Effects of Alternative Missouri River Management Plans on Ground-Water Levels in the Lower Missouri River Flood Plain

Water-Resources Investigations Report 00–4052

Prepared in cooperation with the
Missouri Department of Natural Resources
Division of Geology and Land Survey, and
Missouri Levee and Drainage District Association

U.S. Department of the Interior
U.S. Geological Survey

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CONVERSION FACTORS

Multiply	By	To obtain
centimeters	0.3937	inches
meter	3.281	feet
kilometer	0.6215	mile
square meter	10.76	square feet
hectare	2.471	acre
square kilometer	0.3861	square mile
cubic meters	8.110×10^{-4}	acre-feet
cubic meters per day	4.087×10^{-4}	cubic feet per second

Sea Level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NVGD 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.

Effects of Alternative Missouri River Management Plans on Ground-Water Levels in the Lower Missouri River Flood Plain

By Brian P. Kelly

Abstract

In 1998, the U.S. Army Corps of Engineers (USACE) proposed eight Alternative River Management Plans (ARMPs) for managing reservoir levels and water-release rates for the Missouri River. The plans include the Current Water Control Plan (CWCP), Conservation 18, 31, and 44 (C18, C31, and C44) that provide different levels of water conservation in the reservoirs during droughts, Fish and Wildlife 10, 15, and 20 (FW10, FW15, and FW20) that vary water-release rates to provide additional fish and wildlife benefits, and Mississippi River 66 (M66) that maintains a 66,000 cubic feet per second discharge at St. Louis to provide navigation support for the Mississippi River. Releases from Gavin's Point Dam affect both the lower 1,305 kilometers of the Missouri River and ground-water levels in the lower Missouri River flood plain. Changes in the magnitude and timing of ground-water-level fluctuations in response to changes in river management could impact agriculture, urban development, and wetland hydrology along the lower Missouri River flood plain. This study compared simulated ground-water altitude and depth to ground water for the CWCP in the Missouri River alluvial aquifer near the Kansas City area between 1970 and 1980 with each ARMP, determined the average change in simulated ground-water level for selected river-stage flood pulses at selected distances from the river, and compared simulated flood pulse, ground-water responses with actual flood pulse, and ground-water responses measured in wells located at three sites along the lower Missouri River flood plain.

For the model area, the percent total shallow ground-water area (depth to ground water less than 0.3048 meter) is similar for each ARMP because of overall similarities in river flow between ARMPs. The percent total shallow ground-water area for C18 is the most similar to CWCP followed by C31, M66, C44, FW10, FW15, and FW20. ARMPs C18, C31, C44, and M66 do not cause large changes in the percent shallow ground-water area when compared to CWCP. FW10 and FW15 each cause a spring increase and a summer decrease in the shallow ground-water area. FW20 has a larger spring increase in the shallow ground-water area, but the largest decrease is delayed into November. Analysis of daily changes between the ARMPs indicate large differences can exist in both duration and extent of shallow ground-water areas.

A series of 12 flood pulses of 0.5-, 1-, and 3-meters in magnitude and 1-, 8-, 32-, and 128-days in duration were simulated using the ground-water flow model. A ground-water response factor (GWRF, defined as the change in ground-water level at a known distance from the river, at a specified time after the beginning of a flood pulse divided by the magnitude of the flood pulse) was determined daily for selected distances from the river. The GWRF multiplied by the magnitude of the flood pulse can be used to estimate the change in ground-water level at a known time after the beginning of a flood pulse for a known distance

from the river. Flood-pulse simulation results indicate the relatively small impact on ground-water levels of small river-stage fluctuations of short duration as might occur daily or weekly. The larger impact on ground-water levels from larger river-stage increases of longer duration indicate the importance of river management flow releases, seasonal changes in river flow, and the effects of continuous high-river stage for long periods on ground-water levels of the lower Missouri River flood plain.

A comparison of model results to well hydrographs from three areas along the lower Missouri River flood plain was used to determine how closely the simulated GWRFs matched the measured GWRFs for similar flood pulses and the transferability of GWRFs to other parts of the lower Missouri River flood plain. The comparison between the measured and simulated ground-water responses indicate that the simulated ground-water responses can provide a reasonable estimate of the ground-water response to river-stage changes in the lower Missouri River flood plain. The standard deviations of the GWRF can be used to provide a reasonable estimate of the uncertainty caused by different aquifer properties, recharge rates, antecedent conditions, or hydrograph characteristics.

INTRODUCTION

The Missouri River flows through seven states, drains approximately one-sixth of the land mass of the contiguous United States, and, at 3,767 km (kilometers) long, is the longest river in the United States. The U.S. Army Corps of Engineers (USACE) operates a system of six main-stem reservoirs on the upper Missouri River to provide flood control, irrigation, navigation, water supply, hydropower, fish and wildlife, and recreation benefits to the basin by adjusting the amount of water stored and released from the reservoirs.

Releases from Gavin’s Point Dam, the most downstream dam in the system, affect the lower 1,305 km of the Missouri River. The Missouri River flood plain from Gavin’s Point Dam to the mouth at St. Louis, Missouri, is referred to in this report as the lower Missouri River flood plain. The stage of the Missouri River has a direct effect on ground-water levels in the lower Missouri River flood plain. Changes in the magnitude and the timing of ground-water-level fluctuations in response to changes in river management could impact future agricultural productivity, urban development, and wetland hydrology along the lower Missouri River flood plain. In agricultural areas, increases in river stage can cause ground-water levels to rise, and limit surface drainage when levee floodgates are closed. High ground-water levels increase soil moisture and may limit infiltration of rainfall into soils or cause plant stress, thereby limiting crop production. Local rainfall, high ground-water levels, or closed floodgates can singly, or in combination, reduce or prevent access to fields during the planting season. In urban areas, increased hydrostatic pressure in soils caused by high ground-water levels can decrease the ability of soils to accommodate heavy loads and cause roadway or building failure. High ground-water levels also may cause flooding in basements. Water levels in numerous wetland areas of the lower Missouri River flood plain are largely affected by ground-water levels. Ground-water-level fluctuations caused by river-stage changes may alter wetland species habitat by changing the hydroperiods of these wetlands. Knowledge of the effect of river stage on ground-water levels in the Missouri River flood plain will be critical when determining the impact of the various river management plans on agriculture, existing and potential flood plain infrastructure and development, and wetland hydrology.

Background

The Current Water Control Plan (CWCP) for the Missouri River Basin initially was developed in 1960, but the drought from 1987 to 1993 raised concerns about the operation of the Missouri River using this plan. In addition, the floods of 1993 and 1995 drew attention to the problems associated with the management of the lower Missouri River flood plain. The USACE is revising the Missouri River Mainstem System Master Water Control Manual (Master Manual) that describes the Current Water Control Plan in an effort to balance river operations with recent hydrologic conditions within the Missouri River Basin. Rainfall in the basin was normal for the 20 years preceding the drought, and development within the Missouri River Basin had been based on normal inflows into the Missouri River system. Operating the reservoir system to allow navigation along the lower Missouri River during the 1987 to 1993 drought decreased upstream reservoir levels and affected recreation and fishing. The floods of 1993 and 1995 impacted large areas of the flood plain below Gavin's Point Dam. The resulting damage to cropland and urban infrastructure focused attention on flood control and bank stabilization in those areas. These two extremes of flow in the basin and the effect on different areas within the basin illustrate how balancing flood control, irrigation, navigation, water supply, hydropower, fish and wildlife, and recreation interests for the entire basin is difficult because increased benefits to one use may be detrimental to other uses.

In 1994, the USACE released a Draft Environmental Impact Statement (DEIS) that presented a preferred river management alternative (U.S. Army Corps of Engineers, 1994). During the public comment period, additional technical analyses were requested and basinwide efforts began to reach agreement on river management. The next document normally released in the National Environmental Policy Act (NEPA) process is a Revised DEIS (RDEIS) that would identify either the same or another preferred river management plan. Instead, in 1998, the USACE released a Preliminary Revised DEIS (PRDEIS) that proposed eight different river management plans that provided a range of options for managing reservoir levels and water-release rates, and an opportunity for further public comment (U.S. Army Corps of Engineers, 1998).

The plans released in the PRDEIS by the USACE include the CWCP, three plans that provide different levels of water conservation in the reservoirs during droughts (C18, C31, and C44), three plans that vary water-release rates to provide additional fish and wildlife benefits (FW10, FW15, and FW20), and one plan (M66) that maintains a 66,000-ft^3/s (cubic feet per second) discharge at St. Louis to provide navigation support for the Mississippi River (U.S. Army Corps of Engineers, 1998).

The Missouri Department of Natural Resources, Division of Geology and Land Survey (DGLS), the Missouri Levee and Drainage District Association (MLDDA), and the U.S. Geological Survey (USGS) undertook a cooperative study to investigate the effects of the USACE proposed alternative river management plans (ARMP) on ground-water levels in the lower Missouri River flood plain. The study uses an existing ground-water flow model of a selected 80-km reach of the lower Missouri River near Kansas City, Missouri (Kelly, 1996a), to determine ground-water altitude and depth to ground water for all river management plans proposed by the USACE (U.S. Army Corps of Engineers, 1998).

Purpose and Scope

Objectives of this study were to compare simulated ground-water altitude and depth to ground water for the CWCP in the lower Missouri River flood plain near the Kansas City area between 1970 and 1980 with each river management plan proposed by the USACE, determine the average change in simulated ground-water level for selected river-stage flood pulses at selected distances from the river, and compare simulated flood-pulse, ground-water responses with actual flood-pulse, ground-water responses measured in wells located at three sites along the lower Missouri River flood plain.

The purpose of this report is to compare ground-water altitude and depth to ground water in the lower Missouri River flood plain near the Kansas City area for each ARMP with the CWCP. The analysis period is 1970 through 1980, which coincides with the analysis period used by the USACE in their ground-water studies at other locations (U.S. Army Corps of Engineers, 1998). However, ground-water simulation between 1965 and 1969 was used to determine initial conditions for the period of interest between 1970 and 1980, and data from this time are included in this report when necessary. This report also presents a comparison of the average change in ground-water level for selected changes in river stage at selected distances from the river. Finally, the average change in ground-water altitude in response to river-stage change in the modeled area is compared with ground-water level changes, caused by changes in river stage, in wells located at three other areas along the lower Missouri River flood plain. A mathematical relation is described to estimate ground-water-level changes at selected distances from the river caused by river-stage changes.

The International System of Units (SI) is used in this report. However, the ARMPs generally are identified based on inch/pound units of measure. To allow readers to easily identify each ARMP, references to these plans will remain based on the inch/pound system.

Description of Study Area

The study area includes the Missouri River flood plain in the Kansas City metropolitan area and three sites on the Missouri River flood plain near Forest City, Atherton, and Hermann, Missouri. The modeled area covers approximately 475 km^2 (square kilometers), extends from 5 km north of the Leavenworth County-Wyandotte County line in Kansas to 3.75 km east of the Jackson County-Lafayette County line in Missouri, and is bounded by the Missouri River alluvial valley walls on the north and south (fig. 1). The Missouri River flood plain in the model area is underlain by clay, silt, sand, gravel, cobbles, and boulders (Missouri River alluvial aquifer) that overlie shale, limestone, and sandstone bedrock of Pennsylvanian age (Kelly and Blevins, 1995). Grain size generally increases with depth from the uppermost fine-grained clay, silt, and sandy silt deposits, through sand in the middle of the aquifer, to coarser sand and gravel at the base of the aquifer. Generally, ground water flows from the valley walls toward the Missouri River and down the river valley. However, this general pattern of ground-water flow may be altered by local recharge from precipitation, the presence of smaller rivers and streams on the flood plain, drainage ditches, and ground-water pumpage. Depth to ground water is typically greater than 4.5 m (meters).

About two-thirds of the modeled area is row-crop agriculture, and about one-third is industrial. Small parts of the modeled area consist of single and multiple family dwellings, commercial establishments, undeveloped land, and publicly-owned land including airports, sewage and water treatment plants, and parks (Kelly and Blevins, 1995). A more complete description of the hydrology and geology of the modeled area is given in Kelly (1996a).

In November and December 1995 the USGS, in cooperation with the USACE, installed 25 water-level monitoring wells at 3 sites on the Missouri River flood plain to collect information needed to assess the response of ground-water levels to changes in river stage of the Missouri River. Nine wells were installed in Holt County near Forest City, Missouri; eight wells were installed in Jackson County near Atherton, Missouri; and eight wells were installed in Warren and Montgomery Counties near Hermann, Missouri (fig. 2). In a 1997 cooperative study between the USGS and the DGLS, monthly water-level measurements were continued in the 25 monitoring wells.

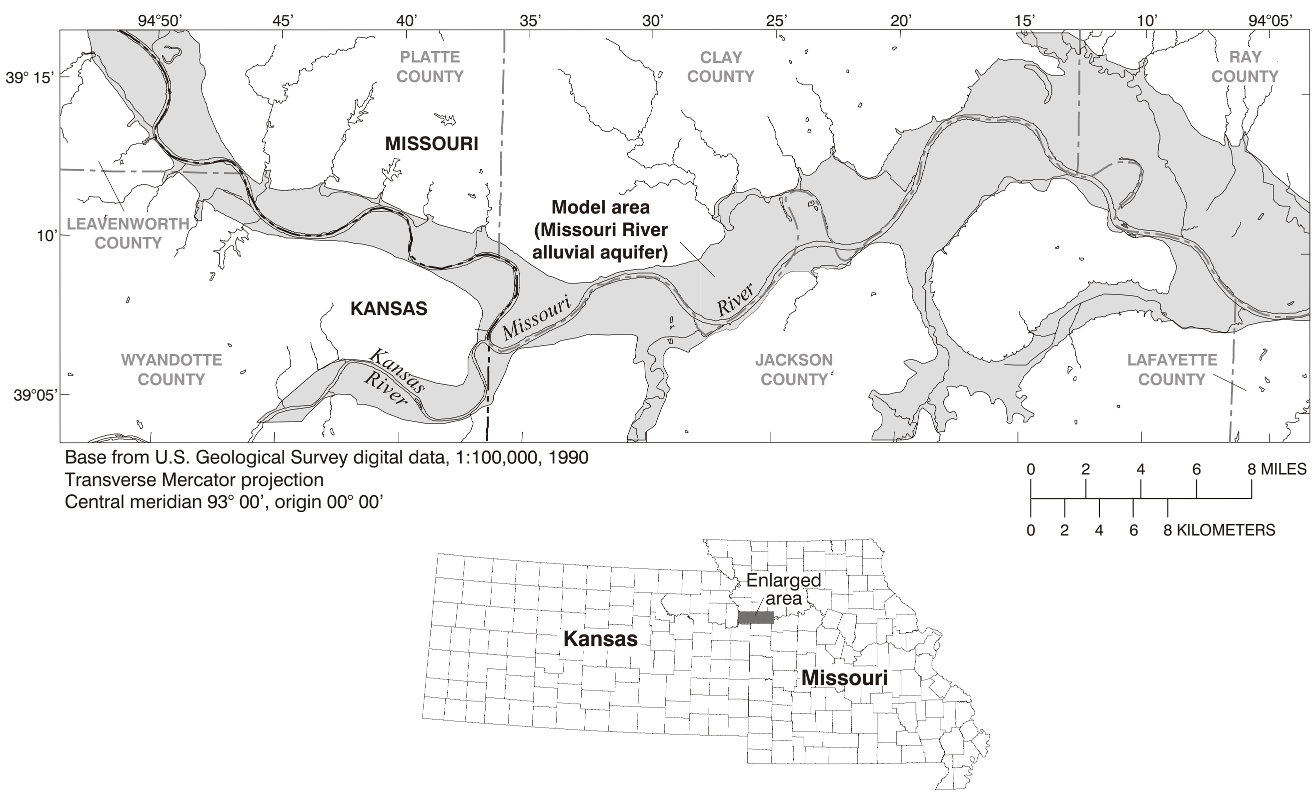

Figure 1. Model area location.

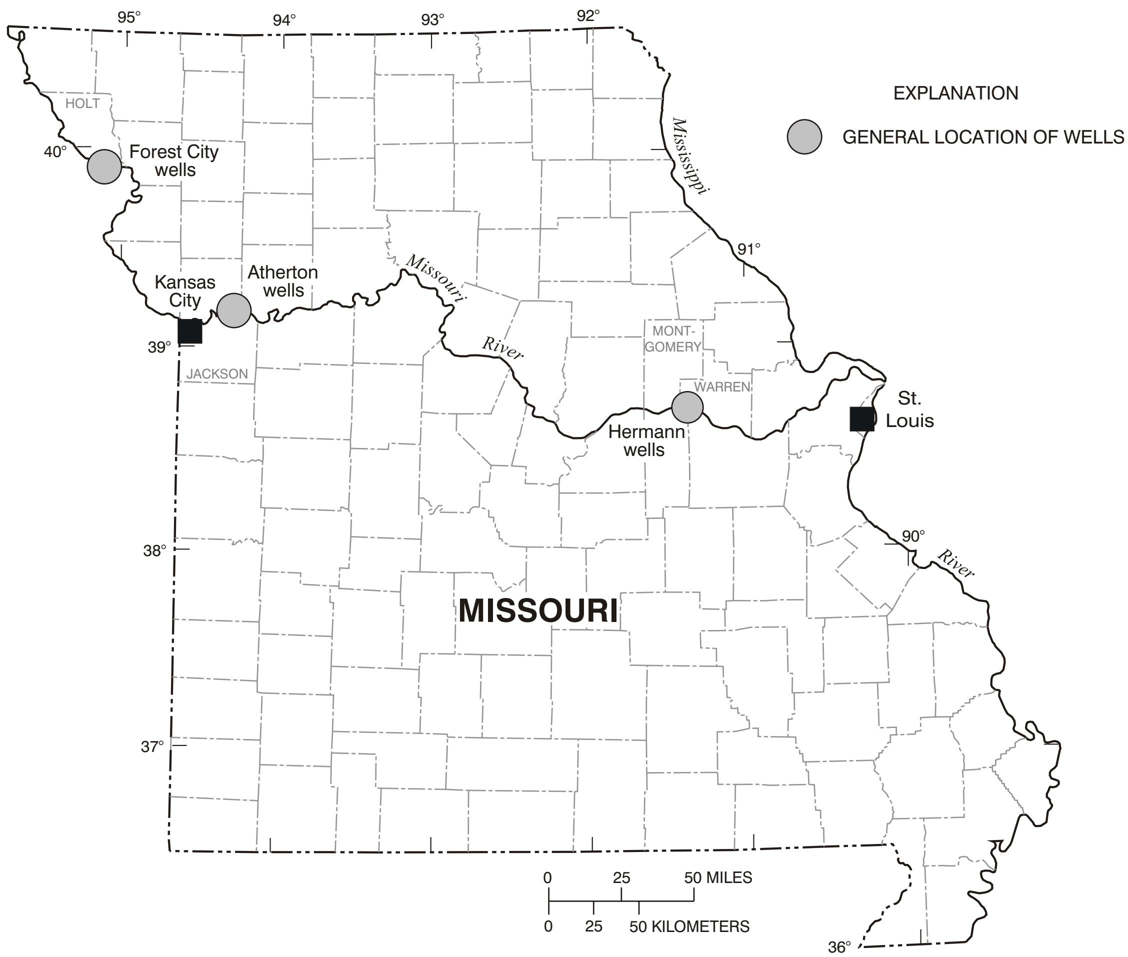

Figure 2. Forest City, Atherton, and Hermann well locations.

Previous and Ongoing Investigations

Detailed descriptions of the geology and aquifer characteristics of the Missouri River flood plain can be found in McCourt and others (1917), K.E. Anderson and F.C. Greene (Missouri Department of Natural Resources, Division of Geology and Land Survey, written commun., 1948), Fischel (1948), Hasan and others (1988), and Gentile and others (1994). Numerous reports on the aquifer characteristics for the Missouri River flood plain (Fischel and others, 1953; Emmett and Jeffery, 1970; Nuzman, 1975; Layne-Western Co., 1978, 1979, 1980, 1981; Crabtree and Older, 1985) have been completed.

Several previous and ongoing investigations of the Missouri River flood plain have added to knowledge of the interaction of river stage and ground-water levels. In a cooperative study between the USGS and the Mid-America Regional Council, a geographic information system (GIS) containing hydrogeologic data for more than 1,400 locations within the Kansas City metropolitan area was interfaced with the ground-water flow model MODFLOWARC (Orzol and Mcgrath, 1992) and the particle-tracking program MODPATH (Pollock, 1994) to determine the contributing recharge areas for 11 public-water-supply well fields and numerous industrial wells (Kelly and Blevins, 1995; Kelly, 1996a). In 1995, the GIS, ground-water flow model, and particle-tracking program were used by the USGS in cooperation with the City of Independence, Missouri, to recalculate the contributing recharge area and aid in the design of a monitoring well network for an expanded Independence well field (Kelly, 1996b).

The combined use of the GIS, MODFLOWARC, and MODPATH has proven to be a powerful and versatile method for analysis and management of ground-water resources of the Missouri River flood plain in the Kansas City metropolitan area. The modeled area represents a selected 80-km reach of the lower Missouri River flood plain containing agricultural, urban, and wetland areas. Hydrogeologic data and results from these recent studies of the Missouri River flood plain provide the regional background and description of the ground-water flow simulation for the model analyses presented in this report.

A related study on the economic impacts of ground-water-level fluctuations on agricultural production has been completed by the Food and Agricultural Policy Research Institute (1999) (FAPRI). That study takes crop production data from several farms in the modeled area and combines them into a "representative farm" typical of those located in the lower Missouri River flood plain. Model-derived ground-water levels and depth to ground water for each field in the representative farm were provided by the USGS to FAPRI for the 1970 to 1980 period. These data were used to help determine the access, type of crop planted, plant stress, growth rates, and planting times for each field. Once determined, these data were put into an economic model that calculated economic impacts on the representative farm for each ARMP.

ALTERNATIVE RIVER MANAGEMENT PLANS

The eight ARMPs proposed by the USACE (1998) include three conservation alternatives, three fish and wildlife alternatives, one alternative to target flow from the Missouri into the Mississippi River, and the CWCP. A description of each ARMP is summarized in table 1.

The permanent pool level is maintained for hydroelectric power generation. A permanent pool below 18 million acre feet prevents efficient hydroelectric power generation and a permanent pool above 44 million acre feet was not desired by the public (U.S. Army Corps of Engineers, 1998). Non-navigation service levels are specified primarily to protect water supply intakes on the lower Missouri River below Gavin's Point Dam. At discharges below 9,000 ft^3/s, river stage is too low for water supply intakes when tributary inflow on the lower Missouri River also is low. Navigation guide curves indicate support for navigation on the lower Missouri River. Generally, the higher the guide curve, the less navigation support, and the more conservation of water within the reservoir system during drought. Higher spring and summer releases are part of the fish and wildlife ARMPs. These releases are designed to more closely emulate the natural river hydrograph. The higher releases are provided unless navigation service cutbacks or flood control constraints decrease release rates. Flood control constraints are increased by the spring and summer release targets indicated for each fish and wildlife plan.

