	-567	-630	-610	-630	-369	-265	-192	-535	-650	-666	-712	-6,450
1980	-727	-691	-746	-729	-758	-324	-182	-91	-550	-680	-698	-746	-6,921
1981	-762	-698	-780	-761	-791	-230	-58	45	-534	-681	-704	-755	-6,710
1982	-774	-709	-794	-775	-805	-119	82	198	-503	-667	-696	-751	-6,314
1983	-772	-710	-795	-777	-808	3	234	360	-465	-646	-681	-739	-5,796
1984	-763	-728	-790	-773	-804	132	387	521	-428	-626	-667	-728	-5,266
1985	-754	-696	-784	-767	-800	261	545	689	-387	-602	-650	-714	-4,660
1986	-743	-688	-776	-762	-795	393	705	860	-347	-580	-634	-702	-4,069
1987	-733	-681	-770	-756	-790	531	873	1,038	-303	-554	-614	-685	-3,444
1988	-720	-695	-760	-748	-782	675	1,048	1,226	-252	-521	-589	-664	-2,782
1989	-702	-656	-745	-735	-771	826	1,232	1,422	-199	-487	-563	-641	-2,018
1990	-682	-641	-730	-722	-759	983	1,423	1,626	-146	-454	-537	-619	-1,260
1991	-664	-627	-716	-710	-747	1,147	1,620	1,832	-93	-422	-513	-599	-492
1992	-647	-636	-704	-700	-738	1,309	1,813	2,037	-38	-389	-488	-579	241
1993	-630	-601	-691	-689	-728								

For any particular month and for the annual totals, a decrease in net leakage from the alluvial aquifer to the river followed by an increase in net leakage from the river to the alluvial aquifer is apparent. The above pattern reflects the declining potentiometric surface of the aquifer due to increased pumpage. The monthly deviations from the average (1970-78) estimated winter base flow of 16.5 ft^3/s for March 1970 through May 1993 are given in table 7.

The block-type distribution going into the final irrigation season of projection 2A is shown in figure 10 and includes all grid-block types. A large number of the blocks either have a maximum well-discharge rate dependent on their saturated thickness (type-5) or have a saturated thickness of less than 13 ft and, therefore, a well-discharge rate of zero (type-1). Type-5 and type-1 blocks are not available for further development.

The computed water budget for the last summer pumping period (August 1979) of the model calibration is compared with the final pumping period (May 1993) of projection 2A in table 8.

Surface-Water Diversion at 50 Percent of Average 1970-78 Rate (Projection 2B)

In projection 2B, pumpage conditions were the same as those in projection 2A. However, simulated surface-water diversions into Osborne Irrigation Canal were decreased by 50 percent by decreasing canal leakage by 50 percent in the canal grid blocks.

The altitude of the February 1990 potentiometric surface for projection 2B ranged from about 1,830 ft near Webster Reservoir to about 1,450 ft near Waconda Lake. Decreased recharge in projection 2B resulted in virtually the same potentiometric surface as for projection 2A, except in the area where irrigation canals are present. In the vicinity of the irrigation canals, the surface was lower than that shown in figure 8 by as much as 3 ft.

The simulated saturated thickness for projection 2B during February 1990 (near the end of the projection) differs from that shown in figure 9 only along the irrigation canal on the north side of the river. There the differences are small, with a maximum difference of 3-ft less thickness than that shown for projection 2A.

Simulated net monthly and annual leakage between the river and the alluvial aquifer for projection 2B (from March 1970 through May 1990) are given in table 9. Leakage occurred from the aquifer to the river and vice versa. As was the case for projection 2A, a seasonal pattern of net monthly leakage is evident. In comparison to projection 2A, however, net monthly leakage from the aquifer to the river was less during the nonirrigation season, while net monthly leakage from the river to the aquifer was greater during the summer irrigation season. The decreased recharge to the aquifer in projection 2B as compared to 2A, due to the decrease in surface-water

Table 7.--*Deviation from average (1970-78) estimated winter base flow, projection 2A, March 1970 through May 1993*

