HYDROLOGIC DESCRIPTION OF THE TAMARACK WILDLIFE AREA AND VICINITY, LOGAN COUNTY, COLORADO, AND SIMULATED EFFECTS OF POSSIBLE WATER-MANAGEMENT ACTIVITIES

By Alan W. Burns

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CONVERSION FACTORS

Inch-pound units used in the report may be converted to metric SI (International System of Units) units by use of the following conversion factors:

Multiply inch-pound unit	*By*	*To obtain SI units*
acre-foot (acre-ft)	1233	cubic meter
acre	4047	square meter
cubic foot per second (ft^3/s)	28.3162	liter per second
foot (ft)	.3048	meter
foot per day (ft/d)	.3048	meter per day
foot per year (ft/yr)	.3048	meter per year
foot per mile (ft/mi)	.1894	meter per kilometer
gallon per minute (gal/min)	.06309	liter per second
inch (in.)	25.4	millimeter
inch per year (in./yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square miles (mi^2)	2.590	square kilometer

To convert degrees Celsius (°C) to degrees Fahrenheit (°F) use the following formula: ($°C \times 9/5 + 32 = °F$).

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ABSTRACT

The stream-aquifer hydrologic system of the Tamarack Wildlife Area and vicinity in Logan County, Colorado, is described qualitatively, based on quantitative analyses of water level, water temperature, and specific conductance data. Data for 58 sites including the South Platte River, sloughs, wells completed in the river bottom, and wells completed in the valley meadow and sandhills were collected at 3- to 6-week intervals. Correlation between water levels at each pair of monitoring stations was used in a statistical cluster analysis to determine that water levels in the wells completed in the river bottom more closely relate to water levels in the river than with water levels in wells completed in the upgradient valley meadow. Computed water-table surfaces showed most of the water movement was parallel to the river with a small gradient toward the river. Water-temperature data at sites on the river showed the largest annual fluctuation; wells yielding water from more than 10 feet below land surface showed no fluctuation. Sloughs and shallow ground water showed intermediate fluctuations. Specific conductance data were indicative of the source of water: water from wells completed in the sandhills averaged 264 microsiemens per centimeter at 25° Celsius; whereas the river averaged 1,540 microsiemens.

A ground-water flow model was calibrated to evaluate possible water-management activities in the study area. Results showed that new ground-water pumpage or lower river stage caused by upstream diversions would decrease ground-water inflow to the slough, with a corresponding water-temperature decrease. An artificial-recharge project would increase ground-water inflow to the slough and increase water temperature in the slough. Using a simplified slough-temperature model that assumed the temperature in a slough was a linear combination of fluctuating river temperature and constant ground-water temperature, the changes in slough temperature were estimated based on changes in ground-water inflow to the slough computed by the ground-water flow model.

A plan to pump ground water to create wildlife-habitat ponds was simulated to evaluate the effects of the plan on streamflow. Simulated results showed stream depletions throughout the year except during the nonpumping period, June through August, when there was a small net stream gain.

INTRODUCTION

The Tamarack Wildlife Area in northeastern Colorado (fig. 1) is comprised of about 10,000 contiguous acres along the South Platte River near Crook, Colo. Owned and operated by the Colorado Department of Natural Resources, Division of Wildlife, this wildlife area is managed to provide sustained yields of resident and migratory wildlife species for sport harvest, non-consumptive wildlife recreation, education, and research.

Cognizant of potential water-management activities throughout the South Platte River basin and planned changes in its own water-resource activities, the Division of Wildlife entered into a cooperative study with the U.S. Geological Survey to study the area. The purpose of this study was to define the hydrologic system in and near the Tamarack Wildlife Area and to evaluate effects of possible changes in water-management activities.

Purpose and Scope

The purpose of this report is twofold: (1) Description of the hydrologic system; and (2) evaluation of effects on that system resulting from possible water-management activities. Although the South Platte River basin has been the subject of numerous hydrologic investigations for many years, this study considered a somewhat unique set of hydrologic parameters and size of area. Ground-water and surface-water interrelations are described qualitatively with selected quantitative analyses of data to substantiate these hydrologic descriptions.

Possible stresses resulting from proposed or hypothesized water-management activities were imposed on the quantitative analyses. Resultant effects from these added stresses then can be evaluated on the total hydrologic system.

Physiographic Setting

Although the study area is small (about 12 mi^2), considerable difference occurs in physiographic setting and land use. The South Platte River was considered the northern boundary for this study. Except during flood flows, the South Platte River flows in a distinct, though extensively braided, sand channel with 5- to 10-ft banks.

The flood plain (or river bottom) is a low-lying area covered with grasses, cottonwood trees, and many other native riparian phreatophytes. Hydrologic conditions on the flood plain vary with the flow in the river. During moderate to low flow, the flood plain is generally dry. During high flows, much of the area becomes marshy; during flood conditions, flowing water can be almost anywhere.

An important hydrologic characteristic of the flood plain is the secondary channel system, known locally as sloughs. These sloughs are the primary hydrologic characteristic of interest to the Division of Wildlife.

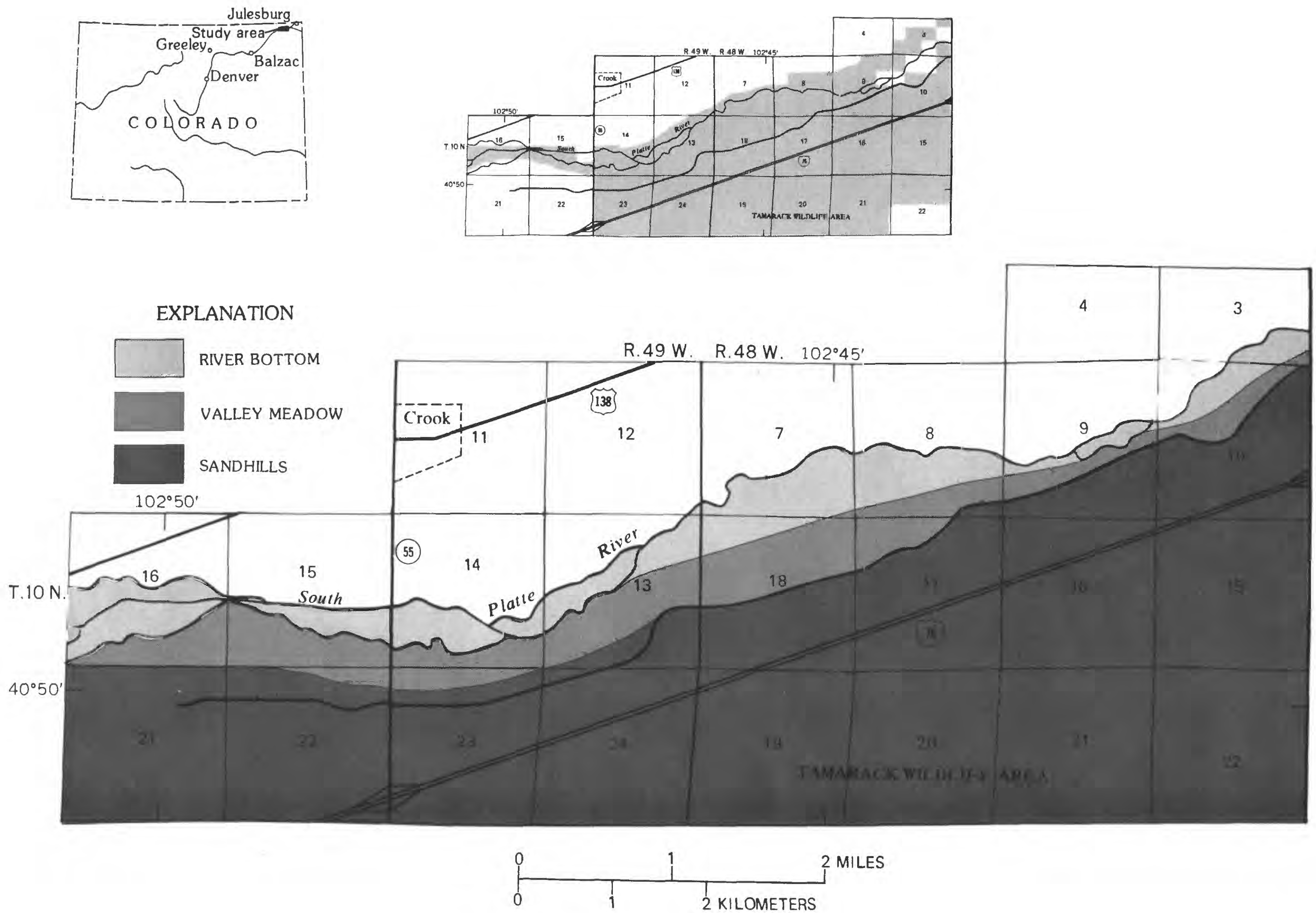

Figure 1.--Location of study area.

These sloughs reportedly contained warm water during the winter months. Because they reportedly did not completely freeze as did the nearby river, these sloughs were considered an important resource to wildlife and waterfowl. Possible effects caused by various water-development actions on these "warm-water" sloughs was the primary concern resulting in this study.

On the south side of the flood plain, a relatively narrow strip of flat, grassy land is defined as the valley meadow. Slightly elevated from the flood plain, this meadow area is still susceptible to extreme floods. Few trees exist on the valley meadow, except where planted by man. Hay meadows dominate this area, although the Division of Wildlife cultivates part of this area by planting corn, which remains unharvested for wildlife forage. No domestic grazing animals are allowed on the wildlife area; however, the valley meadow on an adjacent property to the west represents a primary winter-grazing area for cattle.

An area of sand dunes due south of the valley meadow rise as much as 100 ft above the nearby valley meadow. Numerous small peaks and depressions are covered with dry grasses and cacti, typical of uncultivated and ungrazed semiarid prairies. There is no evidence of any channelization in the sand-hills, indicating that all water resulting from the intense thunderstorms common to this area quickly infiltrates into the sandy soil.

DATA COLLECTION

Three major data-collection efforts were included as part of this project: (1) Aerial imagery; (2) aquifer tests; and (3) periodic collection of hydrologic data from a network of sites. The data collected will not be presented in this report, but a brief summary of each will be given.

Aerial Imagery

The original intent of the aerial imagery was to locate the "warm-water" sloughs. Color-infrared photography was to be taken early in the project during the coldest part of the winter, when the river most likely would be frozen. Open water, indicative of warmer sloughs, appears in color-infrared photography as dark blue, compared to the grey or white of the ice-covered river. Later in the spring, before higher flows would occur from snowmelt runoff, thermal imagery was to be collected to depict the areal distribution of water temperature within 0.5°C (Celsius), showing sources of warmer water and its mixing in the river.

Because of delays in getting the project started, contracting procedures to obtain vendors, and abnormally warm winters, the aerial imagery was completed too late for the project-planning phase of this study. However, this imagery, taken over the South Platte River from Greeley to Julesburg (fig. 1), will be helpful to the Division of Wildlife and other agencies for regional planning. The thermal imagery was collected on March 13, 1980, in the predawn hours to prevent solar heating of the water surfaces. Ground-truth data was collected from midnight until 7:00 a.m. by continuous recorders near Greeley and near Balzac, and manual measurements were made at about 30 sites along the entire Greeley to Julesburg reach. Ground-water seepage throughout the river bottom can easily be seen, even on black-and-white copies (fig. 2) of the original color imagery. The scene depicted in figure 2 shows the water in several slough channels to be about 2°C warmer than the water in the main channel. The color-infrared imagery was photographed on February 12, 1982, 2 days after the coldest day during the study. The main channel can be seen (fig. 3) as both a bright white, where there is ice cover, and a black, where there is open water. The main slough in the study area also is easily seen in this figure on the south side of the river. The various land use and physiographic settings can easily be distinguished in both figures 2 and 3. The river bottom is dominated by the scattered phreatophytes; most of the valley meadow in these scenes is characterized by the somewhat unusual farming techniques on the wildlife area, and all of the southern area is the sand dunes.

Aquifer Tests

During this study, water levels in observation wells were intensively monitored to measure the responses of the aquifer system to three specific stresses: a standard pumping test on the wildlife property; an artificial-recharge test in the sandhills about 10 mi to the west; and a pumping-recharge test in the wildlife area.

An aquifer test to determine aquifer characteristics in the study area was conducted in November 1979. Tamarack well 6, one of seven large-capacity wells installed in the sandhills by the Division of Wildlife, was selected for testing because of its central location and proximity to existing observation wells. Three additional 100-ft observation wells were drilled by the U.S. Geological Survey near this well. To decrease the effects of recharge on pumping drawdowns, the pump discharge was transported about 2,000 ft to the valley meadow through 6-in. irrigation pipe. Discharge averaged about 800 gal/min. Ten observation wells were monitored during the 7 days of pumping and during an additional 2 days of recovery.

A different type of test was occurring at the same time at a nearby site. Maynard Sonnenburg, a local landowner, informed the U.S. Geological Survey that he would be conducting an artificial-recharge experiment during the 1979-80 winter at a site about 10 mi west of the wildlife area. Water-level measurements in the vicinity of the recharge experiment were monitored during routine field trips to the wildlife area because of the similarity in hydrologic settings and because the recharge experiment was similar to a proposed plan by the Division of Wildlife to pump water from wells into depressions in the sandhills to create waterfowl-habitat ponds. The most interesting observation during Sonnenburg's recharge experiment was that no ponding of water occurred while about 900 gal/min were discharged into a depression in the sandhills. Rather, all the water infiltrated into the sandy soil before it could run downhill to the bottom of a depression. A report by Burns (1984) details these measurements and evaluates the effects of this pumpage-recharge experiment on the South Platte River.

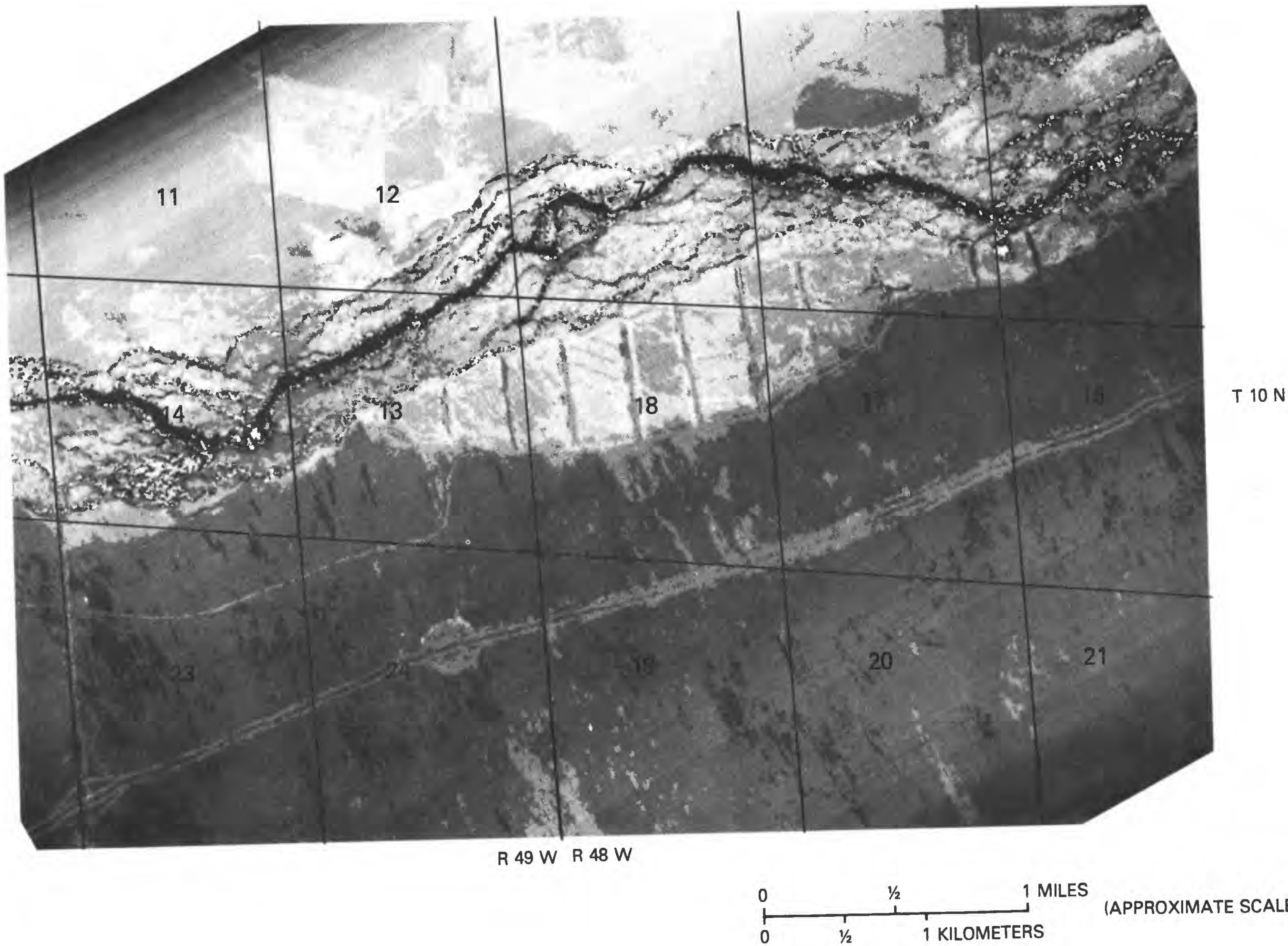

Figure 2.--Black-and-white print of thermal imagery of part of the Tamarack Wildlife Area taken on March 13, 1980.