Table 1. Summary of the eight Alternative River Management Plans

[ARMP, Alternative River Management Plans; ft^3/s, cubic feet per second; CWCP, Current Water Control Plan; modified from Table 1, Summary of the Preliminary RDEIS, U.S. Army Corps of Engineers, 1998]

ARMP	Permanent pool level (millions of acre feet)	Non-navigation service level (1,000 ft^3/s)			Navigation guide curves	Higher spring/summer releases than CWCP (1,000 ft^3/s)	Mississippi River target
		Winter	Spring/Fall	Summer			
CWCP	18	12	9	9	Current	0	No
C18	18	12	9	18	Current	0	No
C31	31	12	9	18	Intermediate	0	No
C44	44	12	9	18	High	0	No
FW10	31	12	9	18	Intermediate	10	No
FW15	31	12	9	18	Intermediate	15	No
FW20	18	12	9	9	High	20	No
M66	18	12	9	18	Current	0	Yes

Water-Release Effects on the Lower Missouri River

Water released from Gavin's Point Dam affects flow in the lower Missouri River from the dam to the mouth at St. Louis. However, tributary inflow to the Missouri River below Gavin's Point Dam progressively increases in a downstream direction, and the water released from Gavin's Point Dam becomes a smaller part of total flow in the river. This results in a decreased impact on river flow of any release at Gavin's Point Dam as each downstream tributary contributes to total Missouri River flow. The average ratio of Gavin's Point Dam discharge to average discharge at selected USGS gaging stations on the lower Missouri River and at St. Louis on the Mississippi River below the mouth of the Missouri River between 1965 and 1980 is shown in table 2.

The stage at each gaging station is a function of discharge and channel geometry. Generally, stage increases as discharge increases. However, a narrow channel will have a larger stage increase than a wide channel with the same increase in discharge. Because changes in river stage are controlled by changes in river discharge, river stage effects from water releases at Gavin's Point Dam also decrease downstream. For example, assuming average annual discharge at each gaging station, a 10,000-ft^3/s increase in discharge from Gavin's Point Dam will cause a progressively smaller stage increase in the downstream direction. This relation for selected USGS gaging stations on the lower Missouri River for hypothetical 10,000- and 20,000-ft^3/s releases from Gavin's Point Dam is summarized in table 3. Slight variations in the general trend are caused by different channel geometries between stations.

River-Stage Data

Simulated daily Missouri River flow data for 1965 to 1980 for each ARMP was supplied by the USACE for the USGS gaging station at Kansas City and converted to stage data using the current rating table for that gaging station. The USGS maintains a current rating table by regularly measuring discharge and stage concurrently at the gaging station. Local stage information was converted to river stage in meters above sea level.

A description of river stage at Kansas City for each plan is shown in table 4 and includes the 0.1, 0.25, 0.5, 0.75, and 0.9 percentiles, the maximum, the minimum, the average, and the standard deviation. Percentiles for river stage indicate the fraction of time the river is below a certain stage. For example, for the 0.1 percentile, river stage was below this value 10 percent of the time and above this value 90 percent of the time. Maximum and minimum river stages are almost identical for each plan because of the extremes of flooding in late 1973 and low river stage of early 1977. Average

Table 2. U.S. Geological Survey gaging station, river mile, and ratio of average daily discharge for Gavin's Point Dam to average daily discharge at U.S. Geological Survey gaging station between 1965 and 1980

[USGS, U.S. Geological Survey]

USGS gaging station	Missouri River mile at gaging station	Ratio of average daily discharge at Gavin's Point Dam to average daily discharge at USGS gaging station between 1965 and 1980
Sioux City, Iowa	732.2	0.923
Omaha, Nebraska	615.9	.882
Nebraska City, Nebraska	562.6	.774
St. Joseph, Missouri	448.2	.707
Kansas City, Missouri (within modeled area)	366.1	.634
Boonville, Missouri	196.6	.567
Hermann, Missouri	97.9	.473
St. Louis, Missouri (Mississippi River)	15 miles downstream of the mouth of the Missouri River	.207

Table 3. U.S. Geological Survey gaging station, river mile, average annual discharge, and stage increase from 10,000- and 20,000-cubic feet per second releases at Gavin's Point Dam

[ft^3/s, cubic feet per second; ft, feet]

USGS gaging station	Missouri River mile	Average annual discharge (ft^3/s)	Stage increase from 10,000-ft^3/s release at Gavin's Point Dam (ft)	Stage increase from 20,000-ft^3/s release at Gavin's Point Dam (ft)
Sioux City, Iowa	732.2	31,500	2.39	4.50
Omaha, Nebraska	615.9	37,400	2.0	3.66
Nebraska City, Nebraska	562.6	46,000	2.08	3.99
St. Joseph, Missouri	448.2	51,100	1.8	3.46
Kansas City, Missouri	366.1	65,100	1.78	3.46
Boonville, Missouri	196.6	85,500	1.01	2.08
Hermann, Missouri	97.9	116,000	.83	1.66
Mississippi River at St. Louis, Missouri	15 miles downstream of Missouri River	280,000	.71	1.43

river stage is almost identical for all plans because the same total amount of water is released for each plan. An increase in water released during one part of the year is offset by a decrease in water released in another part of the year. The standard deviation of river stage indicates the variability of river stage for each plan.The least variable river stages are associated with M66; the most variable river stages are associated with FW20. Daily river stage at Kansas City between 1965 and 1980 for CWCP and FW20 (fig. 3) illustrate the overall similarity of the hydrographs with respect to the timing and magnitude of peak flow.

Table 4. Data pertaining to daily river stage between 1965 and 1980 for each Alternative River Management Plan at Kansas City, Missouri

[All stages are in meters above sea level; ARMP, Alternative River Management Plan]

ARMP	River stage at indicated percentile					Maximum stage	Minimum stage	Average stage	Standard deviation of stage
	0.1	0.25	0.5	0.75	0.9				
CWC	217.93	218.66	219.24	220.22	221.19	227.47	216.16	219.47	1.40
C18	217.93	218.66	219.21	220.22	221.22	227.47	216.16	219.47	1.40
C31	217.93	218.6	219.21	220.22	221.22	227.47	216.16	219.48	1.40
C44	217.9	218.48	219.21	220.28	221.28	227.47	216.16	219.47	1.46
FW10	218.05	218.54	219.18	220.22	221.25	227.47	216.53	219.47	1.40
FW15	218.05	218.51	219.18	220.22	221.25	227.47	216.5	219.47	1.41
FW20	217.76	218.36	219.33	220.31	221.28	227.47	216.16	219.47	1.52
M66	217.96	218.66	219.21	220.16	221.16	227.47	216.26	219.46	1.38

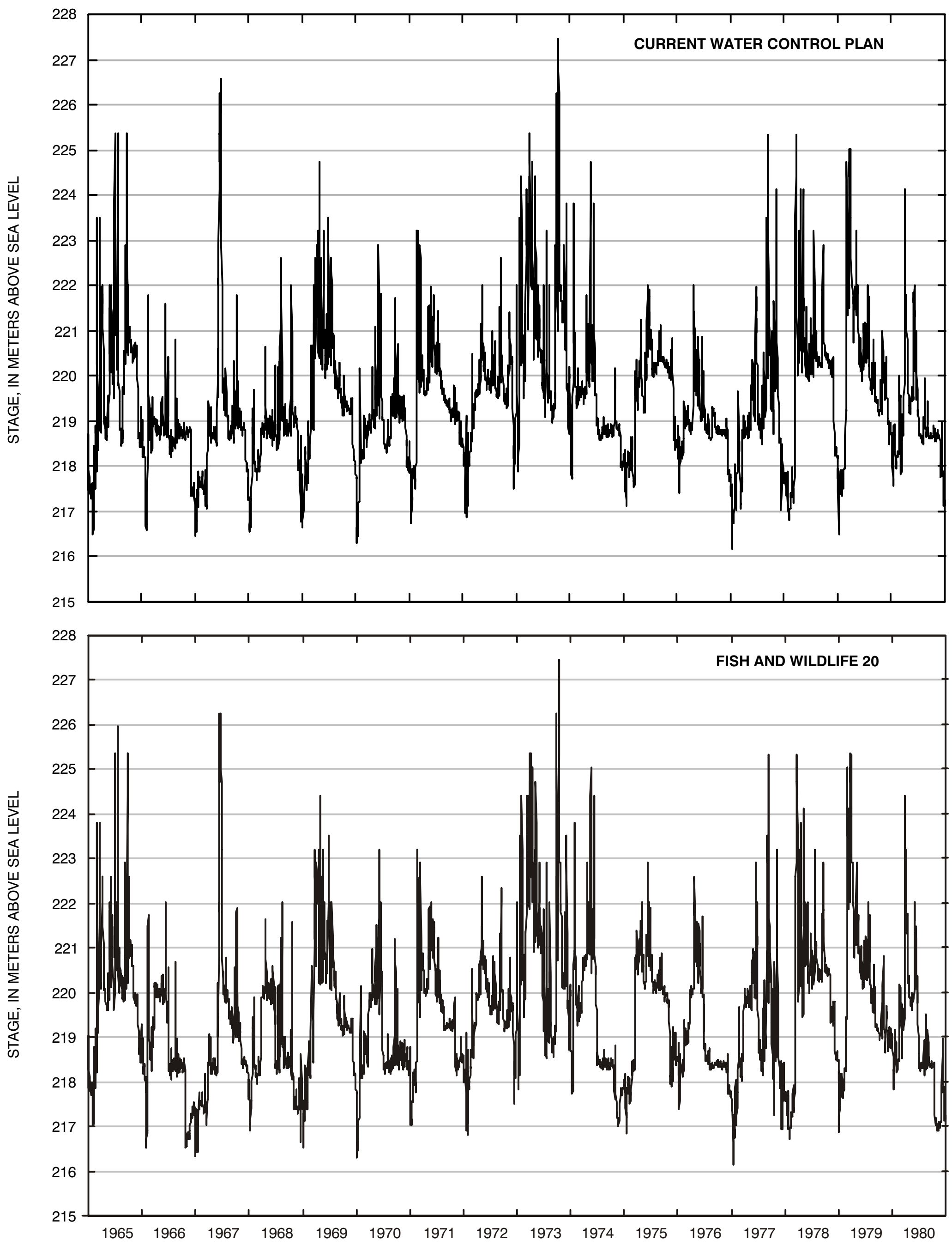

Figure 3. Missouri River stage at Kansas City, Missouri, 1965–80.

Comparison of Daily River Stages

A statistical summary of daily differences in Missouri River stage at Kansas City for C18, C31, C44, FW10, FW15, FW20, and M66 with respect to CWCP between 1965 and 1980 is shown in table 5. As indicated by the standard deviation of the daily difference of each plan to the CWCP, C18 is the most similar followed by C31, M66, C44, FW10, FW15, and FW20 as the least similar. The daily difference in river stage with respect to CWCP at Kansas City between 1970 and 1980 is shown for C18, C31, C44, FW10, FW15, FW20, and M66 in figure 4.

Table 5. Data pertaining to daily river stage differences between each Alternative River Management Plan and the Current Water Control Plan at Kansas City, Missouri, 1965–80

[All stages are in meters above sea level; ARMP, Alternative River Management Plan; CWCP, Current Water Control Plan]

	ARMP river stage minus CWCP river stage			
ARMP	**Maximum daily difference**	**Minimum daily difference**	**Average daily difference**	**Standard deviation of the daily difference**
C18	0.46	-0.58	0.0003	0.0527
C31	1.37	-.58	.00804	.12487
C44	1.62	-1.98	.0067	.33244
F10	1.22	-2.05	.00004	.40159
F15	1.22	-2.05	.00074	.43268
F20	1.65	-2.19	.00243	.56548
M66	.52	-1.03	.01357	.13132

EFFECTS OF ALTERNATIVE MANAGEMENT PLANS ON GROUND-WATER LEVELS

Simulation of Ground-Water Flow

Ground-water flow was simulated using the three-dimensional finite-difference ground-water flow model MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). This model was calibrated to transient and steady-state conditions during a previous study of the Missouri River flood plain (Kelly, 1996a) that determined ground-water flow and the contributing recharge areas around public water-supply well fields for various pumping rates and river stages. Although a detailed description of the model is given in Kelly (1996a), a brief description of the model follows.

The model uses uniform cell areas of 150 by 150 m and contains 310,400 cells in 160 rows, 485 columns, and 4 layers. Layer 1 corresponds to the upper part of the aquifer where clay, silt and fine-grained sand are dominant. Layers 2 and 3 correspond to the middle part of the aquifer where sand and gravelly-sand are dominant. Layer 4 corresponds to the deep parts of the aquifer where gravel and sandy gravel are present. Unconfined ground-water flow was simulated in layer 1, and confined ground-water flow was simulated in layers 2, 3, and 4.

The bedrock was simulated as a no-flow boundary because its hydraulic conductivity is several orders of magnitude less than the hydraulic conductivity of the alluvial aquifer. The channel bottoms of the Missouri and Kansas Rivers were simulated in layer 2 of the model because they intersect the sand and gravel that correspond to layer 2. The bottoms of the smaller rivers were simulated in layer 1. Small streams and drainage ditches were simulated in the model as drains that receive water from the aquifer but do not supply water to the aquifer.

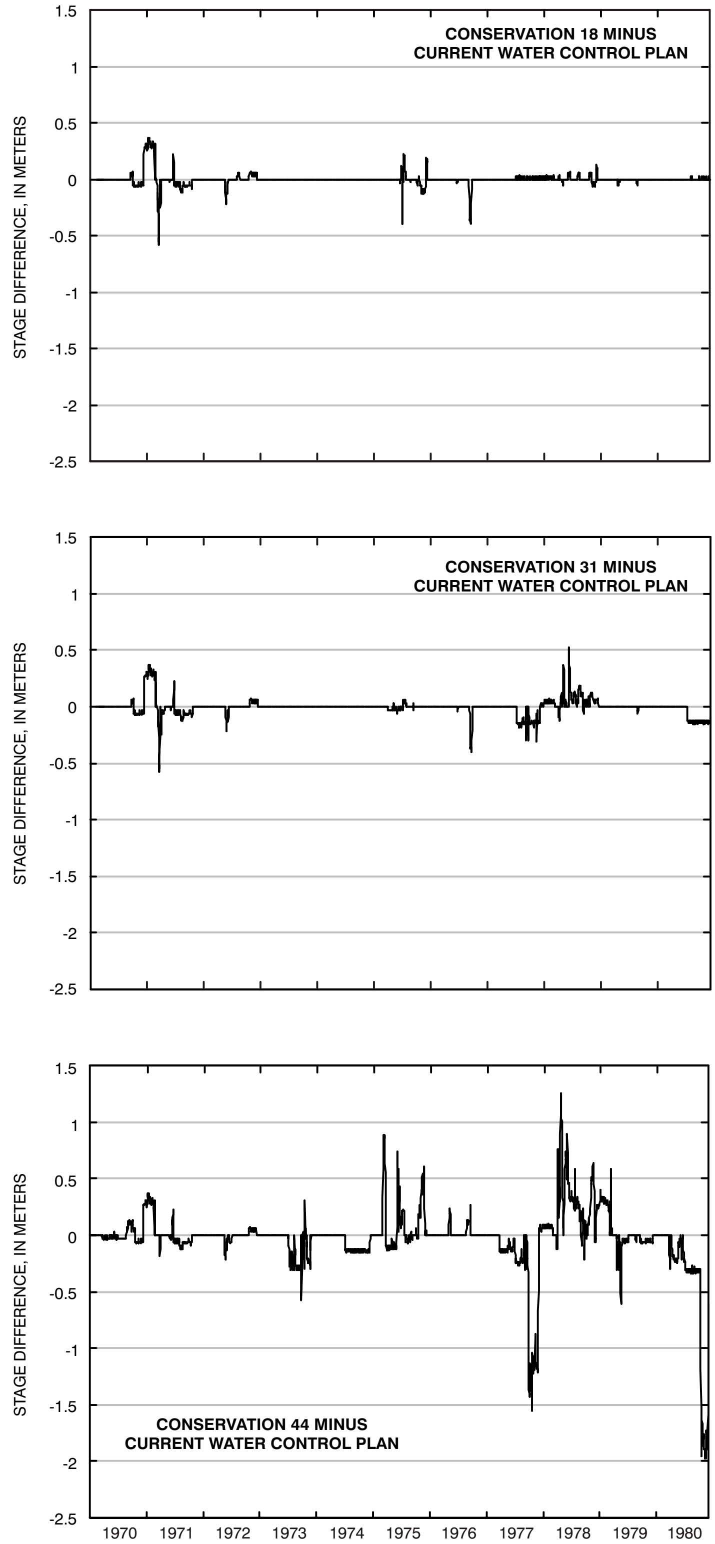

Figure 4. Daily difference in river stage between each Alternative River Management Plan and the Current Water Control Plan at Kansas City, Missouri, 1970–80.

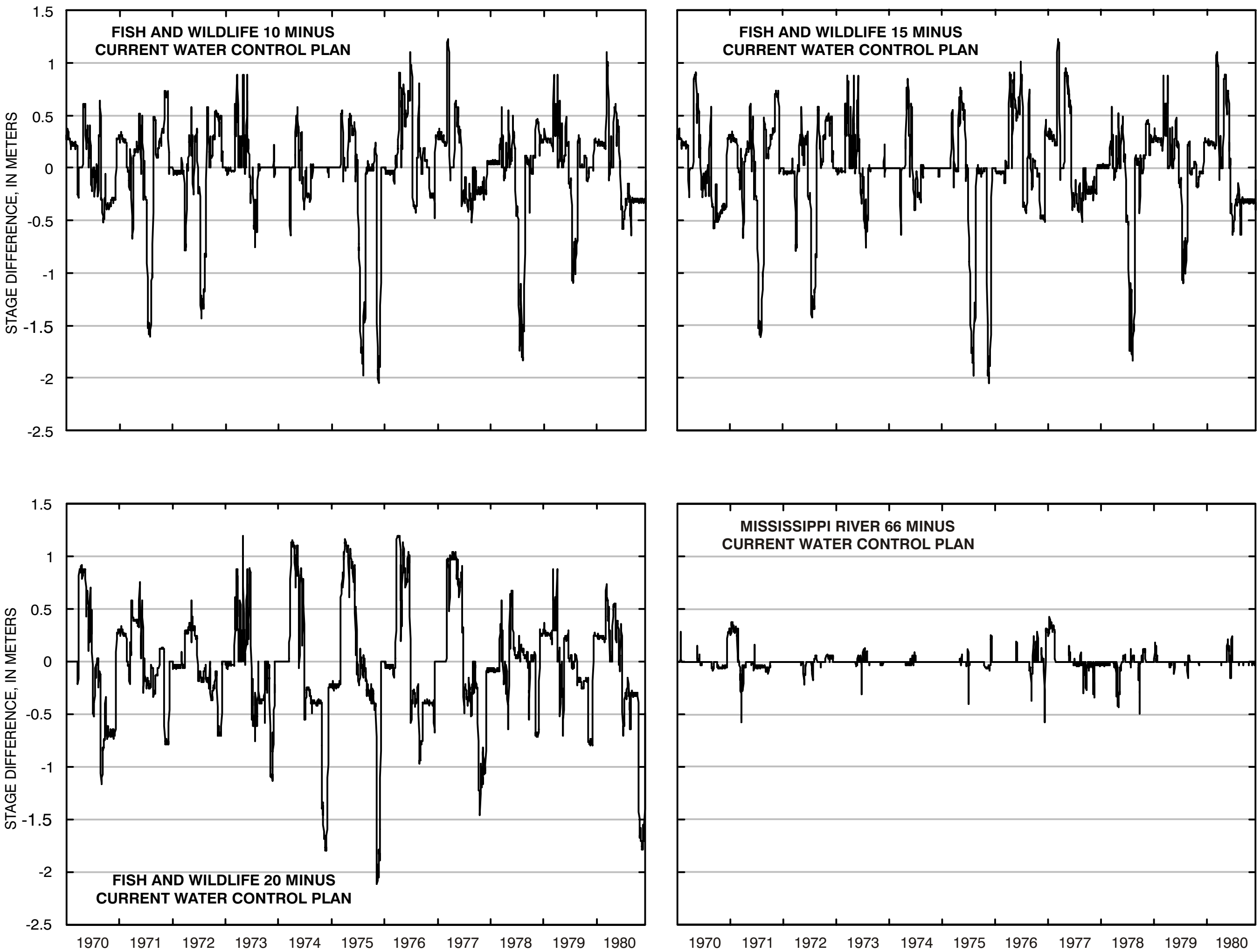

Figure 4. Daily difference in river stage between each Alternative River Management Plan and the Current Water Control Plan at Kansas City, Missouri, 1970–80—Continued.

A steady-state calibration was performed using quasi-steady-state hydraulic head data from a January 1993 synoptic water-level measurement of 155 wells. River stage, precipitation rate, and well pumping are variable with time, and true steady-state conditions probably never exist in the modeled area. A transient calibration used hydraulic-head data collected during the August 1993 flood, and synoptic water-level measurements from 123 wells in October 1993 and from 98 wells in February 1994.

Available information and the steady-state calibration were used to obtain initial estimates of model parameters. The more rigorous transient calibration was used to refine the model parameters using conditions from a period of prolonged aquifer drainage after the August 1993 flood to February 1994, when river stage and ground-water levels had approached typical conditions for that time of year. The root mean square error in simulated hydraulic head was 1.15 m for the steady-state calibration, 0.71m for October 1993 in the transient calibration, and 0.8 m for February 1994 in the transient calibration. A sensitivity analysis indicated the model is most sensitive to changes in hydraulic conductivity values and least sensitive to decreases in vertical conductance between layers 1 and 2 and to increases in riverbed conductance.

Transient Ground-Water Flow

For this study, transient ground-water flow was simulated between 1965 and 1980 for each ARMP. The ground-water studies conducted for the USACE PRDEIS analyzed the period from October 1970 to

September 1979. Approximately the same period of time was chosen for this study because flow conditions along the lower Missouri River were near normal, but still included both high- and low-flow conditions. Steady-state conditions probably never occur in this alluvial ground-water flow system. However, a dynamic equilibrium may be reached in which the seasonal response of ground-water levels to variations in river stage and rainfall are not affected by initial conditions. Therefore, simulation of ground-water flow from 1965 to 1969 was included to minimize any effects starting conditions might have had on model results between 1970 and 1980.

Transient ground-water flow is implemented in a ground-water flow model through the use of stress periods. Each stress period represents a unit of simulation time where all hydrologic variables are constant. A change in the amount of water entering or leaving the system is referred to as a stress on the flow system. Changes in hydrologic conditions, such as fluctuating river stage, are simulated by using a sequence of stress periods, each with a different set of hydrologic conditions as model input. For example, to simulate transient ground-water flow in response to a river stage increase of 2 m over a 10-day period, 5, 2-day stress periods could be used where river stage increases by 0.4 m between each stress period.

River-Stage Data

River-stage data for all model river cells were related to river stage at the Kansas City gaging station. Missouri River stage was concurrently measured during previous studies (Kelly and Blevins, 1995; Kelly, 1996a) at the USGS gaging station at St. Joseph; the Nearman Power Plant water intake in Kansas City, Kansas; the Kansas City Water Department intake in North Kansas City, Missouri; the USGS gaging station at Kansas City; the Kansas City Power and Light - Hawthorne Power Plant water intake; the Missouri Public Service Power Plant water intake at Sibley, Missouri; and the USACE stage gage at Napoleon, Missouri. Other gages within the model area include the USACE stage gage on the Kansas River at 23rd St. in Kansas City, Kansas; the USGS gaging station on the Blue River at 12th St.; and the USGS gaging station on the Little Blue River near Lake City. The average difference in stage at each gage on the Missouri River with respect to the Kansas City gaging station was calculated from concurrent river-stage data. The average slope was calculated between gages on the Missouri River, and the average difference in river stage at the mouth of each tributary with respect to river stage at the Kansas City gaging station was calculated. This relation was used to assign river stage for each river cell in the model for each stress period.