[Values given in acre-feet. Base flow is leakage from the aquifer to the river. The average estimated winter (1970-78) base flow was 16.5 cubic feet per second. Positive numbers are the amount of flow below average, and negative numbers are the amount of flow above average]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1970			-677	-592	-551	-714	-763	-779	-532	-489	-430	-403	-5,929
1971	-363	-296	-293	-251	-229	-216	-191	-173	-130	-130	-113	-100	-2,485
1972	-82	-60	-47	-28	-12	141	191	222	-138	-229	-262	-303	-608
1973	-329	-315	-367	-370	-396	-395	-437	-481	-575	-644	-649	-690	-5,648
1974	-707	-650	-732	-719	-754	-454	-408	-397	-350	-326	-278	-251	-6,028
1975	-217	-169	-160	-129	-109	-54	-37	-49	-90	-107	-94	-82	-1,295
1976	-64	-44	-30	-13	2	250	325	338	136	101	99	111	1,211
1977	123	123	149	157	175	292	338	341	220	197	191	205	2,510
1978	215	204	237	241	259	623	778	857	499	437	398	396	5,143
1979	388	347	382	370	382	611	747	820	445	362	314	301	5,470
1980	285	256	266	251	254	656	831	921	430	332	282	267	5,031
1981	250	216	232	219	221	750	954	1,057	446	331	276	257	5,210
1982	239	205	218	205	207	861	1,095	1,210	477	345	284	261	5,606
1983	240	205	217	203	204	983	1,246	1,372	515	366	299	273	6,124
1984	249	219	222	207	208	1,112	1,400	1,533	552	387	313	284	6,687
1985	258	218	229	213	212	1,241	1,557	1,701	593	410	330	298	7,259
1986	269	226	236	218	217	1,373	1,717	1,872	633	432	346	311	7,850
1987	279	233	243	224	222	1,511	1,885	2,050	677	459	366	327	8,475
1988	293	252	252	232	230	1,655	2,060	2,238	728	491	391	348	9,170
1989	311	258	267	245	242	1,806	2,244	2,435	781	525	417	371	9,901
1990	330	273	282	258	254	1,963	2,435	2,638	834	558	443	393	10,660
1991	348	288	296	270	265	2,127	2,633	2,844	887	590	467	413	11,428
1992	365	311	308	280	275	2,289	2,825	3,049	942	624	492	433	12,194
1993	382	314	321	291	284								