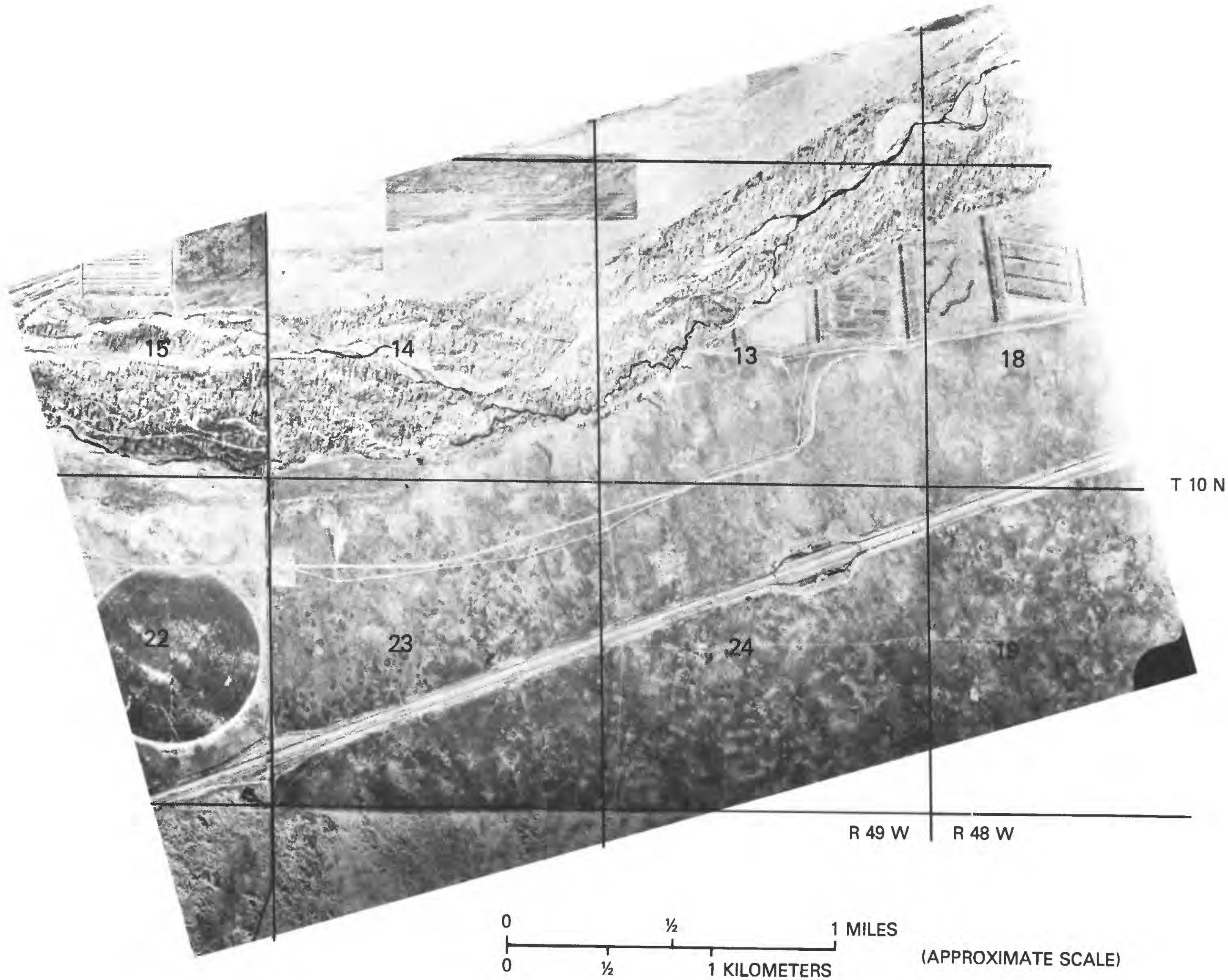

Figure 3.--Black-and-white print of color-infrared imagery of part of the Tamarack Wildlife Area taken on February 12, 1982.

After observing the Sonnenburg experiment results, a second aquifer test was conducted in the wildlife area. This time the water was discharged in a depression in the sandhills. Two 6-in. irrigation pipes were laid from Tamarack well 6 for a distance of 3,000 ft. Unlike the Sonnenburg experiment, which had allowed the water to run downhill toward the depression, the pipeline was brought to the very bottom of the depression, and the gated pipe decreased the velocity of the water hitting the soil. Four additional observation wells were drilled by the U.S. Geological Survey: a 175-ft well near the pumping well to monitor drawdown and three 65-ft wells near the depression to monitor recharge. Three 50-ft galvanized-steel pipes also were installed near the depression, so neutron probes could monitor soil moisture. Well 6 was pumped at a mean rate of about 1,270 gal/min. Water levels in 14 wells were monitored for 13 days of pumpage and for 2 days of recovery. The principal difference between this experiment and the Sonnenburg experiment was that a pond was formed. A staff gage was installed soon after the water started ponding in the depression. Water levels rose rapidly (fig. 4) for the first day, filling the deepest part of the depression. The pond level continued to rise for the next 4 days, spreading over a lateral area of about 2 to 3 acres. The pond level started declining after about 5 days even though the well pumpage stayed about the same. It is believed that as the water spread both vertically and laterally, there was more saturated soil, which can transmit water faster than unsaturated soils; thus, the water seeped out of the pond faster. In addition, as the wetted front moves downward, air bubbles are trapped in the soil matrix. These air bubbles dissolve with time, increasing the degree of saturation and the ability to transmit water. Unfortunately, the test only was run for 2 weeks, so it is not known whether the pond would have continued to decrease in size or whether it would have reached equilibrium with the volume of water entering equaling the volume seeping out. Eighteen hours after the well was turned off, the pond was completely gone, and the depression could be walked on without getting muddy. Data collected using the neutron probe show the movement of the wetted front in the soil profile (fig. 5) as the seepage from the pond moved downward and the water table started moving upward.

Periodic Hydrologic Data

A network of 57 sites (of the 58 available) was selected for data collection, which included 47 wells and 10 surface-water sites. Twenty-five visits from July 1979 through August 1981 at 3- to 6-week intervals were made. Data collected included water levels, air and water temperature, and specific conductance. (Specific conductance is a measure of the ability of water to transmit electricity and directly relates to the quantity of dissolved solids in the water.) In addition to the seven wells that were installed for the aquifer and recharge tests, ten other wells were drilled by the U.S. Geological Survey to supplement existing wells as part of the network. Also, four staff gages were installed, eight bridge measuring points were established, and a cantilever gage was built. A report by Burns (1983) presents all data collected at these sites during periodic visits, plus data from an initial reconnaissance trip. Analysis of these data represents an important part of this current report, and references to specific site numbers will be made throughout. To help in this interpretation, the location of all sites is shown on plate 1 (in the pocket at the back of the report), and a brief

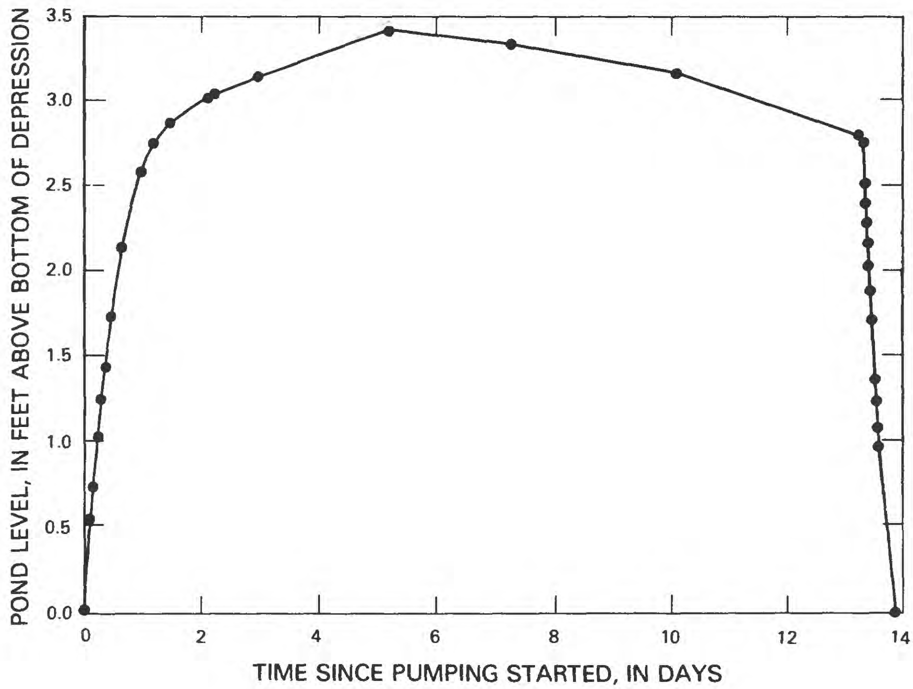

Figure 4.--Water levels in the recharge pond.

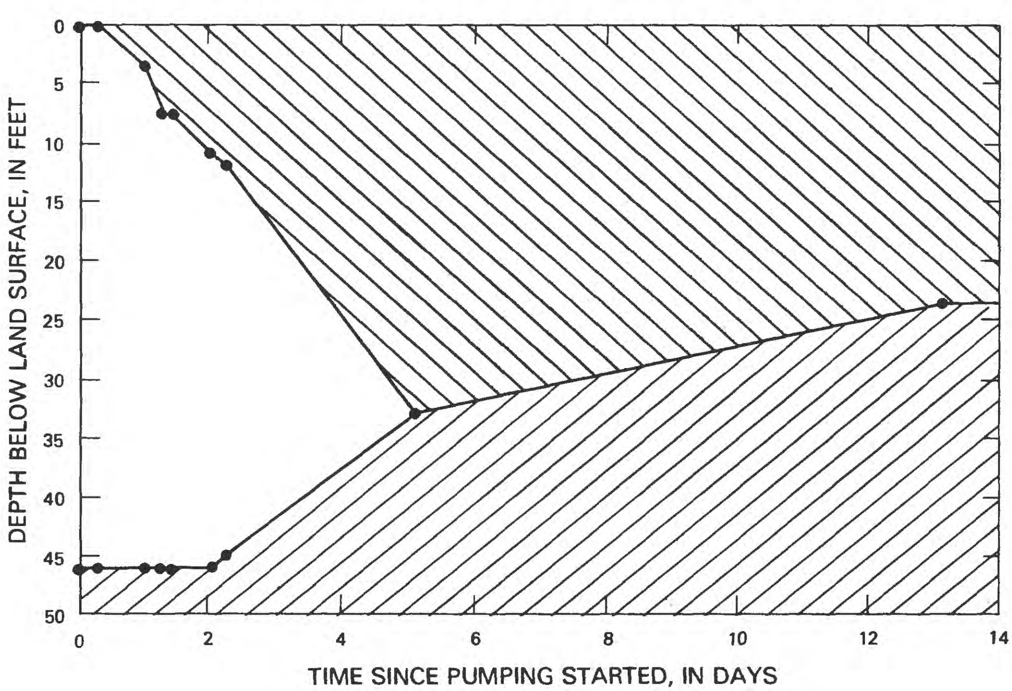

Figure 5.--Profile of soil saturation at a point near the edge of the recharge pond.

description of physiographic setting, site type, and the mean value of each collected parameter is given in table 1.

Data for a site not included in the data report (Burns, 1983) has been added for this interpretive analysis. Gaging station 06764000, South Platte River at Julesburg, has been designated site 58 for the subsequent analyses. It is the closest stream-gaging station to the study area; available data include mean daily discharge and once-per-day water-temperature and specific-conductance values. Data collected in the study area usually were collected during 2 or 3 days. Therefore, values used for site 58 were means of daily values for the appropriate days.

DESCRIPTION OF THE HYDROLOGIC SYSTEM

The hydrologic system of the Tamarack Wildlife Area and vicinity is composed of two major components: the South Platte River (surface water) and the underlying alluvial aquifer (ground water). These two components are complexly linked; the sloughs are one point where that linkage can be observed. Headwaters of the South Platte River are hundreds of miles to the west in the mountains; major flow contributions come from tributaries such as the St. Vrain Creek, Big Thompson River, and Cache la Poudre River to the west of the study area. The South Platte River at Crook is regulated, affected by irrigation and storage diversions and subsequent irrigation return flow. The alluvial aquifer was formed by the ancestral South Platte River eroding a valley into the older bedrock and then depositing alluvial sand and gravel. Along the south side of the river, eolian sand has been deposited to form extensive sand dunes. Much of the eolian sand overlies the alluvial sand and gravel and becomes indistinguishable from the rest of the aquifer system.

Water enters the system from the south and west in the aquifer and from the west in the river. Although severe summer thunderstorms are not uncommon in this area, direct precipitation on the study area provides very little water to the hydrologic system. Potable ground water [specific conductance ranging from 100 to 300 µS/cm (microsiemens per centimeter at 25° Celsius)] enters the study area from the sandhills to the south. Potable ground water (300 to 900 µS/cm) enters from the west. Water in the river normally varies in quality from about 900 to 2,100 µS/cm. Some river water enters the aquifer depending on the stage in the river and the location along the river. The Tamarack Wildlife Area has a low-priority water right on the Tamarack Ditch, which results in infrequent diversion of water from the ditch to the area. Seepage from the ditch and applications in excess of crop consumptive use also provide recharge to the aquifer system. Water leaves the system as: (1) Flow to the east in both the river and the aquifer; (2) evapotranspiration; and (3) ground-water seepage to the river. The river has a net gain of water as it flows through the study reach. Less ground water leaves the study area to the east than enters from the west. The greatest loss of water in the study area is consumptive use by agricultural and riparian vegetation and by evaporation.