For the ground-water flow simulations in this study, a new stress period was assigned when river stage changed at least 0.5 m, or when 10 days of simulation time had elapsed. For example, if river stage was 210.5 m on day 1, 210.8 m on day 2, and 211.2 m on day 3, the change in river stage for the 3 days would be 0.7 m. Therefore, the stress period would be 3 days in length. River stage for this 3-day stress period would be the average of the river stages for the 3 days (210.83 m). This criterion ensured that the ground-water level response to all significant river-stage changes would be simulated and the ground-water level response to long periods of relatively constant river stage would be calculated and recorded at least every 10 days. The total number of stress periods and the number of 1-, 2-, 3-, 4-, 5-, 6-, 7-, 8-, 9-, and 10-day stress periods for each ARMP simulation are listed in table 6. Differences in the total number and lengths of stress periods are caused by differences in river flow between each ARMP.

Rainfall and Well Pumping Data

Rainfall data from the National Oceanic and Atmospheric Administration (NOAA) was recorded daily at Kansas City Municipal Airport and at Kansas City International Airport. Rainfall data from 1965 to 1980 (NOAA, 1999) were used in the ground-water flow model simulation (fig. 5). Rainfall data from the Kansas City Municipal Airport, located in the middle of the modeled area, were the primary data. Any gaps in the data were supplemented with rainfall data from the Kansas City International Airport located north of the modeled area. Daily rainfall to the model area was calculated by dividing the total rainfall for each stress period by the number of days within the stress period. That average for the stress period was applied to each day of the stress period. Rainfall provides recharge to the ground-water flow system. Simulated recharge was assumed to be 20 percent of the rainfall and then adjusted to account for variations in the vertical permeability of the soil (Kelly, 1996a). Daily pumping rates for all wells and well fields in the simulation were derived from average annual rates (Kelly, 1996a).

Table 6. Numbers of stress periods between 1965 and 1980 for each Alternative River Management Plan ground-water simulation

[ARMP, Alternative River Management Plans]

ARMP	Total number of stress periods	Distribution of stress periods by length									
		1 day	2 day	3 day	4 day	5 day	6 day	7 day	8 day	9 day	10 day
CWC	1,204	275	218	114	80	59	46	38	36	31	307
C18	1,205	277	220	109	83	58	44	38	39	31	306
C31	1,202	276	224	105	81	60	42	37	34	29	314
C44	1,194	270	218	107	87	58	41	36	29	28	320
FW10	1,203	286	217	105	77	59	38	37	44	30	310
FW15	1,195	274	221	104	75	67	31	43	38	27	315
FW20	1,200	284	206	129	72	46	43	34	44	22	320
M66	1,203	276	221	102	85	63	46	36	37	26	311

Ground-Water Simulation Results

Results from the ground-water simulations include ground-water altitude for each cell in the model for each stress period of each simulation. These data can be readily mapped for each stress period of each simulation. However, interpretation and presentation of model results by comparing ground-water-level maps would be difficult at best. To present study results that are readily interpreted, ground-water altitude data were extracted from the GIS database for each stress period of each simulation. These data describe how ground-water altitude in the modeled area, as a whole, responds to changes in river management.

Depth to Ground Water

Shallow depth to ground water impacts many human activities and natural ecosystems in the lower Missouri River flood plain. Ground-water depth less than 0.3048 m (1 ft), referred to as shallow ground water for the remainder of this discussion, is a convenient indicator of the impact of high ground-water level on the flood plain because ground water at this shallow depth can prevent access to fields, cause plant stress to crops, may decrease load capacities of flood-plain roads, and can help create wetland habitat. Using the GIS, model-generated ground-water altitudes for each model cell were subtracted from land-surface altitudes derived from USGS 30-m Digital Elevation Maps (DEM) to calculate the depth to ground water for each stress period of each simulation. Each model cell is 150 m on a side (22,500 m^2). The number of active model cells for layer 1 is 20,835, and the total model area is 46,879 hectares. The calculated depth-to-ground-water data were interpolated onto a grid with cells 75 m on a side (5,625 m^2). The number of cells with a depth-to-ground-water value less than 0.3048 m (1 ft) was summed for each stress period of each ARMP simulation to obtain the model area with shallow ground water. This value was divided by the total active model area to obtain the percent of shallow ground-water area in the total active model area for each stress period of each simulation. The use of the absolute value of the percent shallow ground-water area for each simulation is limited. Several sources of error exist both within the model results and within the DEM data that may add to or subtract from the calculated value of the percent shallow ground-water area. However, by comparing how the shallow ground-water area changes between each ARMP, a better understanding of the impact of each ARMP on shallow ground water can be attained. The percent shallow ground-water area for each simulation is similar because of overall similarities in the river flow between ARMPs. The percent of the model area with shallow ground water between 1970 and 1980 is shown in figure 6 for the CWCP and FW20 to illustrate the similarity between ARMPs with the greatest difference in flow releases. The most notable increase in the shallow ground-water area was during the flood of 1973, when about 25 percent of the modeled area was under shallow ground-water conditions for all ARMPs.

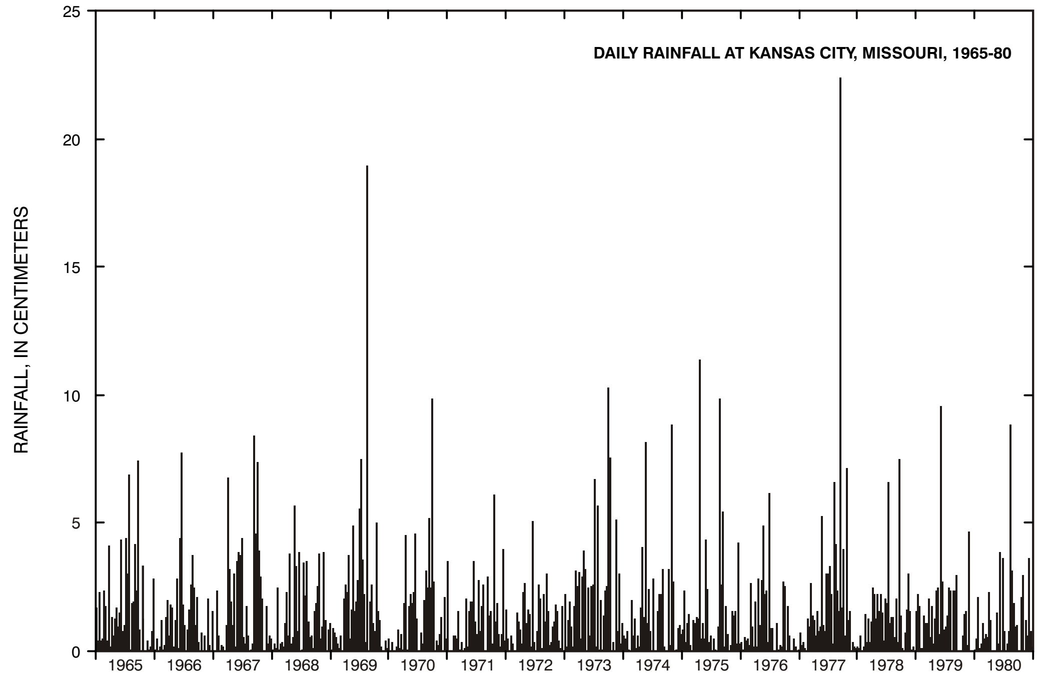

Figure 5. Daily rainfall at Kansas City, Missouri, 1965–80.

The shallow ground-water area and the average number of days during which shallow ground-water conditions exist for any given month are shown for the CWCP and the ARMPs in table 7. The total area of shallow ground-water was divided into intervals for each day of each simulation. The 11-year (1970–1980) average number of days during which each interval of shallow ground-water area existed for each month of each ARMP simulation was then determined. These data are useful for assessing the differences between each ARMP and the CWCP with respect to the number of days per month during which areas of shallow ground water are present. For example, 4 percent of the model area had shallow ground-water conditions for an average of 7.4 days in May for the CWCP but for the F20 plan 4 percent of the model area had shallow ground-water conditions for an average of 10.4 days in May.

Change in Depth to Ground Water for each ARMP

By using the CWCP as a baseline for comparison with model results of each proposed ARMP, a better understanding of how each plan affects depth to ground water can be obtained. The area of shallow ground water was calculated for each stress period of each simulation as described above. Because the length and distribution of stress periods for each simulation was different, each day of a stress period within a simulation was assigned the shallow ground-water area for that stress period. The daily shallow ground-water area for the CWCP was then subtracted from the daily shallow ground-water area for each ARMP to allow a daily comparison of shallow ground-water areas between simulations. A statistical summary of daily differences in shallow ground-water area for C18, C31, C44, FW10, FW15, FW20, and M66 compared to CWCP between 1970 and 1980 is shown in table 8. The standard deviation of the difference between the ARMP and the CWCP show that C18 is the most similar followed by C31, M66, C44, FW10, FW15, and FW20 as the least similar. This follows the same trend as that indicated for daily river stage shown previously in table 5. Daily changes during 1970 to 1980 in the percent shallow ground water in the model area for C18, C31, C44, FW10, FW15, FW20, and M66, are shown on figure 7.

The change in shallow ground-water area and the average number of days per month during which the change in shallow ground-water conditions existed are shown for each ARMP in table 9. The total area of shallow ground-water was divided into intervals for each day of each ARMP simulation. The 11-year (1970–1980) average number of days per month during which each interval of shallow ground-water area existed for each

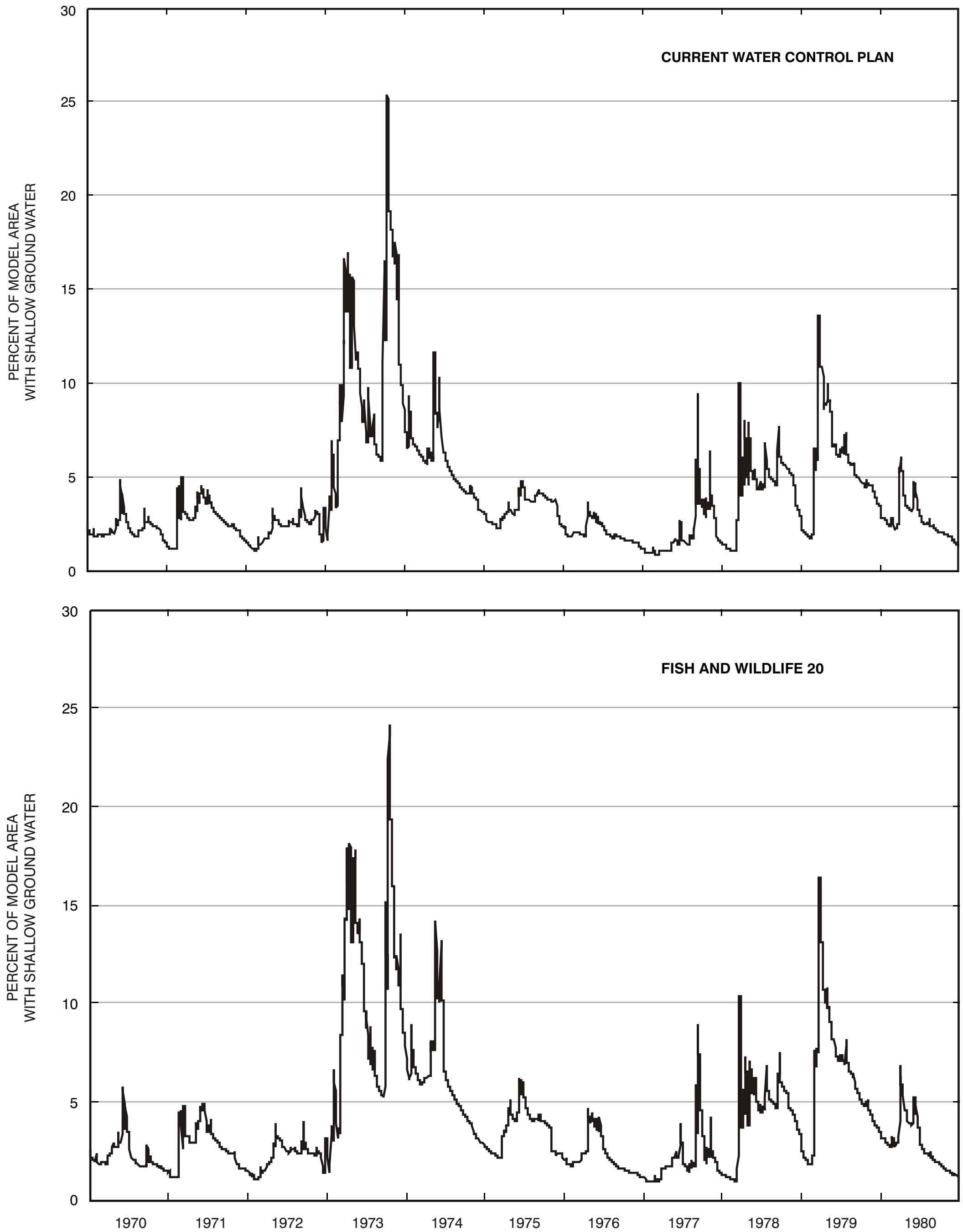

Figure 6. Percentage of model area with shallow ground water for the Current Water Control Plan and the Fish and Wildlife 20 Plan, 1970–80.

Table 7. Average number of days per month for each shallow ground-water area for the Current Water Control Plan and each Alternative River Management Plan (1970–80)

Area of shallow ground water, (in percent)	Average number of days											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
					CWCP							
1	1.5	2.0	1.9									
2	14.5	14.0	9.2	7.6	3.2	1.7	2.9	7.5	2.7	3.5	5.5	13.8
3	8.9	6.5	8.3	5.8	8.9	6.6	10.8	7.0	9.1	11.5	7.0	4.8
4	3.2	1.0	1.8	3.4	7.4	6.3	4.4	5.1	2.0	4.4	7.3	8.2
5	.1	1.6	.7	1.9	1.0	6.8	3.5	3.5	8.5	6.0	4.5	1.1
7.5	1.6	2.8	5.3	5.6	4.4	4.3	7.8	7.1	6.5	2.8	3.0	.3
10	1.2	.4	1.9	1.5	2.7	3.4	1.5	.7	.8			1.3
12.5			.7	1.6	2.3	.9			.1	.5		.7
15			1.2	1.0	.7					.4		.5
17.5				1.5	.5				.3	.2	2.0	.4
20										1.1	.7	
22.5										.1		
25										.5		
27.5										.2		
					C18							
1	1.5	2.0	1.9									
2	13.1	14.0	9.2	7.6	2.8	1.7	2.6	7.2	2.7	3.5	5.5	14.0
3	10.3	6.5	9.5	6.4	9.0	6.5	11.1	7.4	9.1	10.8	6.9	4.5
4	3.0	1.0	.5	2.8	7.6	5.6	4.3	5.2	2.3	5.0	6.8	8.3
5	.3	1.6	1.1	2.3	1.3	7.6	3.6	2.5	8.2	6.0	5.5	1.4
7.5	1.6	2.8	4.9	5.4	4.1	4.3	7.8	8.0	6.4	2.8	2.6	
10	1.2	.4	2.2	1.5	2.7	3.4	1.5	.7	1.0			1.3
12.5			.5	1.6	2.3	.9			.1	.5		.7
15			1.2	1.1	.7					.4		.5
17.5				1.4	.5				.3	.2	2.2	.4
20										1.1	.5	
22.5										.1		
25										.5		
27.5										.2		

Table 7. Average number of days per month for each shallow ground-water area for the Current Water Control Plan and each Alternative River Management Plan (1970–80)–Continued

Area of shallow ground water, (in percent)	Average number of days											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
					C31							
1	1.5	2.0	1.9									
2	12.9	13.3	6.8	6.9	2.8	1.7	2.5	7.0	2.7	5.4	5.5	14.2
3	10.1	7.2	11.5	8.0	9.5	6.5	11.3	7.5	9.1	9.6	6.9	4.0
4	3.4	1.0	1.0	2.7	7.2	5.6	4.4	5.1	2.0	4.4	7.5	8.6
5	.3	1.6	.8	1.1	.7	7.5	3.5	1.5	8.8	6.0	4.5	1.1
7.5	1.6	2.8	5.2	5.7	4.6	4.5	7.8	9.2	6.2	2.8	3.0	.3
10	1.2	.4	2.2	1.5	2.6	3.4	1.5	.7	.8			1.3
12.5			.5	1.6	2.4	.9			.1	.5		.7
15			1.2	1.1	.7					.4		.5
17.5				1.4	.5				.3	.2	2.0	.4
20										1.1	.7	
22.5										.1		
25										.5		
27.5										.2		
					C44							
1	0.5	4.4	3.5	0.2								
2	12.3	10.1	5.9	6.9	2.8	1.7	2.8	6.7	4.1	6.8	6.5	13.7
3	12.6	8.0	9.4	7.1	8.1	6.5	11.3	7.8	7.7	10.1	8.1	4.7
4	2.5	1.0	2.5	3.5	8.3	5.5	3.1	4.5	2.4	2.3	3.9	8.4
5	.3	1.6	.8	1.1	.5	4.3	2.9	3.5	6.7	6.2	6.1	1.1
7.5	1.6	2.8	5.5	4.6	4.2	8.0	8.9	8.3	8.2	2.8	2.7	.3
10	1.2	.4	1.8	2.5	3.5	3.1	2.0	.2	.6			1.3
12.5			.5	1.6	2.5	.8				.5		.7
15			1.2	1.1	.7				.2	.5	.7	.5
17.5				1.4	.5				.1		2	.3
20										1.0		
22.5										.3		
25										.5		

Table 7. Average number of days per month for each shallow ground-water area for the Current Water Control Plan and each Alternative River Management Plan (1970–80)–Continued

Area of shallow ground water, (in percent)	Average number of days											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
					F10							
1		1.0										
2	17.3	13.2	9.7	5.9	2.6	1.2	6.6	10.7	5.2	5.6	6.4	15.3
3	7.6	7.9	1	8.0	5.5	6.0	9.7	9.5	6.5	9.4	7.8	4.6
4	3.2	1.5	1.5	3.2	11.0	5.6	4.2	2.4	6.3	4.7	5.6	7.5
5		1.5	1.0	1.5	1.0	6.2	2.0	2.1	6.3	8.1	7.2	.8
7.5	1.7	2.8	4.8	5.7	3.8	5.7	6.5	6.3	4.9	.4	.3	
10	1.2	.4	.8	.2	1.6	3.2	1.9	.1	.5			1.3
12.5			1.5	1.5	2.6	1.5			.1	.5		.7
15			.5	2.0	2.2	.6				.4		.5
17.5			1.2	1.5	.5				.3	.2	2.2	.3
20				.5	.1					1.1	.5	
22.5										.1		
25										.6		
					F15							
1	0.5	1.4										
2	16.8	13.3	11.4	6.7	1.7	1.1	5.7	10.9	5.6	5.9	8.2	15.3
3	7.5	7.5	8.4	7.2	6.2	5.9	10.4	9.5	6.4	9.1	6.0	4.6
4	3.3	1.5	1.5	3.2	9.1	5.9	4.7	2.1	6.0	4.7	5.6	7.4
5		1.5	.8	1.5	2.7	5.8	1.7	2.2	5.8	8.1	7.2	.9
7.5	1.7	2.8	5.0	5.7	3.6	6.0	6.5	6.2	5.4	.4	.3	
10	1.2	.4	.8	.2	2.1	3.2	1.9	.1	.5			1.3
12.5			1.5	1.5	2.5	1.5			.1	.5		.7
15			.5	1.8	2.4	.6				.4		.5
17.5			1.2	1.5	.5				.3	.2	2.2	.3
20				.6	.1					1.1	.5	
22.5										.1		
25										.6		

Table 7. Average number of days per month for each shallow ground-water area for the Current Water Control Plan and each Alternative River Management Plan (1970–80)–Continued

Area of shallow ground water, (in percent)	Average number of days											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
						F20						
1	1.5	2.0	1.6									
2	14.5	14.7	8.9	4.5	1.7		3.9	7.2	6.2	8.3	10.5	15.9
3	8.0	5.2	6.8	7.5	4.2	4.6	10.2	8.3	7.1	7.7	7.5	6.0
4	4.2	1.8	3.7	3.7	10.4	5.0	2.6	1.5	1.5	4.3	3.6	4.5
5		1.4	.9	3.3	4.1	8.8	4.0	4.5	7.0	4.1	4.9	1.7
7.5	2.1	2.8	4.5	5.2	2.2	5.1	8.2	9.3	7.5	3.8	.7	
10	.7	.4	1.3	.5	4.1	2.2	2.1	.4	.4			2.0
12.5			1.5	1.4	1.0	3.3				.8	2.4	.5
15			.5	1.6	2.7	1.0			.2	.2		.3
17.5			1.2	1.7	.5				.1		.3	
20				.6	.2					1.1	.1	
22.5										.4		
25										.4		
						M66						
1	0.3	1.6	1.9									
2	15.9	14.4	9.2	7.6	3.2	1.7	2.7	7.5	3.4	5.6	5.5	14.2
3	8.8	6.5	9.5	6.4	7.9	6.7	10.5	7.0	8.5	9.4	6.9	4.1
4	3.0	1.0	.5	4.0	8.4	6.2	4.9	5.1	2.1	4.4	7.4	8.4
5	.3	1.6	.9	1.2	2.2	6.8	3.6	3.6	8.9	6.0	7.0	1.5
7.5	1.6	2.8	5.1	5.4	3.3	3.8	7.5	7.0	6.4	2.8	.5	
10	1.2	.4	2.2	1.4	2.6	3.6	1.7	.7	.5			1.3
12.5			.5	1.6	2.3	1.1			.1	.5		.7
15			1.2	1.1	.7					.4		.5
17.5				1.4	.5				.3	.2	2.0	.4
20										1.1	.7	
22.5										.1		
25										.5		
27.5										.2		

ARMP simulation was then determined and the CWCP simulation results were subtracted to calculate the change in shallow ground-water area. These data are useful for assessing the monthly differences between each ARMP and the CWCP. For example, the area with shallow ground water increased by 0.5 percent for 18.3 days under the C18 plan and increased by 0.5 percent for 6.9 days under the FW20 plan. However, no increase in shallow ground-water area occurred in May above the 0.5 percent level for the C18 plan but increases of 1, 1.5, 2, 2.5, 3, and 3.5 percent occurred in May for 11.5, 5.5, 2.5, 1.8, 0.6, and 0.5 days, respectively, for the FW20 plan. This example indicates large differences can exist between the ARMPs in both the duration and extent of areas with shallow ground water.

Average Monthly Changes in Depth to Ground Water

An important factor controlling the impact of each ARMP on ground water in the lower Missouri River flood plain is the timing of ground-water-level fluctuations. The timing of the rise or fall of ground-water levels can be as important as the magnitude of the rise or fall. High ground-water levels in the spring may limit field access and delay planting, whereas low ground-water levels may decrease wetland habitat. The average monthly changes in model area with shallow ground water compared to the CWCP for each ARMP between 1970 and 1980 are shown in figure 8. C18, C31, C44, and M66 do not cause large changes in the percent of model area with shallow ground water. FW10 and FW15 each cause a spring increase and a summer decrease in the shallow ground-water area. FW20 has a larger spring increase in the shallow ground-water area, but the largest decrease is delayed until November.

