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Effects on Ground-Water Levels in the Missouri River Alluvial Aquifer Caused by Changes in Missouri River Stage, Fremont and Monona Counties, Iowa

Water-Resources Investigations Report 98–4235

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By KEITH J. LUCEY, BRYAN D. SCHAAP, and EDWARD E. FISCHER

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1999

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
foot per second (ft/s)	30.48	centimeter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
square foot (ft^2)	0.0929	square meter
acre-foot (acre-ft)	1,233	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
foot squared per day (ft^2/d)	0.09294	square meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level.

Water year is the 12-month period October 1 through September 30. The water year is designated by the calendar year in which it ends; thus, the year ending September 30, 1996, is called the "1996 water year."

Effects on Ground-Water Levels in the Missouri River Alluvial Aquifer Caused by Changes in Missouri River Stage, Fremont and Monona Counties, Iowa

By Keith J. Lucey, Bryan D. Schaap, *and* Edward E. Fischer

Abstract

An analysis of available hydrologic data was conducted to evaluate the effects on ground-water levels in the Missouri River alluvial aquifer caused by changes in Missouri River stage at selected sites in Fremont and Monona Counties in western Iowa. Daily mean ground-water levels and river stage measured during November 1995–September 1996, simulated daily mean river stage for November 1995–December 1996 derived from simulated daily mean discharge for eight alternative water-management plans for the Missouri River, and simulated daily mean ground-water levels for November 1995–December 1996 for selected water-management plans were used in the study. The measured data represent hydrologic conditions for the Current (1998) Water-Control Plan of the U.S. Army Corps of Engineers.

Ground-water levels in the alluvial aquifer vary in response to river stage, precipitation, proximity to drainage ditches, evapotranspiration, and pumpage. In Fremont County, measured ground-water levels generally were lower than river stage during the spring, summer, and fall months. In Monona County, measured ground-water levels generally were higher than river stage. Water levels in wells at distances greater than about 8,000 feet from the river in Fremont County and about 6,500 feet in Monona County likely were more affected by precipitation or proximity to drainage ditches than by river stage.

Changes in river stage likely affect ground-water levels in Fremont County to a greater degree than in Monona County. In Fremont County, the hydraulic gradient generally is from the river to the aquifer; in Monona County, the gradient generally is from the aquifer to the river. The response of ground- water levels to changes in river stage in Monona County is less apparent than in Fremont County. The higher ground-water levels in Monona County indicate that the effects of other factors, such as differences in recharge from precipitation and aquifer properties, are more dominant than in Fremont County.

Generally, the effects of simulated river stage caused higher simulated ground-water levels in Fremont and Monona Counties at distances less than 10,000 feet from the river during the spring months for selected alternatives to the Current Water-Control Plan that target increased benefits to fish and wildlife. Local hydrogeologic conditions will determine how significantly the possible 1- to 4-foot change in ground-water levels affects land use within 10,000 feet of the river. For example, lower river stage and ground-water levels during the mid-summer months could improve drainage in lowland areas during periods of greater-than-normal precipitation. Actual depth to ground water might be controlled by factors other than river stage, such as proximity to drainage ditches and local differences in recharge by precip-

itation, discharge from evapotranspiration, aquifer properties, and land-surface altitude.

INTRODUCTION

The U.S. Army Corps of Engineers (COE) operates several dams upstream from Iowa that modify flows of the Missouri River. At certain times of the year, specific flow regimes are required for specific needs, such as agriculture, flood control, navigation, recreation, water supply, and wildlife habitat. Eight alternative water-management plans are proposed by the COE—the Current (1998) Water-Control Plan (CWCP), three alternatives for different levels of water conservation during drought conditions in the three upper reservoirs (Fort Peck Lake upstream from Fort Peck Dam in Montana, Lake Sakakawea upstream from Garrison Dam in North Dakota, and Lake Oahe upstream from Oahe Dam in South Dakota), three alternatives to provide additional fish and wildlife benefits with increased flows during the spring and summer months, and one alternative that established a Mississippi River target flow at St. Louis, Missouri, to benefit transportation needs on the Mississippi River (U.S. Army Corps of Engineers, 1998a, b). The plans are identified and summarized in table 1.

Technical information is needed by water managers and planners and landowners to determine whether depths to ground water at selected distances from the Missouri River might be greater or less under the eight alternative water-management plans. For example, hydrologic conditions that cause poor drainage and high ground-water levels can reduce agricultural productivity in the flood plain (U.S. Army Corps of Engineers, 1998b). The U.S. Geological Survey (USGS), in

Table 1. Description of U.S. Army Corps of Engineers alternative water-management plans for the Missouri River
[from U.S Army Corps of Engineers, 1998a, b]

Plan name	Description
CWCP	Current Water-Control Plan with a permanent pool level of 18 million acre-feet in the six reservoirs on the Missouri River. This plan produces a 5.5-month minimum navigation season and balances effects of intrasystem storage equally in the three upstream reservoirs.
C18	Conservation plan during drought with a permanent pool level of 18 million acre-feet. This plan produces a 5.5-month minimum navigation season and unbalances effects of storage in the three upstream reservoirs on a 3-year cycle.
C31	Conservation plan during drought with a permanent pool level of 31 million acre-feet. This plan produces a 6-month minimum navigation season and unbalances effects of storage in the three upstream reservoirs on a 3-year cycle.
C44	Conservation plan during drought with a permanent pool level of 44 million acre-feet. This plan produces a 6-month minimum navigation season and unbalances effects of storage in the three upstream reservoirs on a 3-year cycle.
FW10	Fish and wildlife benefits plan with an additional release of 10,000 cubic feet per second from Gavins Point Dam in the spring and early summer. The permanent pool level would be 31 million acre-feet, and this plan produces minimum navigation service from July 15 to August 15, when no flood storage releases would be made. Unbalances effects of storage in the three upstream reservoirs on a 3-year cycle.
FW15	Fish and wildlife benefits plan with an additional release of 15,000 cubic feet per second from Gavins Point Dam in the spring and early summer. The permanent pool level would be 31 million acre-feet, and the plan produces minimum navigation service from July 15 to August 15, when no flood storage releases would be made. Unbalances effects of storage in the three upstream reservoirs on a 3-year cycle.
FW20	Fish and wildlife benefits plan with an additional release of 20,000 cubic feet per second from Gavins Point Dam in spring and early summer. The permanent pool level would be 18 million acre-feet. This plan produces a 7-month minimum navigation season, with full service in July, minimum service from August through October, and no navigation in November in many years. Unbalances effects of storage in the three upstream reservoirs on a 3-year cycle.
M66	A variation of plan C18 with a target release of 66,000 cubic feet per second at St. Louis, where the Missouri River flows into the Mississippi River, to benefit navigation needs on the Mississippi River. The target is not always met due to release constraints related to endangered species and ice conditions. Unbalances effects of storage in the three upstream reservoirs on a 3-year cycle.

cooperation with the Fremont County Board of Supervisors, conducted an analysis of available hydrologic data to evaluate the effects on ground-water levels in the alluvial aquifer caused by changes in Missouri River stage in Fremont and Monona Counties in western Iowa.

Daily mean ground-water levels and river stage measured by the COE and USGS during November 1995–September 1996 and simulated daily mean river stage for November 1995–December 1996 derived from simulated daily mean discharge developed by the COE for the eight alternative water-management plans were used in the study. Mathematical simulations of daily mean ground-water levels caused by changes in daily mean river stage were made for water-management plans CWCP, FW10, and FW20 for November 1995–December 1996. This report presents results of the evaluation of the effects on ground-water levels in the Missouri River alluvial aquifer caused by changes in Missouri River stage at selected sites in Fremont and Monona Counties (fig. 1).

Results of the study can be used by water managers and planners and landowners to evaluate effects on ground-water levels under alternative water-management plans for the Missouri River. Users of the river and those affected by the river will be aided in making informed decisions about possible effects of the proposed alternative plans. Results will have transfer value to studies of ground-water levels in similar hydrogeologic settings adjacent to the Missouri River or other large rivers or streams.

Land use at the study sites adjacent to the Missouri River in Fremont and Monona Counties is predominantly agricultural, and a levee complex extends along the river to protect lowland areas from flooding during high river stage. A network of drainage ditches is used

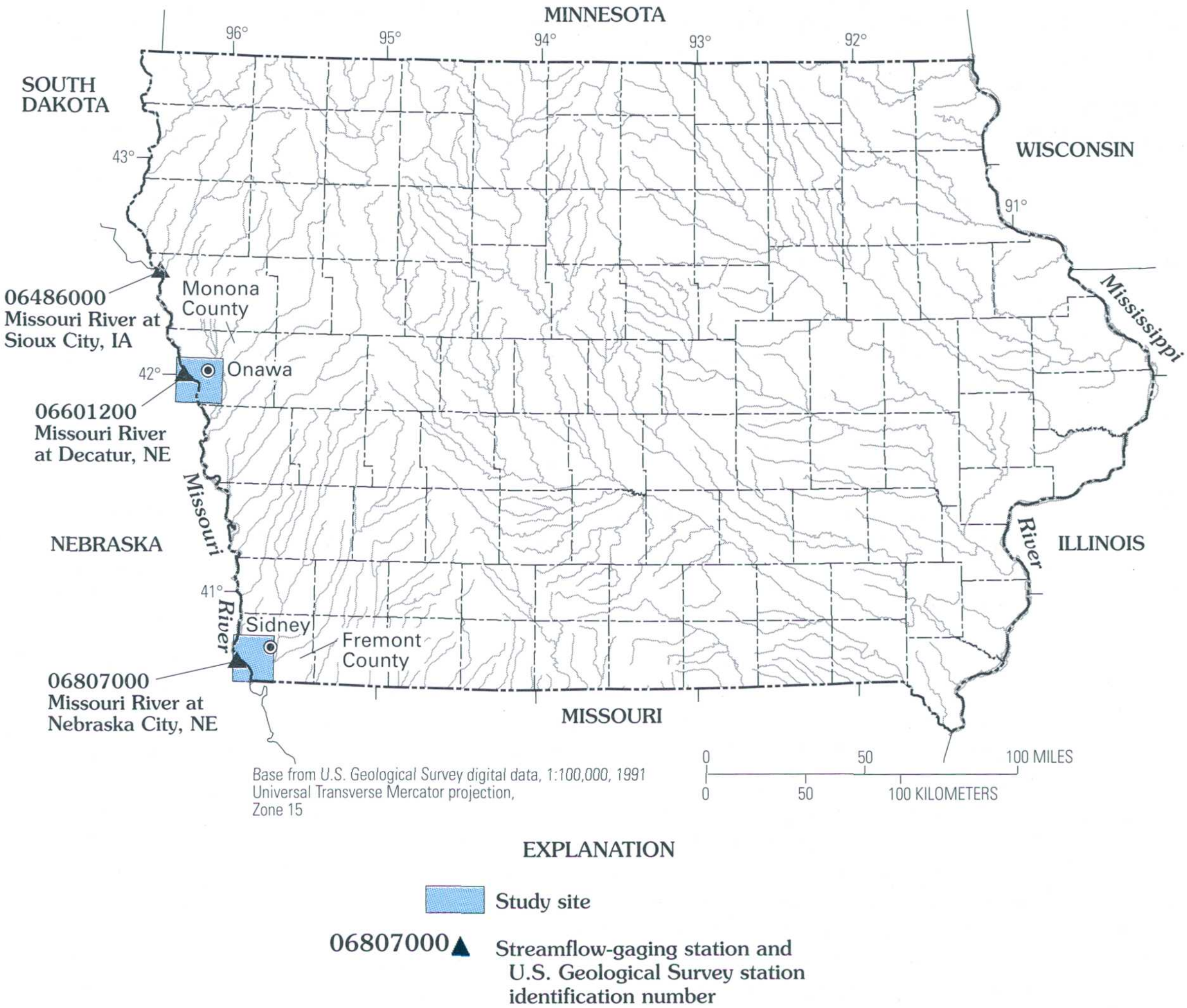


Figure 1. Location of study sites.

to convey water to the Missouri River from tributary streams entering the valley and lowland areas in the flood plain to maintain water levels favorable for agricultural production.