Table 1.--*Site descriptions and mean values of selected measurements*
[μS/cm, microsiemens per centimeter at 25° Celsius;
dashes indicate no data available]

Site number (plate 1)	Physiographic setting	Site type	Elevation of measuring point (feet above sea level)	Mean depth to water (feet)	Mean water temperature (degrees Celsius)	Mean specific conductance (μS/cm)
1	River bottom	Well	3,715.97	6.17	12.2	1,210
2	River bottom	Well	3,713.65	4.68	11.5	591
3	River bottom	Well	3,710.09	1.28	--	--
4	River bottom	Well	3,715.97	6.63	12.7	1,170
5	River bottom	Well	--	4.05	--	--
6	River bottom	Slough	3,706.89	1.93	13.3	979
7	River bottom	River	3,712.61	9.19	14.6	1,600
8	River bottom	Well	3,709.49	3.63	9.8	1,300
9	River bottom	Slough	3,715.14	8.78	12.1	1,440
10	River bottom	Well	3,708.37	2.06	--	--
11	River bottom	Slough	3,714.99	8.47	14.0	528
12	Valley meadow	Well	3,711.09	4.69	--	--
13	River bottom	Slough	3,704.84	1.78	12.5	1,280
14	Valley meadow	Well	3,716.84	6.83	13.6	422
15	Sandhills	Well	3,749.61	37.36	--	--
16	Sandhills	Well	3,743.83	36.23	13.2	256
17	Sandhills	Well	3,757.24	55.26	14.6	255
18	River bottom	Slough	3,695.26	.38	11.3	1,210
19	Valley meadow	Well	3,703.28	7.60	11.7	654
20	Valley meadow	Well	3,703.93	11.18	14.7	332
21	Sandhills	Well	3,769.84	78.27	14.7	304
22	Sandhills	Well	3,777.58	91.54	14.6	243
23	Valley meadow	Well	3,696.93	12.62	14.8	303
24	Sandhills	Well	3,769.85	89.98	14.6	269
25	Sandhills	Well	3,769.09	89.45	--	--
26	Sandhills	Well	3,768.65	88.89	--	--
27	Sandhills	Well	3,768.52	89.07	--	--
28	Sandhills	Well	3,726.72	47.35	--	--
29	Sandhills	Well	3,725.30	48.81	--	--
30	Valley meadow	Well	3,684.29	7.86	14.3	361
31	River bottom	River	--	--	12.0	1,510
32	Sand hills	Well	3,750.29	74.84	14.5	244
33	Valley meadow	Well	3,676.71	4.73	11.5	951
34	Valley meadow	Pond	3,671.98	-.38	11.9	622
35	Valley meadow	Well	3,678.03	6.65	11.8	889
36	River bottom	River	3,666.38	2.07	12.6	1,470
37	Sandhills	Well	3,742.22	72.71	14.5	265
38	Valley meadow	Well	3,676.76	8.87	--	--
39	Valley meadow	Well	3,670.21	7.02	12.2	1,200
40	Sandhills	Well	3,691.01	29.63	--	--

Table 1.--*Site descriptions and mean values of selected measurements*--Continued

Site number (plate 1)	Physiographic setting	Site type	Elevation of measuring point (feet above sea level)	Mean depth to water (feet)	Mean water temper-ature (degrees Celsius)	Mean specific conduct-ance (µS/cm)
41	Sandhills	Well	3,707.09	45.93	14.2	238
42	Sandhills	Well	3,709.43	51.47	15.1	263
43	River bottom	River	3,665.55	11.91	11.8	1,520
44	Sandhills	Well	3,732.20	69.99	--	--
45	Sandhills	Well	3,722.59	52.43	--	--
46	Sandhills	Well	3,762.49	78.07	--	--
47	Sandhills	Well	3,751.17	57.54	--	--
48	Sandhills	Well	3,765.23	62.57	14.3	309
49	Sandhills	Well	--	--	14.9	319
50	Valley meadow	Well	3,722.94	8.04	12.5	1,580
51	Sandhills	Well	3,749.23	39.61	--	--
52	Sandhills	Well	3,707.69	46.52	--	--
53	Sandhills	Well	3,732.97	18.48	--	--
54	Sandhills	Well	3,769.76	90.19	--	--
55	Sandhills	Well	--	58.92	--	--
56	Sandhills	Well	--	55.38	--	--
57	Sandhills	Well	--	53.09	--	--

The sloughs are a visible link between the aquifer and river. The sloughs are distinct channels in the flood plain that normally flow to the river. These sloughs are abandoned river channels either eroded into the flood plain by overbank flow during floods or remanent parts of the former river. During the flood flows of May 1980, river water was flowing in all the sloughs. During low to moderate river flows, the sloughs contain a mixture of ground and surface water, depending on the hydraulic connection of the various channels. In the simplest cases, the sloughs are merely topographic lows whose bottoms are below the water table (for example, sites 6 and 11). Ground water seeps into these channels and then begins flowing downgradient in the surface-water channel. Another similar feature in the study area is a pond (site 34) with no surface-water inlet or outlet. While the pond contains water only because it was dug out below the water table, it is different than the sloughs, because there is no opportunity for surface-water outflow.

The three hydrologic parameters collected during hydrologic monitoring of the system were: water level; water temperature; and specific conductance. Analyses of these data consist of describing how the values change both temporally at a point and spatially at one time. Because flow rates of surface water normally are orders of magnitude greater than those of ground water, temporal changes normally occur much faster in surface water. The different rates of change were used to distinguish surface water from ground water, and then water in the sloughs were compared to each.

Water Levels

Hydrographs of water levels at all sites in the observation network are presented in Burns (1983). A comparison of water-level data for all sites was made by computing the correlation coefficient of the time series of water levels at each site with every other site. The degree of correlation between every pair of sites is shown in figure 6. Beyond the obvious significant correlation between sites close to one another (24-27 and 55-57), many other sites correlate quite well with one another.

A statistical procedure called cluster analysis was used to group the sites, based on their correlation matrix. Given a desired number of groups, this analysis places each site into the appropriate group to explain as much of the variation between sites as possible. This analysis was computed to see if statistical similarities in this complex, interrelated hydrologic system would relate to physical attributes. While some unexplained sites occur in certain groups, the analysis produced results that appear feasible from the physical viewpoint.

During the initial analysis, site 54 was eliminated because it appeared to be a plugged well. Selecting five clusters, the analysis identified four groups that had some physiographic consistency, plus a fifth group of misfits. That group included site 3, a well under the slough in which the water level did not change very much during the study; sites 5 and 41, which both had very short records; site 46, a well which seemed to have an inaccurate water level for 1 month; and sites 2 and 15, for unexplained reasons. The analysis was

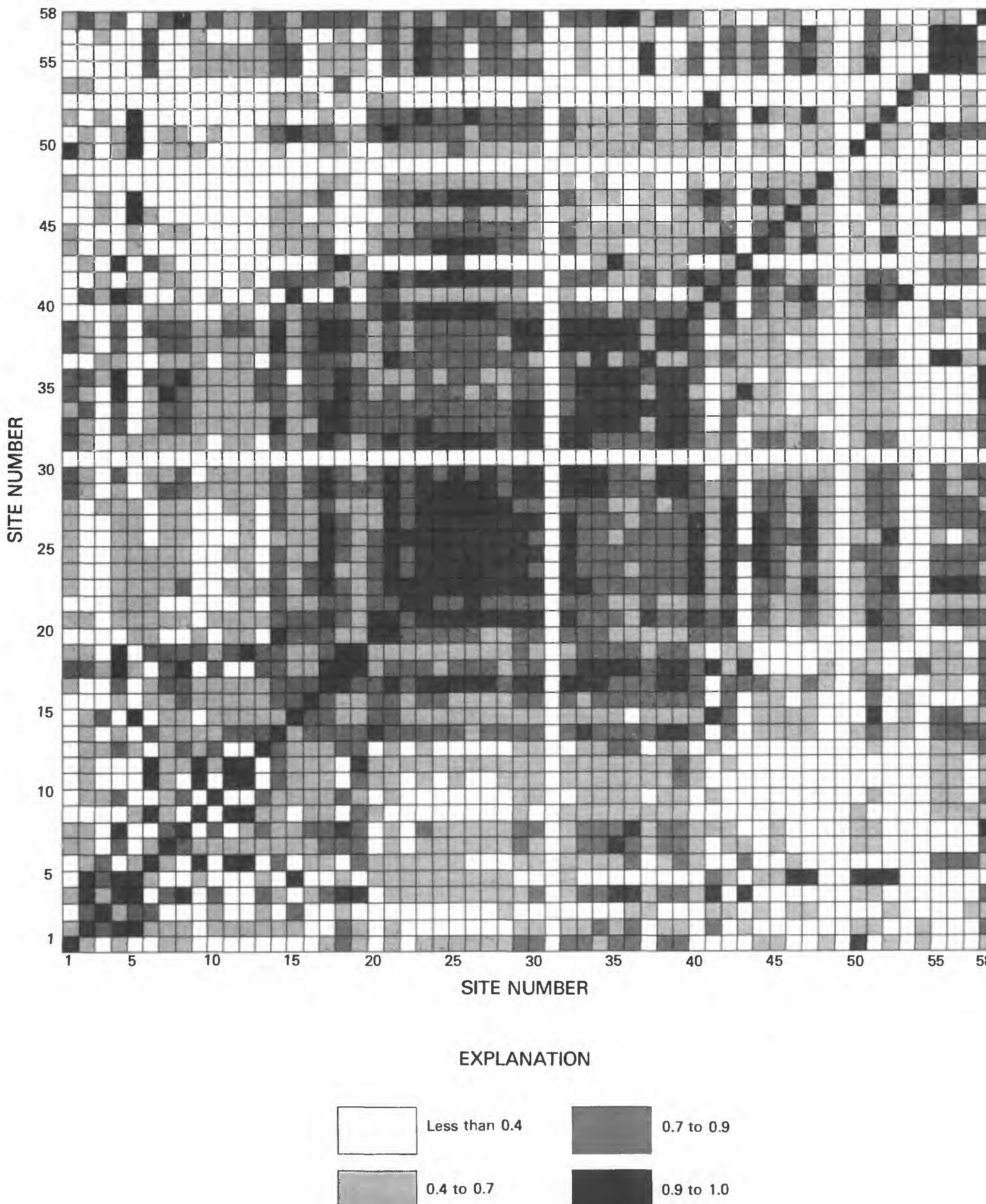

Figure 6.--Correlation coefficients of water levels at the 58 sites.

recomputed, eliminating sites 3, 5, 41, 46, and 54. The sites as grouped by the analysis with four clusters, along with the author's qualitative description of each group, are listed in table 2.

Table 2.--*Statistical groupings (clusters) of sites based on their water-level correlations*

General description	Group	Site numbers
Wells in central and eastern sandhills	1	22, 23, 24, 25, 26, 27, 28, 29, 32, 40, 42, 44, 45, 47, 48, 50, 52, 55, 56, 57
Surface-water sites and nearby wells	2	1, 2, 4, 7, 8, 10, 13, 18, 30, 33, 34, 35, 36, 38, 39, 43, 58
Sloughs	3	6, 9, 11, 12, 19
Wells in western sandhills	4	14, 15, 16, 17, 20, 21, 37, 51, 53

Group 1 includes all wells in the sandhills and some in the valley meadow on the edge of the sandhills, from site 22 east, except site 37. Based on physiographic setting, only site 50 does not fit in with this group. Group 2 includes all surface-water sites, except the most westward sloughs, and most of the wells in the river bottom and valley meadow. Based on their physical setting, only sites 19 and 50 are absent from this group. Group 3 includes the western sloughs and an adjacent well plus site 19, which is farther east but is adjacent to a slough. Group 4 includes all wells in the sandhills and in the valley meadow on the edge of the sandhills from site 21 west. Site 37 seems misplaced in this group even though it is in the sandhills but much farther east.

The similarity within each of these groups can best be shown by plotting hydrographs of all sites within each cluster on the same graph. These hydrographs, of all the sites for each of the groups identified by the four-group cluster analysis computation, are shown in figures 7 through 10. Datum for each site was adjusted such that the mean water level was 5 ft, so that all of the hydrographs would be approximately centered.

Perhaps the most illuminating result from this cluster analysis is that most of the wells in the river bottom are grouped with surface-water sites rather than with other ground-water sites. The importance of the river on the aquifer system is clearly demonstrated.

Although the water-level data from the river, sloughs, and wells show temporal changes that allow them to be grouped separately, the elevation of the water-level surface at any one time is quite smooth and illustrates the

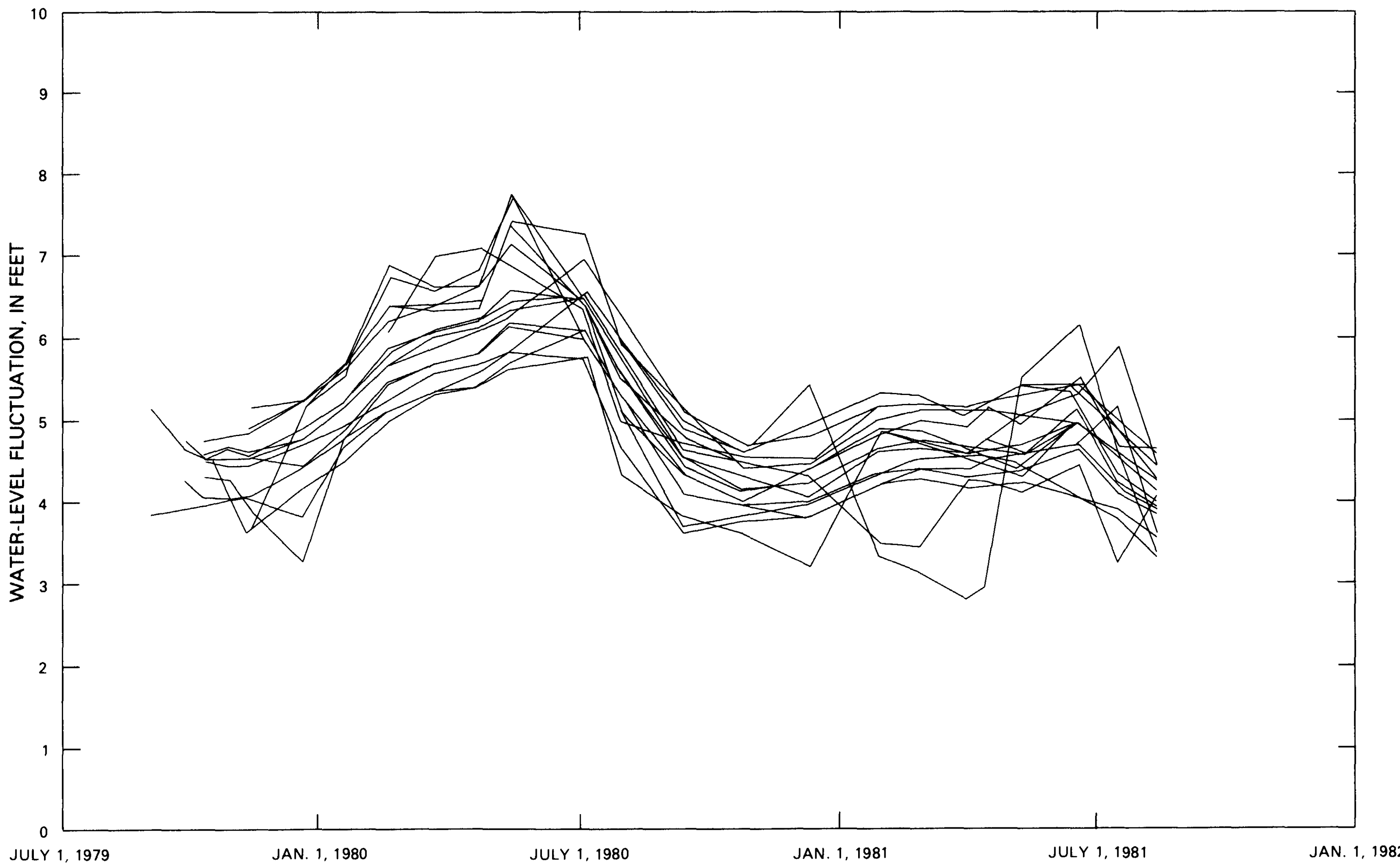

Figure 7.--Hydrographs for 20 wells in the central and eastern sandhills, (group 1).