Flood Pulse and Ground-Water-Level Response Analysis

Knowledge of the response of ground-water altitude to changes in Missouri River stage of known magnitude and duration can be used to help assess the impact of the currently proposed ARMPs on flood plain activities and ecosystems. In addition, estimates of the impact of droughts and floods on ground-water levels can be made using knowledge of ground-water-level changes in response to changes in river stage. To determine these relations, a series of flood pulses of known magnitude and duration were simulated using the ground-water flow model, and the daily change in ground-water levels in response to the flood pulse was determined at selected distances from the river.

Table 8. Summary of daily differences in percentage of the model area with shallow ground water for Alternative River Management Plans C18, C31, C44, FW10, FW15, FW20, and M66 with respect to the Current Water Control Plan

Comparison	Maximum daily difference (percent)	Minimum daily difference (percent)	Average mean daily difference (percent)	Standard deviation of the daily difference (percent)
C18 - CWCP	0.49	-0.44	0.009	0.05
C31 - CWCP	.65	-1.71	.015	.10
C44 - CWCP	2.65	-2.69	-.026	.41
FW10 - CWCP	4.45	-2.61	-.024	.61
FW15 - CWCP	4.44	-2.65	-.01	.63
FW20 - CWCP	4.6	-5.86	.079	.82
M66 - CWCP	1.23	-1.58	-.027	.13

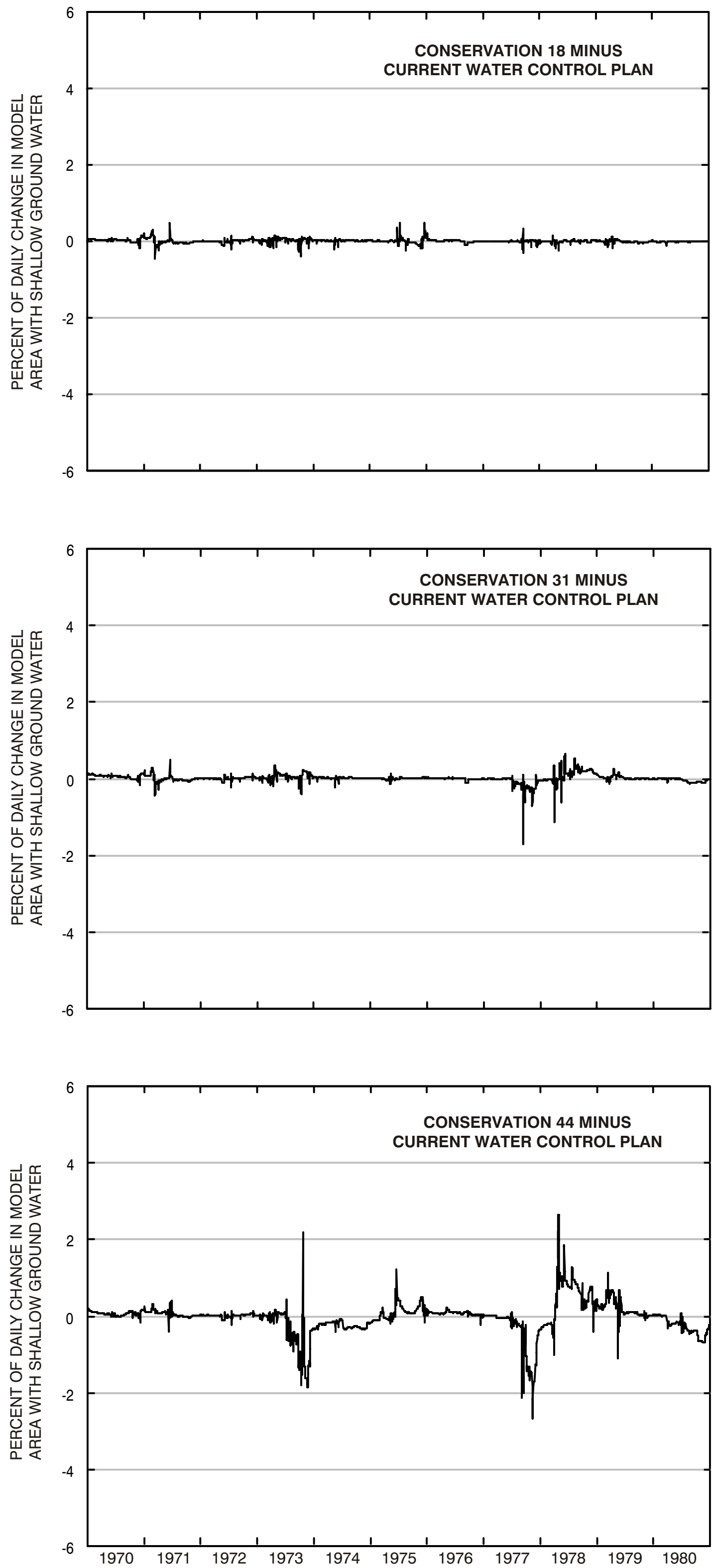

Figure 7. Percentage of daily change in model area with shallow ground water for each Alternative River Management Plan compared to the Current Water Control Plan, 1970–80.

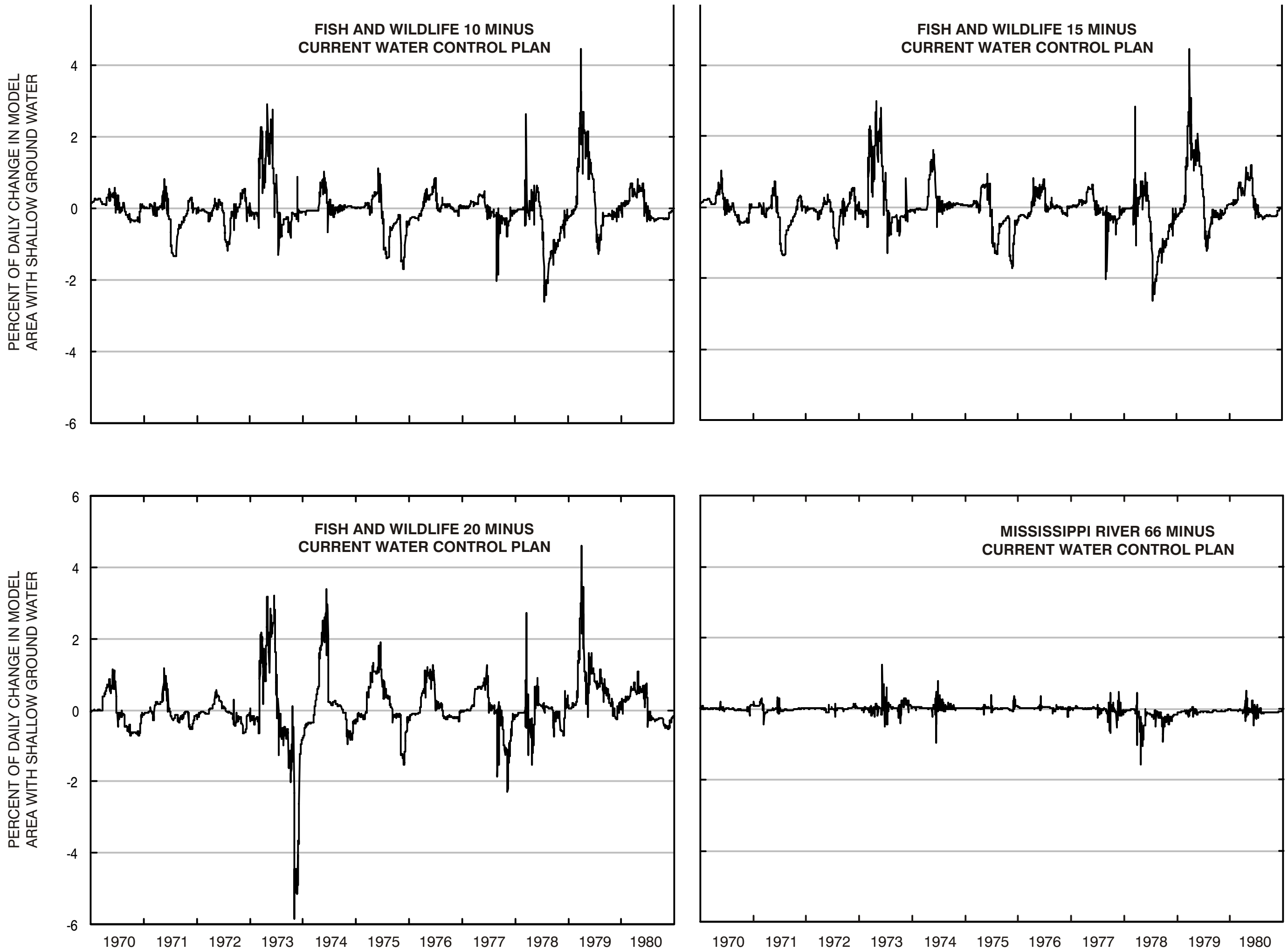

Figure 7. Percentage of daily change in model area with shallow ground water for each Alternative River Management Plan from the Current Water Control Plan, 1970–80—Continued.

Twelve flood-pulse simulations of known duration and magnitude were conducted to determine the ground-water response factor (GWRF). Each simulation had a single flood pulse. Flood-pulse durations were 1, 8, 32, and 128 days in length. Flood pulses were 0.5, 1, and 3 m in magnitude. These durations and magnitudes were chosen to provide a range of conditions that encompass river-stage changes and ground-water level changes that may occur on the lower Missouri River flood plain. To allow each flow simulation to approach steady-state conditions before applying the flood pulse ground-water flow was simulated for 2 years and 10 months (1,033 days; each stress period equals 1 day) with constant river stage (220 m above sea level at the USGS gage at Kansas City), daily recharge rate derived from average annual recharge, and no well pumping. Each flood-pulse simulation consisted of an instantaneous increase in river stage of the specified flood-pulse magnitude, maintenance of the flood pulse for the specified duration, an instantaneous decrease in river stage back to the original stage and a period of constant river stage at the original stage. Simulated recharge and no well pumping was maintained throughout the simulation. The simulated ground-water-level increase or decrease in response to the flood pulse was recorded daily for each simulation. Flood-pulse durations and the associated flood-pulse magnitudes used in the 12 simulations are listed in table 10.

Table 9. Average number of days per month for each change of shallow ground-water area for each Alternative River Management Plan (1970–80)

Percent change in total area of shallow ground water	Average number of days											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
					C18							
-0.5	3.5	4.9	13.5	14.5	12.6	8.5	9.1	6.0	11.2	16.1	18.1	7.6
0	1.1		1.0		.1	.1	.9		.7	1.9	.2	
0.5	26.4	23.4	16.5	15.5	18.3	21.4	21.0	25.0	18.1	13.0	11.7	23.4
					C31							
-2									0.1			
-1.5				0.1								
-1					0.1				.2		0.3	
-0.5	6.5	3.9	11.9	10.5	7.3	7.1	11.2	10.5	11.6	13.8	13.5	10.3
0	1.1		.3	3.4	1.7	.5	.1	.1	.2	.8		.6
0.5	23.4	24.4	18.8	16.0	21.9	22.0	19.7	20.2	17.9	16.4	16.3	20.1
1						.4		.3				
					C44							
-3											0.2	
-2.5									0.2		.3	
-2										1.0	2.9	
-1.5				0.1	0.2				.9	3.9	2.1	1.0
-1			0.3				0.9	1.3	2.5	2.2	2.7	1.4
-0.5	8.8	8.0	8.7	11.7	12.9	9.9	13.9	11.3	9.8	6.4	5.8	9.8
0		.5				.2				.5	.1	
0.5	22.2	19.8	20.4	15.3	14.4	16.5	13.4	15.6	14.1	16.8	13.7	18.7
1			1.5	2.0	2.4	2.5	2.5	2.8	2.5	.1	2.2	.2
1.5			.1	.5	1.0	.9	.3					
2					.2	.1						
2.5				.1						.1		
3				.4								
					F10							
-3							0.2					
-2.5							.6	1.6	0.1			
-2							.1	.9	.4		0.7	0.3
-1.5							4.5	5.3	2.4	0.8	.9	.6

Table 9. Average number of days per month for each change of shallow ground-water area for each Alternative River Management Plan (1970–80)–Continued

Percent change in total area of shallow ground water	Average number of days											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
F10–Continued												
-1			0.3			0.3	3.7	5.7	3.5	2.5	3.0	1.9
-0.5	17.0	14.9	12.1	8.0	1.2	4.1	13.6	12.3	18.5	21.0	17.4	16.9
0	.2			.5								
0.5	13.8	13.4	12.2	15.5	20.2	15.1	6.8	5.2	5.2	6.6	7.5	11.2
1			2.3	1.8	4.6	7.8	1.4				.5	.1
1.5			1.6	.8	1.1	1.9						
2			.3	1.5	1.7	.1						
2.5			1.8	1.1	1.7	.6						
3			.5	.6	.5	.1						
3.5				.1								
4				.1								
4.5				.1								
F15												
-3							0.2					
-2.5							.6	1.7	0.1			
-2							.1	.8	.4		1.3	0.3
-1.5				0.1			4.4	5.1	2.4	0.8	.7	.6
-1			0.4			0.3	4.4	6.5	3.5	2.9	2.8	1.9
-0.5	20.1	16.4	12.1	9.4	0.9	4.0	11.9	12.0	18.7	21.4	17.1	18.1
0			.2					.6				
0.5	10.9	11.9	11.6	13.7	11.0	12.4	7.5	4.2	4.9	5.9	7.7	1
1			2.5	1.8	11.9	8.5	1.9				.4	.1
1.5			1.6	2.2	3.8	3.0						
2			.3	2.1	1.4	1.1						
2.5			1.8	.2	1.5	.7						
3			.5	.2	.5	.1						
3.5				.2								
4				.1								
4.5				.1								

Table 9. Average number of days per month for each change of shallow ground-water area for each Alternative River Management Plan (1970–80)–Continued

Percent change in total area of shallow ground water	Average number of days											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
					F20							
-6											0.2	
-5.5											.6	
-5											.5	
-4.5											1.0	
-4												0.5
-3.5												
-3												.2
-2.5										0.1	.5	
-2				0.1					0.5	.5	.5	
-1.5				.1	0.3		0.1		.4	2.5	3.7	1.3
-1	0.9		0.3	.6	.5		.5	2.0	3.2	4.4	11.2	6.4
-0.5	24.2	21.0	12.4	1.9	.9	0.5	12.3	14.8	17.4	2	10.7	18.9
0		.5										
0.5	5.9	6.8	10.2	9.9	6.9	8.4	12.5	11.4	7.9	3.5	1.0	3.5
1			3.9	10.6	11.5	9.0	5.5	2.6	.6	.1		.1
1.5			1.7	3.6	5.5	6.5		.2				
2			.5	1.4	2.5	1.4						
2.5			.9	1.1	1.8	2.5						
3			.8	.3	.6	1.5						
3.5			.4	.1	.5	.2						
4				.1								
4.5												
5				.2								
					M66							
-2				0.1								
-1.5				.1	0.2							
-1				.5	1.3	0.1			0.9	0.3	0.1	
-0.5	9.8	8.5	13.4	10.8	14.2	15.3	19.3	20.9	22.4	20.4	19.5	14.1
0	.2	.5	1.8	2.2	.8	.1	9		.5	.9	.2	
0.5	21.1	19.4	15.8	16.3	14.5	14.0	10.6	10.1	6.2	9.5	10.3	16.9
1						.4	.2					
1.5						.2						

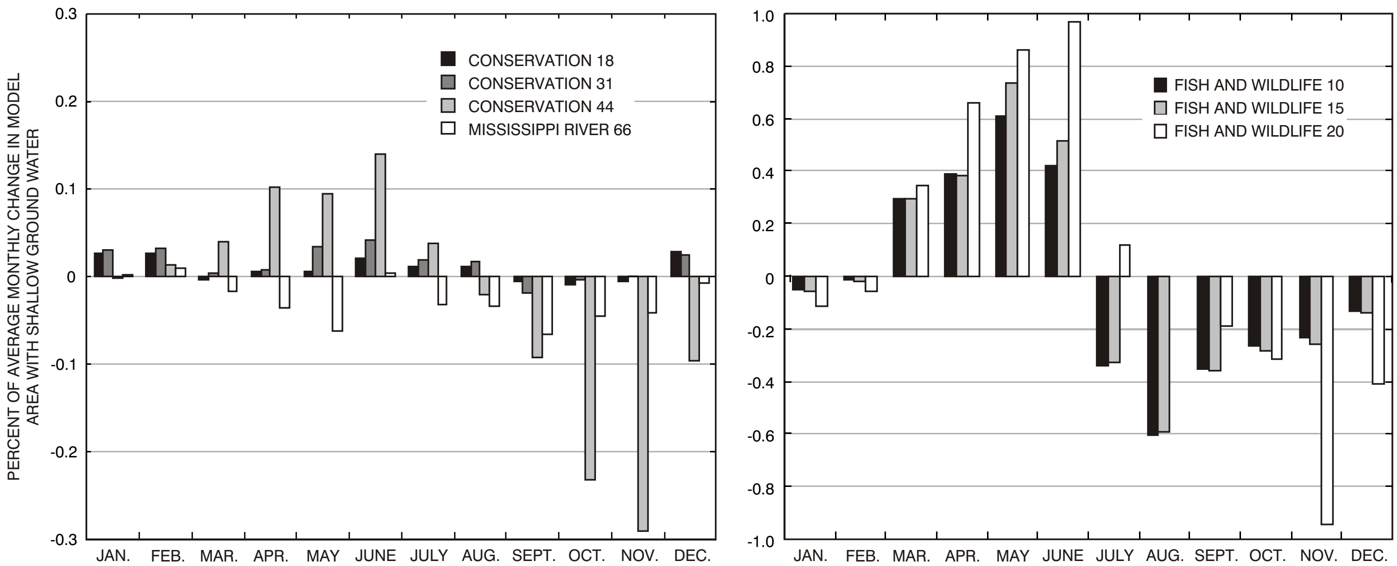

Figure 8. Percentage of average monthly change in model area with shallow ground water for each Alternative River Management Plan from the Current Water Control Plan, 1970–80.

Ground-water levels were generated for each model cell for each stress period of every simulation. To present study results that are readily interpreted, the GIS was used to extract the average change in ground-water level at selected distances from the river for each stress period of each simulation. The altitude of the ground-water potentiometric surface decreases in a down-valley direction because ground water flows in a down-valley direction. This down-valley slope was removed from the data by calculating the change in ground-water level at each model cell. This facilitated comparison of the response of ground-water level to river-stage change at different locations in the modeled area. To determine the change in ground-water level at each cell for each simulation, a separate baseline simulation was run using the same input parameters that were used for each flood-pulse simulation, with the exception of the flood pulse itself. For the same stress period of each simulation, ground-water altitude from each cell of the baseline simulation was subtracted from the ground-water altitude of the same cell of each flood-pulse simulation. In this way, the simulated effect of river stage on ground-water level was isolated from changes in ground-water level because of recharge, aquifer drainage, or other transient aquifer response. The GIS was then used to calculate the shortest distance from the center of each cell to the closest river cell as defined in the model. Cells were grouped in 100-m-distance intervals and, for each stress period of each simulation, the average change in ground-water level for all the cells within each distance interval was calculated. In addition, a statistical summary of the ground-water-level data for each distance interval and each stress period of each simulation was created using the GIS.

The GWRF, defined as the change in ground-water level at a known distance from the river divided by the magnitude of the flood pulse, at a specified time after the beginning of a flood pulse, was calculated for each simulation at selected times and distances from the river after the beginning of the flood pulse. Results of the flood-pulse analysis are presented in figures 9 through 12. The change in ground-water level caused by the change in river stage, the GWRF, is presented in each figure. By multiplying the magnitude of the flood pulse by the GWRF, the change in ground-water level is estimated for any magnitude change in river stage. For example, in figure 9, a 0.316 GWRF for the 0.5-m flood pulse at 200 m from the river on day 1 of the flood-pulse simulation translates into an actual

Table 10. Data pertaining to 12 flood-pulse simulations

Flood-pulse duration (days)	Flood-pulse magnitude (meters)	Number of stress periods (days)	Missouri River stage at Kansas City (meters above sea level)
	0	1,033	220
1	0.5	1	220.5
	0	52	220
	0	1,033	220
1	1	1	221
	0	52	220
	0	1,033	220
1	3	1	223
	0	52	220
	0	1,033	220
8	0.5	8	220.5
	0	272	220
	0	1,033	220
8	1	8	221
	0	272	220
	0	1,033	220
8	3	8	223
	0	272	220
	0	1,033	220
32	0.5	32	220.5
	0	512	220
	0	1,033	220
32	1	32	221
	0	512	220
	0	1,033	220
32	3	32	223
	0	512	220
	0	1,033	220
128	0.5	128	220.5
	0	512	220
	0	1,033	220
128	1	128	221
	0	512	220
	0	1,033	220
128	3	128	223
	0	512	220

0.158-m rise in ground-water level at that distance. In figure 11, a 0.5 GWRF for the 3-m flood pulse at 600 m from the river on day 32 of the simulation translates into a 1.5-m rise in ground-water level at that distance.

The GWRF normalizes the response of ground-water levels to river-stage changes, and, therefore, can be used to predict ground-water level changes caused by changes in river stage. The GWRF can be multiplied by

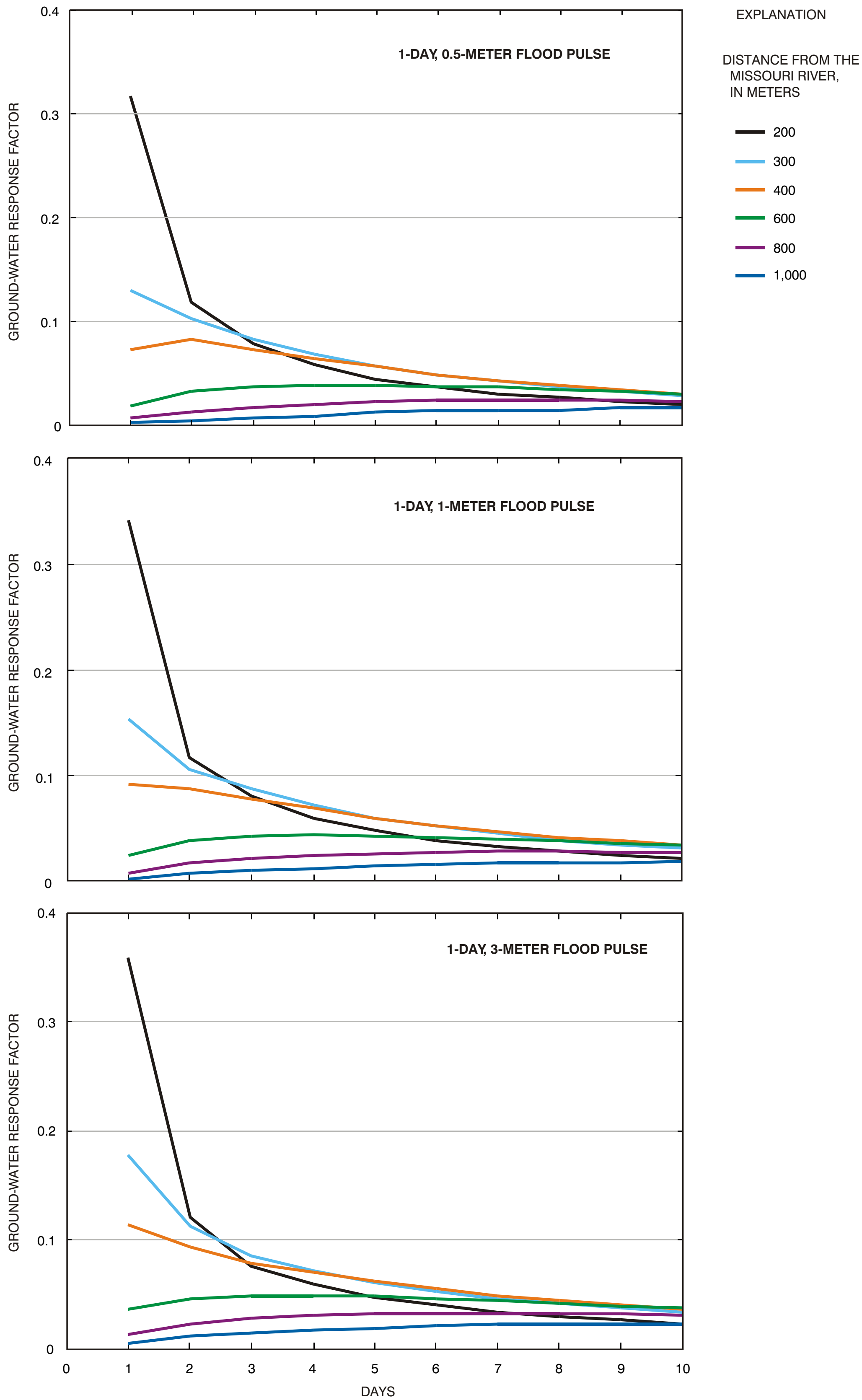

Figure 9. One-day, 0.5-, 1-, and 3-meter flood-pulse simulation results.