The Missouri River alluvial aquifer underlies the study sites. The aquifer consists of clay, silt, sand, and gravel, and grain size generally increases with depth. The aquifer is typically bowl shaped in cross section with relatively steep walls and a broad base. The lateral extent of the aquifer usually coincides with the location of the alluvial-valley walls. Depth to underlying bedrock can be as much as 160 ft (Buchmiller, 1986).

Wetter than normal hydrologic conditions occurred during the period for which data were used in this study (November 1995–December 1996). Mean annual precipitation for 1961–90 at Onawa in Monona County was 29.29 in., whereas annual precipitation during 1996 (January–December) was 36.09 in. at Onawa and 42.79 in. at Sidney in Fremont County (National Oceanic and Atmospheric Administration, 1996). The mean annual flow of the Missouri River for water years 1958–96 (October 1–September 30), which represents post-regulation of Missouri River flows by upstream dams, was 39,490 ft^3/s at Nebraska City, Nebraska (USGS station number 06807000), whereas the annual mean flow for water year 1996 was 57,150 ft^3/s. The highest historical annual mean flow was 61,700 ft^3/s for water year 1984, and the lowest historical annual mean flow was 27,810 ft^3/s for water year 1958 (May and others, 1997).

METHODS OF INVESTIGATION

Ground-water levels and river stages measured by the COE and USGS during November 1995–September 1996 were used to document hydrologic conditions for the CWCP. Aquifer properties determined during previous work by the COE and USGS are presented and were used in computations for this study. A computer program was used to simulate changes in ground-water levels in response to changes in river stage at selected distances from the Missouri River, and daily mean river stages were simulated on the basis of daily mean discharges provided by the COE for the eight alternative water-management plans. Ground-water levels and river stages generally are expressed in this report in terms of altitude for direct comparison purposes.

Well Construction and Nomenclature

During September–November 1995, 36 observation wells (19 in Fremont County and 17 in Monona County) were drilled to depths ranging from 42 to 51 ft below land surface in the Missouri River alluvial aquifer (table 2; figs. 2 and 3). The wells were installed using 4.25-in. inside-diameter continuous-flight hollow-stem augers. The hollow-stem auger assembly was used as a temporary casing during well construction to prevent collapse of the borehole wall. A string of 3-in. outside-diameter polyvinyl chloride (PVC) pipe with attached 5-ft slotted screen was installed inside the auger column. The auger flights then were rotated in reverse while slowly being withdrawn, allowing formation materials to collapse around the well screen and act as a natural filter pack. Bentonite was used as a seal in the upper 3 ft of all boreholes to prevent infiltration of surface water along the outside of the well casing. Each well was equipped with a lockable, protective steel casing, and a concrete apron was placed around the casing at land surface. Horizontal position (latitude-longitude) and reference to common vertical datum (sea level) were determined using a combination of global positioning system (GPS) and conventional surveying techniques.

The well identifiers are based on the county location, the purpose of the well, the relative position along the Missouri River, the relative position from the Missouri River, and the depth of the well (table 2; figs. 2 and 3). The Fremont County well identifiers start with 'FRE' and the Monona County well identifiers start with 'MO'. A 'T' after the county prefix indicates the four wells in Fremont County and two wells in Monona County that were installed specifically to measure water levels for aquifer transmissivity analysis. The wells were installed in lines roughly perpendicular to the Missouri River, and the next number in the identifier indicates the upstream-to-downstream position of the line within the county. The upstream line is 1, the middle line is 2, and the downstream line is 3. Monona County has a fourth line of wells used only for transmissivity analysis; that line number is 1. Within each line, relative position to the Missouri River is denoted by a letter. The well closest to the river is the 'A' well, the second closest well to the river is the 'B' well, and so forth. The number at the end of the well identifier is the drilled depth of the well below land surface.

Table 2. Well depths, land-surface altitudes, and measuring points for observation wells used in this study

Well identifier (figs. 2–3)	Well identification number	Well depth, in feet below land surface	Land surface altitude, in feet above sea level	Measuring point, in feet above land surface
		Fremont County, Iowa		
FRE1A50	404634095495501	50	934.97	5.26
FRE1B51	404635095492101	51	932.27	3.69
FRE1C51	404622095481601	51	932.26	3.81
FRE1D51	404622095470201	51	929.74	4.02
FRE1E51	404625095452401	51	931.46	3.90
FRE2A51	404135095500701	51	927.01	4.19
FRE2B51	404123095491101	51	921.35	4.73
FRE2C51	404124095472801	51	923.19	5.02
FRE2D48	404120095444001	48	915.61	4.76
FRE2E51	404116095431001	51	916.96	4.48
FRE3A46	403605095443601	46	912.25	5.14
FRE3B40	403604095440701	40	910.57	4.10
FRE3C42	403602095425801	42	906.74	4.94
FRE3D51	403602095411501	51	904.31	5.55
FRE3E51	403602095400201	51	902.84	4.25
FRET1A47	404629095500501	47	934.99	5.08
FRET1B50	404634095494801	50	934.38	3.90
FRET2A49	404035095550401	49	924.40	4.67
FRET2B43	404035095495801	43	922.25	4.81
		Monona County, Iowa		
MO1A51	420321096114001	51	1055.35	4.02
MO1B50	420318096092201	50	1050.82	5.30
MO1C51	420315096070801	51	1051.16	3.77
MO1D51	420337096042301	51	1051.13	3.81
MO1E50	420334096025701	50	1048.83	4.81
MO2A49	420135096130801	49	1054.53	5.17
MO2B50	420136096121501	50	1051.08	4.77
MO2C50	420134096111701	50	1049.84	4.37
MO2D50	420124096073601	50	1050.45	3.98
MO2E48	420137096043101	48	1046.77	1.67
MO2F50	420149096011701	50	1051.55	4.37
MO3A41	415847096073701	41	1037.84	3.50
MO3B48	415846096062901	48	1049.07	3.96
MO3C50	415855096051901	50	1044.92	3.90
MO3D43	415853096015001	43	1043.17	2.15
MOT1A45	415501096081201	45	1032.46	5.19
MOT1B51	415501096080501	51	1037.01	4.96

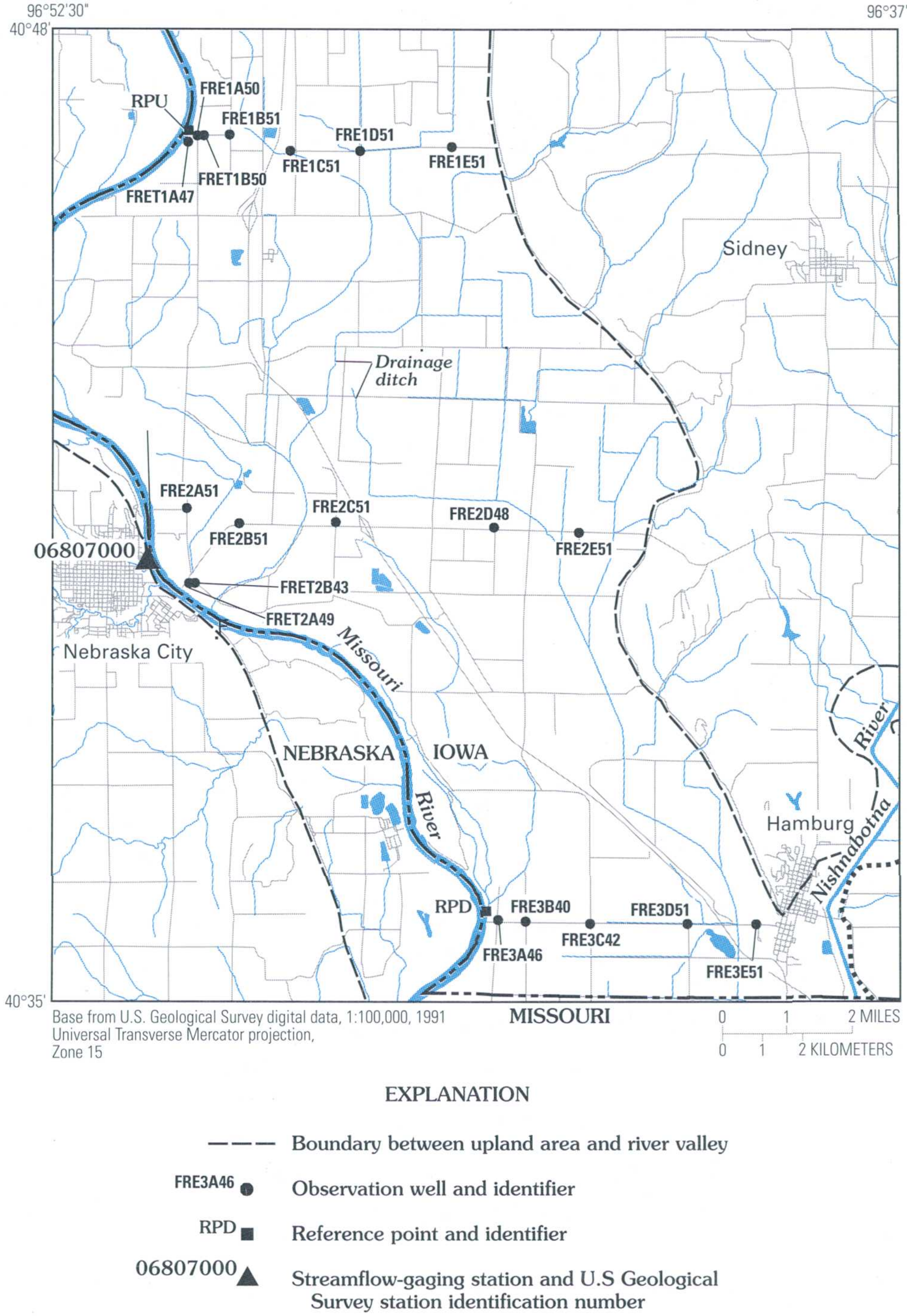
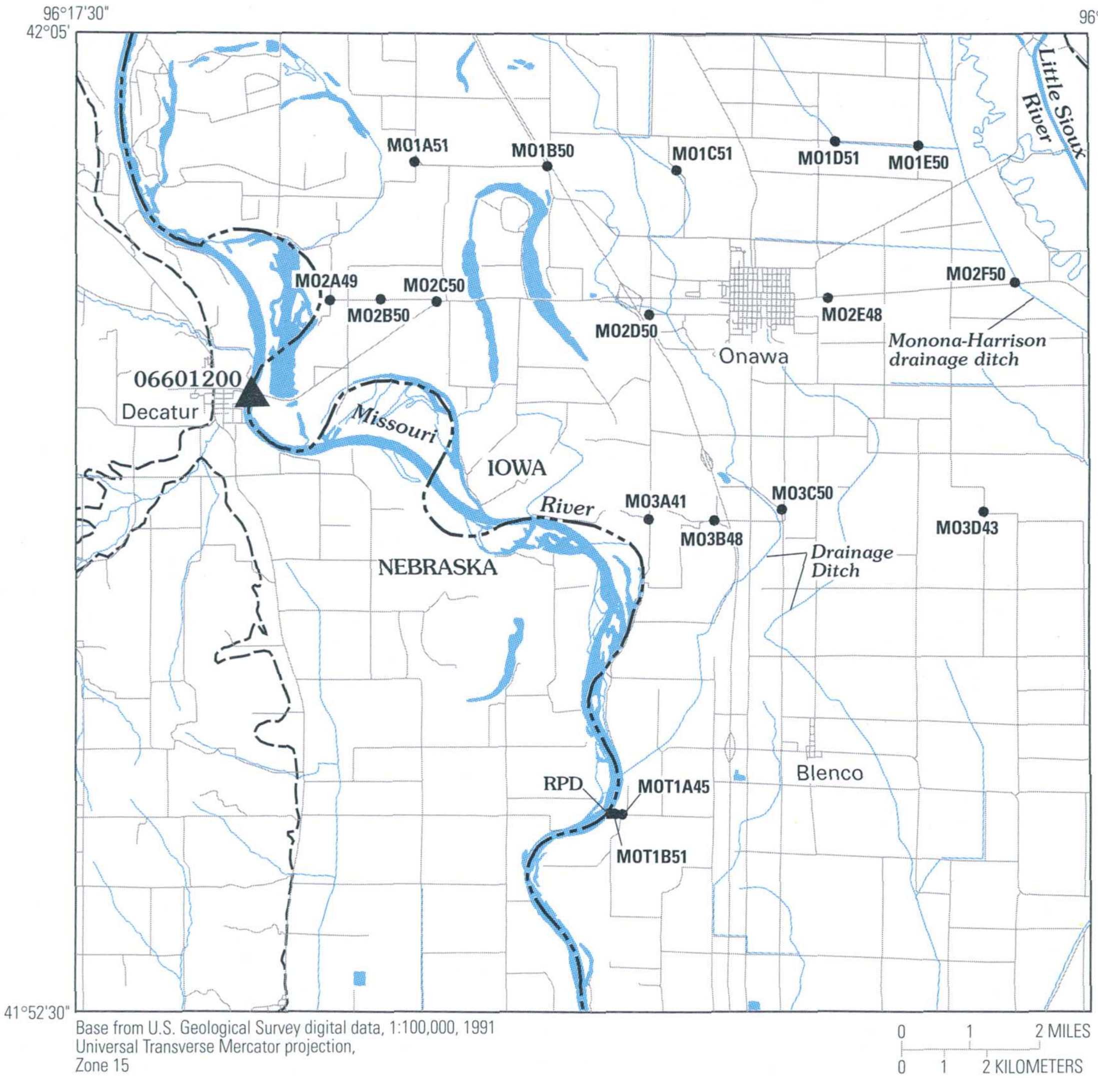