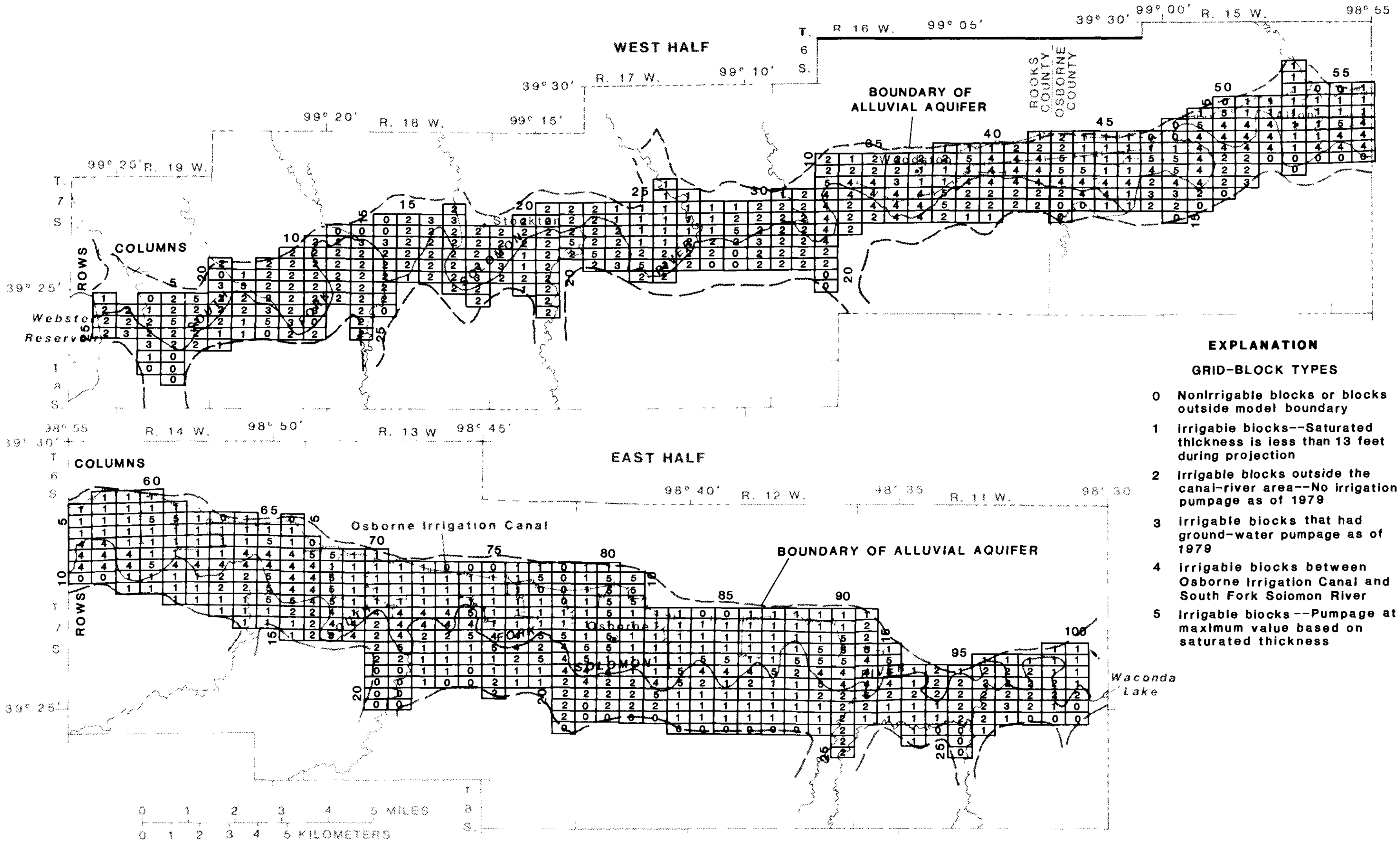

Figure 10.--Grid-block types, June 1992, projection 2A.

Table 8.--*Cumulative mass balance for projection 2A*

[Cumulation began March 1970]

	August 1979 (cubic feet x 10^6)	May 1993 (cubic feet x 10^6)
Recharge to aquifer		
Precipitation	3,733	9,071
Canal leakage	2,196	4,464
Boundary inflow	561	1,492
Leakage from river	1,960	6,490
Discharge from aquifer		
Evapotranspiration	-176	-330
Pumpage	-1,930	-7,811
Boundary outflow	-60	-148
Leakage to river	-7,294	-14,236
Change in storage	997	997
Percent of imbalance	0.1	0.05

diversions into the Osborne Irrigation Canal, lead to a lower projected potentiometric surface in the aquifer and the differences in net monthly leakage observed between tables 9 and 6. The lower potentiometric surface in the alluvial aquifer due to decreased recharge also resulted in less leakage from the aquifer to the river and termination of the simulation 3 years sooner than in projection 2A.

Simulated monthly and annual deviations from the average (1970-78) estimated winter base flow of 16.5 ft^3/s before June 1, 1990, for projection 2B (March 1970 through May 1990) are given in table 10. As was the case for projection 2A, below-average flow (indicating lower base flow) for projection 2B generally increased in magnitude as the projection progressed in time. Again, due to the lower potentiometric surface of the alluvial aquifer in projection 2B, the below-average flows were slightly larger than for projection 2A. The block-type distribution for the final irrigation season in projection 2B is shown in figure 11 and includes all grid-block types.