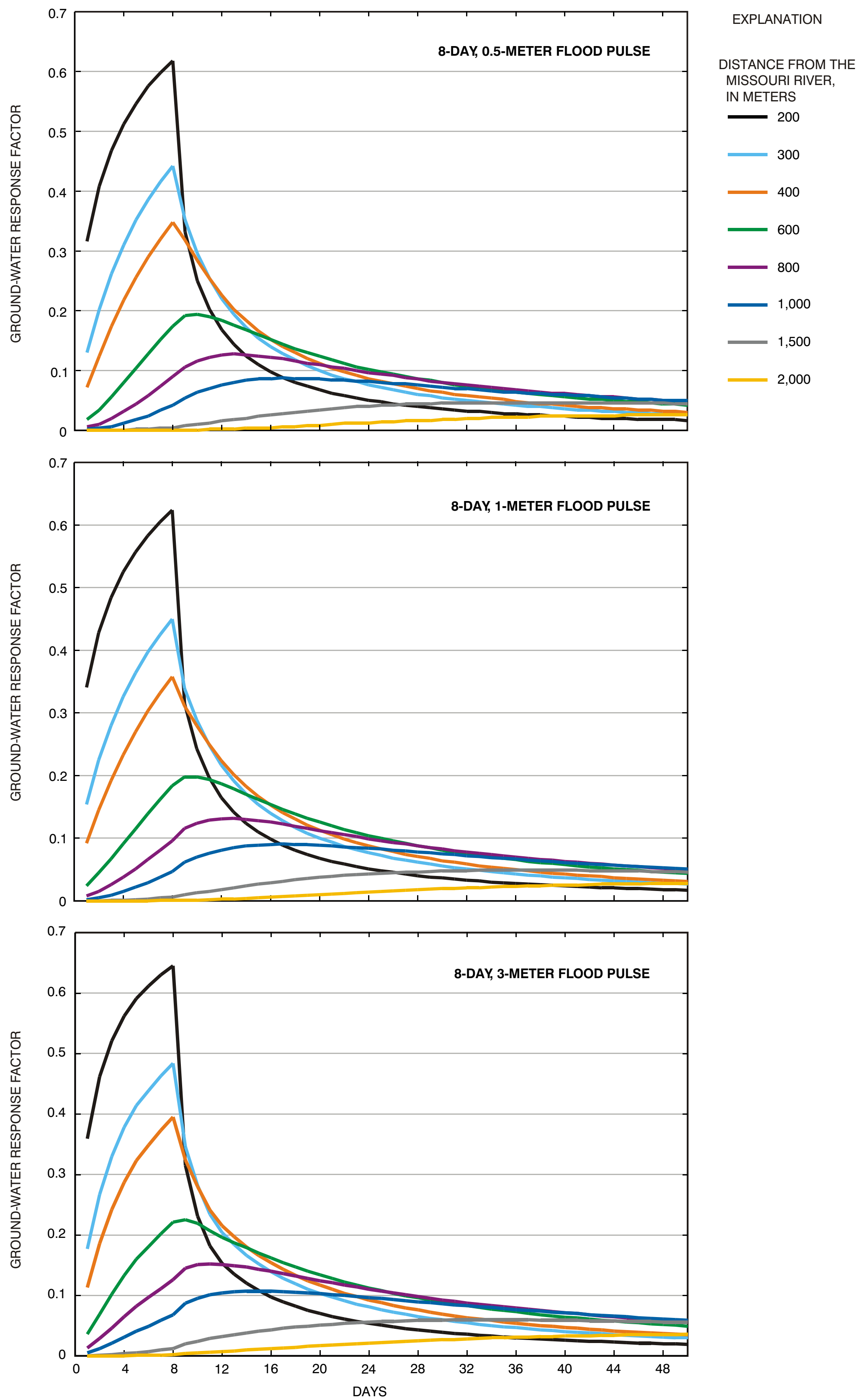

Figure 10. Eight-day, 0.5-, 1-, and 3-meter flood-pulse simulation results.

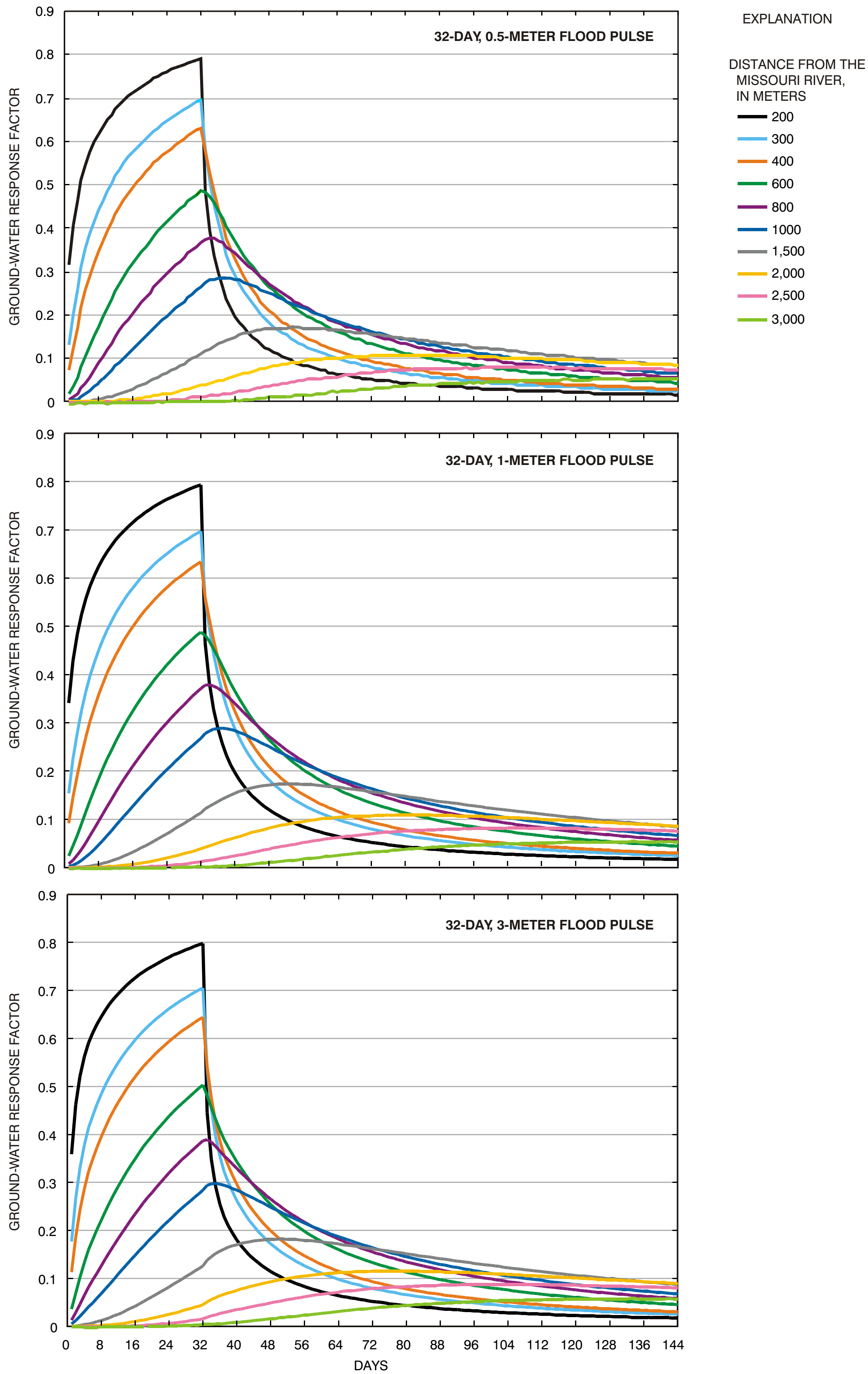

Figure 11. Thirty-two-day, 0.5-, 1-, and 3-meter flood-pulse simulation results.

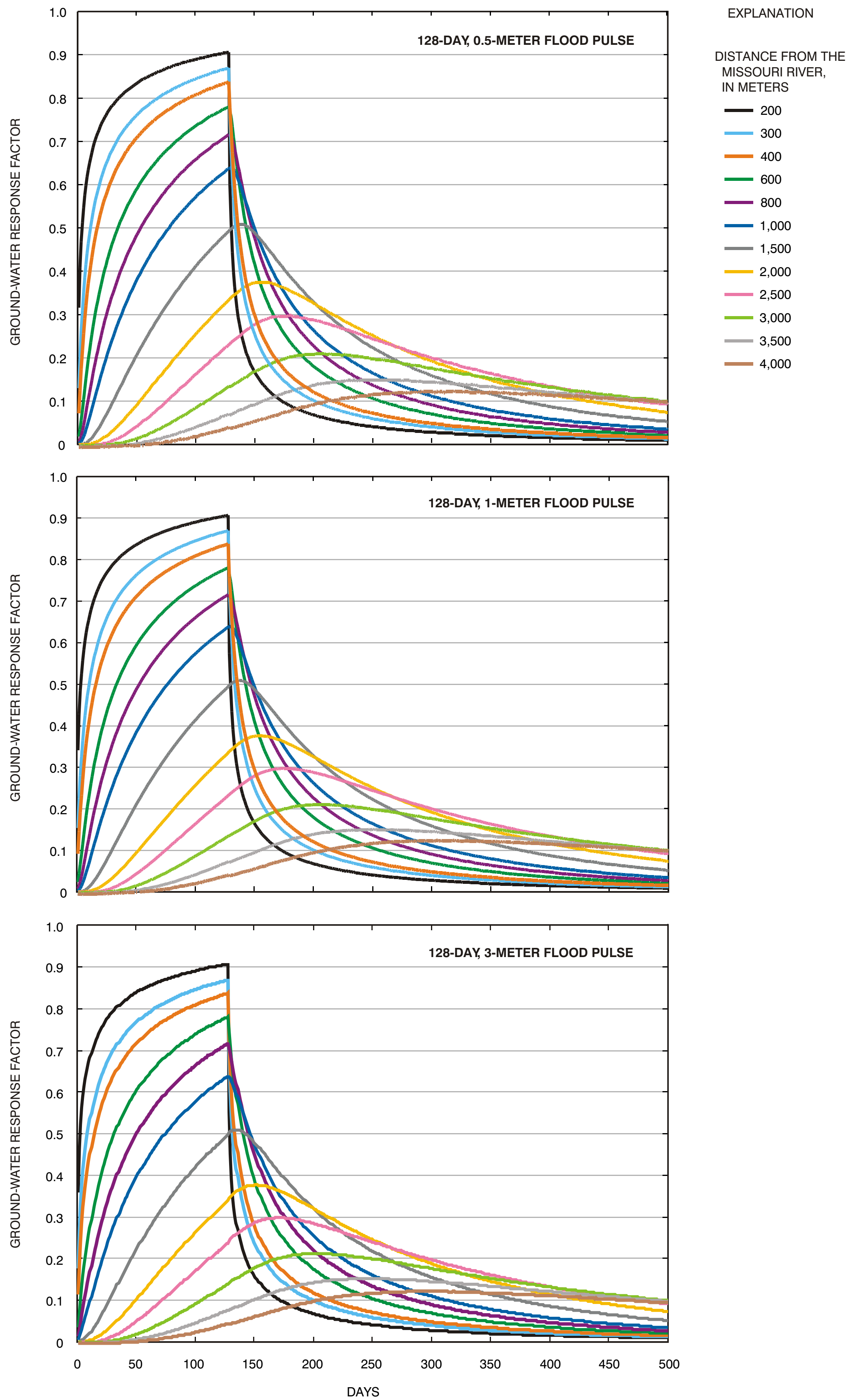

Figure 12. One-hundred-twenty-eight-day, 0.5-, 1-, and 3-meter flood-pulse simulation results.

a flood pulse of any magnitude to obtain an estimated ground-water level change at various distances from the river. This approach was taken to provide a method for estimating ground-water level changes in areas of the lower Missouri River flood plain where little or no data exist.

Several trends in the GWRF are illustrated by the flood-pulse analysis. As would be expected, at a given distance, the GWRFs for shorter duration flood pulses are smaller than the GWRFs for longer duration flood pulses. The 0.5-m flood pulses of 1, 8, 32, and 128 day durations shown in figures 9, 10, 11, and 12 show a larger GWRF at all distances with increasing flood-pulse duration. This relation also is apparent for the 1- and 3-m flood-pulse simulation results. Also, for flood pulses of the same duration, the greater the magnitude of the flood pulse, the greater the initial GWRF. However, the GWRF at a specified distance becomes, with time, more similar among flood pulses of the same duration but different magnitude. This trend is best shown in the 1-day duration results illustrated in figure 9 and the 128-day duration results illustrated in figure 12. The initial GWRF at 200 m from the river for the 1-day, 0.5-m flood pulse was 0.316, for the 1-day, 1-m flood pulse was 0.34, and for the 1-day, 3-m flood pulse was 0.359. The initial GWRF factor at 200 m from the river for the 128-day, 0.5-, 1-, and 3-m flood pulse simulations is identical to the 1-day duration results, but after 128 days the GWRF for the 0.5-m flood pulse was 0.906, for the 1-m flood pulse it was 0.907, and for the 3-m flood pulse it was 0.907. A third important trend is the timing of the maximum ground-water-level change at a given distance for a given flood pulse. Figures 9 through 12 show that ground-water levels rise continuously during the flood pulse, especially at shorter distances from the river, and decline after the pulse ends. However, at farther distances, ground-water levels may continue to rise for some time after the flood pulse has ended. The 1-day, 0.5-m flood-pulse simulation results, shown in figure 9, indicate that beyond a distance of between 300 and 400 m from the river, the greatest GWRF occurs one day or more after the flood pulse has ended. All other flood-pulse simulation results indicate that beyond a distance of between 400 to 600 m from the river, the maximum GWRF occurs one day or more after the flood pulse has ended.

The day of arrival and magnitude of the largest GWRF for each flood-pulse simulation at selected distances from the river are shown in figures 13 through 16. One point indicates which distance interval had the largest GWRF for each day and the other point indicates the magnitude of the GWRF. These data can be used to estimate the arrival time of the largest ground-water level change at selected distances for each of the simulated flood pulses. Each figure has two points plotted for each day of the simulation. For example, on day 5 of the 1-day, 1-m flood-pulse simulation (fig. 13) a GWRF of 0.06 occurred at 300 m from the river. This translates into a ground-water level rise of 0.06 m at that time and distance.

During each flood pulse, the maximum GWRF occurs nearest the river as shown in figures 13 through 16. With increasing time after the flood pulse, the largest GWRF occurs at farther distances from the river and decreases in magnitude. A comparison of the data presented for the 1-day, 0.5-m flood pulse (fig. 13) and the 128-day,3-m flood pulse (fig. 16) illustrates the range of GWRFs possible for flood pulses of these durations and magnitudes. The maximum GWRF for the 1-day, 0.5-m flood pulse was between 0.3 and 0.32 (0.15 to 0.16 m) at 200 m from the river. However, after 3 days, the GWRF is less than 0.1 (0.05 m) at 300 m from the river. The maximum GWRF for the 128-day, 3-m flood pulse was about 0.9 (2.7 m) at 200 m from the river. Thirty-two days after the end of the flood pulse (day 160) the GWRF was about 0.45 (1.35 m) at 1,400 m from the river, and 160 days after the end of the flood pulse (day 288) the GWRF was about 0.21 (0.63 m) at 2,200 m from the river. These results indicate the relatively small impact on ground-water levels of small changes in river stage of short duration as might occur daily or weekly. The larger impact on ground-water levels of larger river stage increases of longer duration indicate the importance of river management flow releases, seasonal changes in river flow, and the effects of continuous high-river stage for long periods on ground-water levels of the lower Missouri River flood plain.

TRANSFERABILITY OF GROUND-WATER RESPONSE FACTORS TO UNMODELED AREAS

If hydrologic properties in the model area are typical of the lower Missouri River flood plain, GWRFs would be expected to be transferable to other parts of the lower Missouri River flood plain for estimating ground-water level changes in response to

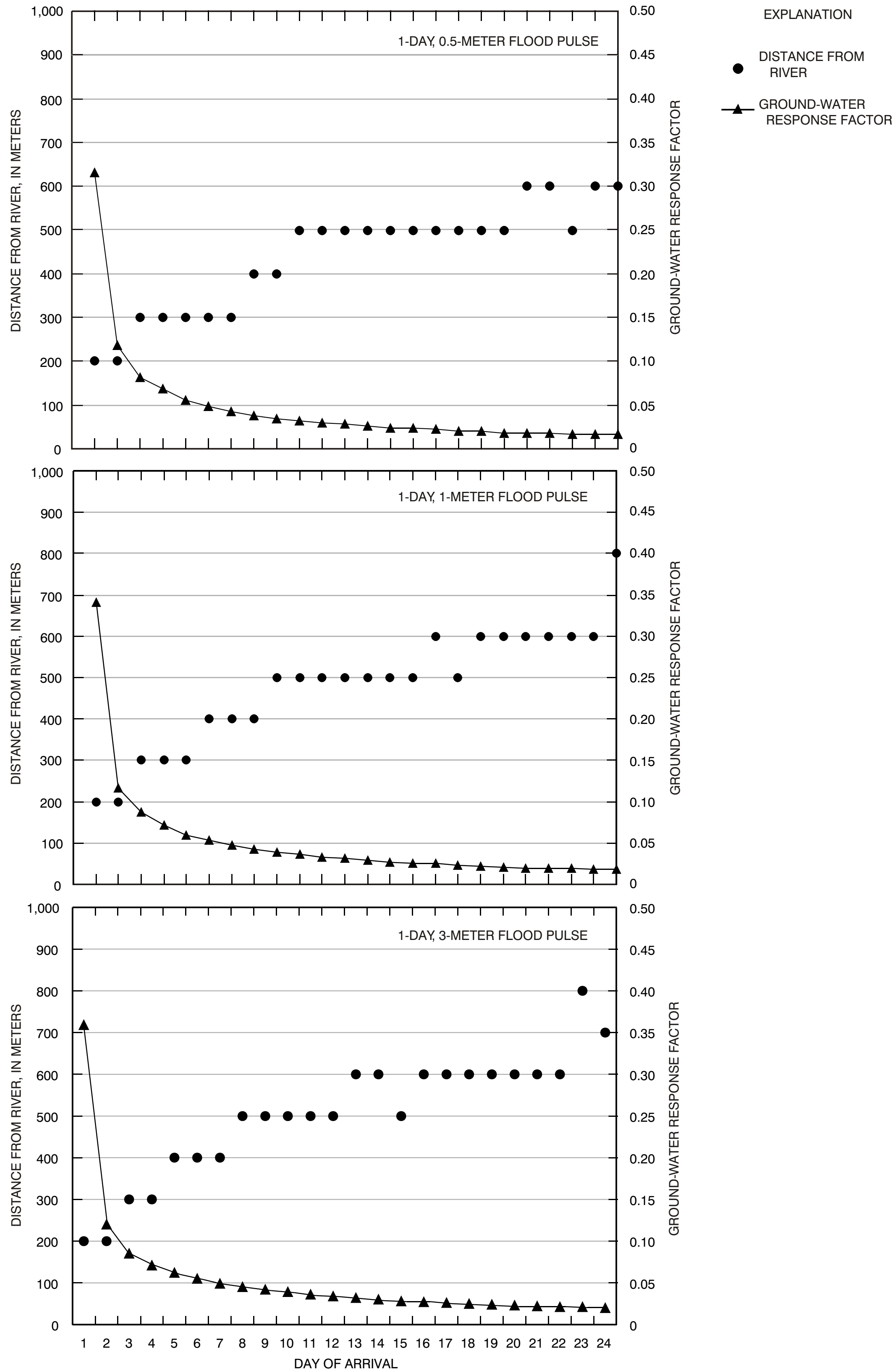

Figure 13. Day of arrival of largest ground-water response factor for selected distances from the river for the 1-day, 0.5-, 1-, and 3-meter flood pulses.