Figure 2. Location of data-collection sites in Fremont County.

Measurement of Ground-Water Levels and River Stage

Ground-water levels in the alluvial aquifer measured during November 1995–September 1996 at the 36 observation wells were used in the study. Water levels were recorded hourly at the observation wells using unvented pressure transducers that are affected by barometric pressure. Barometric pressure was recorded hourly at well FRE2C51 in Fremont County and at well MO2D50 in Monona County. A series of water-level measurements using a graduated steel tape were collected manually on an approximately monthly basis to determine the relation between the measured water



EXPLANATION

Boundary between upland area and river valley

MOT1B51 ● Observation well and identifier

RPD ■ Reference point and identifier

06601200 ▲ Streamflow-gaging station and U.S. Geological Survey station identification number

Figure 3. Location of data-collection sites in Monona County.

levels at the wells and the values recorded by the transducers before the appropriate pressure-related corrections were applied. Daily mean ground-water levels at each well were derived from the corrected hourly ground-water levels.

Daily mean Missouri River stage during November 1995–December 1996 was measured at streamflow-gaging stations operated by the USGS and COE. The Missouri River at Nebraska City, Nebraska, streamflow-gaging station (USGS station number 06807000) is located at river mile 562.6 across the river from the middle line of Fremont County observation wells. The Missouri River at Decatur, Nebraska, streamflow-gaging station (USGS station number 06601200) is located at river mile 691.0 across the river and near the middle line of Monona County observation wells.

River stages at ungaged locations near lines of observation wells were determined from gradients measured between temporary reference points and the streamflow-gaging stations at Nebraska City and Decatur, Nebraska. Reference points in Fremont County were established at the upstream and downstream lines of observation wells, indicated by 'RPU' and 'RPD' in figure 2. On the basis of eight measurements made during March–September 1996 at various river stages, the mean hydraulic gradient between the upstream or downstream reference points and the gaging station in Fremont County was 1.08 ft per river mile. A reference point in Monona County was established near the line of wells used for transmissivity analysis, indicated by 'RPD' in figure 3. On the basis of nine measurements made during February–September 1996 at various river stages, the mean gradient between the reference point and gaging station in Monona County was 0.98 ft per river mile.

Determination of Aquifer Properties

Estimates of aquifer hydraulic diffusivity and transmissivity were obtained from previous work conducted by the COE and USGS that was based on changes in ground-water levels caused by rapid stage fluctuations in the Missouri River (tables 3–5). Ground-water levels respond to changes in river stage, and the effect decreases with increasing distance from the river. A computer program was used to calculate theoretical type curves for the change in hydraulic head in a homogenous, isotropic, semi-infinite aquifer in response to changes in river stage (E.L. Nickerson, U.S. Geological Survey, written commun., 1996) (appendix 1). Pinder and others (1969) described the calculation of theoretical type curves by:

$$v = \frac{T}{S} = \frac{x^2}{u^2 \cdot \Delta t} \quad , \qquad (1)$$

where v = hydraulic diffusivity, in feet squared per day;
T = transmissivity, in feet squared per day;
S = storage coefficient, dimensionless;
x = distance from the stream, in feet;
u = function of calculated type curve, dimensionless; and
Δt = time interval, in days (1 hour = 0.0417 days).

The computer program generated a family of theoretical type curves by changing the variable, u, which is the function of the calculated type curves. Then, the theoretical type curve that most closely matched the observed change in hydraulic head with time was determined graphically. The u of the type curve that most closely matched the measured data was used to calculate hydraulic diffusivity using equation 1, and transmissivity was determined by multiplying diffusivity by the storage coefficient. The storage coefficient (specific yield) for unconfined aquifers varies from 0.1 to 0.3 and averages about 0.20 (Lohman, 1979).

River stage used in the analysis was determined at streamflow-gaging stations or was estimated from gradient information between the streamflow-gaging stations and the temporary reference points. Ground-water levels used in the study were measured hourly at the wells used for transmissivity analysis and at well FRE1A50.

For each period of analysis, three hydraulic diffusivity and transmissivity estimates were made for each site. The first estimate was made by comparing changes in river stage to the water-level response at the nearest observation well. The second estimate was made by comparing changes in river stage to the water-level response at the next closest observation well. The third estimate for the period was made by comparing the water-level changes in the observation well used for the first estimate to the water-level changes in the observation well used for the second estimate. Equation 1 was solved for transmissivity by using the calculated hydraulic diffusivity and varying the storage coefficient from 0.1 to 0.3 (tables 3–5).

The limitations of estimating hydraulic diffusivity and transmissivity by the Pinder and others (1969) method should be realized and might explain some of the variation in hydraulic diffusivity in tables 3–5. Armoring of the riverbed, the existence of a zone of low hydraulic conductivity around the riverbed, or the presence of vertical gradients near the river caused by partial river penetration into the aquifer may cause the estimated hydraulic diffusivity and transmissivity between the river and an observation well to be lower than the actual aquifer properties. Changes in the regional ground-water gradient between the alluvial valley walls and the river during the analysis period or recharge from local precipitation may cause estimated hydraulic diffusivity and transmissivity to be either higher or lower than actual values. Potential fluctuations between unconfined and confined conditions may

Table 3. Estimated aquifer properties at upstream line of observation wells used for aquifer transmissivity analysis in Fremont County

Storage coefficient	River to well FRET1A47		River to well FRE1A50		Well FRET1A47 to well FRE1A50	
	Hydraulic diffusivity, in feet squared per day	Transmissivity, in feet squared per day	Hydraulic diffusivity, in feet squared per day	Transmissivity, in feet squared per day	Hydraulic diffusivity, in feet squared per day	Transmissivity, in feet squared per day
Analysis for December 4–12, 1995						
0.10	100,000	10,000	270,000	27,000	830,000	83,000
0.15	100,000	15,000	270,000	41,000	830,000	120,000
0.20	100,000	20,000	270,000	54,000	830,000	170,000
0.25	100,000	25,000	270,000	68,000	830,000	210,000
0.30	100,000	30,000	270,000	81,000	830,000	250,000
Analysis for January 20–23, 1996						
0.10	120,000	12,000	240,000	24,000	610,000	61,000
0.15	120,000	18,000	240,000	36,000	610,000	92,000
0.20	120,000	24,000	240,000	48,000	610,000	120,000
0.25	120,000	30,000	240,000	60,000	610,000	150,000
0.30	120,000	36,000	240,000	72,000	610,000	180,000
Analysis for June 23–29, 1996						
0.10	100,000	10,000	340,000	34,000	3,300,000	330,000
0.15	100,000	15,000	340,000	51,000	3,300,000	500,000
0.20	100,000	20,000	340,000	68,000	3,300,000	660,000
0.25	100,000	25,000	340,000	85,000	3,300,000	830,000
0.30	100,000	30,000	340,000	100,000	3,300,000	990,000

Table 4. Estimated aquifer properties at downstream line of observation wells used for aquifer transmissivity analysis in Fremont County

Storage coefficient	River to well FRET2A49		River to well FRET2B43		Well FRET2A49 to well FRET2B43	
	Hydraulic diffusivity, in feet squared per day	Transmissivity, in feet squared per day	Hydraulic diffusivity, in feet squared per day	Transmissivity, in feet squared per day	Hydraulic diffusivity, in feet squared per day	Transmissivity, in feet squared per day
Analysis for December 4–12, 1995						
0.10	290,000	29,000	190,000	19,000	190,000	19,000
0.15	290,000	44,000	190,000	29,000	190,000	29,000
0.20	290,000	58,000	190,000	38,000	190,000	38,000
0.25	290,000	73,000	190,000	48,000	190,000	48,000
0.30	290,000	87,000	190,000	57,000	190,000	57,000
Analysis for January 20–23, 1996						
0.10	340,000	34,000	230,000	23,000	270,000	27,000
0.15	340,000	51,000	230,000	35,000	270,000	41,000
0.20	340,000	68,000	230,000	46,000	270,000	54,000
0.25	340,000	85,000	230,000	58,000	270,000	68,000
0.30	340,000	100,000	230,000	69,000	270,000	81,000
Analysis for June 23–29, 1996						
0.10	170,000	17,000	150,000	15,000	47,000	4,700
0.15	170,000	26,000	150,000	23,000	47,000	7,100
0.20	170,000	34,000	150,000	30,000	47,000	9,400
0.25	170,000	43,000	150,000	38,000	47,000	12,000
0.30	170,000	51,000	150,000	45,000	47,000	14,000

Table 5. Estimated aquifer properties at observation wells used for aquifer transmissivity analysis in Monona County

Storage coefficient	River to well MOT1A45		River to well MOT1B51		Well MOT1A45 to well MOT1B51	
	Hydraulic diffusivity, in feet squared per day	Transmissivity, in feet squared per day	Hydraulic diffusivity, in feet squared per day	Transmissivity, in feet squared per day	Hydraulic diffusivity, in feet squared per day	Transmissivity, in feet squared per day
Analysis for December 4–12, 1995						
0.10	13,000	1,300	33,000	3,300	56,000	5,600
0.15	13,000	2,000	33,000	5,000	56,000	8,400
0.20	13,000	2,600	33,000	6,600	56,000	11,000
0.25	13,000	3,300	33,000	8,300	56,000	14,000
0.30	13,000	3,900	33,000	9,900	56,000	17,000
Analysis for January 18–21, 1996						
0.10	14,000	1,400	25,000	2,500	56,000	5,600
0.15	14,000	2,100	25,000	3,800	56,000	8,400
0.20	14,000	2,800	25,000	5,000	56,000	11,000
0.25	14,000	3,500	25,000	6,300	56,000	14,000
0.30	14,000	4,200	25,000	7,500	56,000	17,000
Analysis for June 25–July 1, 1996						
0.10	22,000	2,200	62,000	6,200	730,000	73,000
0.15	22,000	3,300	62,000	9,300	730,000	110,000
0.20	22,000	4,400	62,000	12,000	730,000	150,000
0.25	22,000	5,500	62,000	16,000	730,000	180,000
0.30	22,000	6,600	62,000	19,000	730,000	220,000

be caused by water-table fluctuations that intersect the silt-clay cap present over most of the aquifer. Transmissivity estimated during confined conditions using a storage coefficient characteristic for unconfined conditions will be higher than the actual aquifer transmissivity.