Table 9.--*Net leakage between river and alluvial aquifer, projection 2B, March 1970 through May 1990*

[Values given in acre-feet. Positive numbers indicate leakage from the river to the aquifer. Negative numbers indicate leakage from the aquifer to the river]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1970			-1,689	-1,572	-1,563	-1,694	-1,775	-1,791	-1,512	-1,501	-1,410	-1,415	-15,922
1971	-1,375	-1,210	-1,306	-1,231	-1,241	-1,196	-1,203	-1,185	-1,110	-1,142	-1,093	-1,112	-14,405
1972	-1,094	-1,007	-1,059	-1,008	-1,024	-839	-821	-790	-1,118	-1,242	-1,242	-1,316	-12,560
1973	-1,341	-1,230	-1,379	-1,350	-1,408	-1,375	-1,449	-1,493	-1,555	-1,657	-1,629	-1,703	-17,568
1974	-1,719	-1,565	-1,745	-1,699	-1,766	-1,434	-1,421	-1,409	-1,330	-1,338	-1,258	-1,263	-17,947
1975	-1,229	-1,083	-1,172	-1,109	-1,121	-1,034	-1,049	-1,061	-1,070	-1,119	-1,074	-1,094	-13,215
1976	-1,076	-991	-1,043	-993	-1,010	-730	-688	-674	-844	-911	-881	-901	-10,742
1977	-889	-792	-864	-823	-837	-688	-674	-671	-760	-815	-789	-808	-9,409
1978	-797	-710	-775	-739	-753	-357	-234	-155	-481	-575	-582	-616	-6,777
1979	-624	-567	-630	-610	-630	-312	-183	-89	-476	-596	-617	-664	-5,999
1980	-683	-651	-706	-690	-720	-231	-62	49	-457	-592	-617	-667	-6,027
1981	-687	-632	-711	-696	-725	-108	92	216	-419	-571	-603	-655	-5,499
1982	-678	-626	-705	-692	-722	26	257	393	-375	-546	-584	-641	-4,894
1983	-666	-617	-697	-685	-716	164	421	564	-337	-526	-570	-630	-4,295
1984	-658	-633	-692	-680	-712	304	591	744	-293	-499	-550	-613	-3,692
1985	-644	-600	-681	-671	-703	447	762	926	-246	-471	-528	-594	-3,004
1986	-628	-588	-668	-660	-693	595	943	1,119	-193	-437	-502	-572	-2,283
1987	-609	-573	-654	-648	-682	749	1,131	1,319	-139	-402	-475	-548	-1,529
1988	-589	-578	-639	-635	-670	908	1,323	1,524	-84	-367	-448	-526	-781
1989	-570	-542	-624	-622	-658	1,072	1,519	1,731	-30	-334	-423	-505	15
1990	-552	-529	-611	-611	-647								

Table 10.--*Deviations from average (1970-78) estimated winter base flow, projection 2B, March 1970 through May 1990*

[Values given in acre-feet. Base flow is leakage from the aquifer to the river. The average (1970-78) estimated winter base flow was 16.5 cubic feet per second. Positive numbers are the amount of flow below average, and negative numbers are the amount of flow above average]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1970			-677	-592	-551	-714	-763	-779	-532	-489	-430	-403	-5,929
1971	-363	-296	-293	-251	-229	-216	-191	-173	-130	-130	-113	-100	-2,485
1972	-82	-60	-47	-28	-12	141	191	222	-138	-229	-262	-303	- 608
1973	-329	-315	-367	-370	-396	-395	-437	-481	-575	-644	-649	-690	-5,648
1974	-707	-650	-732	-719	-754	-454	-408	-397	-350	-326	-278	-251	-6,028
1975	-217	-169	-160	-129	-109	-54	-37	-49	-90	-107	-94	-82	-1,295
1976	-64	-44	-30	-13	2	250	325	338	136	101	99	111	1,211
1977	123	123	149	157	175	292	338	341	220	197	191	205	2,510
1978	215	204	237	241	259	623	778	857	499	437	398	396	5,143
1979	388	347	382	370	382	668	829	923	504	417	363	348	5,921
1980	330	296	307	290	293	749	950	1,061	523	420	363	345	5,926
1981	326	282	302	284	287	872	1,104	1,228	561	441	377	357	6,421
1982	334	288	307	288	290	1,006	1,269	1,405	605	467	396	372	7,026
1983	346	297	315	295	296	1,144	1,433	1,577	643	486	410	382	7,625
1984	355	314	321	300	300	1,284	1,603	1,756	687	513	430	399	8,261
1985	368	314	331	309	309	1,427	1,774	1,938	734	542	452	418	8,916
1986	384	327	344	320	319	1,575	1,955	2,131	787	576	478	440	9,637
1987	403	341	358	332	331	1,729	2,143	2,332	841	611	505	464	10,391
1988	423	369	373	345	342	1,888	2,335	2,536	896	645	532	486	11,171
1989	442	372	388	358	354	2,052	2,531	2,744	950	679	557	508	11,934
1990	460	386	401	369	365								