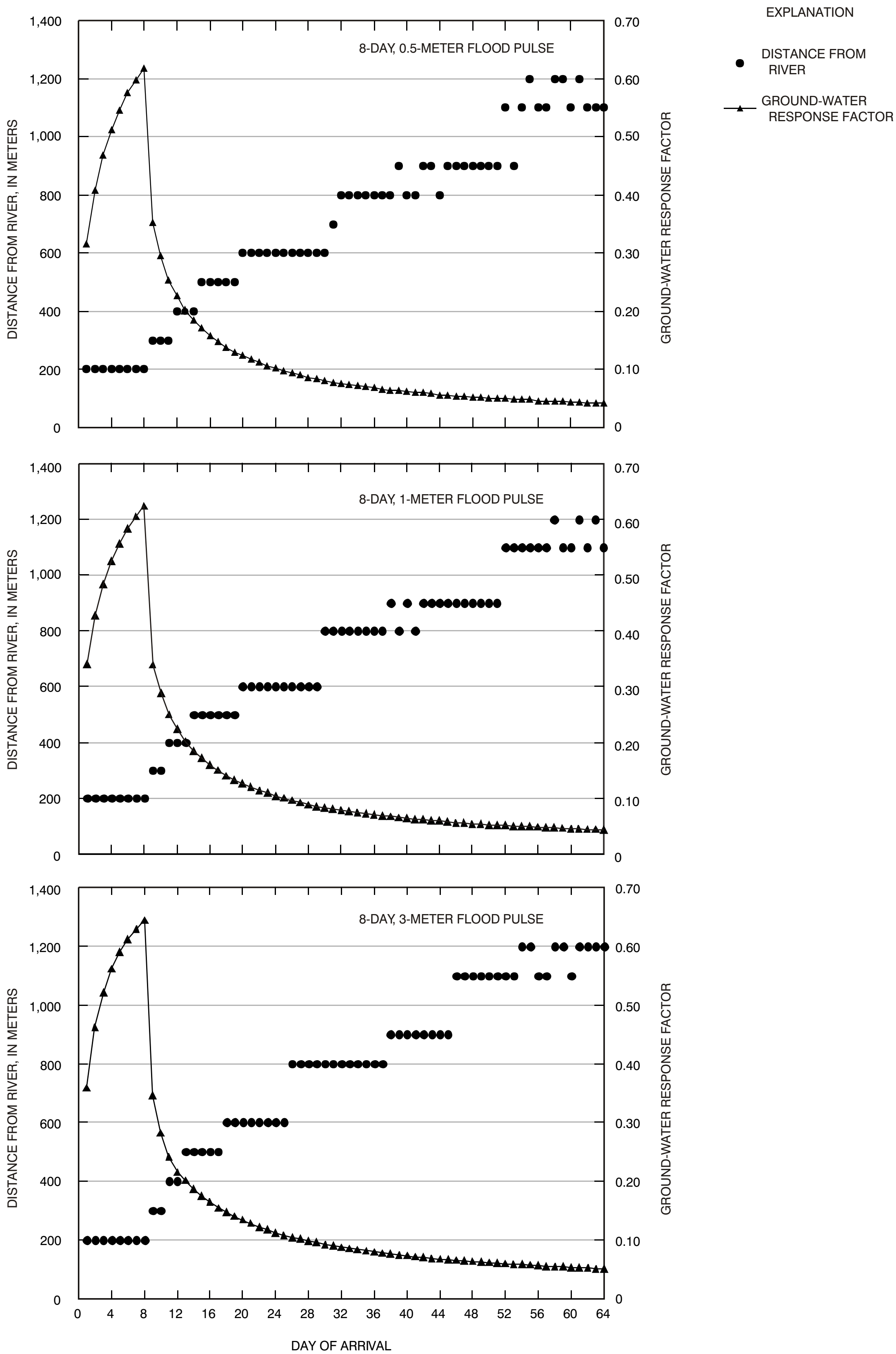

Figure 14. Day of arrival of largest ground-water response factor for selected distances from the river for the 8-day, 0.5-, 1-, and 3-meter flood pulses.

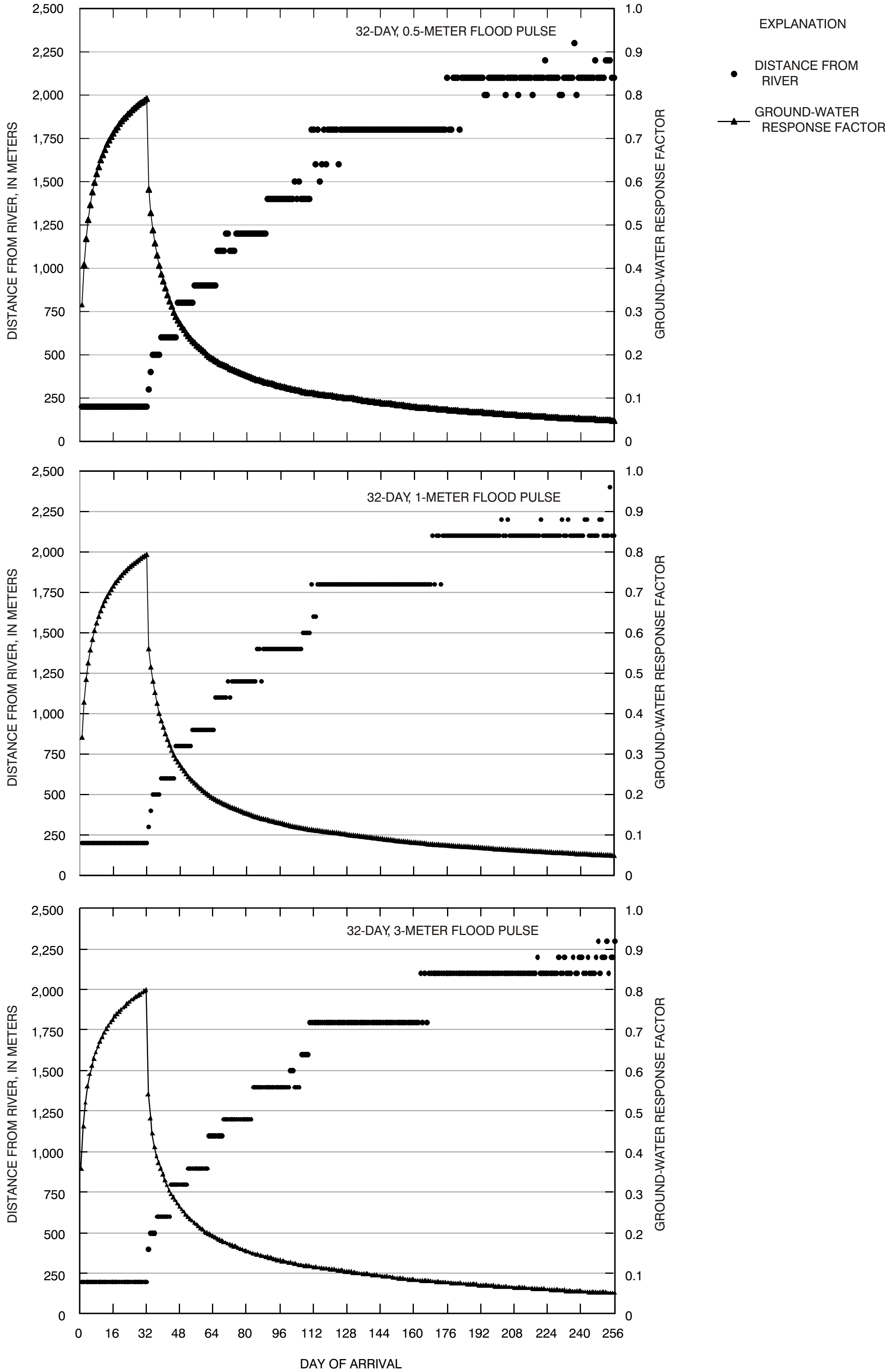

Figure 15. Day of arrival of largest ground-water response factor for selected distances from the river for the 32-day, 0.5-, 1-, and 3-meter flood pulses.

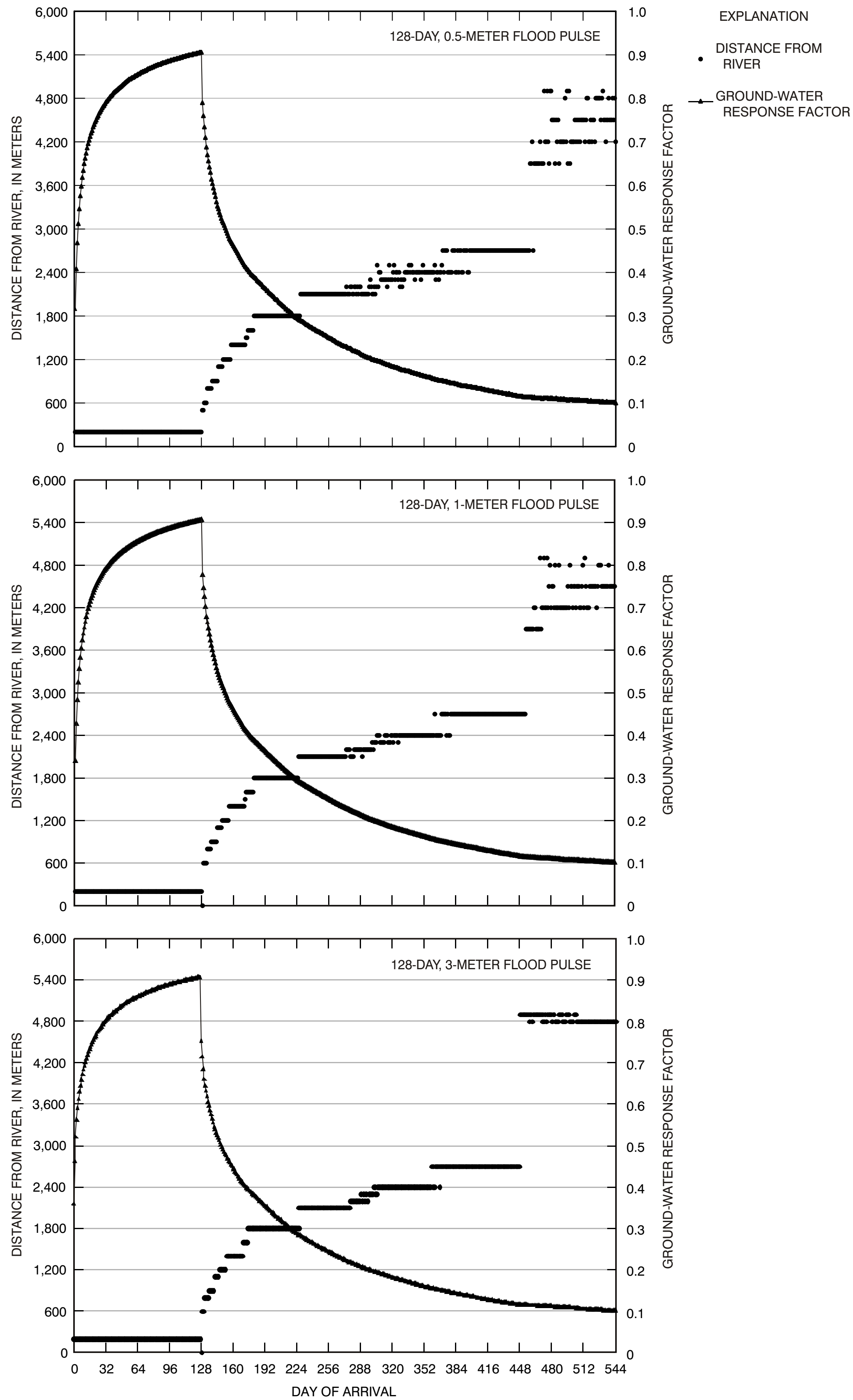

Figure 16. Day of arrival of largest ground-water response factor for selected distances from the river for the 128-day, 0.5-, 1-, and 3-meter flood pulses.

river-stage changes. Numerous investigations have determined the hydrologic properties of the lower Missouri River flood plain at various locations (fig. 17). A summary of the hydrologic properties from selected studies is shown in table 11.

The transmissivities listed in table 11 range from 32.3 to 8,197.2 m^2/day. The transmissivities used as input to the ground-water flow model of the Missouri River flood plain near Kansas City range from 0.017 to 16,915.5 m^2/day (Kelly, 1996a). Hydraulic conductivity is one of the few physical parameters than can range over 13 orders of magnitude (Freeze and Cherry, 1979). Transmissivity is the hydraulic conductivity multiplied by the saturated thickness of an aquifer and also can range over many orders of magnitude. The range of transmissivities measured in the lower Missouri River flood plain range over three orders of magnitude and fall well within the values input to the ground-water-flow model. However, because the range of transmissivity values used in the ground-water-flow model were calculated for each active cell of the model, the five orders of magnitude range is larger than that measured directly from aquifer tests in the flood plain. The lower values are caused by including model cells near the walls of the flood plain where depth to bedrock is small and low-hydraulic-conductivity clays and silts are present; higher values result from including model cells that coincide with deep bedrock channels filled with gravel. During aquifer tests (the source of most of the values listed in table 11), extremes of transmissivity typically are eliminated because these tests are not frequently conducted in areas where depth to bedrock is small or in the deepest parts of the aquifer; thus, the measured transmissivity values would be expected to fall in the middle of the range of transmissivity values used in the model, if the model area is typical of the Missouri River flood plain.

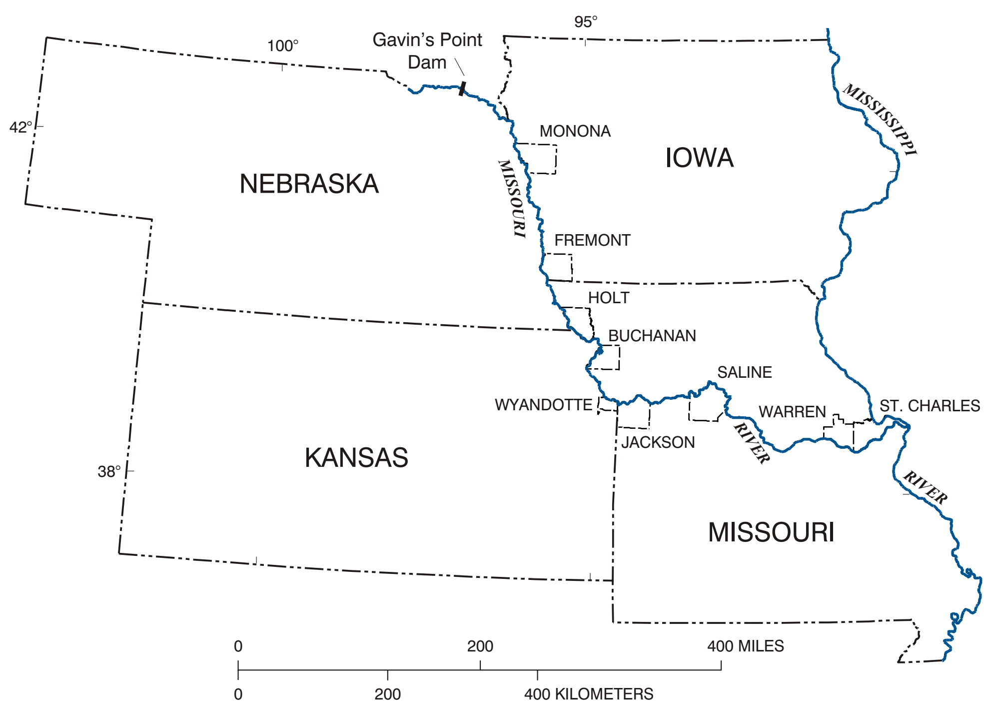

Figure 17. Location of hydrologic property data of the lower Missouri River flood plain.

Table 11. Summary of hydrologic properties of the lower Missouri River flood plain from selected studies

[m²/day, square meters per day; m/day, meter per day; USGS, U.S. Geological Survey; --, not reported]

Location of measurement (upstream to downstream)			Study reference	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)	Storage coefficient
State	County	Nearest city or park				
Iowa	Monona	Onawa	Bryan Schaap, USGS, written communication, 1996	32 – 1,863	--	0.2
Iowa	Fremont	Sidney	Bryan Schaap, USGS, written communication, 1996	248 – 8,197	--	.2
Iowa	Fremont	Sidney	Bryan Schaap, USGS, written communication, 1996	117 – 845	--	.2
Missouri	Holt	Squaw Creek National Wildlife Refuge	Emmet and Jeffery, 1969	2,732	--	.001
Missouri	Holt	Forest City	Bryan Schaap, USGS, written communication, 1996	273 – 1,615	--	.2
Missouri	Buchannan	Lewis and Clark State Park	Emmet and Jeffery, 1969	3,105	126	.17
Kansas	Wyandotte	Kansas City	Fischel, 1948	--	124	--
Kansas	Wyandotte	Kansas City	Fischel, 1948	--	137	--
Missouri	Jackson	Kansas City	Bechtel National Inc. and others, 1984	932 – 1,242	--	--
Missouri	Jackson	Kansas City	Crabtree and Malone, 1984	1,490	--	--
Missouri	Jackson	Sugar Creek	Nuzman, 1975	6,024	--	--
Missouri	Jackson	Atherton	Bryan Schaap, USGS, written communication, 1996	174 – 1,863	--	.2
Missouri	Saline	Glasgow	Granneman and Sharp, 1979	2,972 – 4,877	--	--
Missouri	Warren	Hermann	Bryan Schaap, USGS, written communication, 1996	45 – 1,863	--	.2
Missouri	St. Charles	Weldon Springs	Emmet and Jeffery, 1968	3,353	122	.2

In 1995 the USGS, in cooperation with the USACE, installed 25 ground-water level monitoring wells at three sites on the lower Missouri River flood plain in Missouri. Nine wells were installed at levee districts L488/L497, in Holt County near Forest City, Missouri; eight wells were installed at levee district R351, in Jackson County near Atherton, Missouri (within the modeled area); and eight wells were installed at Tri-County levee district no. 2, in Warren and Montgomery Counties near Hermann, Missouri (fig. 2). Water levels were measured hourly in all 25 wells for 10 months from December 1995 to October 1996. The DGLS and the USGS conducted monthly water-level measurements of this same well network from June 1997 through June 1998. Each of the three sites had one well with an hourly recorder; the remainder of the wells were measured monthly. Hourly measurements or estimates of the stage of the Missouri River at each site also were made between December 1995 and June 1998.

A comparison of model-derived GWRFs from the Kansas City area to GWRFs calculated from measured river stage and well hydrographs for these three sites was done for similar flood pulses. The criteria for data selection included: flood pulses of similar magnitude and duration to the simulated flood pulses, a complete period of record for river-stage and ground-water-level data, and a well-defined flood pulse with a rapid rise and fall of river stage. After eliminating flood pulse events that did not meet the above criteria, two events of differing magnitude and duration were randomly selected for each of the three sites.

Several important differences between the simulated and measured flood pulse and ground-water-level-change data exist. River stage typically changes over a period of several days on the lower Missouri River, but the simulated flood pulses change instantaneously. As stated earlier, ground-water altitude from each cell of the baseline simulation was subtracted from the ground-water altitude of the same cell of each flood pulse simulation. In this way, the simulated effect of river stage on ground-water level was isolated from changes in ground-water level because of recharge, aquifer drainage, or other transient aquifer response. Actual and simulated flood pulses are not identical with respect to duration and magnitude, and measured ground-water levels may be affected by previous river-stage changes, infiltration of precipitation, local well pumping and evapotranspiration if these rates of discharge change during the period of analysis. Because of these differences, the use of GWRFs from the modeled area to predict ground-water-level changes in unmodeled areas has some limitations. However, by comparing the simulated GWRFs to the GWRFs calculated from measured flood pulse and ground-water-level response data, the uncertainty of predicting ground-water-level changes from river stage changes in unmodeled and unmonitored areas can be estimated.

The maximum GWRF for a single flood pulse at each selected well was calculated and compared to the simulated GWRF for the distance interval closest to the well's distance from the river, or for the distance intervals that bracketed the distance from the river to the well for the same day on which the actual maximum GWRF occurred. The standard deviation of the simulated GWRFs for all model cells within each distance interval was determined using the GIS. If a normal distribution of ground-water-level changes within each distance interval is assumed, and if the GWRFs predicted by the model are indicative of the GWRFs throughout the lower Missouri River flood plain, then about 68 percent of the actual GWRFs for each distance interval should be within one standard deviation of the mean of the simulated GWRFs, and about 95 percent of the actual GWRFs should be within two standard deviations.

The magnitude of the change in ground-water levels is important when determining how closely the calculated GWRFs estimate actual changes in ground-water level. Because the GWRF is normalized to the flood pulse, larger flood pulses will have a larger amount of uncertainty than smaller flood pulses if the standard deviations of the GWRFs are similar. The largest standard deviations of the GWRFs indicate the upper range of uncertainty for using GWRFs to estimate actual ground-water changes. To obtain the estimate of the ground-water-level change at a selected distance from the river, the GWRF is multiplied by the magnitude of the flood pulse. To calculate the magnitude of the uncertainty of using the GWRF to estimate the change in ground-water level at a selected distance from the river, the standard deviation of the GWRF is multiplied by the magnitude of the flood pulse. Tables 15, 16, 17, and 18, at the back of this report list GWRF and the standard deviation of the GWRF for the 1-, 8-, 32-, and 128-day flood pulses of 0.5, 1, and 3 m in magnitude. For the 8-, 32-, and 128-day, 3-m flood-pulse simulations, the largest standard deviation of the ground-water-level change is 0.675 m (a 0.225 standard deviation of the GWRF multiplied by the 3-m flood pulse) on day 5 at the 200-m distance interval. For the 1-day, 3-m flood-pulse simulation, the largest standard deviation of the ground-water-level change is 0.591 m (a 0.197 standard deviation of the GWRF multiplied by the 3-m flood pulse) on day 1 at the 200-m distance interval. Thus, the largest uncertainty for estimating ground-water-level changes within one standard deviation of the GWRF is about 0.59 to 0.68 m for flood pulses up to 3 m in magnitude. The magnitude of the largest standard deviation of the ground-water-level change decreases with a decrease in flood pulse magnitude. For the 8-, 32-, and 128-day, 0.5-m flood-pulse simulations, the largest standard deviation of the ground-water level change is 0.112 m (a 0.224 standard deviation of the GWRF) on day 7 at the 200-m distance interval. For the 1 day, 0.5-m flood-pulse simulation, the largest standard deviation of the ground-water-level change is 0.092 m (a 0.184 standard deviation of the GWRF) on day 1 at the 200-m distance interval. The uncertainty for estimating ground-water-level changes from smaller flood pulses within one standard deviation can be as small as 0.09 m. Therefore, with the previously mentioned limitations in mind, the simulated GWRFs can be considered a useful method for estimating ground-water-level changes if the actual GWRFs are within one standard deviation of the mean of the simulated GWRFs.

The Missouri River stage near Forest City, Missouri, between April 1996 and August 1998, and the two periods selected for comparison to model results are shown in figure 18. The first period was a 7-day, 2.36-m flood pulse between May 7 and May 15, 1996 (fig. 19). The second period was an 18-day, 3.4-m flood pulse between June 7 and June 25, 1998 (fig. 20). Selected results from the most relevant simulated flood pulses and the actual Forest City flood pulses for these two periods are listed in table 12.

The actual GWRFs for the 7-day, 2.36-m flood pulse at Forest City well 12 (158 m from the Missouri River) were compared to the simulated GWRFs for the 8-day, 1-m and 8-day, 3-m flood pulses at the 200-m distance interval for day 4. The actual GWRF for well 12 of 0.51 is within one standard deviation of each of the simulated GWRFs to which it was compared. The GWRF at Forest City well 11 (326 m from the Missouri River) was compared to the simulated GWRFs for the 8-day, 1-m and 8-day, 3-m flood pulses at the 300- and 400-m distance interval for day 4. The actual GWRF of 0.30 was larger than the simulated GWRF at 400 m, and smaller than the simulated GWRFs at 300 m, but within one standard deviation of each of the simulated GWRFs to which it was compared. The GWRF at Forest City well 9 (908 m from the Missouri River) was compared to the simulated 8-day, 3-m flood pulse, GWRF at 900-m distance interval for day 10. The actual GWRF of 0.19 was larger than each of the simulated GWRFs to which it was compared. The actual GWRF at well 9 is within two standard deviations of the simulated GWRF at day 10 for the 8-day, 1-m flood pulse and within one standard deviation of the simulated GWRF at day 10 for the 8-day, 3-m flood pulse. Precipitation records for Oregon, Missouri (National Oceanic and Atmospheric Administration, 1999) indicate 6.8 cm of precipitation fell between the beginning of the flood pulse on May 7 and the maximum of the flood pulse on May 10, 1996. Assuming recharge is 20 percent of precipitation and is rapidly effective, the resulting 1.38 cm of recharge may have contributed to the increase in ground-water level.