Simulation of Ground-Water Levels and River Stage

The computer program listed in appendix 2 was used to simulate changes in daily mean ground-water levels in response to daily mean river stage at selected distances from the Missouri River for the CWCP, FW10, and FW20 water-management plans. Computations are based on principles described in Pinder and others (1969) and Hall and Moench (1972):

$$H = h \cdot erfc\sqrt{\frac{r^2}{4 \cdot v \cdot t}}, \qquad (2)$$

where H = change in ground-water level in the well, in feet;
h = change in river stage, in feet;
$erfc$ = the complementary error function;
r = distance between the well and the river, in feet;
v = hydraulic diffusivity, in feet squared per day; and
t = time, in days.

The computer program generated simulated changes in ground-water levels with time from inputs of river stage with time, distance between the well and the river, and an assumed hydraulic diffusivity.

For this study, v used in equation 2 was 240,000 ft^2/d for the simulation in Fremont County and 40,000 ft^2/d for the simulation in Monona County. These numbers are the approximate mathematical averages of hydraulic diffusivity estimates in each county for the aquifer response between the river and the second closest observation well used in the analysis (tables 3–5). Hydraulic diffusivity between the river and the second closest observation well is assumed to be representative because the largest amount of aquifer material is accounted for in the estimates.

Daily mean river stages at both study sites were simulated for November 1995–December 1996 and are based on daily mean discharges for the alternative water-management plans (U.S. Army Corps of Engineers, 1998a) (figs. 4 and 5). The stages were estimated from stage-discharge rating tables developed by the USGS for the streamflow-gaging stations on the Missouri River located at the study sites. Stages for the Missouri River at Nebraska City, Nebraska (USGS station number 06807000) were estimated using the current stage-discharge rating table, number 8, developed October 1996 (on file at USGS, Iowa City, Iowa). Because simulated discharges for the Missouri River at Decatur, Nebraska (USGS station number 06601200) were not available, those discharges were synthesized from the daily mean discharges provided for the Missouri River at Sioux City, Iowa (USGS station number 06486000), which is located 41 river miles upstream (fig. 1). The streamflow records for both stations for the study period were retrieved from the USGS NWIS (National Water Information System) streamflow data base, and linear regression was performed to relate the streamflows (Q). The relation was $Q_{Decatur} = 0.985*Q_{Sioux\ City} + 1{,}971$; the correlation coefficient (r^2) was 0.983. After estimating streamflows at USGS station number 06601200, the current rating table, number 7 (on file at USGS, Iowa City, Iowa), was used to estimate river stages.

The simulated river stages produced by this method are estimates only. No shifts were applied to the stages determined from the rating tables; that is, no adjustments were made to correct for variability in the stage-discharge relation commonly associated with alluvial streams. More precise stage estimates could be obtained using hydraulic modeling techniques. Such techniques, however, were beyond the scope of this study.

EFFECTS ON GROUND-WATER LEVELS CAUSED BY CHANGES IN RIVER STAGE

Ground-water levels in the alluvial aquifer vary in response to river stage, precipitation, evapotranspiration, proximity to drainage ditches, and pumpage. Effects on ground-water levels caused by changes in river stage were evaluated by using measured ground-water levels and measured and estimated river stages for November 1995–September 1996. The magnitude of changes in ground-water levels caused solely by river stage cannot be estimated accurately from measured data because of the complex response by the ground-water system to other stresses and because of the uncertainty about the distance from the river within the aquifer that river stage could affect ground-water levels. Therefore, simulated ground-water levels and river stages were determined for November 1995–December 1996 to estimate effects caused solely by changes in river stage for selected water-management plans.

Measured Water Levels

Daily mean ground-water levels measured at the middle lines of observation wells in Fremont and Monona Counties were compared to measured daily mean river stages at the two streamflow-gaging stations—Missouri River at Nebraska City, Nebraska, and Missouri River at Decatur, Nebraska. Daily mean ground-water levels measured at the upstream and downstream lines of observation wells were compared to estimated daily mean river stage computed from data obtained at temporary reference points and correlated with measured river-stage data. Daily precipitation data from Sidney and Onawa, Iowa, are presented for comparison (figs. 6 and 7). The measured data represent hydrologic conditions for the CWCP (table 1).

In Fremont County, ground-water levels generally were lower than river stage during the spring, summer, and fall months, indicating a gradient from the river to the aquifer (fig. 6). Water levels decreased in wells located less than about 8,000 ft from the river (wells FRE1A50, FRE1B51, FRE1C51, FRE2A51, FRE2B51, FRE2C51, FRE3A46, and FRE3B40) in response to the abrupt decrease in river stage that occurred during December 1995. Water levels measured in all wells increased during May, July, and August 1996 in apparent response to local precipitation. Therefore, water levels in wells at distances greater than about 8,000 ft from the river likely are more affected by precipitation or proximity to drainage ditches than by river stage.

In Monona County, factors that affect changes in ground-water levels appear to be more complex than in Fremont County, and the gradient generally is from the aquifer to the river (fig. 7). Ground-water levels generally were higher than river stage at upstream wells and middle wells, except for wells MO1E50 and MO2F50, which are located near the Monona-Harrison drainage ditch (fig. 3), and at downstream wells located more than 9,000 ft from the river (wells MO3B48, MO3C50,

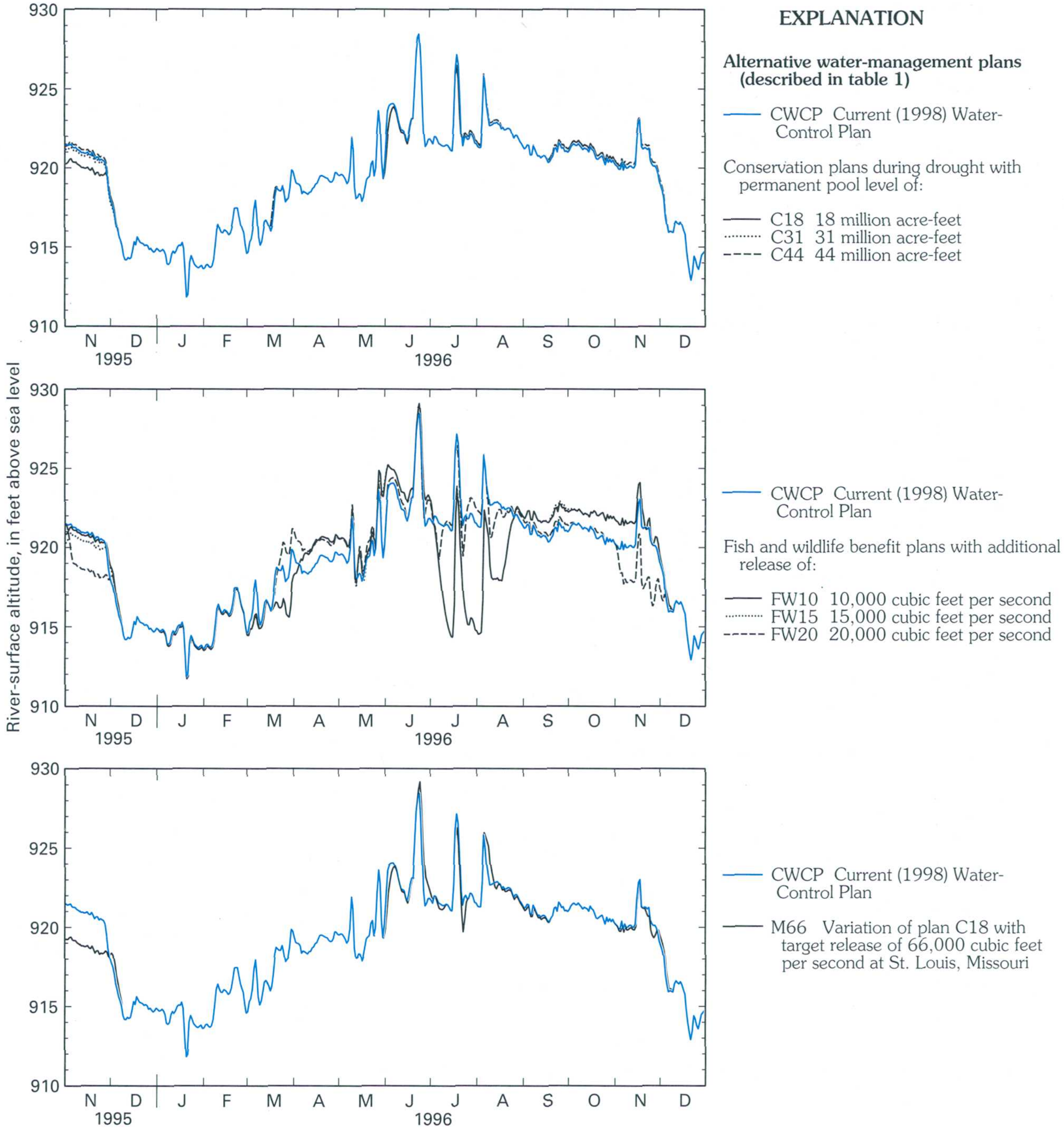


Figure 4. Simulated altitude of the Missouri River at the Nebraska City, Nebraska, streamflow-gaging station for the eight alternative water-management plans, November 1995–December 1996.

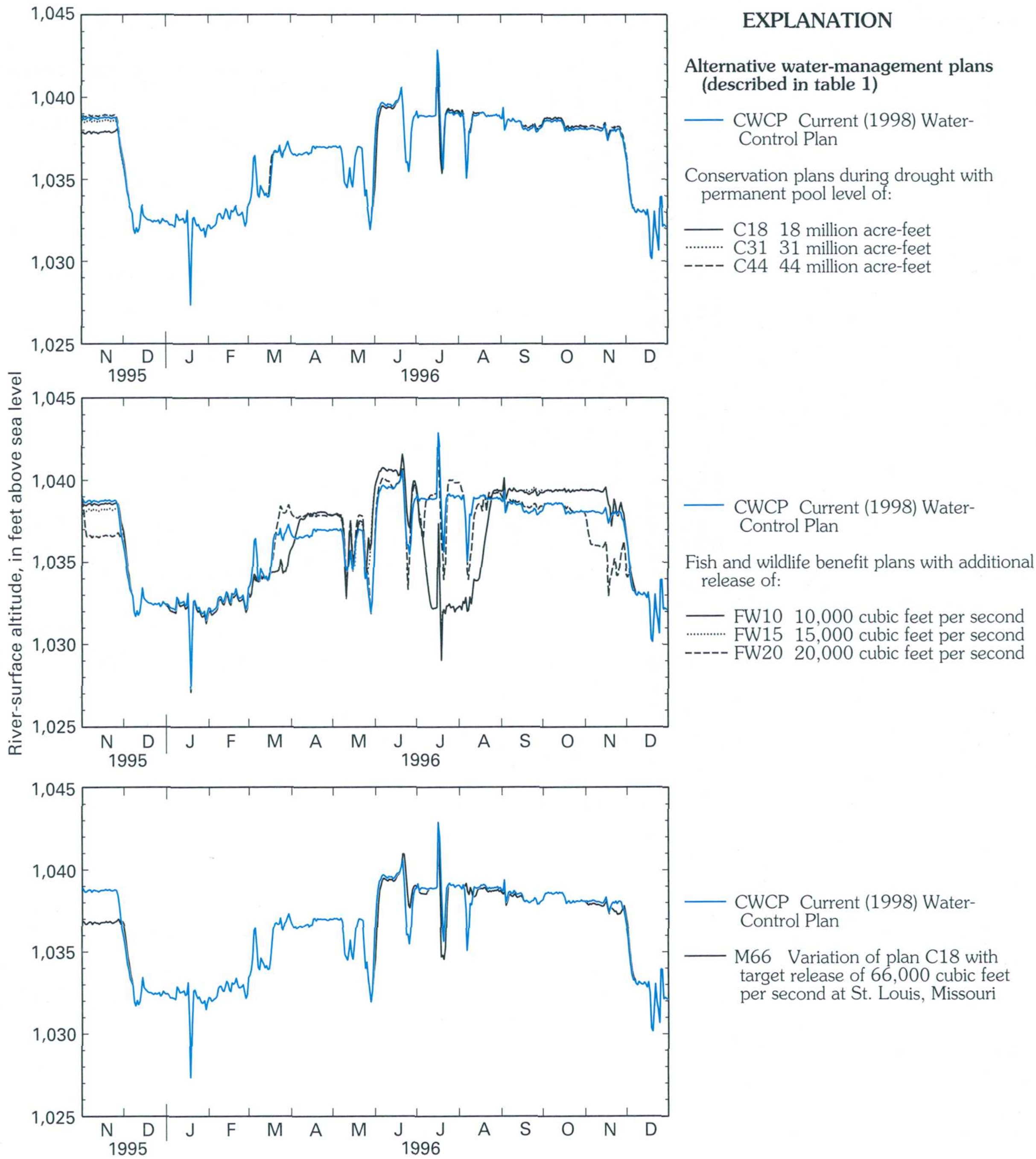


Figure 5. Simulated altitude of the Missouri River at the Decatur, Nebraska, streamflow-gaging station for the eight alternative water-management plans, November 1995–December 1996.