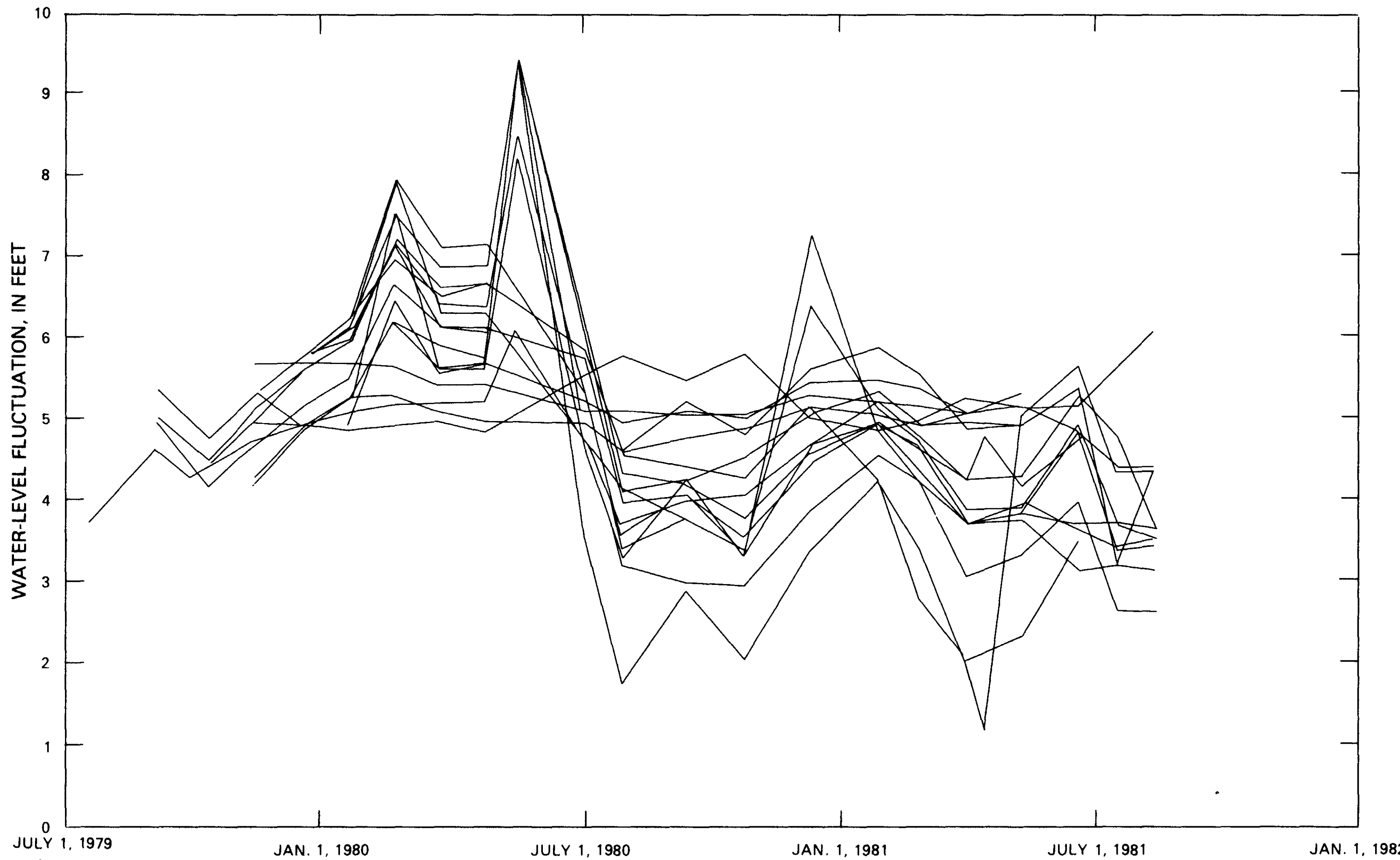

Figure 8.--Hydrographs for 17 river sites and nearby wells (group 2).

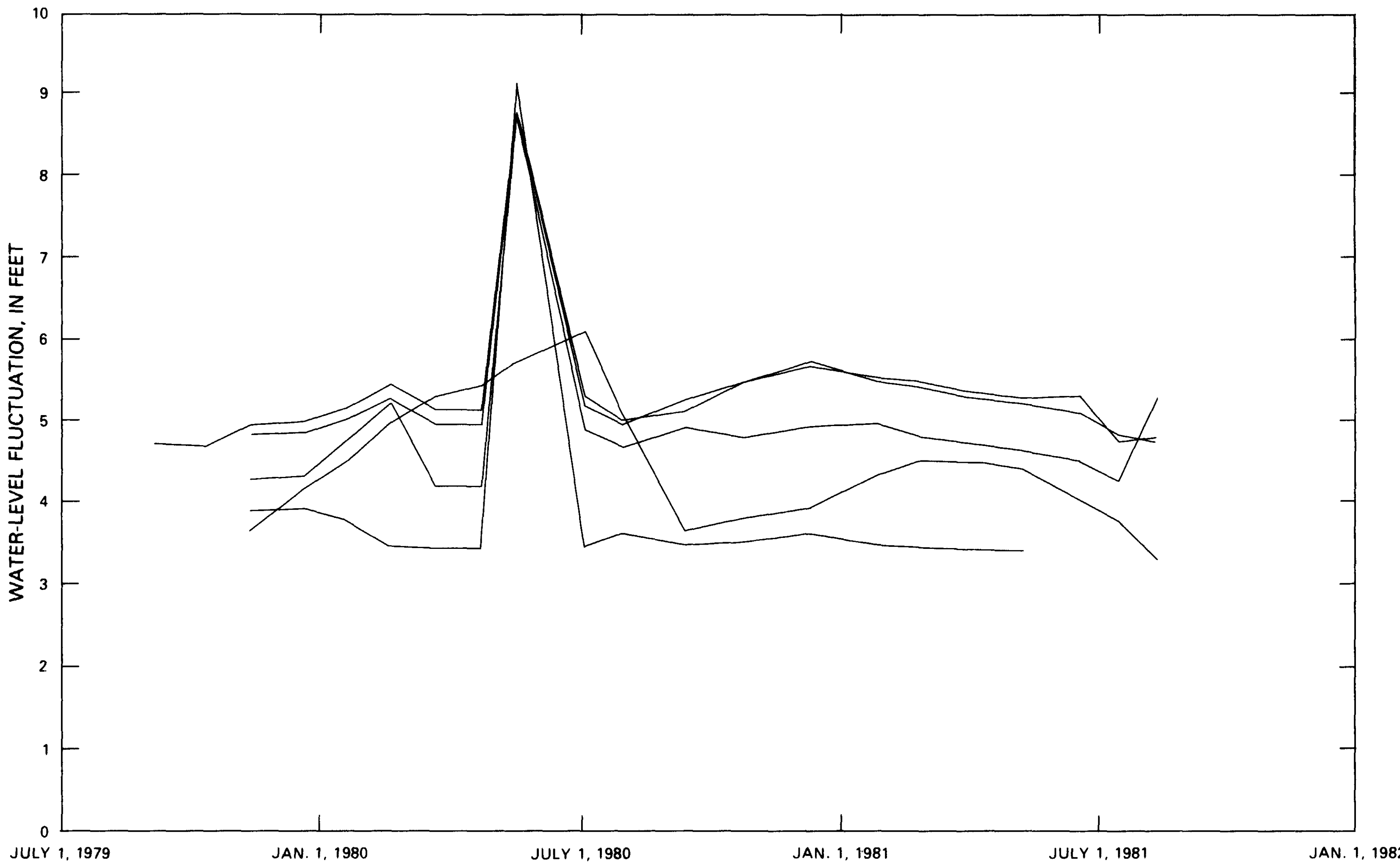

Figure 9.--Hydrographs for 5 slough sites and nearby wells (group 3).

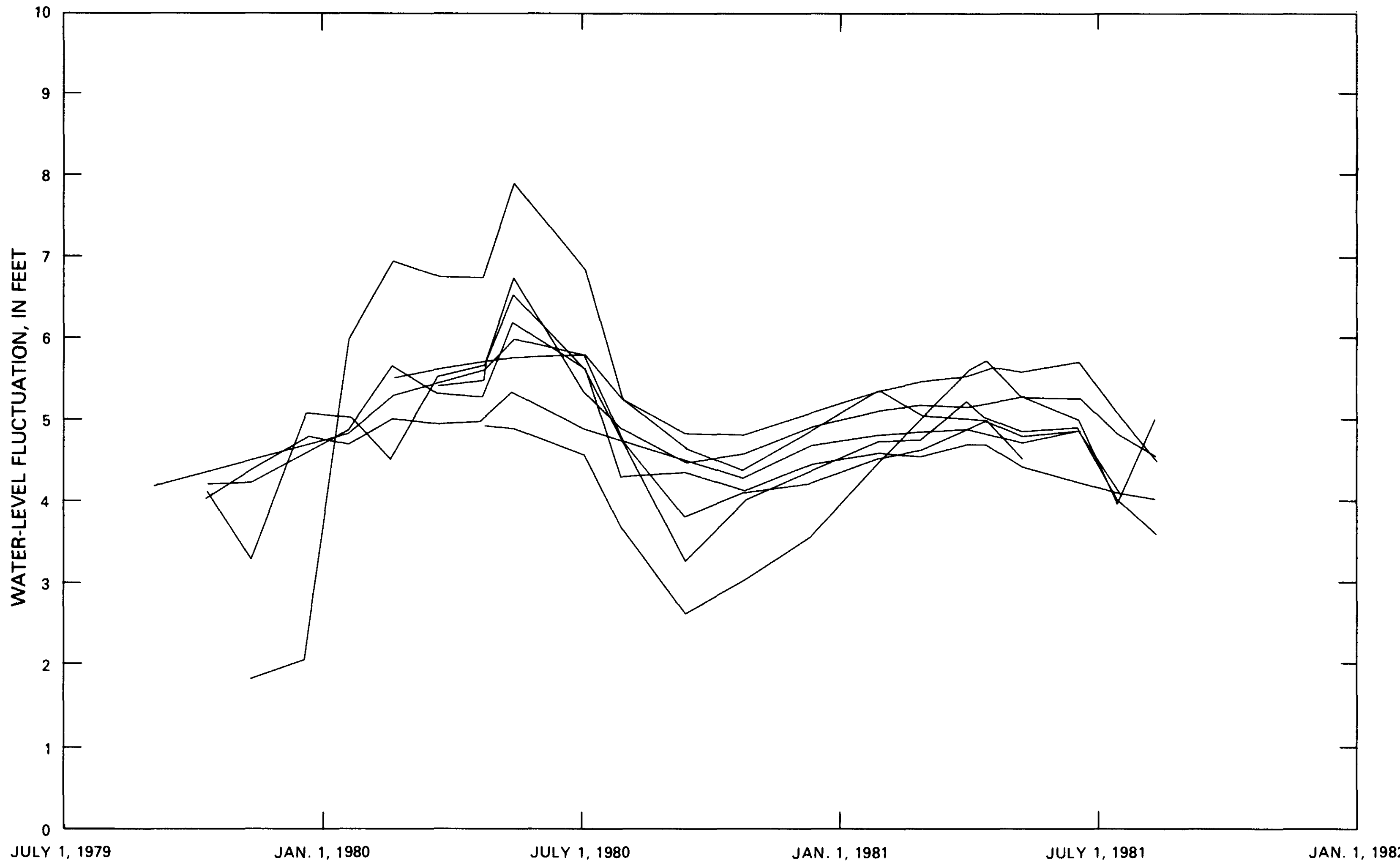

Figure 10.--Hydrographs for 9 wells in the western sandhills (group 4).

hydraulic connection between surface and ground water. A three-dimensional plot computed from the water-level elevations for May 4-5, 1981, is shown in figure 11. Note that the water surface slopes predominantly eastward at about 8 ft/mi. A slight northward slope also occurs indicating a small flow of ground water to the river. Water-level surfaces for all the other sampling periods looked very similar, with only minor local differences.

Water-Temperatures

Water temperature varied considerably, depending on site, time of day, and time of year. As discussed earlier, temperature differences during the winter between the sloughs and the river was of major concern to the Division of Wildlife.

Considerable literature exists discussing the annual cycle of water temperature in streams (Ward, 1963; Tasker and Burns, 1974; Steele, 1978). A simple first-order harmonic (sine curve) analysis generally has been used to describe annual variation. Periodic data at monthly intervals are adequate to statistically describe the curve. Data collected during this study were fit to the equation:

$$T(d) = M + A \cos[(d-d_m)\ 2\ \pi/365] \qquad (1)$$

where T = water temperature, in degrees Celsius;
M = mean of the harmonic function, in degrees Celsius;
A = amplitude of the harmonic function, in degrees Celsius;
d_m = Julian date when the maximum temperature occurs; and
d = Julian date where Julian date is the number of days since December 31.

Parameter values and statistics of the regression analysis for the five river sites (7, 31, 36, 43, and 58) are given in table 3, and water-temperature data, with the predicted curves for those five river sites, are shown in figure 12. Mean water temperature ranged from 11.4 to 13.6°C, whereas the amplitudes ranged from 8.9 to 13.2°C.