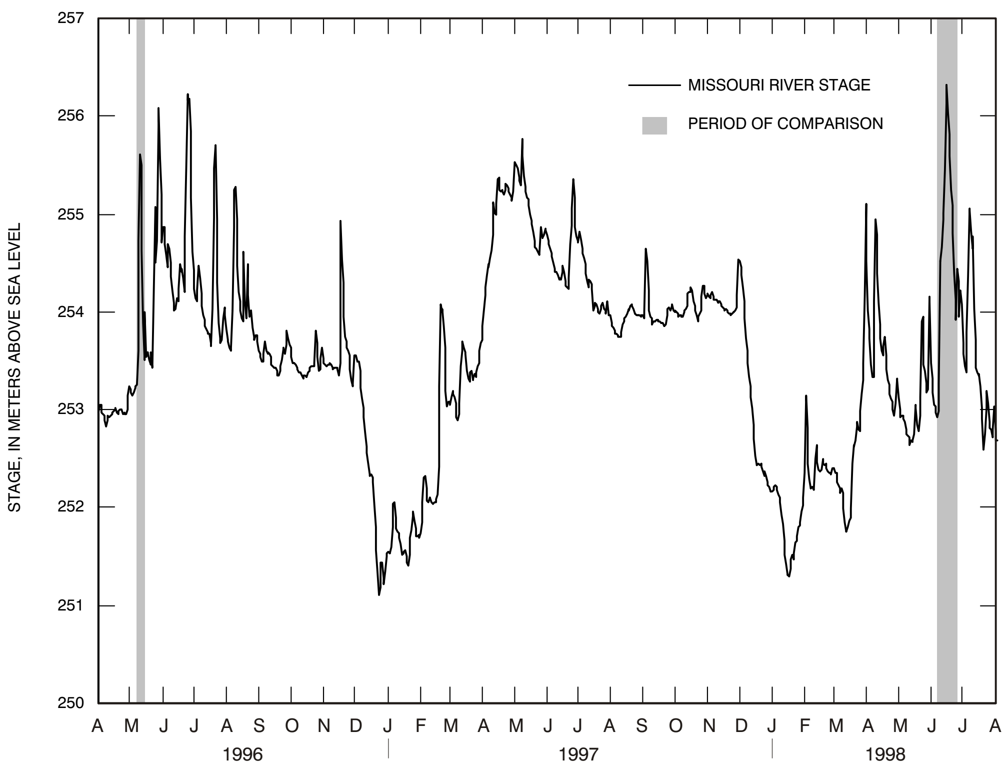

Figure 18. Missouri River stage near Forest City, Missouri, April 1996 to August 1998, and periods of comparison.

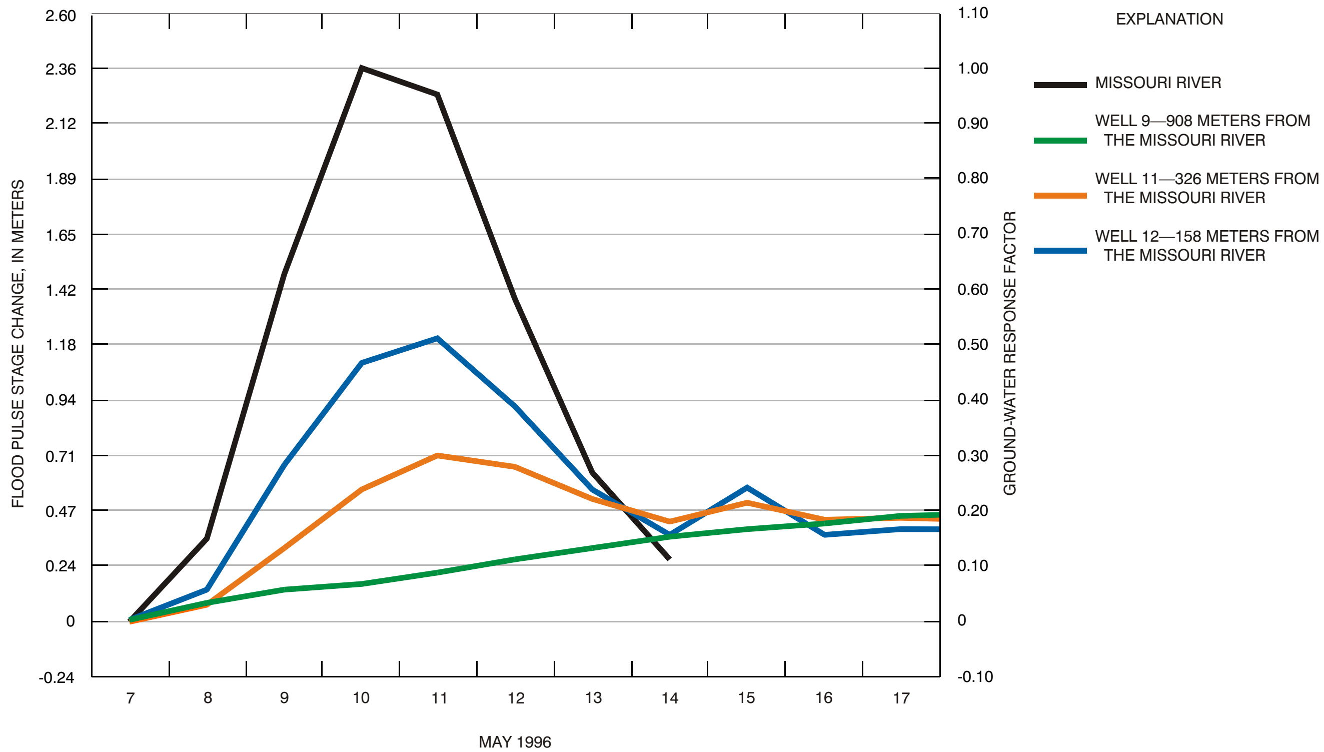

Figure 19. Seven-day, 2.36-meter flood pulse and ground-water response factor in Forest City, Missouri, wells 9, 11, and 12.

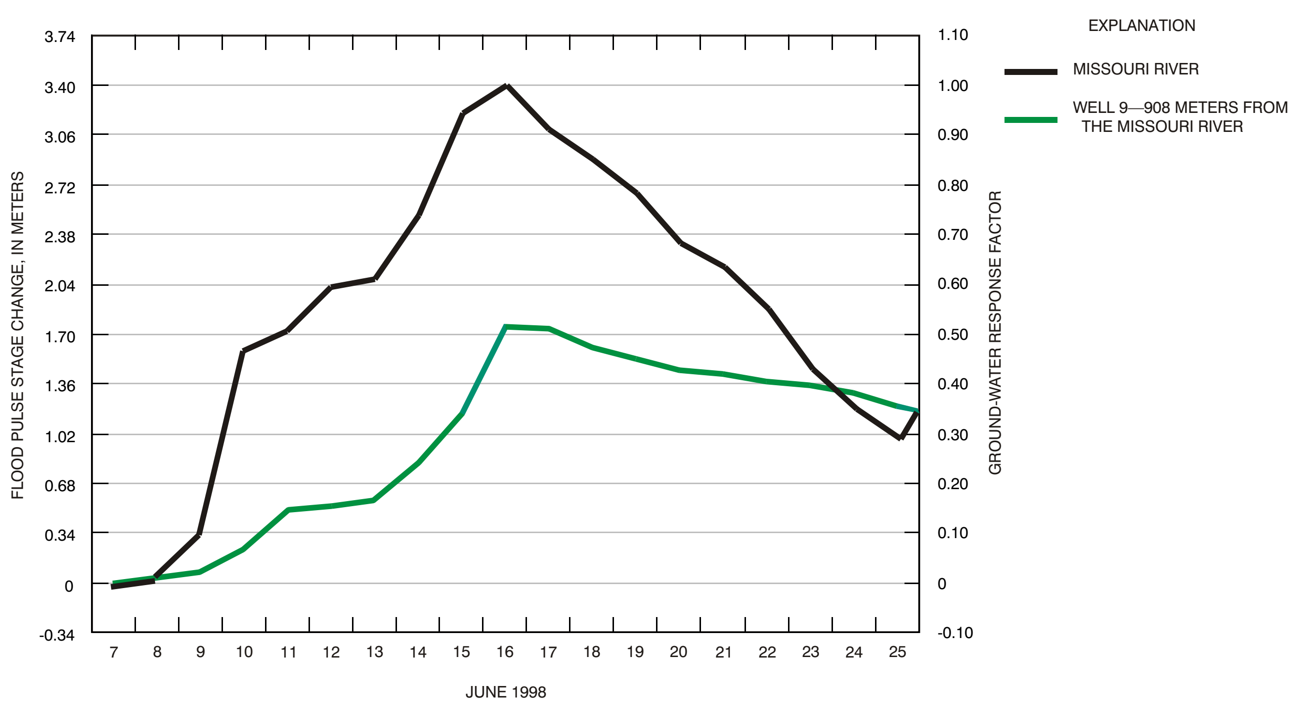

Figure 20. Eighteen-day, 3.4-meter flood pulse and ground-water response factor in Forest City, Missouri, well 9.

Table 12. Comparison of actual flood-pulse results at Forest City, Missouri, to simulated flood-pulse results

[GWRF, ground-water response factor; cm, centimeters; -, not applicable]

Flood pulse	Simulated flood-pulse duration (days)	Simulated flood-pulse magnitude (meters)	Distance from river (meters)	Day of actual maximum flood pulse	Day of actual maximum GWRF	Day of comparison	GWRF	Standard deviation of simulated GWRF	Actual GWRF minus simulated GWRF	Recharge (rain x 0.2) (cm)
Forest City Well 12 - 7 day, 2.36-meter flood pulse (fig. 19)										
Actual	-	-	158	3	4	-	0.51	-	-	1.38
Simulated	8	1	200	-	-	4	.52	0.22	-0.01	-
Simulated	8	3	200	-	-	4	.56	.22	-.05	-
Forest City Well 11 - 7 day, 2.36-meter flood pulse (fig. 19)										
Actual	-	-	326	3	4	-	0.30	-	-	1.38
Simulated	8	1	300	-	-	4	.33	0.17	-0.03	-
Simulated	8	3	300	-	-	4	.38	.19	-.08	-
Simulated	8	1	400	-	-	4	.23	.14	.07	-
Simulated	8	3	400	-	-	4	.29	.16	.01	-
Forest City Well 9 - 7 day, 2.36-meter flood pulse (fig. 19)										
Actual	-	-	908	3	10	-	0.19	-	-	1.38
Simulated	8	1	900	-	-	10	.09	0.07	0.10	-
Simulated	8	3	900	-	-	10	.12	.08	.07	-
Forest City Well 9 - 18 day, 3.4-meter flood pulse (fig. 20)										
Actual	-	-	908	9	9	-	0.51	-	-	2.09
Simulated	8	3	900	-	-	9	.11	0.08	0.40	-
Simulated	32	3	900	-	-	9	.10	.08	.41	-

The GWRF for the 18-day, 3.4-m flood pulse at Forest City well 9 was compared to the simulated GWRFs for the 8-day, 3-m and 32-day, 3-m flood pulses at the 900-m distance interval for day 9. The actual GWRF for this event is greater than the mean plus two standard deviations for each simulated GWRF with which it was compared. Precipitation records for Oregon, Missouri (National Oceanic and Atmospheric Administration, 1999) indicate 10.46 cm of precipitation fell between June 3 and June 15, 1998. The assumed 2.09 cm of recharge may have contributed to the increase in ground-water level.

The Missouri River stage near Atherton, Missouri, between April 1996 and August 1998, and the two periods selected for comparison to model results are shown in figure 21. The first period was an 18-day, 2.66-m flood pulse between May 3 and May 21, 1996, shown in figure 22. The second period was a 22-day, 1.09-m flood pulse between June 21 and July 13, 1997, shown in figure 23. Selected results from the most relevant simulated flood pulse, and the actual Atherton flood pulse, for these two periods are listed in table 13.

The GWRF for the 18-day, 2.66-m flood pulse at Atherton well 9 (120 m from the Missouri River) was compared to the simulated 8-day, 1-m and 8-day, 3-m GWRFs for the 200-m distance interval on day 8. The actual response of 0.69 was larger than, but within one standard deviation of each of, the simulated responses with which it was compared. The GWRF at Atherton well 8 (277 m from the Missouri River) was compared to the simulated 8-day, 1-m and 8-day, 3-m GWRFs for the 200- and 300-m distance intervals on day 9. The

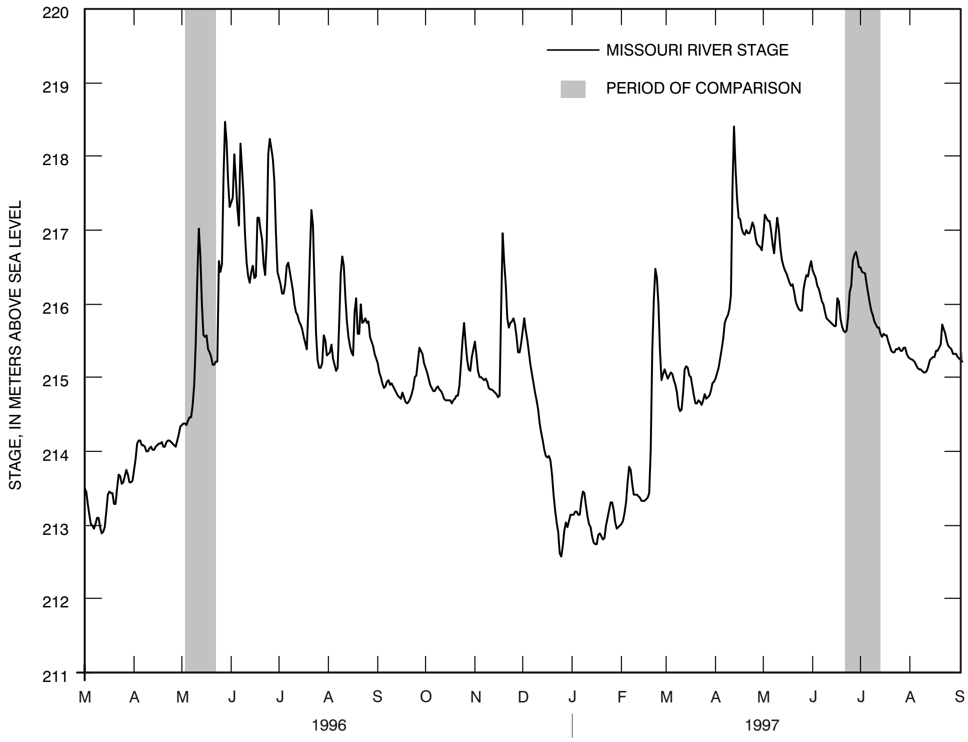

Figure 21. Missouri River stage near Atherton, Missouri, March 1996 to September 1997, and periods of comparison.

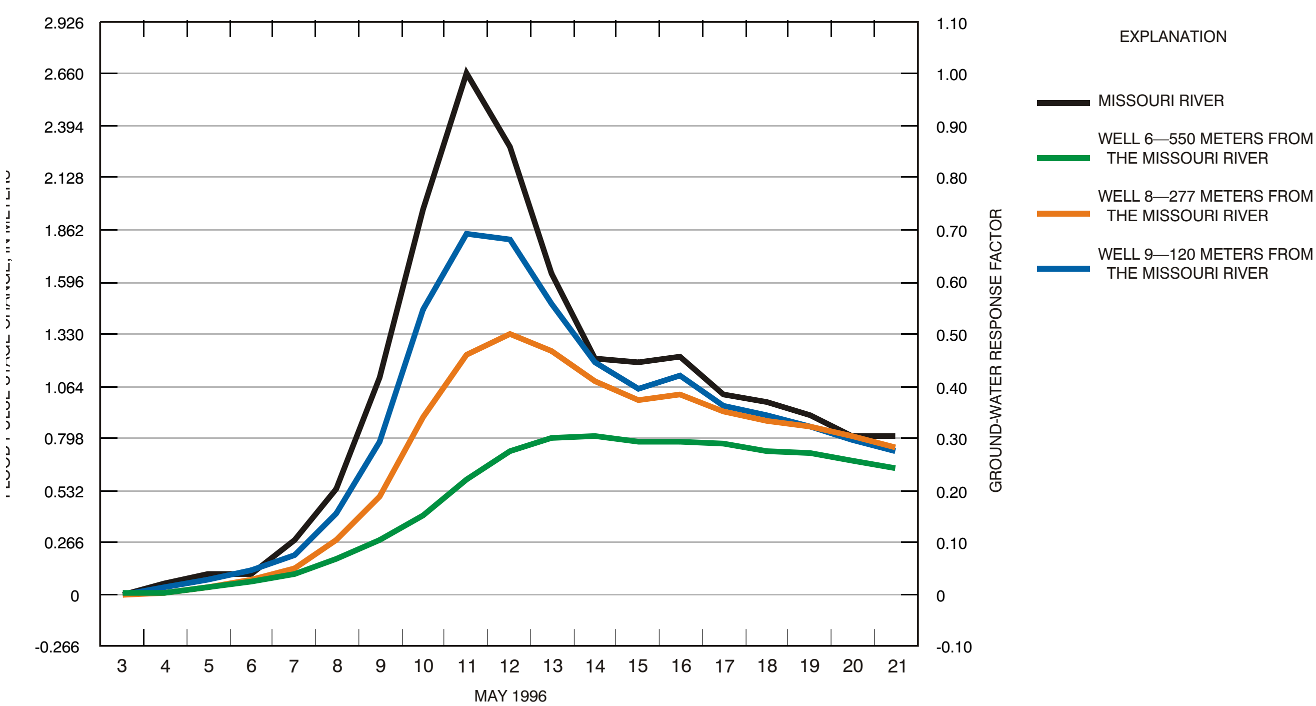

Figure 22. Eighteen-day, 2.66-meter flood pulse and ground-water response factor in Atherton, Missouri, wells 6, 8, and 9.

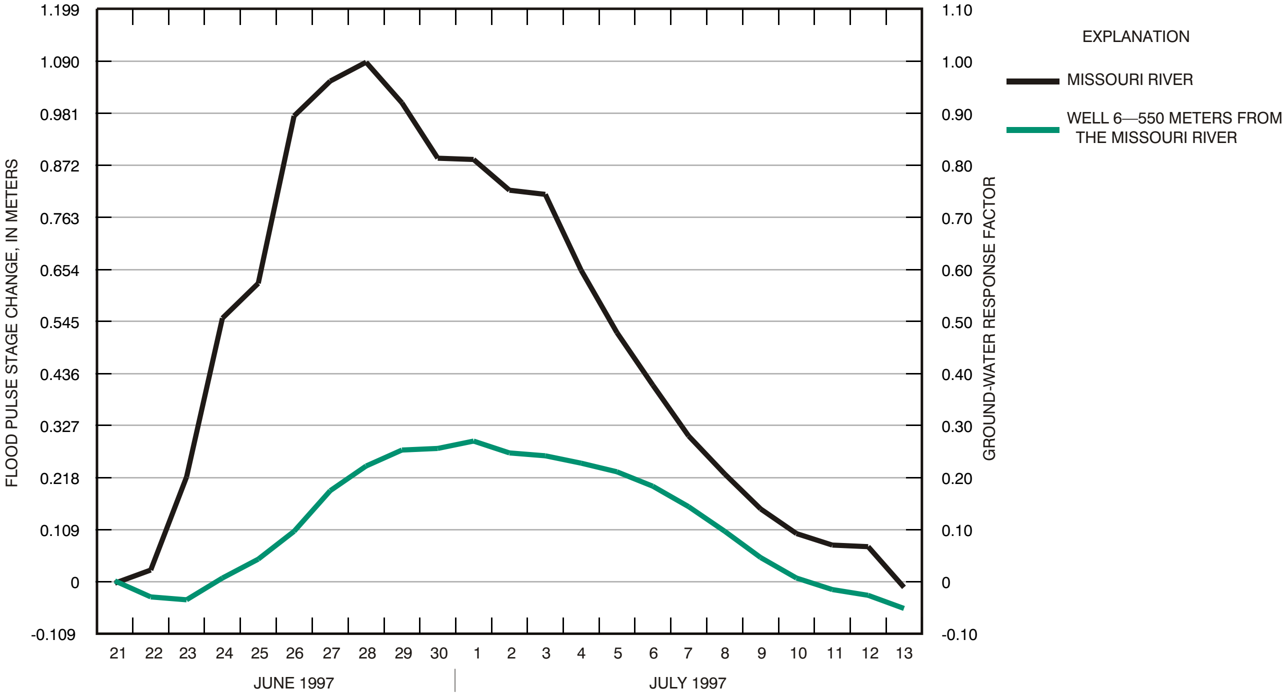

Figure 23. Twenty-two-day, 1.09-meter flood pulse and ground-water response factor in Atherton, Missouri, well 6.

actual response of 0.5 was larger than, but within two standard deviations of, each simulated GWRF with which it was compared. The GWRF at Atherton well 6 (550 m from the Missouri River) was compared to the simulated 8-day, 1-m and 8-day, 3-m GWRFs for the 500- and 600-m distance intervals on day 10. The actual response of 0.3 was larger than, but within one standard deviation of, each simulated GWRF with which it was compared. Rainfall records for Independence, Missouri, located approximately 8 miles to the southwest of Atherton, Missouri, indicate that 9.4 cm of precipitation fell between June 3 and June 11, 1996. Assuming recharge is 20 percent of precipitation and is rapidly effective, the resulting 1.88 cm of recharge may have added to the increase in ground-water levels.

The GWRF for the 22-day, 1.09-m flood pulse at Atherton well 6 (550 m from the Missouri River) was compared to the simulated 8-day, 1-m and 32-day, 1-m GWRFs for the 500- and 600-m distance intervals on day 10. The actual response of 0.27 was larger than the 8-day, 1-m GWRFs for the 500- and 600-m distance intervals and for the 32-day, 1-m GWRF for the 500-m distance interval, but less than the 32-day, 1-m GWRF for the 600-m distance interval. The actual GWRF was within one standard deviation of all the simulated GWRFs with which it was compared. Rainfall records for Independence, Missouri, indicate that 1.07 cm of precipitation fell between June 21 and June 28, 1997. The resulting 0.21 cm of recharge probably did little to affect ground-water levels, and may explain why the actual GWRF for Atherton well 6 during the 22-day, 1.09-m flood pulse was closer to the simulated responses than was the actual GWRF for Atherton well 6 during the 18-day, 2.66-m flood pulse. The larger than predicted actual GWRF is most likely caused by the presence of aquifer materials between the Missouri River and Atherton well 6 with a higher hydraulic conductivity than average for the Missouri River alluvium in the modeled area (table 11).

The Missouri River stage near Hermann, Missouri, between May 1996 and September 1996, and the two periods selected for comparison to model results are shown in figure 24. The first period was a 7-day, 1.13-m flood pulse between June 17 and June 24, 1996 shown in figure 25. The second period was a 9-day, 3.08-m flood pulse between July 20 and July 29, 1996 shown in figure 26. Selected results from the most relevant simulated flood pulse, and the actual Hermann flood pulse, for these two periods are summarized in table 14.