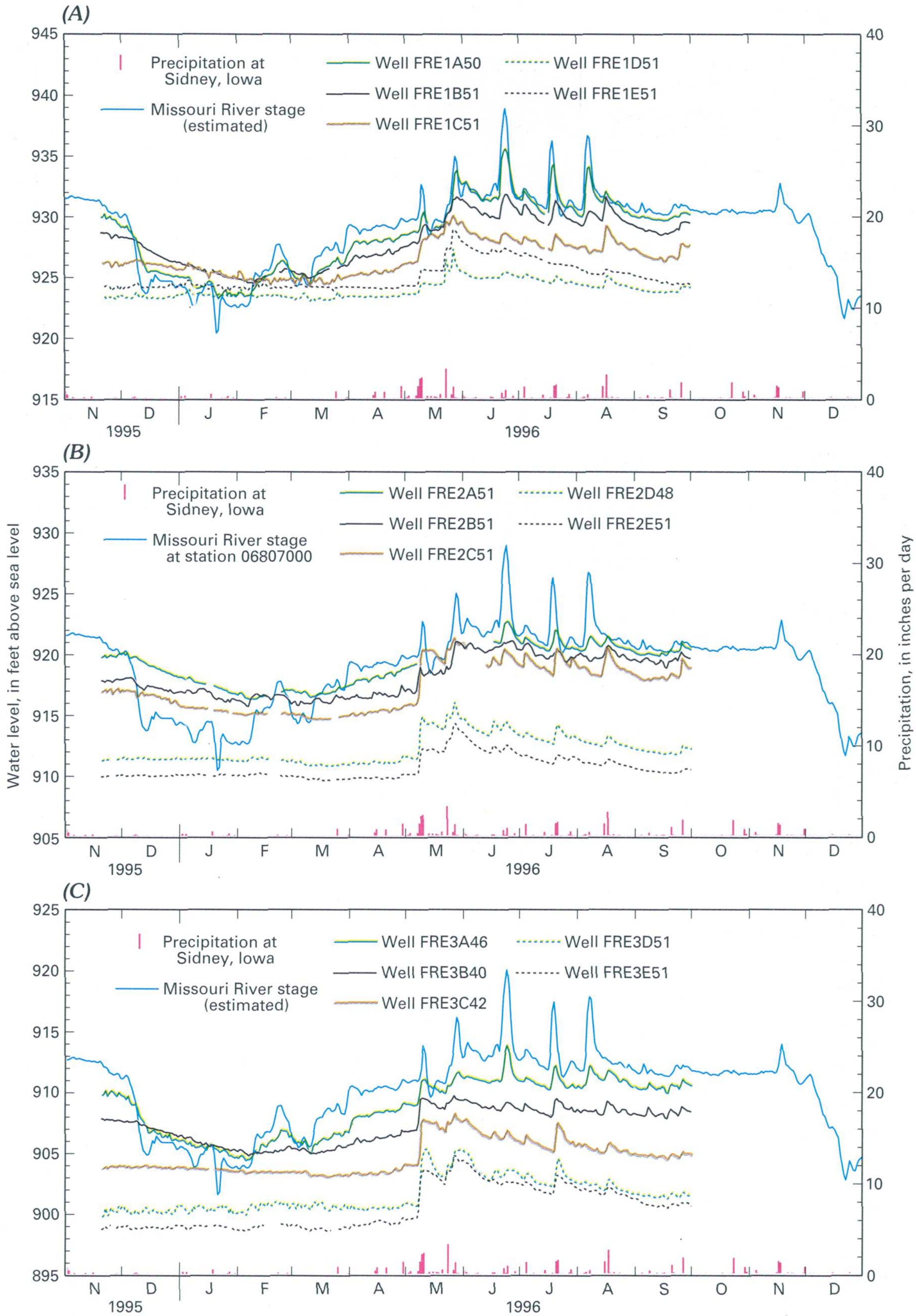


Figure 6. Measured or estimated altitudes of the Missouri River and water levels at *(A)* upstream, *(B)* middle, and *(C)* downstream lines of observation wells in Fremont County, and precipitation at Sidney, Iowa, November 1995–December 1996.

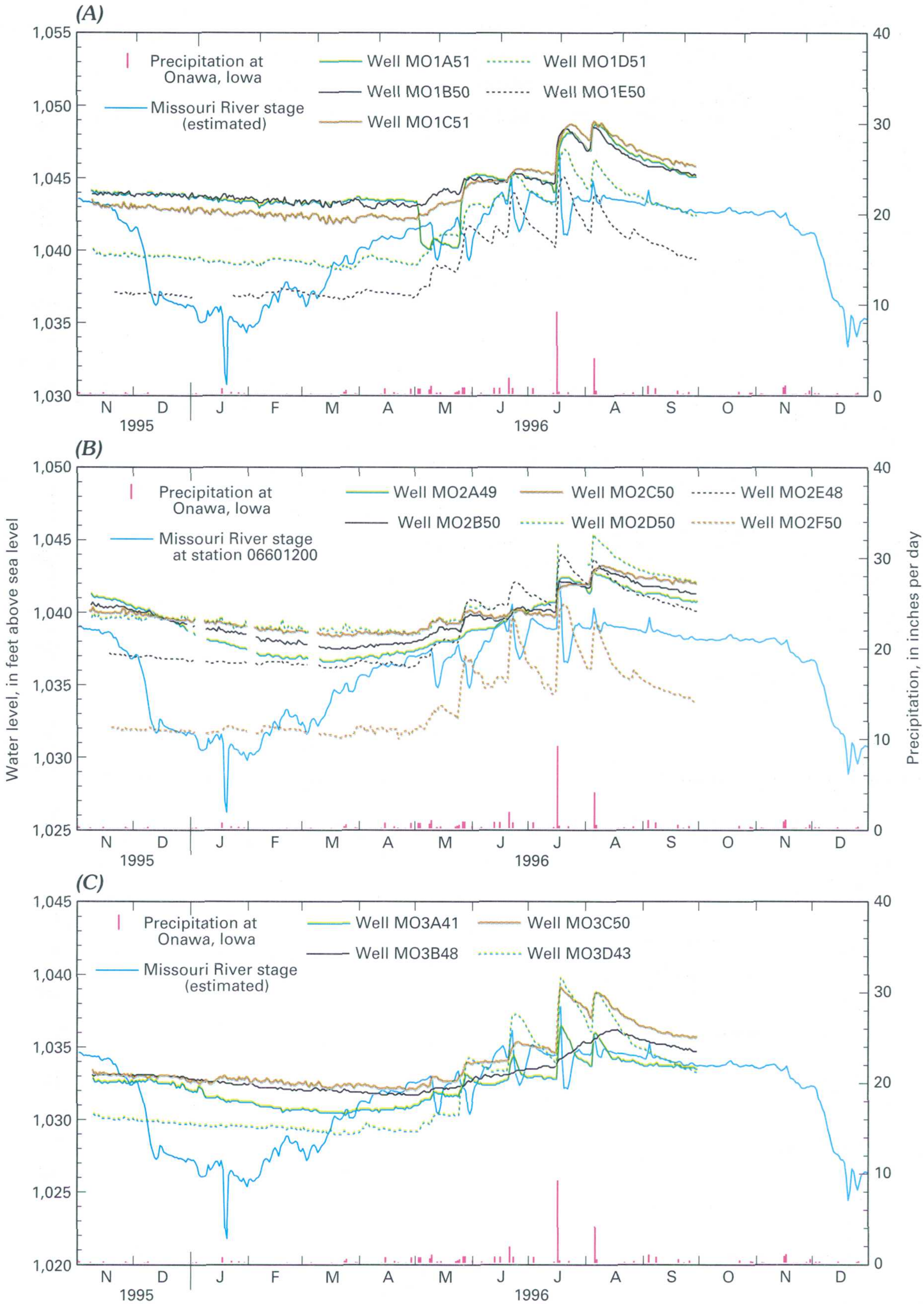


Figure 7. Measured or estimated altitudes of the Missouri River and water levels at *(A)* upstream, *(B)* middle, and *(C)* downstream lines of observation wells in Monona County, and precipitation at Onawa, Iowa, November 1995–December 1996.

MO3D43). The abrupt decrease in river stage that occurred during December 1995 appears to have affected water levels at wells located within about 6,500 ft of the river (wells MO2A49, MO2B50, and MO3A41). Water levels measured in all wells increased during May–August 1996 in apparent response to precipitation. Therefore, water levels in wells at distances greater than about 6,500 ft from the river likely were more affected by precipitation or proximity to drainage ditches than by river stage. The decrease in water levels in well MO1A51 during May 1996 was caused by nearby pumping.

Daily mean depths to water at selected wells in Fremont and Monona Counties during November 1995–September 1996 are shown in figure 8. In Fremont County at well FRE2B51, located about 7,100 ft

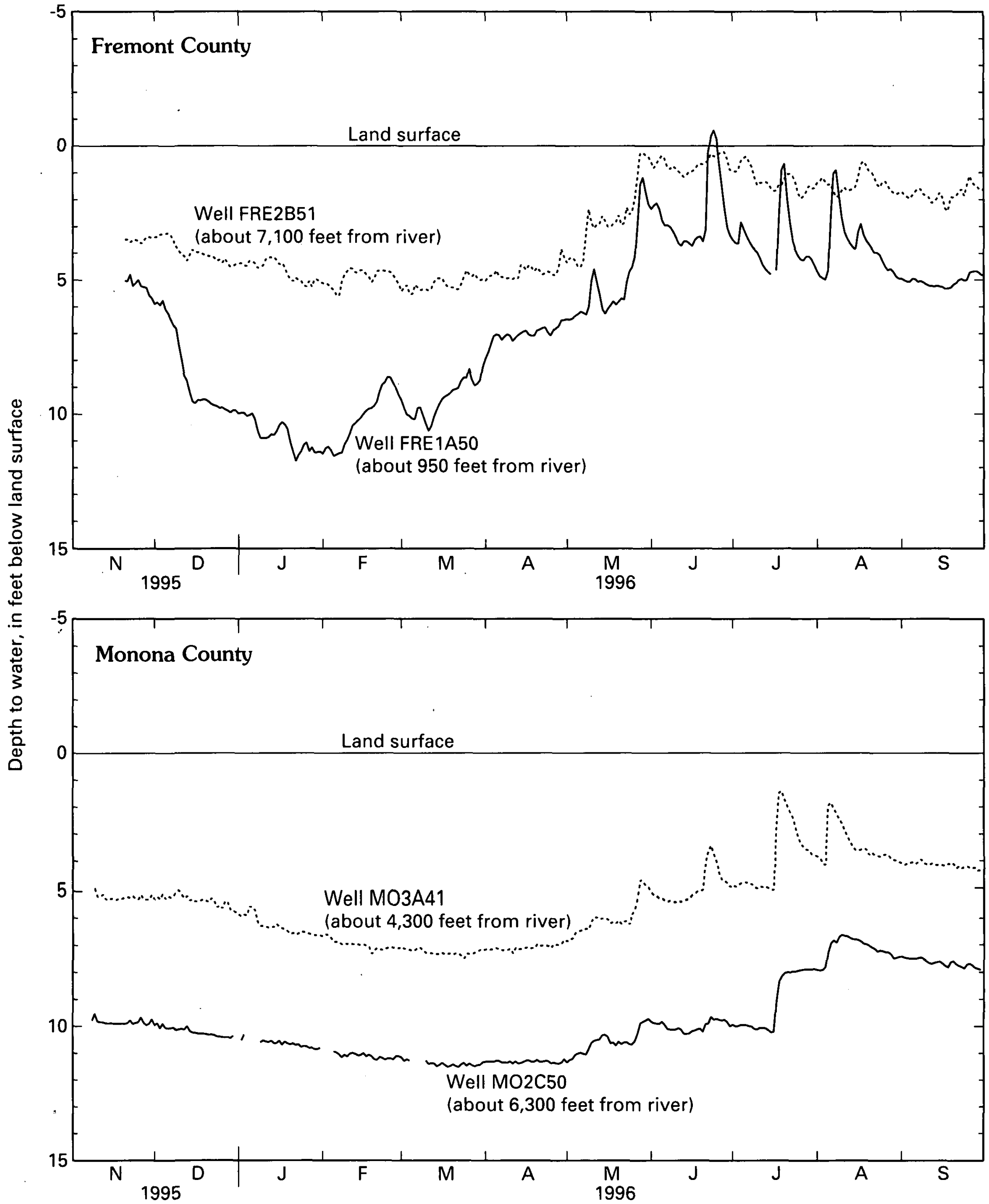


Figure 8. Measured depth to water, in feet below land surface, in wells FRE1A50, FRE2B51, MO2C50, and MO341, November 1995–September 1996.