Table 3.--*Regression parameters and statistics of water temperature at the five river sites*

Site	Harmonic		Maximum day	Correlation coefficient	Standard error (degrees Celsius)
	Mean (degrees Celsius)	Amplitude (degrees Celsius)			
7	12.6	13.2	July 17	0.90	3.4
31	13.6	12.4	July 16	.89	1.6
36	13.0	12.0	July 14	.86	3.8
43	12.0	11.5	July 12	.84	3.9
58	11.4	8.9	July 19	.84	3.1

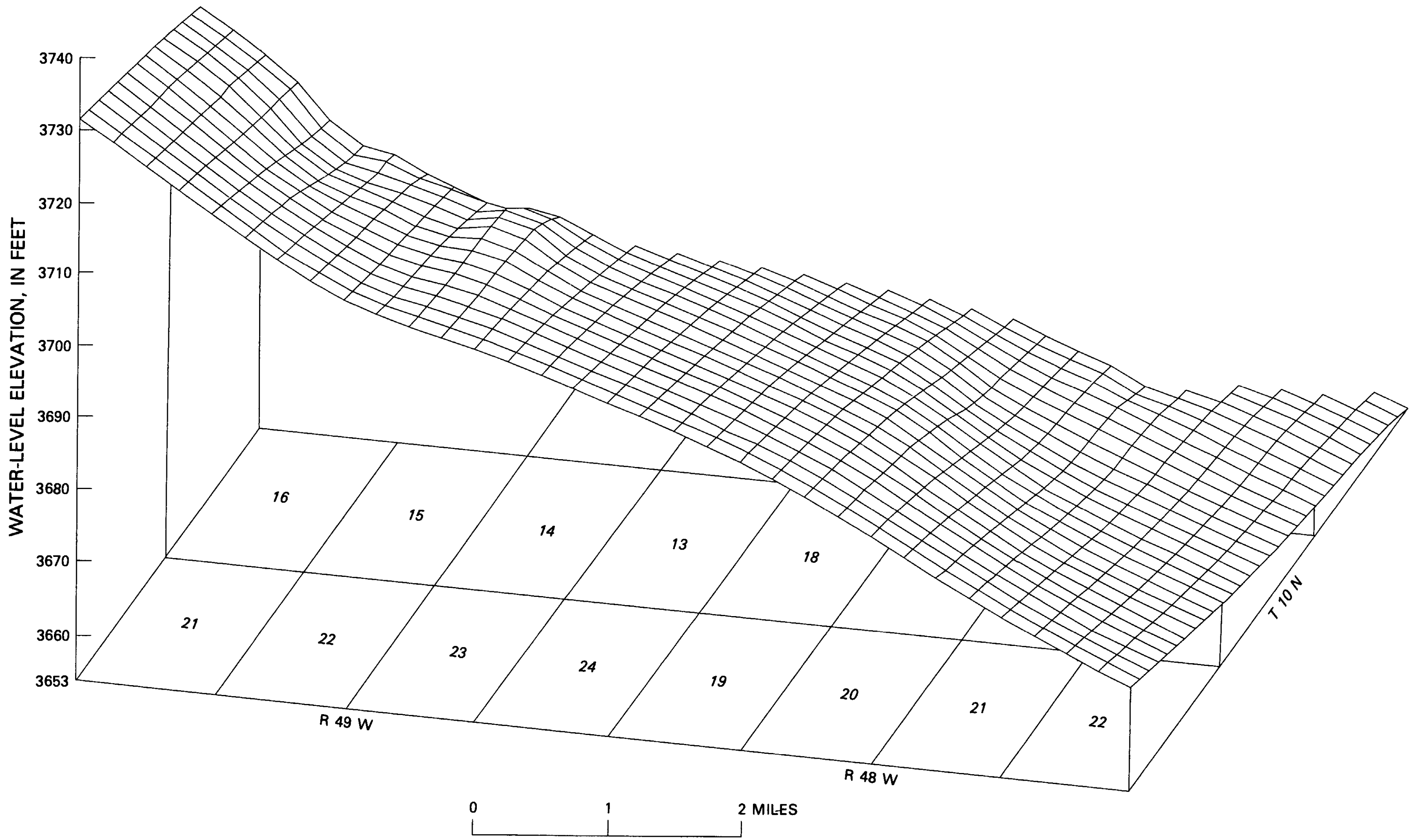

Figure 11.--Computed water-level surface for May 4-5, 1981.

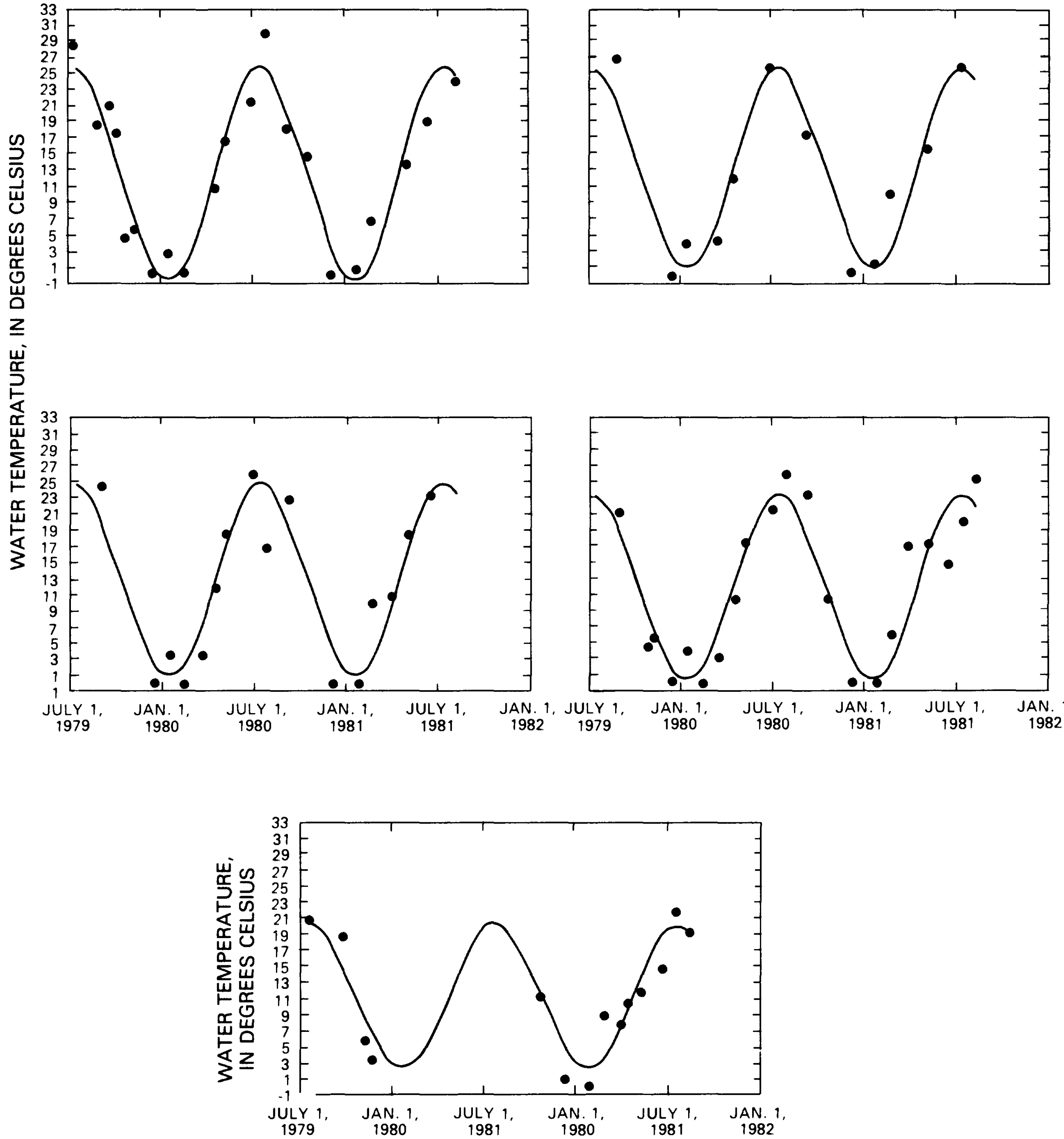

Figure 12.--Water-temperature data and predicted curves for river sites.

All water-temperature data for the well sites were fit to equation 1. Water from several of the wells had seasonal temperature variation. The computed harmonic mean and amplitude were both plotted versus mean depth to water in wells (fig. 13). These data are reasonably consistent. Ground water at depths greater than 10 ft had almost no seasonal variation (amplitude less than 1°C, mean about 14.5°C). Only the water temperature at site 16 did not agree with this conclusion; the reason for this anomalous data cannot be explained. Although the mean depth to water was less than 10 ft at sites 20, 23 and 30, ground water at all had mean temperatures greater than 14°C with very small seasonal amplitudes. This lack of variation can be explained because two of these wells are large capacity irrigation wells and the other a domestic well that draw their water from the entire saturated column, which is more than 60 ft thick.

Water temperature of the sloughs is the most difficult to describe as a class. Data from the slough sites were fit to equation 1 and are shown in figure 14. Site 6 had a harmonic mean of 13.4°C, with a harmonic amplitude of 4.8°C. The harmonic mean at site 11 was 13.3°C, with a harmonic amplitude of 8.3°C. Sites 9, 13, and 18 are all known to contain river water at most stages; their curves are, therefore, more similar to those for the river sites (fig. 12). Ice as thick as 4 in. was found at site 13 during the winter because of the pooling of water where subfreezing air temperature could easily affect water temperature. Even at site 11, where the minimum water temperature recorded in the flowing channel was 3.0°C, periods of ice cover occurred in adjacent pooled areas.

The pond at site 34 is illustrative of the complexities of warmer ground water being exposed to subzero air temperatures when pooled at land surface. It was not uncommon at the pond to chop through several inches of ice and measure water temperatures ranging from 3 to 5°C.

Seasonal water-temperature variation, as indicated by the harmonic mean and amplitude, can be used to distinquish the source of water, as shown in table 4. Deep ground water is relatively warm and does not change seasonally. Shallow ground water and sloughs unaffected by river water inflow have lower mean water temperatures with greater amplitudes. River water has about the same range of mean temperatures but distinctly greater amplitudes.

Specific Conductance

Unlike water temperature, which had an annual variation, specific conductance was relatively invariant except in the river; variation in the river seemed to be a function of flow rather than season. Specific conductance generally was an excellent indicator to distinguish sources of water. The following statistics of specific conductance by physiographic setting are shown in table 5: range of measured values, the means, and the standard deviation for five selected groups. These five groups are wells in the sandhills, wells in the valley meadow, wells in the river bottom, sloughs, and the river. Disregarding the small values measured during the May 1980 flood (700 μS/cm), the river had a mean of 1,570 μS/cm with a standard deviation of 173 μS/cm. When considering only those slough sites unaffected by river flow (sites 6 and 11), the mean was 710 μS/cm with a standard deviation of 265 μS/cm.

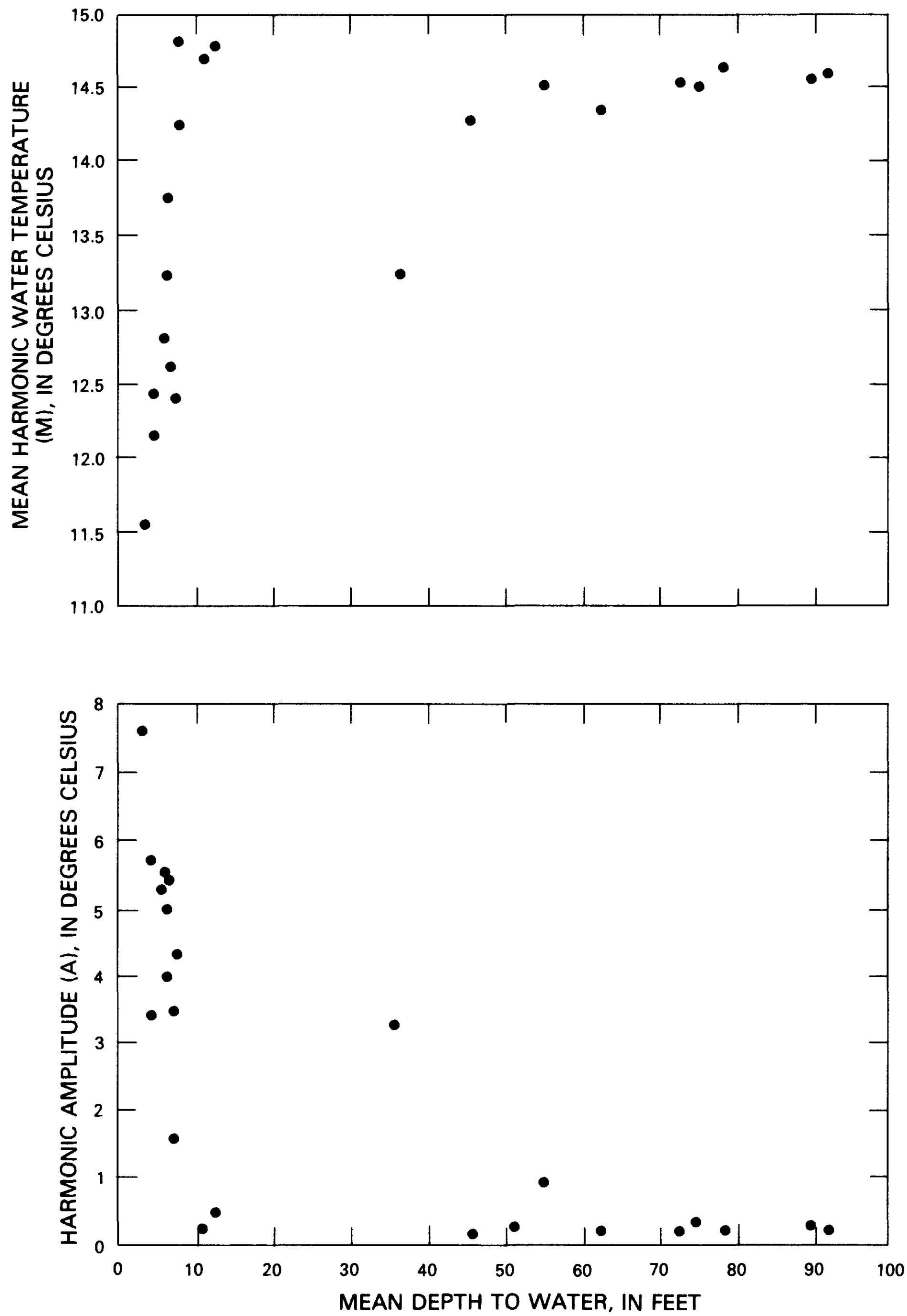

Figure 13.--Relation of harmonic mean water temperature (M) and harmonic amplitude (A) to mean depth to water.

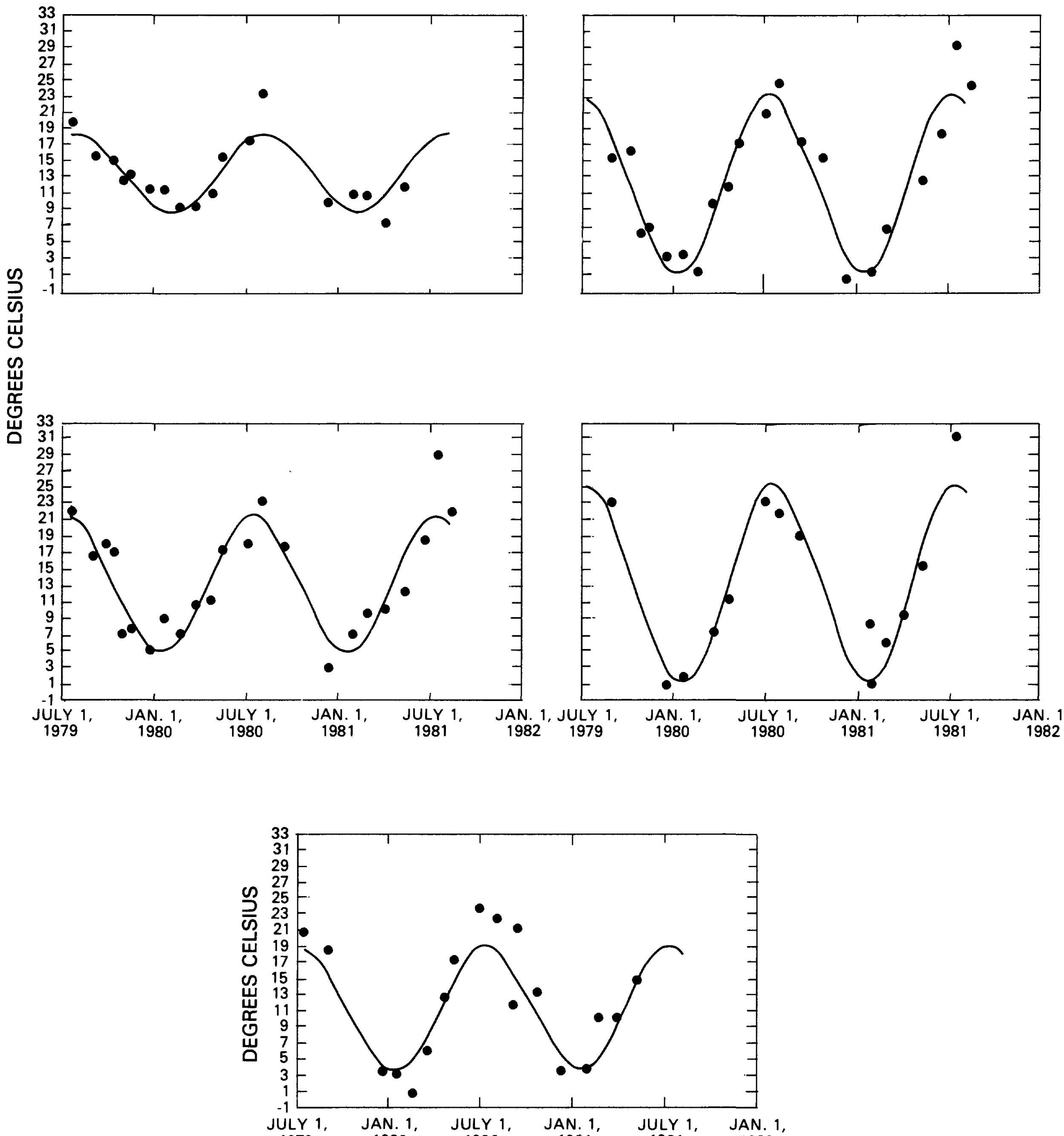

Figure 14.--Water-temperature data and predicted curves for slough sites.