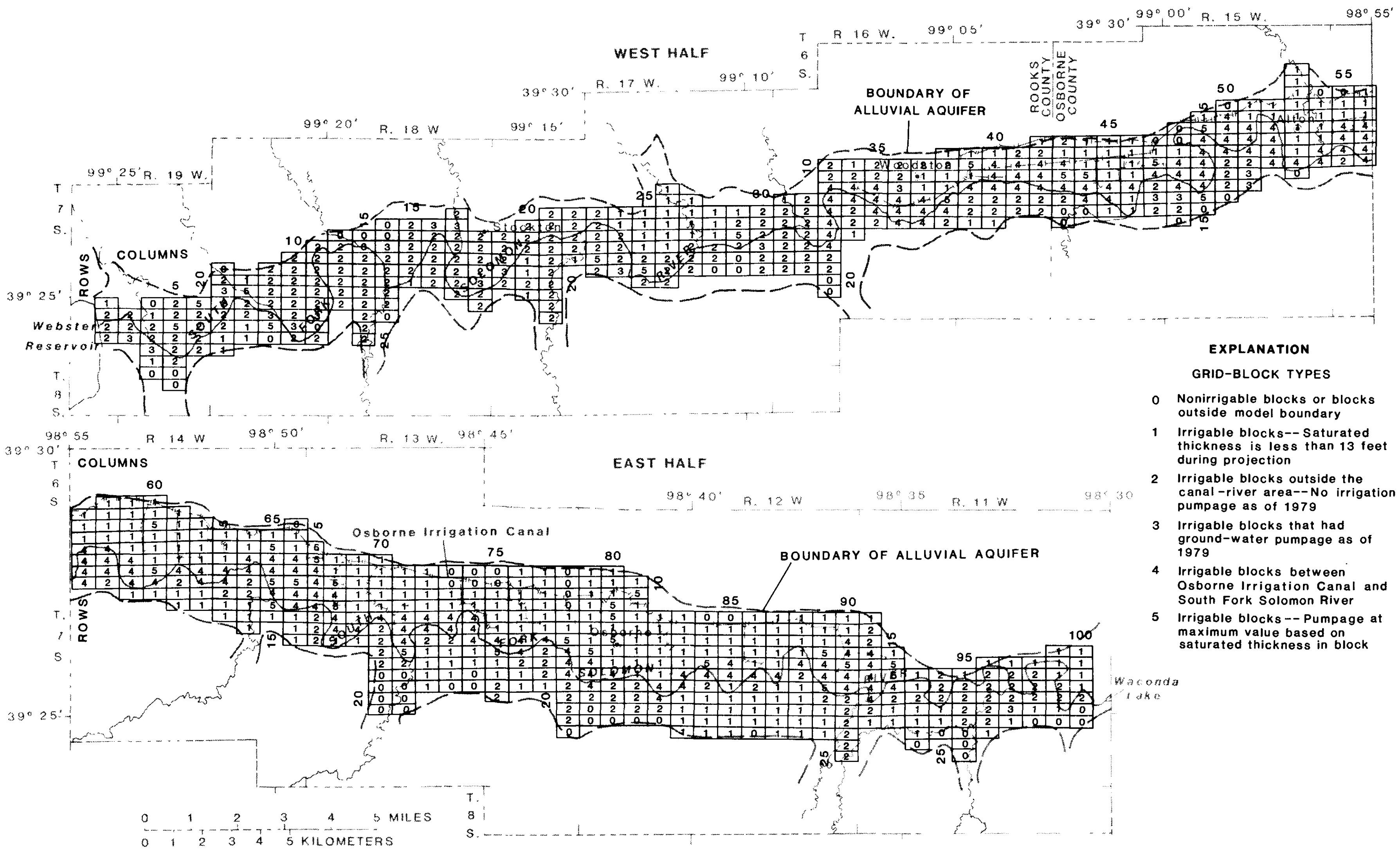

Figure 11.--Grid-block types, June 1989, projection 2B.