from the river, depth to water was less than 3 ft from May–September 1996. At well FRE1A50, located about 950 ft from the river, depth to water was less than 3 ft intermittently from May–August 1996, and the water level was above land surface for a few days during June 1996. In Monona County at well MO3A41, located about 4,300 ft from the river, depth to water was less than 3 ft intermittently during July–August 1996. At well MO2C50, located about 6,300 ft from the river, depth to water was greater than 6 ft throughout the study period. Factors that affect differences in depth to water include altitude of land surface, proximity to drainage ditches or the river, aquifer properties, river stage, and local recharge from precipitation.

If differences in hydrologic conditions shown in figures 6–8 are representative for the study sites, changes in river stage likely affect ground-water levels in Fremont County to a greater degree than in Monona County. In Fremont County, ground-water levels generally are lower than river stage, indicating a gradient from the river to the aquifer. In Monona County, the ground-water levels generally are higher than river stage, indicating a gradient from the aquifer to the river. The response of ground-water levels to changes in river stage is less apparent in Monona County than in Fremont County. The higher ground-water levels in Monona County indicate that the effects of other factors, such as differences in recharge from precipitation and aquifer properties, are more dominant than in Fremont County.

Simulated Water Levels

By comparing the CWCP river stage during November 1995–September 1996 to simulated river stages for the other seven alternative water-management plans during the same time (table 1; figs. 4 and 5), an estimate of the effects of simulated river stage on ground-water levels can be made. For example, higher ground-water levels than those under CWCP conditions might have been expected from the higher river stages during mid-March through mid-May 1996 under plan FW10, FW15, and FW20 conditions and during September–November 1996 under plan FW10 and FW15 conditions. Lower ground-water levels than during CWCP conditions might have been expected during July–August 1996 under plan FW10 and FW15 conditions and during November 1996 for plan FW20 conditions. However, the magnitude of these changes in ground-water levels caused by river stage for the other seven alternative water-management plans cannot be determined directly from the comparison because of the complex response by the ground-water system to other stresses and because of the uncertainty about the distance from the river within the aquifer that river stage could affect ground-water levels.

A simulated ground-water response to daily mean river stage was determined using equation 2 (computer program in appendix 2) to estimate the effects on ground-water levels caused solely by changes in river stage. Simulated responses of ground-water levels to daily mean river stage at 1,000, 5,000, and 10,000 ft from the river for the CWCP and plans FW10 and FW20 are shown in figures 9 and 10. The daily mean water-level changes shown are relative to November 1, 1995. Only plans FW10 and FW20 were selected for comparison with the CWCP because simulated river stages for plans C18, C31, C44, and M66 are similar to the CWCP and those for plan FW15 are similar to plan FW10 during the study period (figs. 4 and 5).

For the CWCP in Fremont County, simulated changes in ground-water levels at 1,000 ft from the river closely followed changes in river stage but with less magnitude. The approximate 8-ft decrease in river stage during December 1995–January 1996 caused about a 6.5-ft decrease in ground-water levels, whereas the approximate 7-ft increase in river stage during a short time period in June 1996 caused about a 3-ft increase in ground-water levels. Greater lag times are required for ground-water levels to respond to the effects of river stage at greater distances from the river. About a 3-ft decrease in ground-water levels occurred after about 2 months at 5,000 ft from the river in response to the December 1995–January 1996 decrease in river stage, and about a 1.5-ft decrease in ground-water levels occurred after about 4 months at 10,000 ft from the river. The subsequent rise in river stage from February–August 1996 resulted in ground-water levels at 5,000 ft from the river returning to near the initial (November 1, 1995) level by September 1996.

Increased flows during the spring, early summer, and fall months in Fremont County for plan FW10 compared to the CWCP resulted in higher simulated river stage and ground-water levels, whereas decreased flows during mid-summer months resulted in lower simulated river stage and ground-water levels. Simulated ground-water levels at 1,000 ft from the river were about 1 ft higher than CWCP ground-water levels

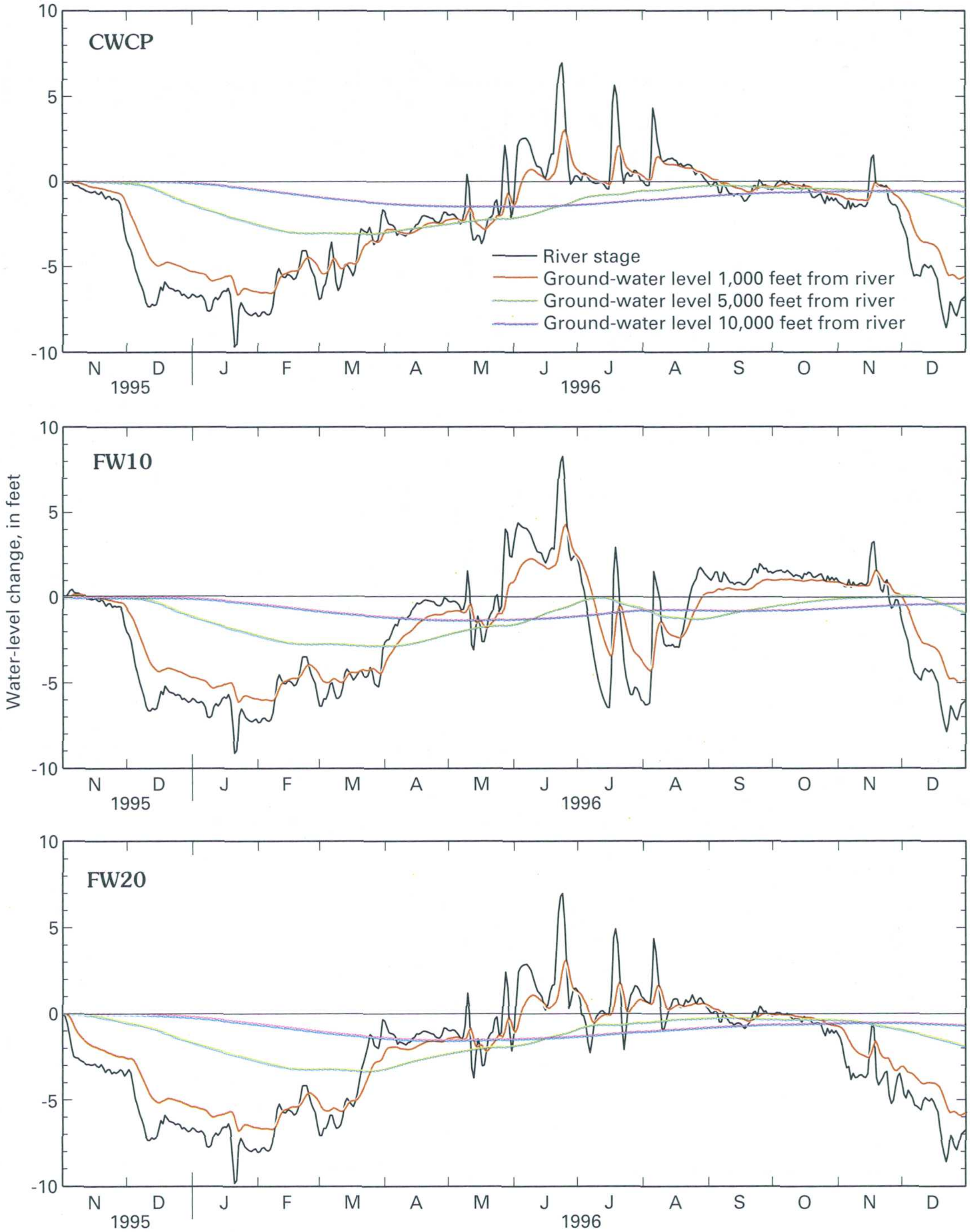


Figure 9. *Simulated change in ground-water levels at 1,000, 5,000, and 10,000 feet from the Missouri River in Fremont County caused by changes in river stage for the CWCP, FW10, and FW20 water-management plans, November 1995–December 1996.*

during late April 1996, about 1–2 ft higher during June 1996, about 3–4 ft lower during July–August 1996, and about 1–2 ft higher during October–November 1996. At 5,000 ft from the river, simulated ground-water levels were about 1 ft higher than CWCP ground-water levels during early July 1996, about 1 ft lower in August–September 1996, and about 1 ft higher during November 1996. Differences between simulated ground-water levels for plan FW10 compared to the CWCP were less than 1 ft at 10,000 ft from the river.