Table 4.--*Comparison of water-temperature harmonic means and amplitudes among site type*

General description	Sites in group	Range in mean water temperature (degrees Celsius)	Range in water-temperature amplitudes (degrees Celsius)
Wells (depth to water greater than 10 feet)	17, 20, 21, 22, 23, 24, 32, 37, 41, 42, 48, 49	14.3-15.1	0.19-0.93
Wells (depth to water less than 10 feet)	1, 2, 4, 8, 14, 19, 33, 35, 39, 50	11.5-14.2	3.4-7.6
River	7, 31, 36, 43, 58	11.4-13.6	8.9-13.2
Sloughs (unaffected by river flow)	6, 11	13.3-13.4	4.8-8.3
Slough and pond	9, 13, 18, 34	12.1-13.6	10.3-12.1

Table 5.--*Statistics of specific conductance by groups*
[in microsiemens per centimeter at 25° Celsius]

Group	Mean	Standard deviation	Minimum	Maximum
Wells in the sandhills	264	28.4	180	350
Wells in the valley meadow	712	383	260	1,800
Wells in the river bottom	1,160	404	370	2,150
Sloughs	1,040	402	360	1,600
River	1,540	237	700	2,000

Water sampled in the sandhills was the least mineralized because it consisted of a large proportion of precipitation recharge. Water in the valley meadow was a mixture of water moving from the sandhills to the south and other valley-meadow water moving from the west. Water quality was still potable although specific conductance was double or triple that of the sandhills. This increase in specific conductance presumably was caused by consumptive use of the water by riparian vegetation and upstream irrigation. Specific conductance in the river showed no detectable changes through the study reach and merely indicated the quality of the water entering the study area. Mean specific conductance of water in the sloughs and wells in the river bottom was in between that of water in the upgradient wells and in the river, indicative of the mixing of ground water and surface water in these areas. Computed areal distribution of specific conductance based on measurements made on February 20-21, 1981, is shown in figure 15.

The graph of specific conductance of water at site 19 (fig. 16) gives an excellent example of how the quality of recharged water can affect the quality of ground water. Although site 19 is adjacent to a slough, specific conductance of water at the site remained rather constant through February 1981. The Tamarack Ditch, which is immediately adjacent to site 19, conveyed no water during this period because of its low priority right. During February and March of 1981, the river had sufficient flow to allow the Division of Wildlife to divert water from the South Platte River into the ditch. Although no specific-conductance measurements were made while the ditch contained water, it is estimated that the river water would have had a specific conductance of about 1,700 μS/cm during this time. Leakage and applied water from the ditch recharged the alluvial aquifer in this part of the valley meadow. The abrupt increase in the specific conductance of the ground water (fig. 16) was a result of recharging water with a specific conductance of about 1,700 μS/cm.

DEVELOPMENT AND CALIBRATION OF MODELS

Models of ground water and slough temperature were developed to describe the hydrologic system. The models were then used to simulate the effects of possible water-management activities of the Division of Wildlife.

Ground-water Models

Ground-water flow models commonly are used for purposes of defining the flow system and then predicting effects of new or hypothetical stresses on the simulated aquifer system. Several different models were used in the process of trying to identify, understand, and describe the aquifer system for this study. These models included a kriging model (Skrivan and Karlinger, 1980) to help describe the water-level and bedrock surfaces; a finite-element and a finite-difference inverse parameter model (Cooley, 1977 and 1979) to help evaluate aquifer parameters and boundaries; and a finite-element (R. L. Cooley, U.S. Geological Survey, written commun., 1976) and a finite-difference (Trescott, 1973) flow model for calibration simulations.

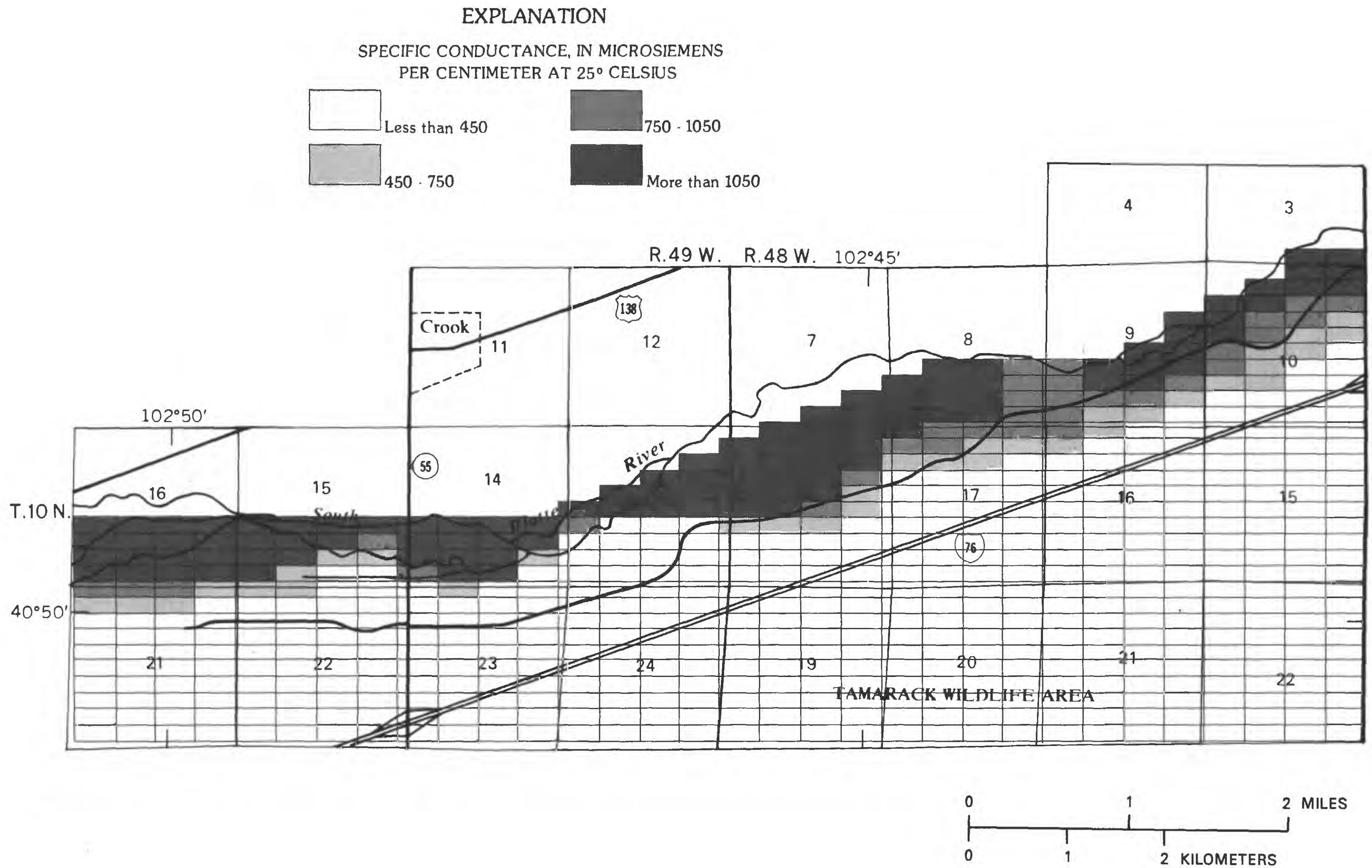

Figure 15.--Computed areal distribution of specific conductance on February 20-21, 1981.

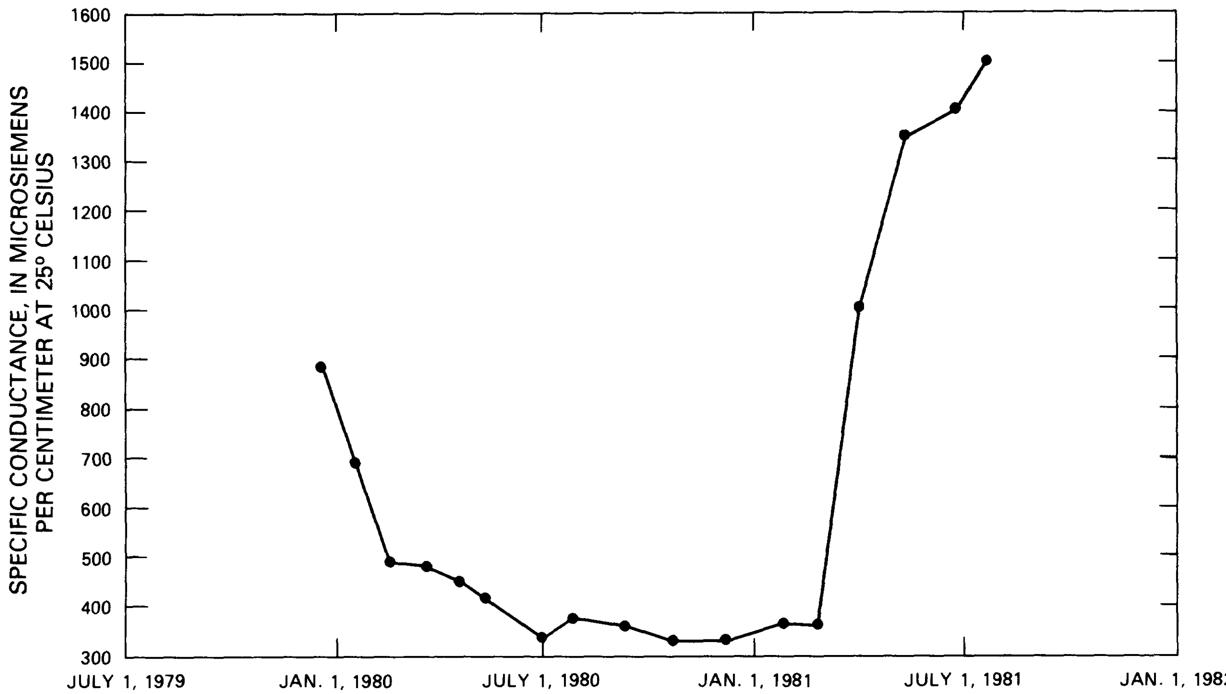

Figure 16.--Specific conductance at site 19.

Ground-water flow models approximate the partial differential equations that describe ground-water flow by using numerical-analysis techniques. All ground-water models used for this study are similar in data requirements and types of results; their internal workings and functions are their primary differences. To model any aquifer, parameters need to be entered at a network of points describing: hydraulic head (water level); hydraulic conductivity (a measure of the ability of an aquifer to transmit water); specific yield (a measure of the ability of an aquifer to store water); elevation of bedrock; and elevation of land surface. For finite-element models, these points can be arbitarily positioned to form irregular polygonal elements; for finite-difference models, these points need to be positioned in a regular rectangular grid. In addition to these parameters, all stresses on the aquifer need to be specified, including boundary conditions, and pumping, recharge, and evapotranspiration rates. Initial estimates of hydraulic head and bedrock surface were taken from published maps (Hurr, Schneider, and others, 1972a and 1972b), and hydraulic conductivity was computed as transmissivity divided by saturated thickness (maps from these same reports). Elevation of land surface was obtained from U.S. Geological Survey topographic quadrangle maps.

The published maps were drawn prior to the drilling of the seven large-capacity irrigation wells installed by Division of Wildlife; thus, the maps were limited in information when drawn. Drilling logs from those wells provided information for redrawing the bedrock surface. The kriging model was used to evaluate bedrock data and to map an objective, quantitative surface to guide the mapping process. Bedrock data from this new map were used as data in the model. Regionally, the bedrock surface did not change substantially; but locally, the deepest part of the bedrock surface was shifted. The aquifer test conducted in the study area generally substantiated the hydraulic-conductivity values computed from the published maps.

The initial purpose in using the ground-water models was to evaluate the flow system under steady-state conditions. Calibrating a model involves adjusting the entered parameters and stresses until the simulated hydraulic heads match the measured hydraulic-head data to an acceptable degree. Steady-state conditions are long-term average conditions with no time changes. Boundary conditions were the critical factors in calibrating a steady-state model of the study area. The necessary values to be determined were: (1) Incoming discharge on the western and southern boundaries; (2) outgoing discharge on the eastern boundary; and (3) discharge to or from each grid (or element) along the sloughs and river (northern boundary). The first step was to select a set of measured hydraulic-head values that would reasonably represent steady-state conditions. Although only 2 years of data were available, little variation was determined; also, little change has occurred in water-related operations or on the few water-level records that have many years of data. Therefore, the March 1981 data were selected as being close to the mean during the study period and were used as the long-term mean representing steady-state conditions.

Next, the kriging model was used as a guide for estimating the water-level surface throughout the study area, based on the 47 sites from the network that had data for March 1981. Based on this technique, initial water levels at all the elements in the finite-element model and all the grids in the finite-difference model were computed and entered into the respective models. Water levels in the river were linearly interpolated based on the distance along the river from sites 7 to 36, and from sites 36 to 43. Some extrapolation upstream from site 7 also was necessary. Similarly, elevations of the bottom of the slough channel were computed using sites 6 and 11.

Calibration was a trial-and-error, iterative process using the parameter-estimation models first and then the flow models. The calibration process was complex, because of the need to adjust, within reasonable limits, transmissivity (or hydraulic conductivity, depending on which model was used), recharge rate, and evapotranspiration rate; and because of the need to determine hydraulic-head values (for constant-head boundaries), or flow values (for constant-flux boundaries), and which type boundaries were most appropriate. Final calibration was computed by using the finite-difference flow model, because it was the model that was to be used for the predictive analyses.

The criterion to determine a reasonable calibration was to decrease toward zero the mean error (ME) and root mean error (RME) between the computed hydraulic-head (H_c) values and the measured hydraulic head (H_o) values:

$$ME = \Sigma(H_c - H_o)/n \text{ and} \qquad (2)$$

$$RME = [\Sigma(H_c - H_o)*(H_c - H_o)]^{1/2}/n \qquad (3)$$

where n = number of hydraulic head values (limited by the number of measured hydraulic heads)

The water-table contour map computed by the model for final steady-state calibration is shown in figure 17, with the components of the computed water budget. The ME of the 47 points with data was 0.09 ft and the RME was 0.53 ft. The largest individual error was 1.4 ft. These errors seem relatively small compared to the computed total hydraulic-head difference of 66 ft across the 8 mi study area. The calibrated model used constant-head boundaries on the north to represent the river and on the east to compute the outflow. Constant-flux boundaries were used for evaluation of the western and southern flow entering the study area. The calibrated hydraulic conductivity was a uniform value of 190 ft/d; the recharge rate was a uniform value of 0.2 in./yr; and the evapotranspiration rate at land surface was a uniform value of 15 in./yr, which decreased to 0 in./yr at 15 ft below land surface. Based on previous modeling efforts in the South Platte River basin (Burns, 1980 and 1981), all these values seem reasonable except the recharge rate. The recharge rate probably is not uniform. The calibrated value is reasonable for the valley meadow and river bottom, but the value for the sandhills may be an order of magnitude greater. This additional recharge is accounted for in the constant flux crossing the southern boundary. Because no wells were close to the southern boundary to calibrate this parameter, and because none of the predictive analyses would be affected by this assumption, the calibration was accepted as adequate. Computed inflow along the western constant-flux boundary was 3.05 ft^3/s, and computed inflow along the southern constant-flux boundary was 3.44 ft^3/s. Outflow along the eastern constant-head boundary was 2.92 ft^3/s. Net flow from the aquifer to the river was 0.32 ft^3/s, based on a total flow entering the river along the reach of 2.89 ft^3/s and a total flow leaving the river of 2.57 ft^3/s. Only the length of slough unaffected by river water (reach from site 6 to a point downstream from site 11) was simulated with the ground-water model. That reach gained a computed 1.12 ft^3/s from the aquifer. Although that flow eventually returns to the river, it is kept separate from the net river gain for accounting purposes.