Table 13. Comparison of actual flood-pulse results at Atherton, Missouri, to simulated flood-pulse results

[GWRF, ground-water response factor; cm, centimeters; -, not applicable]

Flood pulse	Simulated flood-pulse duration (days)	Simulated flood-pulse magnitude (meters)	Distance from river (meters)	Day of actual maximum flood pulse	Day of actual maximum GWRF	Day of comparison	GWRF	Standard deviation of simulated GWRF	Actual GWRF minus simulated GWRF	Recharge (rain x 0.2) (cm)
Atherton Well 9 - 18 day, 2.66-meter flood pulse (fig. 22)										
Actual	-	-	120	8	8	-	0.69	-	-	1.88
Simulated	8	1	200	-	-	8	.62	0.22	0.07	-
Simulated	8	3	200	-	-	8	.65	.22	.05	-
Atherton Well 8 - 18 day, 2.66-meter flood pulse (fig. 22)										
Actual	-	-	277	8	9	-	0.50	-	-	1.88
Simulated	8	1	200	-	-	9	.32	0.12	0.18	-
Simulated	8	3	200	-	-	9	.32	.12	.18	-
Simulated	8	1	300	-	-	9	.34	.13	.16	-
Simulated	8	3	300	-	-	9	.35	.13	.15	-
Atherton Well 6 - 18 day, 2.66-meter flood pulse (fig. 22)										
Actual	-	-	550	8	10	-	0.30	-	-	1.88
Simulated	8	1	500	-	-	10	.25	0.11	0.05	-
Simulated	8	3	500	-	-	10	.26	.11	.04	-
Simulated	8	1	600	-	-	10	.20	.10	.10	-
Simulated	8	3	600	-	-	10	.22	.10	.08	-
Atherton Well 6 - 22 day, 1.09-meter flood pulse (fig. 23)										
Actual	-	-	550	7	10	-	0.27	-	-	0.21
Simulated	8	1	500	-	-	10	.25	0.11	0.02	-
Simulated	8	1	600	-	-	10	.20	.10	.07	-
Simulated	32	1	500	-	-	10	.31	.16	-.04	-
Simulated	32	1	600	-	-	10	.23	.13	.04	-

The GWRF for the 7-day, 1.13-m flood pulse at Hermann well 8 (158 m from the Missouri River) was compared to the 8-day, 1-m and 8-day, 3-m GWRFs for the 200-m distance interval on day 3. The actual response of 0.37 was less than both simulated responses, but within one standard deviation. The GWRF at Hermann well 7 (383 m from the Missouri River) was compared to the 8-day, 1-m and 8-day, 3-m GWRFs for the 300- and 400-m distance intervals on day 3. The actual response of 0.15 was less than the simulated responses, but within one standard deviation of the simulated GWRFs for the 300- and 400-m distance intervals. Rainfall records for Hermann, Missouri, indicate that 0.51 cm of precipitation fell between June 17 and June 20, 1996, (National Oceanic and Atmospheric Administration, 1999). The resulting 0.1-cm recharge probably did little to affect ground-water levels. The larger than predicted actual GWRF is most likely caused by the presence of aquifer materials between the Missouri River and Hermann well 7 with a higher hydraulic conductivity than average for the Missouri River alluvium (table 11).

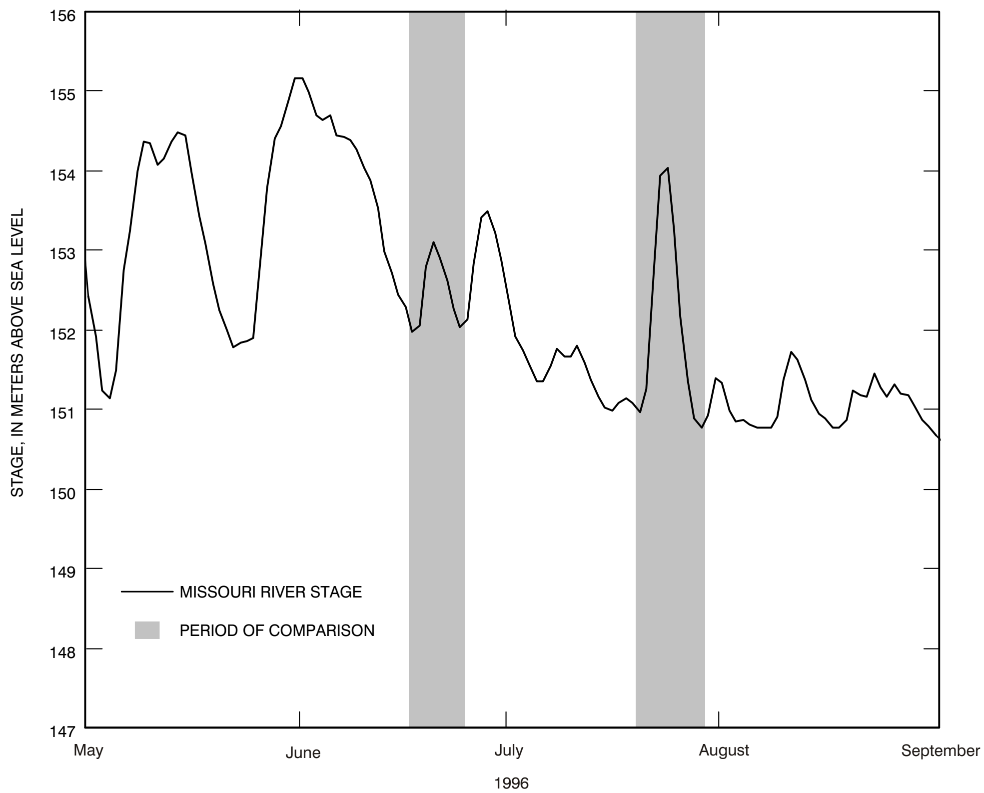

Figure 24. Missouri River stage near Hermann, Missouri, May to September 1996, and periods of comparison.

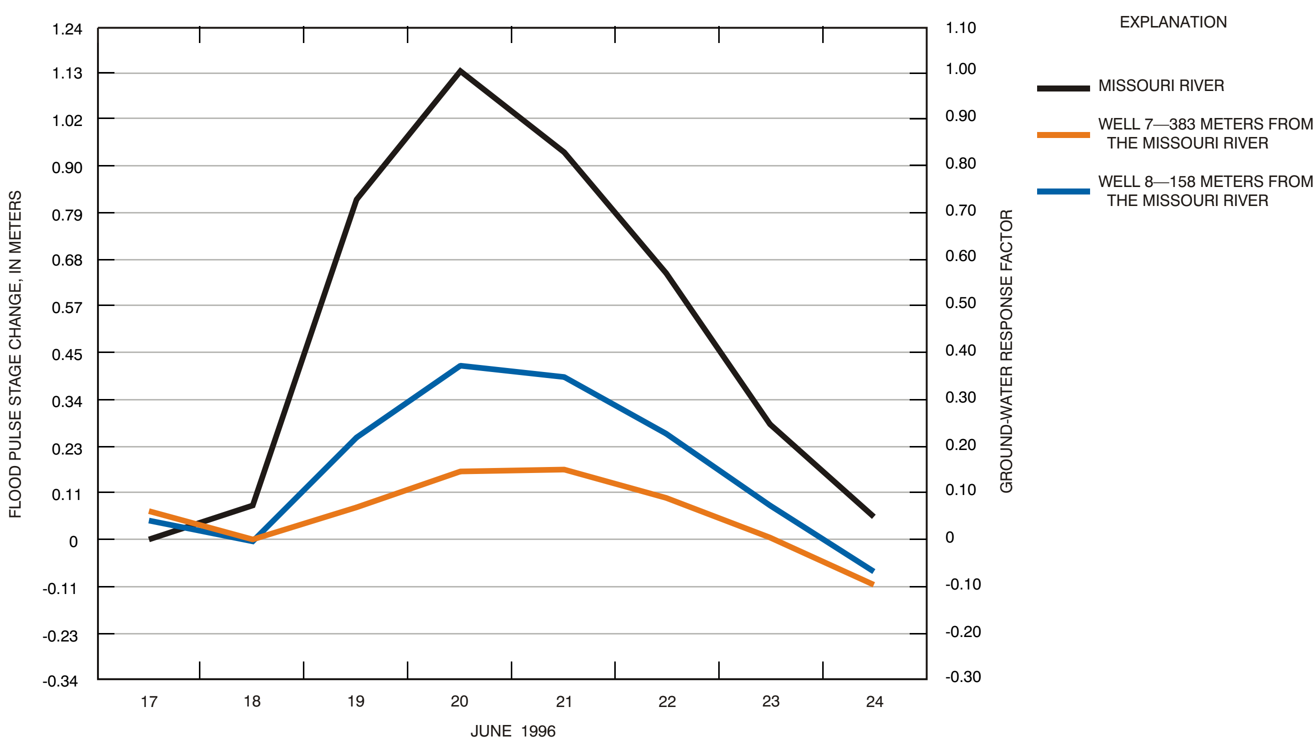

Figure 25. Seven-day, 1.13-meter flood pulse and ground-water response factor in Hermann, Missouri, wells 7 and 8.

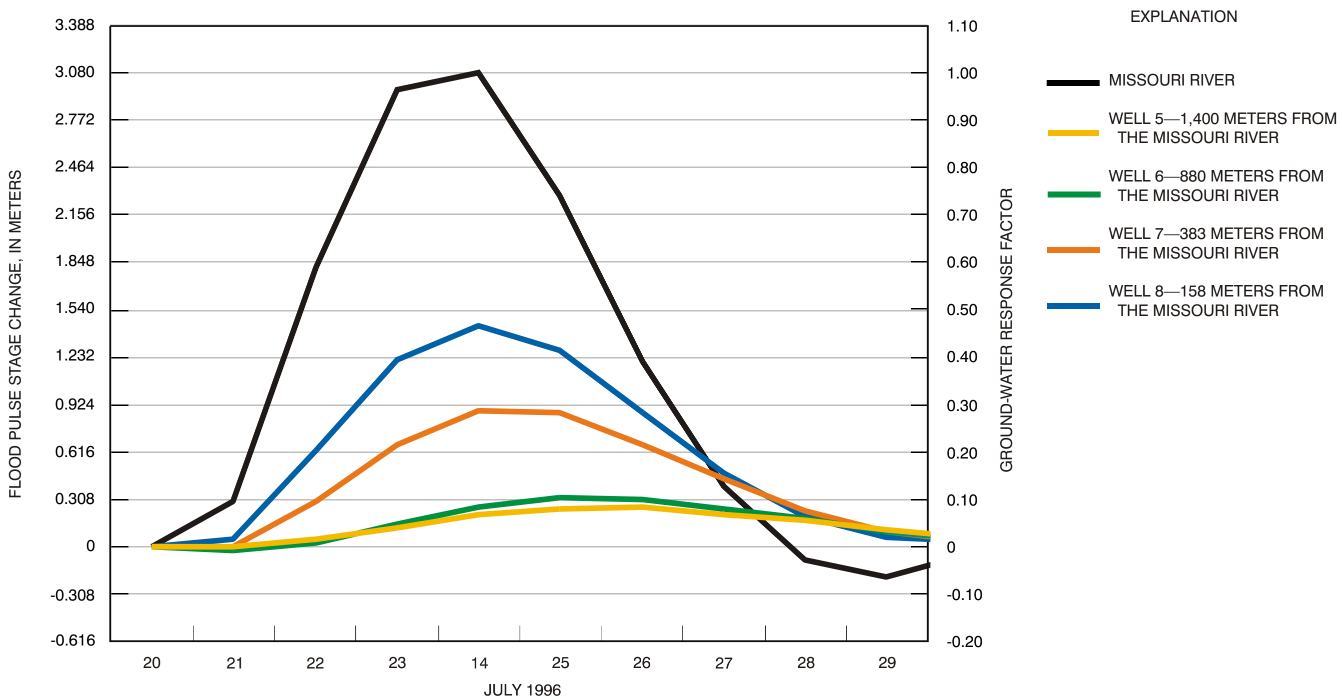

Figure 26. Nine-day, 3.08-meter flood pulse and ground-water response factor in Hermann, Missouri, wells 5, 6, 7, and 8.

The GWRF to the 9-day, 3.08-m flood pulse at Hermann well 8 (158 m from the Missouri River) was compared to the 8-day, 3-m GWRF for the 200-m distance interval on day 4. The actual response of 0.47 was less than the simulated response, but within one standard deviation. The GWRF at Hermann well 7 (383 m from the Missouri River) was compared to the 8-day, 3-m GWRFs for the 300- and 400-m distance intervals on day 4. The actual response of 0.29 was less than the simulated response for the 300-m distance interval, and greater than the simulated response for the 400-m distance interval. The actual response is within one standard deviation of both simulated responses. The GWRF at Hermann well 6 (880 m from the Missouri River) was compared to the 8-day, 3-m GWRFs for the 800- and 900-m distance intervals on day 5. The actual response of 0.1 was greater than both simulated responses, but within one standard deviation. The GWRF at Hermann well 5 (1,400 m from the Missouri River) was compared to the 8-day, 3-m GWRF for the 1,400-m distance interval on day 5. The actual response of 0.08 was greater than the simulated response plus two standard deviations. Rainfall records for Hermann, Missouri, indicate that 4.98 cm of precipitation fell between July 20 and July 24, 1996, (National Oceanic and Atmospheric Administration, 1999). The resulting 1-cm recharge, if rapidly effective, may have added to the increase in ground-water levels. In addition, the larger than predicted actual GWRF also could be caused by aquifer materials between the Missouri River and Hermann well 5 having higher hydraulic conductivity than average for the Missouri River flood plain (table 11).

Thirty-six simulated GWRFs were compared to 14 actual GWRFs calculated from measured flood pulse, ground-water-level changes. From these comparisons, 28 simulated GWRFs were within one standard deviation, 5 were within two standard deviations, and 3 were greater than two standard deviations from the actual GWRFs. The two largest differences between actual and simulated GWRFs occurred at Forest City well 9 (908 m from the Missouri River) and Hermann well 5 (1,400 m from the Missouri River) and can likely be explained by substantial rainfall and subsequent surface recharge that increased the ground-water-level change beyond that caused by the change in river stage alone. At larger distances from the river, the magnitude of ground-water-level changes in response to river-stage changes can be exceeded by ground-water-level changes caused by local surface recharge from rainfall. The comparison between the actual and simulated GWRFs indicate that the simulated GWRFs

Table 14. Comparison of actual flood-pulse results at Hermann, Missouri, to simulated flood-pulse results

[GWRF, ground-water response factor; cm, centimeters; -, not applicable]

Flood pulse	Simulated flood-pulse duration (days)	Simulated flood-pulse magnitude (meters)	Distance from river (meters)	Day of actual maximum flood pulse	Day of actual maximum GWRF	Day of comparison	GWRF	Standard deviation of simulated GWRF	Actual GWRF minus simulated GWRF	Recharge (rain x 0.2) (cm)
Hermann Well 8 - 7 day, 1.13-meter flood pulse (fig. 25)										
Actual	-	-	158	3	3	-	0.37	-	-	0.1
Simulated	8	1	200	-	-	3	.45	0.22	-0.08	-
Simulated	8	3	200	-	-	3	.52	.22	-.15	-
Hermann Well 7 - 7 day, 1.13-meter flood pulse (fig. 25)										
Actual	-	-	383	3	3	-	0.15	-	-	0.1
Simulated	8	1	300	-	-	3	.28	0.16	-0.13	-
Simulated	8	3	300	-	-	3	.33	.18	-.18	-
Simulated	8	1	400	-	-	3	.19	.13	-.04	-
Simulated	8	3	400	-	-	3	.24	.15	-.09	-
Hermann Well 8 - 9 day, 3.08-meter flood pulse (fig. 26)										
Actual	-	-	158	4	4	-	0.47	-	-	1.0
Simulated	8	3	200	-	-	4	.56	0.22	-0.09	-
Hermann Well 7 - 9 day, 3.08-meter flood pulse (fig. 26)										
Actual	-	-	383	4	4	-	0.29	-	-	1.0
Simulated	8	3	300	-	-	4	.38	0.19	-0.09	-
Simulated	8	3	400	-	-	4	.29	.16	.00	-
Hermann Well 6 - 9 day, 3.08-meter flood pulse (fig. 26)										
Actual	-	-	880	4	5	-	0.1	-	-	1.0
Simulated	8	3	800	-	-	5	.08	0.07	0.02	-
Simulated	8	3	900	-	-	5	.06	.06	.04	-
Hermann Well 5 - 9 day, 3.08-meter flood pulse (fig. 26)										
Actual	-	-	1,400	4	5	-	0.08	-	-	1.0
Simulated	8	3	1,400	-	-	5	.01	0.01	0.07	-

can provide a reasonable estimate of the actual ground-water-level change in response to river-stage change for the lower Missouri River flood plain. Tables 15 through 18 can be used for areas in the lower Missouri River flood plain where little or no data exist to estimate the impact of river-stage changes of known magnitudes and durations on ground-water levels at known distances from the river. Differences between the actual and predicted change in ground-water level can be caused by differing aquifer properties, recharge rates, and antecedent river-stage conditions. The standard deviation can provide a reasonable estimate of the uncertainty associated with the use of the GWRF to predict changes in ground-water level caused by river-stage changes.

For example, after 3 days, a flood pulse of 0.5-m magnitude and 1-day duration results in a ground-water-level change of 0.028 m at a distance of 500 m from the river (table 15):

FP x GWRF = GWLC

Where:

FP = the flood-pulse magnitude (0.5 m),
GWRF = the ground-water response factor (0.056), and
GWLC = the estimated ground-water-level change (0.028 m).

The uncertainty associated with the estimated GWLC is 0.019 m, as calculated using the standard deviation of the GWRF (table 15):

FP x STD = UNC

Where:

FP = the flood-pulse magnitude (0.5 m),
STD = the standard deviation of the GWRF (0.038), and
UNC = the uncertainty in the estimated ground-water-level change (0.019 m).

SUMMARY

In 1998, the USACE released a PRDEIS proposing eight Alternative River Management Plans (ARMP) for managing reservoir levels and water-release rates for the Missouri River. The plans include the Current Water Control Plan (CWCP), three plans that provide different levels of water conservation in the reservoirs during droughts (C18, C31, and C44), three plans that vary water-release rates to provide additional fish and wildlife benefits (FW10, FW15, and FW20), and one plan (M66) that maintains a 66,000 cubic feet per second discharge at St. Louis to provide navigation support for the Mississippi River. Objectives of this study were to compare simulated ground-water altitude and depth to ground water for the CWCP in the Missouri River flood plain near the Kansas City area between 1970 and 1980 with each river management plan proposed by the USACE, determine the average change in simulated ground-water level for selected river-stage flood pulses at selected distances from the river, and compare simulated flood-pulse, ground-water responses with actual flood-pulse, ground-water responses measured in wells located at three sites along the lower Missouri River flood plain.

Tributary inflow to the Missouri River below Gavin's Point Dam progressively increases in a downstream direction and the water released from Gavin's Point Dam becomes a smaller part of total flow in the river. The average and standard deviation of the daily difference in river stage of each plan with respect to the CWCP indicate that C18 is the most similar followed by C31, M66, C44, FW10, FW15, and FW20.

The total shallow ground-water area (depth to ground water less than 0.3048 meters) for each stress period of each ARMP simulation was determined. The percent total area of shallow ground water is similar for each ARMP because of overall similarities in the river flow between ARMPs. The most notable increase in the shallow ground-water area was the flood of 1973 when about 25 percent of the modeled area was under shallow ground-water conditions for all Alternative River Management Plans. The shallow ground-water area and the average number of days during which shallow ground-water conditions existed were determined for each month of each ARMP simulation. These data are useful for assessing the differences between each ARMP and the CWCP with respect to the number of days per month during which areas of shallow ground water are present. The change in shallow ground-water area and the average number of days per month during which the change in shallow ground-water conditions existed were determined. These data are useful for assessing the monthly differences between each ARMP and the CWCP and indicate large differences can exist between the ARMPs in both the duration and extent of areas with shallow ground water. The standard deviation of the daily difference in shallow ground-water area between 1970 and 1980 between each ARMP and the CWCP show that C18 is the most similar followed by C31, M66, C44, FW10, FW15, and FW20. The timing of the rise or fall of ground-water levels can be as important as the magnitude of the rise or fall. Alternative River Management Plans C18, C31, C44, and M66 do not cause large changes in the percent area of shallow ground water. FW10 and FW15 each cause a spring increase and a summer decrease in the shallow ground-water area. FW20 has a larger spring increase in the shallow ground-water area, but the largest decrease is delayed into November.

A series of 12 flood pulses of 0.5-, 1-, and 3-meters in magnitude and 1-, 8-, 32-, and 128-days in duration were simulated using the ground-water-flow model. A ground-water response factor (GWRF, defined as the change in ground-water level at a known distance from the river, divided by the magnitude of the flood pulse, at a specified time after the beginning of a flood pulse), was calculated for selected distances from the river daily. The GWRF can be multiplied by a flood pulse of any magnitude to obtain an estimated ground-water-level change at various distances from the river. Flood pulses with shorter durations have a smaller GWRF at a given distance than those with a longer duration. For flood pulses of the same duration, the greater the magnitude of the flood pulse, the greater the initial GWRF. However, as the duration of the flood pulse increases, the GWRF at a specified distance becomes more similar between flood pulses of the same duration, but different magnitude. For a GWRF at a given distance for a given flood pulse, ground-water levels rise continuously during the flood pulse, especially at shorter distances from the river. At farther distances, ground-water levels may continue to rise for some time after the flood pulse has ended. Beyond a distance of between 400 to 600 meters from the river, the greatest GWRF occurs at least one day or more after the flood pulse has ended. During each flood pulse, the largest GWRF occurs nearest the river. With increasing time after the flood pulse ends, the largest GWRF occurs at farther distances from the river, and decreases in magnitude. These results indicate the relatively small impact on ground-water levels of small river-stage fluctuations of short duration as might occur daily or weekly. The larger impact on ground-water levels of larger river-stage increases of longer duration indicate the importance of river management flow releases, seasonal changes in river flow, and the effects of continuous high-river stage for long periods on ground-water levels of the lower Missouri River flood plain.

Transmissivities used in the ground-water flow model of the Missouri River flood plain near Kansas City range from 0.017 to 16,915.5 square meters per day. Transmissivities listed from selected studies for the lower Missouri River range from 32 to 8,197 square meters per day. The range of transmissivities measured in the lower Missouri River flood plain range over three orders of magnitude and fall well within the values used in the ground-water flow model indicating that hydrologic properties in the model area are typical of the lower Missouri River flood plain. Therefore, GWRFs determined using the ground-water flow model should be transferable to other parts of the lower Missouri River flood plain for estimating ground-water level changes in response to river-stage changes.

A comparison of model-derived GWRFs from the Kansas City area to GWRFs calculated from measured river stage and well hydrographs for three sites on the lower Missouri River flood plain was done for similar flood pulses. Thirty-six simulated GWRFs were compared to 14 actual GWRFs calculated from measured flood pulse and ground-water-level changes. From these comparisons, 28 simulated GWRFs were within one standard deviation, 5 were within two standard deviations, and 3 were greater than two standard deviations from the actual GWRF. Recharge from precipitation, in addition to the presence of aquifer material with higher than average hydraulic conductivity between the river and the measured wells, probably accounts for those measured ground-water responses larger than the simulated ground-water responses. The comparison between the actual and simulated GWRFs indicate that the simulated GWRFs can provide a reasonable estimate of the actual ground-water-level change in response to river-stage change for the lower Missouri River flood plain. The standard deviations can provide a reasonable estimate of the uncertainty associated with the use of the GWRF to predict changes in ground-water level caused by river-stage changes.

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