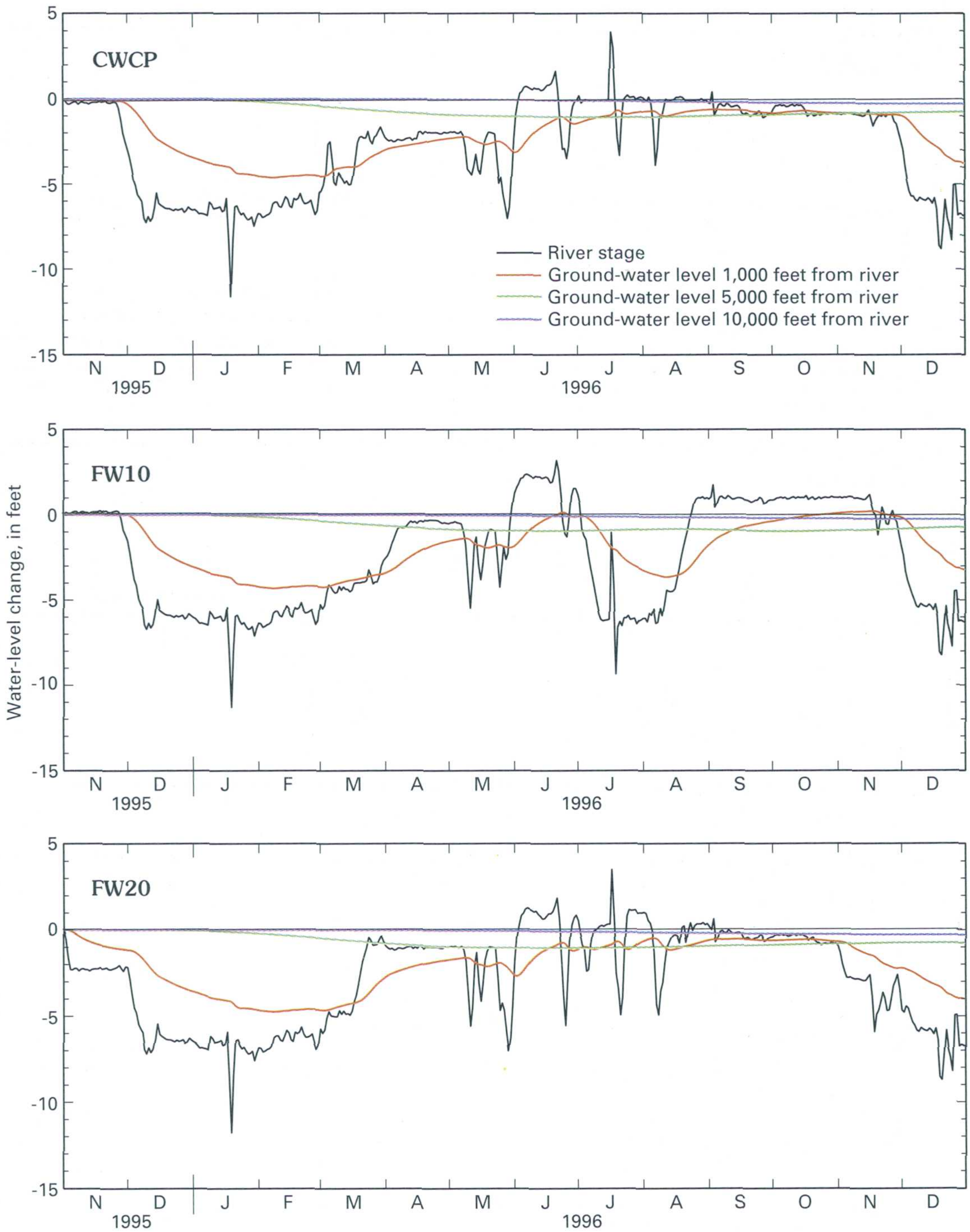


Figure 10. Simulated change in ground-water levels at 1,000, 5,000, and 10,000 feet from the Missouri River in Monona County caused by changes in river stage for the CWCP, FW10, and FW20 water-management plans, November 1995–December 1996.

Increased flows during the spring months in Fremont County for plan FW20 compared to the CWCP resulted in higher simulated river stage and ground-water levels. Simulated ground-water levels at 1,000 ft from the river were about 1 ft higher than CWCP ground-water levels during April–May 1996. Differences between simulated ground-water levels for plan FW20 compared to the CWCP were less than 1 ft at 5,000 and 10,000 ft from the river.

For the CWCP in Monona County, simulated changes in ground-water levels at 1,000 ft from the river did not follow changes in river stage as closely as in Fremont County. The approximate 7-ft decrease in river stage from December 1995–January 1996 caused about a 4.5-ft decrease in ground-water levels after about 2 months. This difference in ground-water-level response probably is due to differences in aquifer properties between the two study sites. About a 1-ft decrease in ground-water levels occurred at 5,000 ft from the river after about 6 months in response to the December 1995–January 1996 decrease in river stage. Ground-water levels at 10,000 ft from the river changed less than 1 ft.

Increased flows during the spring, early summer, and fall months in Monona County for plan FW10 compared to the CWCP resulted in higher simulated river stage and ground-water levels, whereas decreased flows during the mid-summer months resulted in lower simulated river stage and ground-water levels. Simulated ground-water levels at 1,000 ft from the river were about 1 ft higher than CWCP ground-water levels during late April–June 1996, as much as 3 ft lower during August 1996, and about 1 ft higher during October–November 1996. Differences between simulated ground-water levels for plan FW10 compared to the CWCP were less than 1 ft at 5,000 and 10,000 ft from the river.

Increased flows during the spring months in Monona County for plan FW20 compared to the CWCP resulted in higher simulated river stage and ground-water levels. However, differences between simulated ground-water levels for plan FW20 compared to the CWCP were less than 1 ft at 1,000, 5,000, and 10,000 ft from the river.

Generally, the effects of simulated river stage caused higher simulated ground-water levels in Fremont and Monona Counties at distances less than 10,000 ft from the river during the spring months for plans FW10 and FW20 compared to the CWCP and lower ground-water levels during the mid-summer months for plan FW10. Local hydrogeologic conditions will determine how significantly the possible 1- to 4-ft change in ground-water levels affects land use within 10,000 ft of the river. For example, the lower river stage and ground-water levels during the mid-summer months indicated for plan FW10 could improve drainage in lowland areas during periods of greater-than-normal precipitation.

By using principles of superposition, which state that problem solutions can be added together to obtain composite problem solutions (Reilly and others, 1987), a simulated daily mean depth to water caused solely by changes in river stage can be computed from simulated changes in daily mean ground-water levels, simulated daily mean river stage, and measured daily mean depth to water. For example, depth to water in well FRE1A50 (about 950 ft from the river in Fremont County) was considered. Simulated ground-water levels at 1,000 ft from the river for plan FW10 compared to the CWCP were about 1 ft higher during late April 1996, about 1–2 ft higher during June 1996, and about 3–4 ft lower during July and August 1996. By adding these differences to the measured depth to water shown in figure 8, the simulated depth to water in well FRE1A50 for plan FW10 was estimated. Results of the computation indicate that simulated depth to water would be less than 3 ft for longer periods during May and June 1996 compared to the CWCP and would be greater than 3 ft during July–August 1996 compared to intermittently less than 3 ft for the CWCP. This procedure can be used to estimate a simulated daily mean depth to water at other locations in the flood plain if distance from the river and measured daily mean depth to water are known.

The simulated changes in ground-water levels at 1,000, 5,000, and 10,000 ft from the river indicate approximate effects solely caused by changes in river stage. Other factors, such as recharge from precipitation, discharge through evapotranspiration, effects from proximity to drainage ditches, and local differences in aquifer properties are not accounted for; a computer ground-water flow model would properly address these complex interactions. Although simulations used in this report are based on a simplified mathematical representation of the interaction between ground water and the river, results can aid in improving the understanding of the magnitude and extent of the possible effect of the river on ground-water levels.

SUMMARY

Technical information is needed by water managers and planners and landowners to determine whether depths to ground water at selected distances from the Missouri River might be greater or less under eight alternative water-management plans for the Missouri River proposed by the U.S. Army Corps of Engineers (COE). For example, hydrologic conditions that cause

poor drainage and high ground-water levels can reduce agricultural productivity in the flood plain. The U.S. Geological Survey, in cooperation with the Fremont County Board of Supervisors, conducted an analysis of available hydrologic data to evaluate the effects on ground-water levels in the Missouri River alluvial aquifer caused by changes in Missouri River stage at selected sites in Fremont and Monona Counties in western Iowa.

Daily mean ground-water levels and river stage measured during November 1995–September 1996, simulated daily mean river stage derived from simulated daily mean discharge for November 1995–December 1996 developed by the COE for the eight alternative water-management plans, and simulated daily mean ground-water levels for November 1995–December 1996 for selected water-management plans were used in the study. The measured data represent hydrologic conditions for the Current (1998) Water-Control Plan (CWCP).

Ground-water levels in the alluvial aquifer vary in response to river stage, precipitation, evapotranspiration, proximity to drainage ditches, and pumpage. In Fremont County, measured ground-water levels generally were lower than river stage during the spring, summer, and fall months; in Monona County, measured ground-water levels generally were higher than river stage. Water levels in wells at distances greater than about 8,000 ft from the river in Fremont County and about 6,500 ft in Monona County likely were more affected by precipitation or proximity to drainage ditches than by river stage.

Changes in river stage likely affect ground-water levels in Fremont County to a greater degree than in Monona County. The response of ground-water levels to changes in river stage is less apparent in Monona County than in Fremont County. The higher ground-water levels in Monona County indicate that the effects of other factors, such as differences in recharge from precipitation and aquifer properties, are more dominant than in Fremont County.

For the CWCP in Fremont County, simulated changes in ground-water levels at 1,000 ft from the river closely followed changes in river stage but with less magnitude. The approximate 8-ft decrease in river stage during December 1995–January 1996 caused about a 6.5-ft decrease in ground-water levels. Greater lag times are required for ground-water levels to respond to the effects of river stage at greater distances from the river. About a 3-ft decrease in ground-water levels occurred after about 2 months at 5,000 ft from the river in response to the December 1995–January 1996 decrease in river stage, and about a 1.5-ft decrease in ground-water levels occurred after about 4 months at 10,000 ft from the river.

Increased flows during the spring, early summer, and fall months in Fremont County for water-management plan FW10 compared to the CWCP resulted in higher simulated river stage and ground-water levels, whereas decreased flows during mid-summer months resulted in lower simulated river stage and ground-water levels. Simulated ground-water levels at 1,000 ft from the river were about 1 ft higher than CWCP ground-water levels during late April 1996, about 1–2 ft higher during June 1996, about 3–4 ft lower during July–August 1996, and about 1–2 ft higher during October–November 1996. At 5,000 ft from the river, simulated ground-water levels were about 1 ft higher than CWCP ground-water levels during early July 1996, about 1 ft lower in August–September 1996, and about 1 ft higher during November 1996. Differences between simulated ground-water levels for plan FW10 compared to the CWCP were less than 1 ft at 10,000 ft from the river.

Increased flows during the spring months in Fremont County for water-management plan FW20 compared to the CWCP resulted in higher simulated river stage and ground-water levels. Simulated ground-water levels at 1,000 ft from the river were about 1 ft higher than CWCP ground-water levels during April–May 1996. Differences between simulated ground-water levels for plan FW20 compared to the CWCP were less than 1 ft at 5,000 and 10,000 ft from the river.

For the CWCP in Monona County, simulated changes in ground-water levels at 1,000 ft from the river did not follow changes in river stage as closely as in Fremont County. The approximate 7-ft decrease in river stage from December 1995–January 1996 caused about a 4.5-ft decrease in ground-water levels after about 2 months. About a 1-ft decrease in ground-water levels occurred at 5,000 ft from the river after about 6 months in response to the December 1995–January 1996 decrease in river stage. Ground-water levels at 10,000 ft from the river changed less than 1 ft.

Increased flows during the spring, early summer, and fall months in Monona County for water-management plan FW10 compared to the CWCP resulted in higher simulated river stage and ground-water levels, whereas decreased flows during the mid-summer months resulted in lower simulated river stage and ground-water levels. Simulated ground-water levels at 1,000 ft from the river were about 1 ft higher than CWCP ground-water levels during late April–June 1996, as much as 3 ft lower during August 1996, and about 1 ft higher during October–November 1996. Differences between simulated ground-water levels for plan FW10 compared to the CWCP were less than 1 ft at 5,000 and 10,000 ft from the river.

Increased flows during the spring months in Monona County for water-management plan FW20 compared to the CWCP resulted in higher simulated river stage and ground- water levels. However, differences between simulated ground-water levels for plan FW20 compared to the CWCP were less than 1 ft at 1,000, 5,000, and 10,000 ft from the river.

Generally, the effects of simulated river stage caused higher simulated ground-water levels in Fremont and Monona Counties at distances less than 10,000 ft from the river during the spring months for plans FW10 and FW20 compared to the CWCP and lower ground-water levels during the mid-summer months for plan FW10. Local hydrogeologic conditions will determine how significantly the possible 1- to 4-ft change in ground-water levels affects land use within 10,000 ft of the river. For example, the lower river stage and ground-water levels during the mid-summer months indicated that plan FW10 could improve drainage in lowland areas during periods of greater-than-normal precipitation.