Although solute-transport, ground-water models exist, ground-water quality was not a problem for the area so no solute-transport modeling was done. Therefore, temperature and specific conductance of ground water were not modeled for this study. Attempts to fit a regression line to the water-temperature data shown in figure 13 produced too much scatter to be useful. A mean specific-conductance value can be calculated from a mass balance of inflows and outflows. Although the value is worthless for comparing to any point-measured value, it can be used to compare simulated results later in this report. The value is computed by assigning values to the inflow components and computing a total load, then dividing by the outflow from the system. A specific conductance value of 265 µS/cm was assigned to the 3.44 ft^3/s entering from the south. A value of 500 µS/cm was assigned to the 3.05 ft^3/s entering from the west. A value of 1,500 µS/cm was assigned to the 2.57 ft^3/s of river water that entered the aquifer system. Dividing the sum of loads from each of these sources by the total outflow from the system of 6.93 (1.12 ft^3/s to the slough, 2.89 ft^3/s to the river, and 2.92 ft^3/s along the eastern boundary) results in a mean concentration of 908 µS/cm. This value is representative of some hypothetical mean outflow concentration.

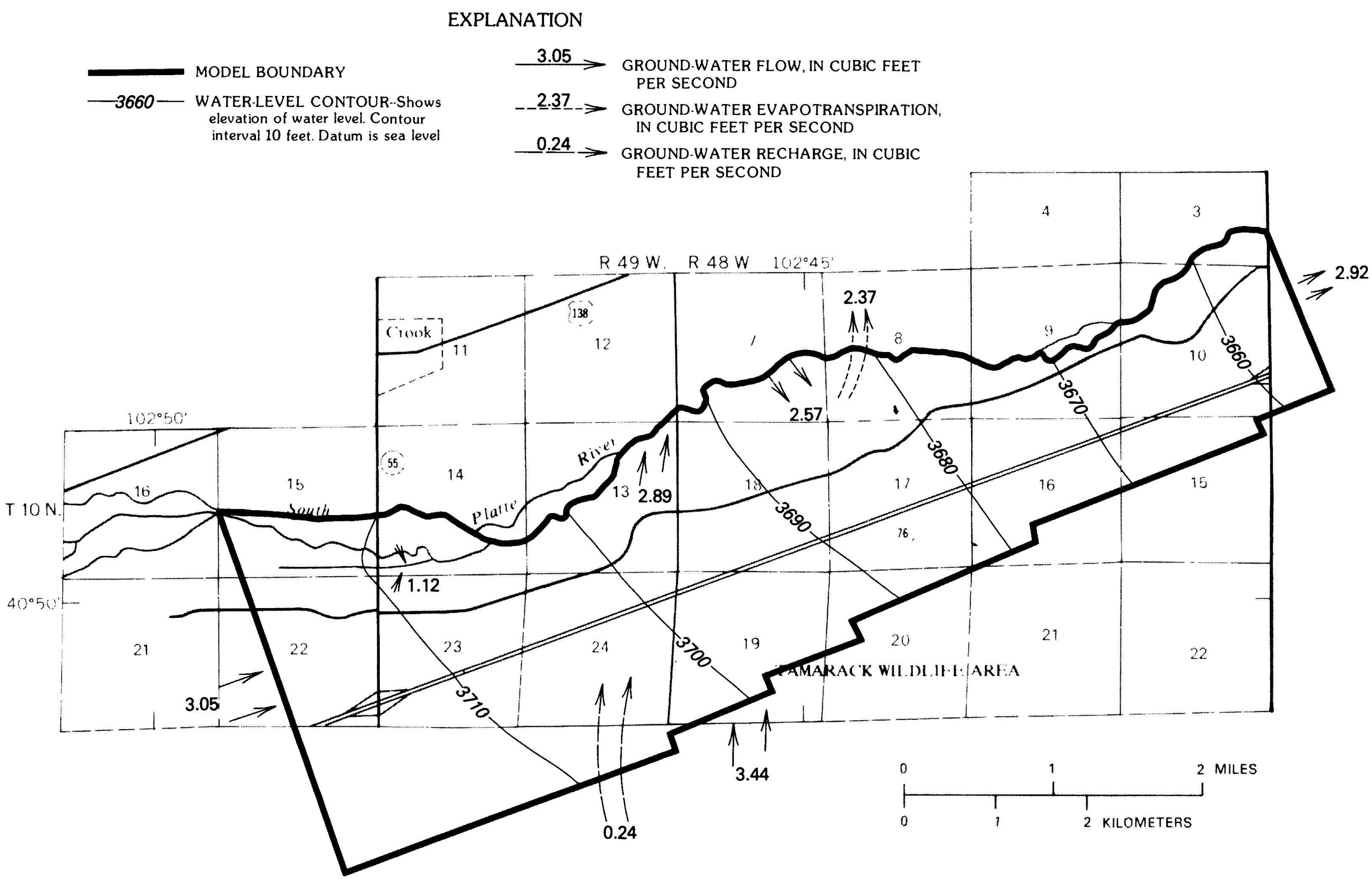

Figure 17.--Water-table contours and water-budget components for final calibration.

Slough Models

The hydraulics of flow in the sloughs is similar to most any flowing stream system but complicated by low flows, pools and riffles, and generally almost flat bed slopes. Because of model complexity and data limitations, the flow in the slough was not modeled. Inflow to a slough reach was computed by the ground-water flow model. Because surface water directly enters all sloughs except the reach between sites 6 and 11, separate accounting was computed only for that reach. For the calibration simulation, 1.12 ft^3/s enters that slough reach (fig. 17).

A simplistic approach is postulated to model water temperature in the sloughs. After some time, water of any temperature entering the slough channel will have the characteristics of surface water and have the cyclic temperature curve common to surface water. Thus, water temperatures in the slough (T_s) can be simply modeled by using a linear combination of an assumed ground-water temperature (14.5°C) and the temperature predicted for the river using equation 1 (in this case using coefficients from site 7):

$$T_s = z(14.5) + (1-z)[12.6 + 13.2 \cos((d-201)\ 2\pi/365)] \qquad (4)$$

where z = percent of the temperature effect from ground water; and
$(1-z)$ = percent of the temperature effect from air.

The z value for any site could be solved for by any of several optimization techniques. Because this model requires many simplifying assumptions, the simplest computation technique for z was selected. That technique is to solve for z such that the mean harmonic temperature for the site is computed by the equation given. Substituting the mean harmonic temperature of a site for T_s, z can be computed algebraically. For site 6, z is 0.42, and for site 11, z is 0.38. Using 0.40 as the z value for the primary slough reach of interest, the mean temperature of the slough would be 13.5°C, and the minimum temperature would be 5.5°C.

Specific conductance should merely equal the specific conductance of the incoming ground water, except for the concentrating effects of evaporation. No attempt to model specific conductance in the sloughs was made.

PREDICTION WITH MODELS

Three possible, steady-state, water-management activities proposed by the Division of Wildlife were simulated, using the ground-water flow model: (1) Ground-water pumpage in the middle of the modeled area; (2) artificial recharge in the same area; and (3) decreased river stage caused by increased upstream surface-water diversions. A transient simulation also was made of the Division of Wildlife's proposed plan to pump ground water to create ponds in the sandhills. All these potential water-management activities of concern to the Division of Wildlife were simulated with the ground-water flow model. Change in computed flows relative to calibrated flows then were used to estimate changes in the rest of the hydrologic system.

Ground-water Pumpage

The ground-water pumpage evaluation assumed that the land south of Interstate Highway 76 was to be converted to agricultural production. A net total of 6 ft^3/s would be pumped from 12 wells; by assuming consumptive use of 2 to 3 ft/yr, this total is equivalent to irrigating 1,500 to 2,000 acres. The simulated water-level surface is shown in figure 18 with the components of the water budget. Net ground-water flow to the river would change to -4.20 ft^3/s; that is, a net flow would occur from the river to the aquifer. Outflow along the eastern boundary would be decreased to 2.45 ft^3/s, and the flow into the modeled slough would be decreased 70 percent to 0.34 ft^3/s. Not only would the flow in the slough be significantly decreased, but by decreasing the linear combination factor z by 70 percent, expected minimum temperature in the slough would decrease from 5.5 to 1.0°C. The computed mean specific conductance of the aquifer outflow would increase to 2,210 µS/cm, assuming the wells pumped water with a specific conductance of 300 µS/cm.

Artificial Recharge

The artificial-recharge evaluation assumed that water from some external source, such as the river, was recharged into the aquifer either by well injection or pond spreading. A total of 6 ft^3/s was recharged and distributed equally throughout the same 12 model nodes where pumpage occurred in the previous simulation. The simulated water-level surface is shown in figure 19 with the components of the water budget. Net ground-water flow to the river would increase to 4.88 ft^3/s. Outflow along the eastern boundary would increase to 3.38 ft^3/s. Flow into the simulated slough would increase by 70 percent from the calibration simulation to 1.90 ft^3/s. By increasing the linear combination factor z by 70 percent and assuming the recharged water did not change the basic assumption that ground-water temperature is 14.5°C, the expected minimum temperature in the slough would increase to 9.5°C. An outflow averaging 699 µS/cm results from assuming the recharged water has a specific conductance of 500 µS/cm. However, if the recharged water has a specific conductance of 1,500 µS/cm, the specific conductance of the resulting outflow would average 1,190 µS/cm.

River Diversions

To account for possible increased diversions in the river upstream from the study area, the hydraulic heads in all the constant-head nodes were decreased by 1 ft. Computing the change in stream discharge needed to decrease the average hydraulic head by 1 ft is difficult without a stochastic model. An approximation of how much water would have to be diverted to lower the hydraulic head 1 ft can be computed, using the rating table for station 06764000, South Platte River at Julesburg, and assuming the period-of-record mean flow of 459 ft^3/s always occurred. A 1-ft change in hydraulic head would then result in a new mean flow of about 150 ft^3/s. The simulated water-table

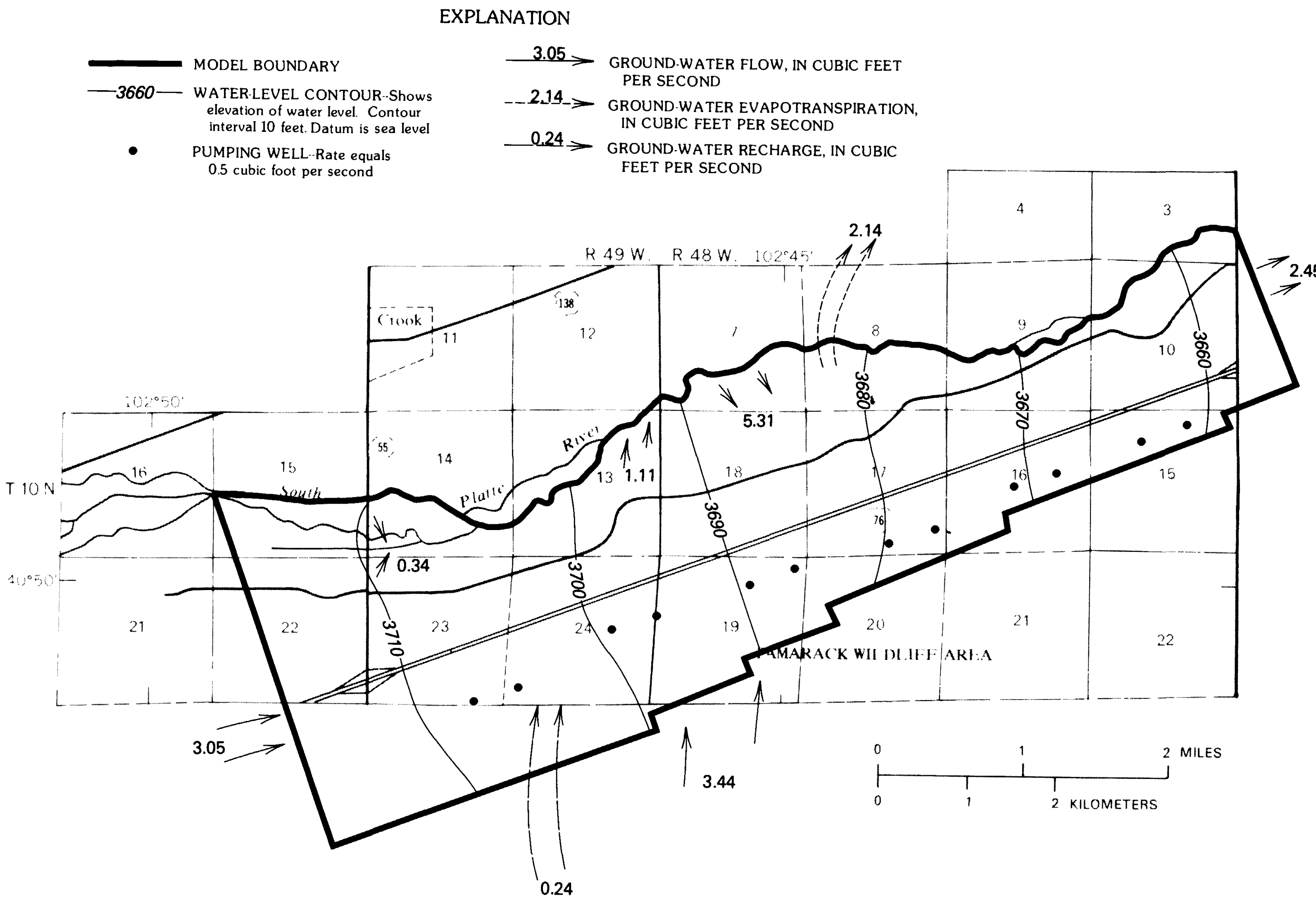

Figure 18.--Water-table contours and water-budget components for the possible water-management activity of ground-water pumpage.