SUMMARY

The ground-water flow in an alluvial aquifer in the South Fork Solomon River valley between Webster Reservoir and Waconda Lake in north-central Kansas was modeled in two dimensions to project changes from 1979 to 2020 in the potentiometric surface, saturated thickness, and river-aquifer leakage. Four projections (1A, 1B, 2A, and 2B) were made using the finite-difference transient model developed in a previous study by Burnett and Reed (1982; 1985). Simulated hydrologic conditions included shortages of surface water and increased ground-water development. In projections 1A and 1B, pumpage was held constant at the 1978 rates throughout the 1979-2020 projection period. In projections 2A and 2B, the 1978 pumpage was increased progressively each year. For projections 2A and 2B, each grid block in the modeled area was classified into one of six types according to irrigable or non-irrigable lard, saturated thickness (13 ft and above or below 13 ft), location in or outside canal-river area, and pumping rate. This classification was necessary to facilitate the annual distribution of increased pumpage to available grid blocks on a priority basis based on type. In projections 1B and 2B, the surface-water diversions into the Osborne Irrigation Canal were decreased by 50 percent and held constant for the projection period.

The amount of base flow (leakage from the aquifer to the river) was less during the irrigation pumping season (June, July, and August) due to the depressed potentiometric surface than during the other months of the year. For projections 1A and 1B, the aquifer leakage to the river reached relatively constant values by the mid-to-late 1990's, indicating the stream-aquifer system had reached a stabilized annual cycle. However, in projections 2A and 2B, because of an annual increase in irrigation pumpage, this stability was not reached. The potentiometric surface was lower during the summer irrigation season for projections 2A and 2B than for projections 1A and 1B. By the early 1980's, the depressed hydraulic heads for projections 2A and 2B fell below river stage during the summer irrigation season, reversing the hydraulic gradient and resulting in net leakage from the river to the aquifer during the summer months. During the nonirrigation months, the potentiometric surface rebounded, resulting in net monthly leakage from the aquifer to the river. By 1993 for projection 2A and 1990 for projection 2B, the net annual (June 1 to May 31) leakage was from the river to the aquifer, and the simulations were stopped with the presumption that there was no water left in the river for depletion.

REFERENCES

Burnett, R. D., and Reed, T. B., 1985, Management simulations of South Fork Solomon River valley between Webster Reservoir and Waconda Lake, north-central Kansas: U.S. Geological Survey Water-Resources Investigations Report 85-4200, 19 p.

_____1986, Availability of water for irrigation in the South Fork Solomon River valley, Webster Reservoir to Waconda Lake, north-central Kansas: U.S. Geological Survey Water-Resources Investigations Report 86-4064, 89 p.

Fleming, E. F., 1977, Soil survey of Osborne County, Kansas: U.S. Soil Conservation Service, 61 p.

Lohman, S. W., and others, 1972, Definitions of selected ground-water terms-Revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

Palmer, C. D., 1982, Soil survey of Rooks County, Kansas: U.S. Soil Conservation Service, 111 p.

Trescott, P. C., Pinder, G. F., and Larson, S. P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 7, Chapter C1, 116 p.

SUPPLEMENTAL MODEL DATA

The following table lists the starting grid-block types used in projections 2A and 2B.