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APPENDICES

APPENDIX 1. PROGRAM (FORTRAN) TO COMPUTE THEORETICAL AQUIFER RESPONSE TO CHANGES IN RIVER STAGE

```
C (E.L. Nickerson, U.S. Geological Survey, written commun., 1996)
C
C Programmed by B.M. Garcia, U.S. Geological Survey, using calculations in
C Determination of Aquifer Diffusivity from Aquifer
C Response to Fluctuations in River Stage
C by
C George F. Pinder, John D. Bredehoeft, and Hilton H. Cooper, Jr.
C U.S. Geological Survey
C in
C WATER RESOURCES RESEARCH
C vol. 5, no. 4, August 1969.
C
C
C INPUT comes from unit values files
C
C The program creates a command plot file to be used in Telagraf.
C The Plot is of computed and observed flood-wave response values.
C Four values of u are used.
C If Telagraf is not available, the program will need to be modified
C to use another plot package.
C
      external erfc
      character*32 outfile,river,well
      character*3 ans
      real rh(4000),u1(4000),u2(4000),u3(4000),u4(4000),time(4000),
     +wt(4000),wh(4000)
      common/blk1/time,rh,ii
      common/blk2/wt,wh,jj
      call get_river_info
      call get_well_info
      write(1,*) 'What is the telagraf file name ?'
      read(1,fmt='(a32)')outfile
      open(105,file=outfile)
      open(101,file='u.values')
      write(1,*) 'enter u1,u2,u3,u4'
      read(1,*)dif1,dif2,dif3,dif4
      write(101,*)dif1,dif2,dif3,dif4
      endfile(101)
      do 210 i=1,ii
```

```
          u1(i)=0.
          do 220 j=1,i
            x=i
            y=j
            if(j.eq.i)go to 220
              u1(i)=u1(i)+rh(j)*erfc(dif1/(2.*sqrt(x-y)))
220         continue
210     continue
      write(105,*)'GENERATE A PLOT.'
      write(105,*)'LEGEND ON.'
      write(105,*)'X AXIS LABEL IS "TIME(t), IN HOURS".'
      write(105,*)'Y AXIS LABEL IS "CHANGE IN HEAD(hm), IN FEET".'
      write(105,*)'INPUT DATA.'
      write(105,*)'"WELL"'
      do 130 i=1,jj
        write(105,*)wt(i),wh(i)
130   continue
      write(105,810)dif1
810   format('"u1 ',f4.1,'"')
      do 240 i=1,ii
       write(105,*)time(i),u1(i)
240   continue
      write(105,820)dif2
820   format('"u2 ',f4.1,'"')
      do 250 i=1,ii
          u2(i)=0.
          do 260 j=1,i
             x=i
             y=j
              if(j.eq.i)go to 260
              u2(i)=u2(i)+rh(j)*erfc(dif2/(2.*sqrt(x-y)))
260          continue
250       continue
      do 270 i=1,ii
        write(105,*)time(i),u2(i)
270   continue
      write(1,*)'*** I am working hard please wait ***'
      do 280 i=1,ii
         u3(i)=0.
         do 290 j=1,i
             x=i
```

```
          y=j
          if(j.eq.i)go to 290
          u3(i)=u3(i)+rh(j)*erfc(dif3/(2.*sqrt(x-y)))
290       continue
280   continue
    write(105,830)dif3
830   format('"u3 ',f4.1,'"')
    do 300 i=1,ii
      write(105,*)time(i),u3(i)
300   continue
    do 310 i=1,ii
      u4(i)=0.
      do 320 j=1,i
          x=i
          y=j
          if(j.eq.i)go to 320
          u4(i)=u4(i)+rh(j)*erfc(dif4/(2.*sqrt(x-y)))
320       continue
310   continue
    write(105,840)dif4
840   format('"u4 ',f4.1,'"')
    do 330 i=1,ii
      write(105,*)time(i),u4(i)
330   continue
    write(105,*)'END OF DATA.'
    write(105,*)'GO.'
    write(105,*)'Q.'
    endfile(105)
    write(1,*)'Do you want to save the river and well data ?'
    read(1,fmt='(a3)')ans
    if(ans(1:1).eq.'y'.or.ans(1:1).eq.'Y')then
      write(1,*)'What is the well file name ?'
      read(1,fmt='(a32)')well
      write(1,*)'What is the river file name ?'
      read(1,fmt='(a32)')river
      open(106,file=well)
      open(107,file=river)
      do 888 i=1,ii
        write(107,*)time(i),rh(i)
888     continue
      do 999 i=1,jj
```

```
            write(106,*)wt(i),wh(i)
999       continue
      endfile(106)
      endfile(107)
      endif
      stop
      end
C
C  Subroutine to compile river head
C  from unit values file
C
      subroutine get_river_info
      logical there
      character*4 date
      character*32 infile
      character*80 record
      real time(4000),rh(4000),rl(4000),rl1(4000)
      common/blk1/time,rh,ii
3      write(1,*)' river unit file name?'
      read(1,fmt='(a32)')infile
      inquire(file=infile,exist=there)
      if (there) then
        open(100,file=infile)
      else
        write(1,*)'*** file does not exist ***'
        go to 3
      end if
4      write(1,*)'enter the starting date mmdd ?'
      read(1,fmt='(a4)')date
      read(date,fmt='(i2,i2)',err=101)it,jt
      go to 102
101   write(1,*)' ** error please **'
      go to 4
102   if(it.gt.12.or.jt.gt.31.or.it.lt.1.or.jt.lt.1)then
        write(1,*)' ** error please **'
        go to 4
      endif
100   write(1,*)'time interval'
      write(1,*)' (1)  15 minutes'
      write(1,*)' (2)   1 hour'
      read(1,*,err=103)ihour
```

```
      go to 104
103   write(1,*)' ** error please enter **'
      go to 100
104   if(ihour.ne.1.and.ihour.ne.2)then
        write(1,*)' ** error please enter **'
        go to 100
      endif
5     write(1,*)'enter the starting time 1-24'
      read(1,*,err=105)itime
      go to 106
105   write(1,*)' ** error please **'
      go to 5
106   if (itime.lt.1.or.itime.gt.24)then
        write(1,*)' ** error please **'
        go to 5
      endif
      if(ihour.eq.1) itime=(itime*4-1)
      itime=itime-1
6     write(1,*)'how many time steps'
      read(1,*,err=107)ip
      ii=ip
      go to 108
107   write(1,*)' ** error please **'
      go to 6
108   ip=ip+1
1     read(100,fmt='(a80)')record
      if(record(1:1).ne.'B')go to 1
      if(record(21:24).ne.date)go to 1
      j=1
      read(record(41:80),*)(rl(i),i=j,j+5)
2     read(100,fmt='(a80)',end=99)record
      if(record(1:1).ne.'B')go to 2
      j=j+6
      read(record(41:80),*)(rl(i),i=j,j+5)
      go to 2
99    do 10 ik=1,ip
        rl(ik)=rl(ik+itime)
10    continue
      xyt=0.
      do 20 i=2,ip
        wxx=rl(i)
```

```
      rl1(i)=rl(i)-rl(i-1)
      if(ihour.eq.1) go to 88
      time(i-1)=i-1
      rh(i-1)=rl1(i)
      go to 20
88     xyt=xyt+.25
      time(i-1)=xyt
      rh(i-1)=rl1(i)
20   continue
    endfile(100)
    return
    end
C
C  Subroutine to calculate well head change
C  from unit values file
C
    subroutine get_well_info
    logical there
    character*4 date
    character*32 infile
    character*80 record
    real wh(4000),wt(4000)
    common/blk2/wt,wh,jj
1    write(1,*)' input well file name?'
    read(1,fmt='(a32)')infile
    inquire(file=infile,exist=there)
    if (there) then
     open(100,file=infile)
    else
     write(1,*)'*** file does not exist ***'
     go to 1
    end if
2    write(1,*)'enter the starting date mmdd ?'
    read(1,fmt='(a4)')date
    read(unit=date,fmt='(i2,i2)',err=3)id,jd
    go to 4
3    write(1,*)' ** error please **'
    go to 2
4    if(id.gt.12.or.id.lt.1.or.jd.gt.31.or.jd.lt.1) then
      write(1,*)' ** error please **'
      go to 2
```

```
      end if
5     write(1,*)'enter the starting time 1-24'
      read(1,*,err=6)itime
      go to 7
6     write(1,*)' ** error please **'
      go to 5
7     itime=itime-1
8     write(1,*)'enter adjustment use decimal'
      read(1,*,err=9)xad
      go to 10
9     write(1,*)' ** error please **'
      go to 8
10    write(1,*)'how many time steps'
      read(1,*,err=11)ip
      go to 12
11    write(1,*)' ** error please enter **'
      go to 10
12    read(100,fmt='(a80)')record
      if(record(1:1).ne.'B')go to 12
      if(record(21:24).ne.date)go to 12
      j=1
      read(record(41:80),*)(wh(i),i=j,j+5)
102   read(100,fmt='(a80)',end=199)record
      if(record(1:1).ne.'B')go to 102
      j=j+6
      read(record(41:80),*)(wh(i),i=j,j+5)
      go to 102
199   jj=ip
      do 110 ik=1,ip-1
        wh(ik)=wh(ik+itime)
110   continue
      do 120 i=1,ip
        wxx=wh(i)
        wh(i)=wh(i)-xad
        wt(i)=i
120   continue
      endfile(100)
      return
      end
```

APPENDIX 2. PROGRAM (FORTRAN) TO COMPUTE SIMULATED GROUND-WATER LEVEL IN RESPONSE TO CHANGES IN RIVER STAGE

```
C  (A.W. Burns, U.S. Geological Survey, written commun., 1998)
      DIMENSION SI(0:500),URF(500)
      character*32 filename
      character*10 idate
C
      write (*,*) ' Enter Diffusivity'
      read (*,*) ALPHA
      write (*,*) ' Enter Distance from River to Well'
      read (*,*) X
      write (*,*) ' Enter filename for the River Stages'
      read (*,*) filename
      open (10,file=filename)
      write (*,*) ' Enter filename for the predict well head'
      read (*,*) filename
      open (11,file=filename)
C
      WRITE (*,*) ' DISTANCE FROM STREAM = ',X,' FEET'
      WRITE (11,*) ' DISTANCE FROM STREAM = ',X,' FEET'
      WRITE (*,*) ' DIFFUSIVITY = ',ALPHA,' FEET 2/DAY'
      WRITE (11,*) ' DIFFUSIVITY = ',ALPHA,' FEET 2/DAY'
C
      NURF = 500
      NSI = 0
  5   NSI = NSI + 1
      read (10,6,end=8) idate,discharge,si(NSI)
  6   format (a10,f11.0,f10.0)
      go to 5
  8   NSI = NSI - 1
      SI(0) = SI(1)
      do 9 I = NSI,NURF
  9   SI(I) = SI(NSI)
C
      FACTOR = X/SQRT(4.*ALPHA)
      DO 10 ITIME = 1,NURF
      TIME = ITIME
      Z = FACTOR/SQRT(TIME)
      URF(ITIME) = ERFC(Z)
 10   continue
C
```

```
C  COMPUTATION
C
      WRITE (*,*) ' '
      WRITE (*,*) '     DAY  STAGE CHANGE   WELL HEAD CHANGE'
      DO 30 I = 1,NURF
      SOO = 0.
      DO 20 K = 1,I
      SOO = SOO + (SI(K)-SI(K-1))*URF(I-K+1)
   20 CONTINUE
      WRITE (*,25) I,SI(I)-si(0),SOO
      WRITE (11,25) I,SI(I)-si(0),SOO
 25   format (i10,2f10.3)
   30 CONTINUE
C
 200  CONTINUE
      STOP
      END
C
      FUNCTION ERFC(Z)
      IF (Z.LT.0.) WRITE (*,*) ' NEGATIVE ARGUMENT FOR COMPLEMENTARY ER
     *ROR FUNCTION'
      IF (Z.LT.0.) STOP
      ERFC=0.
      IF(Z.GE.4.) GO TO 10
      A1=0.0705230784
      A2=0.0422820123
      A3=0.0092705272
      A4=0.0001520143
      A5=0.0002765672
      A6=0.0000430638
      ERFC = 1./(1.+Z*(A1+Z*(A2+Z*(A3+Z*(A4+Z*(A5+Z*A6))))))**16
 10   CONTINUE
      RETURN
      END
```

Lucey and others—Effects on Ground-Water Levels in the Missouri River Alluvial Aquifer Caused by Changes in Missouri River Stage, Fremont and Monona Counties, Iowa—USGS/WRIR 98–4235