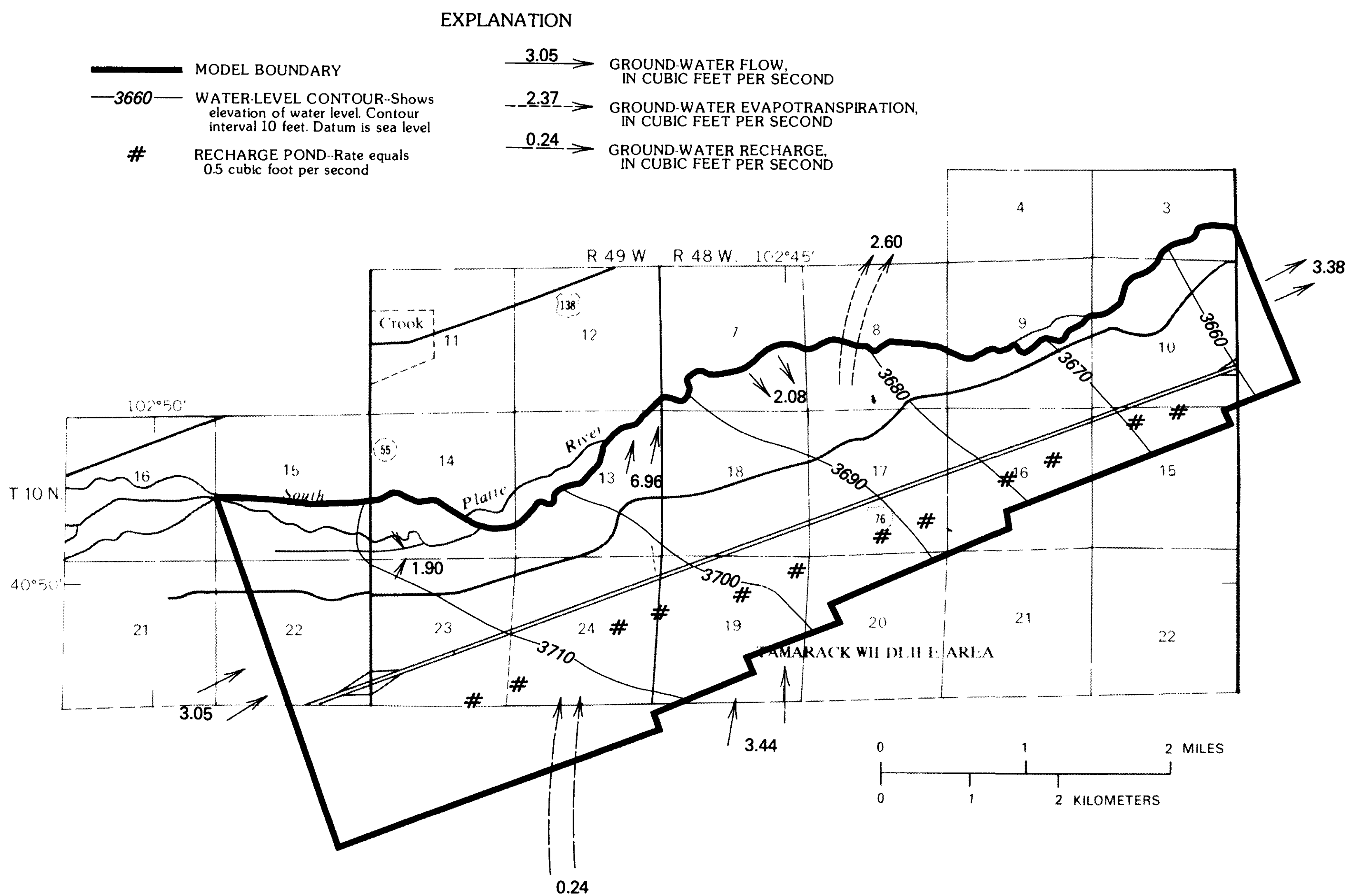

Figure 19.--Water-table contours and water-budget components for the possible water-management activity of artificial recharge.

surface is shown in figure 20 with the components of the water budget. Net ground-water flow to the river would increase to 1.15 ft^3/s, and little change would occur to the outflow along the eastern boundary. The fact that the flow in the slough would decrease 56 percent to 0.49 ft^3/s indicates that part of the 1.12 ft^3/s in the calibration simulation enters the slough from the north, or river side, of the slough. By decreasing the linear combination factor z by 56 percent, the expected minimum temperature in the slough would decrease to 2.0°C. The computed specific conductance of the outflow would be 841 µS/cm.

Wildlife Ponds

The Division of Wildlife has developed a plan to create wildlife-habitat ponds in the sandhills on Tamarack Wildlife Area (State of Colorado District Court, Water Division No. 1, 1981). These ponds would be created by pumping the seven large-capacity wells in the sandhills (sites 21, 22, 24, 32, 37, 41, and 42 on plate 1) and allowing the water to flow into the many depressions. Construction would include several dikes and a conveyance channel that could deliver the pond water to the river, if necessary. The plan would be to fill the ponds in September of each year. Continued pumping would keep them full and ice-free through January. After discontinuing pumpage during February, the wells would be restarted to insure that the ponds were full at the end of May. The court decree allowing this plan had many stipulations to guarantee that water could be delivered to the river to satisfy streamflow depletions caused by the pumpage. The proposal recognized that the ponds would leak and included plans to line the ponds to limit seepage to 63.8 acre-ft per month (about 1 ft^3/s). Evaporation was not accounted for in this simulation. Evaporation probably is minimal from October through March, and the ponds are considered empty from June through August. The only errors caused by ignoring evaporation occur in April and May when the assumed pumpage which supposedly fills the ponds does not really leave the ponds full. This error would not affect leakage or the ground-water modeling.

This proposal was simulated using the ground-water model with the following stresses: (1) Total pond leakage was 1 ft^3/s all year, and the leakage was uniformly distributed throughout 48 model grids with a total surface area of about 1,000 acres; (2) the seven wells were pumped at a rate of 4 ft^3/s each during September (about 1,680 acre-ft); (3) the seven wells were equally pumped at a total rate of 1 ft^3/s to match the pond leakage from October through January; (4) no pumpage was simulated in February, but March pumpage was increased to 2 ft^3/s to account for pond seepage losses during February and March; (5) pumpage was continued at the total rate of 1 ft^3/s during April and May to keep the ponds full; and (6) no pumpage occurred from June through August.

While the proposed plan would be operated annually, the model almost reached steady state after the first year. Water-budget components averaged for the first year and second year are shown on table 6 along with the components for steady-state conditions. After 2 years, about 3 percent of the pumpage would be from ground-water storage, and the river would lose 0.90 ft^3/s through the modeled reach instead of gaining 0.32 ft^3/s as it had for the steady-state conditions. Cyclic results of the first year are

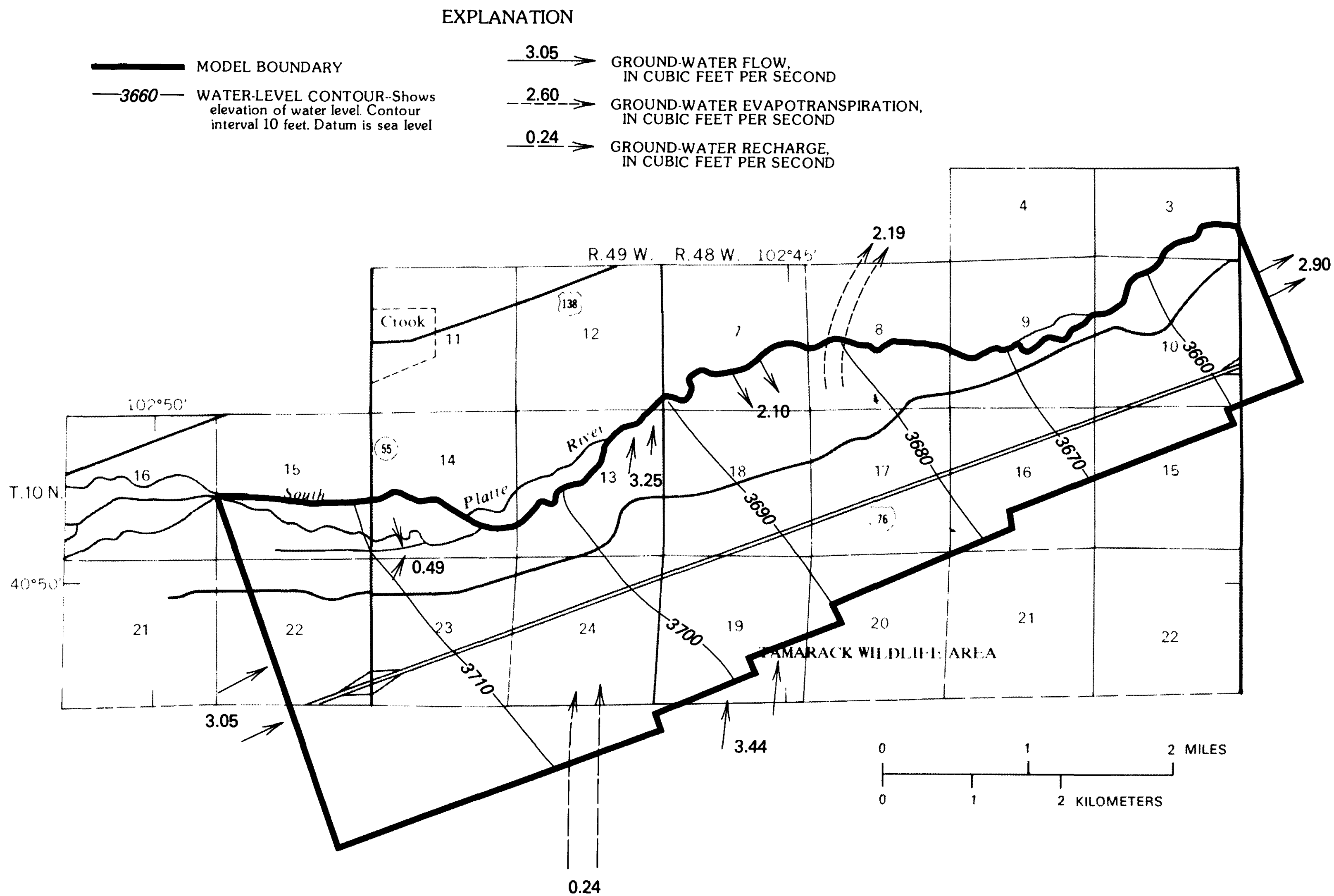

Figure 20.--Water-table contours and water-budget components for the possible water-management activity of upstream river diversions.

presented in table 7 which shows the flow rates of the water-budget components at the end of each pumping period. Stream depletion would be 3.47 ft^3/s during September and would remain at a deficit to the river through the winter and spring. However, during the critical summer months, there would be a net inflow to the river (0.12 ft^3/s), although less inflow than occurred during steady-state conditions (0.32 ft^3/s).

Table 6.--*Mean water-budget components for steady-state conditions and the first and second years of the possible wildlife-ponds activity*
[All values in cubic feet per second]

Mean water-budget component	Steady state	First year	Second year
Inflow			
Ground-water storage	0.00	0.20	0.09
Recharge	.24	.24	.24
Pond leakage	.00	.99	.99
Constant flux	6.49	6.49	6.49
Ground-water inflow from river	2.57	3.11	3.15
Outflow			
Ground-water outflow to slough	1.12	1.12	1.11
Ground-water outflow to river	2.89	2.29	2.25
Evapotranspiration	2.37	2.31	2.30
Eastern boundary constant-head flow	2.92	2.35	2.35
Pumpage	.00	2.97	2.97
Net river gain or loss (-)	.32	-.89	-.90

Table 7.--*Water-budget components for the end of each pumping period for the possible wildlife-ponds activity*
[All values in cubic feet per second]

Period	Ground-water inflow from river	Ground-water outflow to river	Net river gain or loss (-)	Boundary outflow	Ground-water pumpage
Steady-state	2.57	2.89	0.32	2.92	0.00
September	5.19	1.72	-3.47	.25	28.00
October-January	3.12	2.01	-1.11	2.68	.98
February	2.92	2.18	-.74	2.83	.00
March	2.94	2.21	-.73	2.70	2.03
April-May	2.79	2.35	-.44	2.79	.98
June-August	2.58	2.70	.12	2.97	.00

SUMMARY

The hydrologic system of the Tamarack Wildlife Area and vicinity near Crook, Logan County, Colo., is a complex interaction of the South Platte River and the adjoining alluvial aquifer. The sloughs, which are of importance to wildlife and waterfowl, are the visible part of the interface between ground water and surface water.

Data collected during the course of the study included aerial imagery, aquifer tests, and periodic hydrologic data from a monitoring network. The water levels, air and water temperature, and specific conductance collected and collated at 58 sites in and near the study area provided the necessary information for the hydrologic analysis.

The areal distribution of water levels, including the river, sloughs, and ground water, showed a reasonably smooth, continuous surface. Based on that surface, most of the water is moving through the study area from west to east with a very small gradient northward toward the river. Hydrographs of all the sites and correlation of the water levels between sites indicated that the sloughs respond differently compared to both wells in the sandhills and the river. A statistical cluster analysis indicated that shallow wells in the valley meadow and river bottom respond similarily to the river, illustrating their hydraulic connection.

The higher winter temperatures of the water in the sloughs as compared to those in the river are one of the primary attributes contributing to the wildlife values of the sloughs. Temperature variation was greatest in the river. Ground water at depths greater than 15 ft had no variation. Water in shallow wells and the sloughs had moderate temperature variation; the water was warmer than the river in the winter and cooler than the river in the summer.

Specific conductance varied considerably based on physiographic setting. Water from wells in the sandhills was least mineralized, averaging 264 μS/cm. Water from wells in the valley meadow was still potable, averaging 712 μS/cm. The sloughs had the least mineralized water in the river bottom with specific conductance averaging 1,040 μS/cm, compared to an average of 1,160 μS/cm in wells and 1,540 μS/cm in the river.

A finite-difference ground-water flow model was developed for the study area. The model was calibrated by assuming the system is currently not changing and considering it to be in steady state. Calibration consisted of adjusting the western and southern boundary fluxes and the recharge and evapotranspiration rates. These values were adjusted until the mean difference between computed and measured hydraulic heads at 46 points was 0.09 ft, and the root mean error was 0.53 ft. Maximum error was 1.4 ft. The calibrated model was then used to simulate possible water-management activities proposed by the Division of Wildlife.

A theoretical specific-conductance outflow concentration of 908 μS/cm was computed, based on the components from the steady-state calibration and assumptions in the quality of the inflowing water. Also a simplified slough-temperature model was hypothesized, which was a linear combination of a constant-temperature ground-water source and the mechanism that causes the river to display its cyclic variation. Based on this model, the minimum wintertime temperature in the modeled slough would be 5.5°C.

The first water-management activity simulated was ground-water pumpage for irrigation in the southern part of the study area. The simulated 6 ft^3/s pumpage would cause the river to change from a gaining reach (0.32 ft^3/s) to a losing reach (-4.20 ft^3/s). Inflow to the modeled slough would be decreased 70 percent to 0.34 ft^3/s. This decreased inflow would cause the minimum temperature in the slough estimated by the simplified model to decrease to 1.0°C. The computed specific conductance of the mean outflow would be 2,210 μS/cm.

The simulated activity of artificial recharge would cause the net river gain through the study reach to increase to 4.88 ft^3/s. Inflow to the modeled slough would be increased 70 percent to 1.90 ft^3/s. This increased inflow would cause the estimated minimum wintertime water temperature to increase to 9.5°C. The computed specific conductance of the mean ground-water outflow would range from 699 to 1,190 μS/cm depending on the quality of the recharged water.

The possible activity of upstream diversions was simulated by decreasing the assumed constant river head by 1 ft. The river gain was simulated to increase to 1.15 ft^3/s. However, the modeled slough inflow would decrease to 0.49 ft^3/s. This estimated decreased inflow would cause the computed minimum temperature to decrease to 2.0°C. The computed specific conductance of the mean outflow would be 841 μS/cm.

The proposed wildlife-ponds activity also was simulated using the ground-water flow model. A time-varying operation of filling ponds in September and then maintaining the ponds through May was simulated. Results indicate that the cyclic pattern of the pumpage would attain a uniform cyclic effect on the aquifer system rather quickly, with only 3 percent of the second-year pumpage coming from ground-water storage. The activity would cause the naturally gaining reach of the river to lose water, except from June through August, when there would be a net gain to the river.

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