Block-Type Matrix (ITYPE)

1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	4	4	4
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	4	4	4	4	4
	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	4	4	4	4	4	4	4	4	4	4
	4	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			

Block-Type Matrix (ITYPE)--Continued

6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4
	4	4	4	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4
	4	4	4	4	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	2	2	2	2	2	0	0	4	4	4	4	4	4	4	4	4	4	4	4
	4	4	4	4	4	4	4	4	4	4	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2
	2	2	2	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	4	4	4	4	4	4	4	4	4	4	4	4	0	0	0	2	2	0	2	2
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	3	4
	4	4	4	4	4	4	4	4	4	2	2	4	4	4	2	4	4	2	4	4
	2	4	4	2	4	4	4	4	4	4	4	4	0	0	0	4	4	0	2	2
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			

Block-Type Matrix (ITYPE)--Continued

11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	4	4
	4	4	4	4	4	4	4	4	4	2	2	0	0	0	0	0	0	0	2	2
	2	2	2	2	4	4	4	4	4	4	4	4	4	4	4	4	4	0	4	4
	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	3	0	0	0	0	0	0	4	4	4	3	2	4	4	4
	4	4	4	4	4	4	2	4	2	3	0	0	0	0	0	0	0	0	0	0
	2	2	2	2	4	4	4	4	4	4	4	4	4	4	4	4	4	0	4	4
	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	2	2	0	0	0	2	2	4	4	4	4	4	4	2	2
	2	2	2	4	4	4	3	2	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	2	2	2	2	2	4	4	4	4	4	4	4	4	4	4	4	4	4
	4	4	4	0	0	4	4	4	2	2	2	0	0	0	0	0	0	0	0	0
	0																			
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
	2	2	2	2	2	3	2	2	2	2	2	2	4	2	4	4	4	4	2	2
	2	2	0	0	4	4	2	2	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	2	0	2	2	4	4	2	4	4	4	4	4	4	4	4	4	4
	4	4	4	4	4	4	4	4	4	4	2	0	0	0	0	0	0	0	0	0
	0																			
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	3	0	0	2
	2	2	2	2	2	3	2	2	2	2	2	2	4	2	2	4	4	2	2	2
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	2	2	4	4	2	4	2	2	4	4	4	4	4	4	4
	4	4	4	4	4	4	4	4	4	4	2	0	0	0	0	0	0	0	0	2
	0																			

Block-Type Matrix (ITYPE)--Continued

16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2
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	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	2	4	2	3	2	4	4	2	4	4	4
	4	4	4	4	4	4	4	4	4	4	4	4	0	0	0	0	0	0	2	2
	0																			
17	0	0	0	0	0	0	0	0	0	0	2	2	3	3	2	2	2	2	2	2
	2	2	2	2	2	2	2	2	2	3	2	2	4	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	2	2	2	3	2	2	2	2	4	4	4
	4	4	4	4	4	4	4	4	4	4	4	4	0	0	0	2	2	2	2	2
	0																			
18	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2
	2	2	3	2	2	2	2	2	0	2	2	2	2	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	2	2	0	2	2	2	4	4	4
	4	4	4	4	4	4	4	2	4	4	4	4	2	2	2	2	2	2	2	2
	0																			
19	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	3	2
	2	0	2	3	3	2	2	0	0	2	2	2	2	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	2	2	2	4	2
	2	4	4	2	4	2	2	2	4	4	4	4	2	2	2	2	2	2	2	2
	0																			
20	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	3	2	2
	2	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	2	2
	2	4	2	2	2	2	2	2	2	2	4	2	2	2	2	2	2	2	2	2
	0																			

Block-Type Matrix (ITYPE)--Continued

21	0	0	0	0	0	0	3	3	2	2	2	2	2	2	0	0	2	2	0	2
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2
	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	2	2	0
	0																			
22	0	2	0	0	2	3	2	2	2	2	2	2	2	2	0	0	0	2	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0	0	0
	0																			
23	0	2	2	2	2	2	2	2	3	2	3	0	2	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	2	2	2	0	2	2	2	2	0	0	2	0	0	2	0	0	0	0
	0																			
24	0	2	2	2	3	2	2	2	3	3	0	0	2	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0
	0																			
25	0	2	3	2	2	2	3	2	0	2	2	0	2	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
	0																			

Block-Type Matrix (ITYPE)--Continued

26	0	0	0	3	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
27	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0																			