HYDROLOGIC AND GEOMORPHIC STUDIES OF THE PLATTE RIVER BASIN

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1277

Hydrologic and Geomorphic Studies of the Platte River Basin

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1277

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1983

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, *Secretary*

GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publication Data
United States. Geological Survey.
Main entry under title:
Hydrologic and geomorphic studies of the Platte River basin.
(Geological Survey Professional Paper ; 1277)
Bibliography: 258 p.
Supt. of Docs. No.: I 19.16:1277–A
Contents: Hydrologic and morphologic changes in the channels of the Platte River basin, a historical perspective/by T. R. Eschner, R. F. Hadley, and K.D. Crowley—Effects of water development on surface-water hydrology, Platte River basin in Colorado, Wyoming, and Nebraska upstream from Duncan, Nebraska/by J. E. Kircher and M. R. Karlinger—Hydraulic geometry of the Platte River near Overton, south-central Nebraska, by T. R. Eschner—[etc.]
1. Hydrology—Nebraska—Platte river Watershed—Addresses, essays, lectures. 2. Geomorphology—Nebraska—Platte River Watershed—Addresses, essays, lectures. 3. Hydrology—North Platte River Watershed—Addresses, essays, lectures. 4. Geomorphology—North Platte River Watershed—Addresses, essays, lectures. 5. Hydrology—South Platte River Watershed (Colo. and Neb.)—Addresses, essays, lectures. 6. Geomorphology—South Platte River Watershed (Colo. and Neb.)—Addresses, essays, lectures.
I. Geological Survey (U.S.) II. Series.
CB705.N2H93 1983 551.48'3'09782 83–600013

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

PREFACE

The channels of the Platte River and its major tributaries, the South Platte and North Platte Rivers in Colorado, Wyoming, and Nebraska, have undergone major changes in hydrologic regime and morphology since about 1860, when the water resources of the basin began to be developed for agricultural, municipal, and industrial uses. These water uses have continued to increase with growth in population and land development. Diversion of flow from channels, storage of water in reservoirs, and increased use of ground water have affected the distribution and timing of streamflows and the transport of fluvial sediments. All these factors have contributed to changes in channel geometry and the riverine environment.

In 1979, the U.S. Geological Survey began investigations in the Platte River basin to determine the effects of water use on the hydrology and morphology of the Platte River and its major tributaries. These investigations also considered the relationship of hydrologic regime to factors that control or affect the habitat of migratory waterfowl in the Platte River valley.

This volume brings together the results of several research studies on historical changes in channel morphology, surface-water hydrology, hydraulic geometry, sediment-transport and bedform processes, ground-water and surface-water relations, stochastic models of streamflow and precipitation, and methods for estimating discharge required to maintain channel width. In each of the studies, data on some segment of the Platte River hydrologic system were collected and interpreted. All the studies are interrelated; together they provide some degree of understanding of regime changes that are occurring. The hydrologic research described in the following chapters will be useful in decision-making pertaining to the management of water resources and migratory waterfowl habitats.

TABLES

CONTENTS

[Letters designate the chapters]

Hydrologic and Morphologic Changes in Channels of the Platte River Basin in Colorado, Wyoming, and Nebraska: A Historical Perspective

By THOMAS R. ESCHNER, RICHARD F. HADLEY, *and* KEVIN D. CROWLEY

HYDROLOGIC AND GEOMORPHIC STUDIES OF THE PLATTE RIVER BASIN

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1277-A

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1983

CONTENTS

ILLUSTRATIONS

HYDROLOGIC AND MORPHOLOGIC CHANGES IN CHANNELS OF THE PLATTE RIVER BASIN IN COLORADO, WYOMING, AND NEBRASKA: A HISTORICAL PERSPECTIVE

By THOMAS R. ESCHNER, RICHARD F. HADLEY, and KEVIN D. CROWLEY

ABSTRACT

The channels of the Platte River and its major tributaries, the South Platte and North Platte Rivers in Colorado, Wyoming, and Nebraska, have undergone major changes in hydrologic regime and morphology since 1860. These changes are attributed here to agricultural, municipal, and industrial water use.

Although water-resource development varied temporally throughout the basin, the history of development along the Platte River and tributaries followed four stages: (1) Construction of small, crude ditches to irrigate flood plains; (2) constuction of larger canals to irrigate bench lands; (3) construction of reservoirs to store snowmelt runoff; and (4) accelerated development of ground-water resources. Despite differences in rates of development, diversion and storage of water for irrigation, municipal, and industrial use have changed streamflow patterns throughout the basin. At some stations, significant changes in flood peaks, annual mean discharges, and shapes of flow-duration curves have been recorded.

Changes in streamflow patterns are manifested by changes in appearance of channels of the Platte River. Prior to water development in the 19th century, the Platte was a wide (~2- kilometer), shallow (1.8- to 2.4-meter) river characterized by bankfull spring flows and low summer flows. Although timber generally was scarce in the valley, the Platte channels contained hundreds of small, timbered islands. Since development, the channels have changed radically. A comparison of surveyor's maps (General Land Office), drawn during the 1860's, with six sets of aerial photographs, taken between 1938 and 1979, for six 5-kilometer reaches of the rivers shows that the channels have narrowed considerably above the confluence with the Loup River. Above the confluence with the Loup River, the width of the channels in 1979 ranged from 8 to 50 percent of the channel width in 1860, whereas below the confluence with the Loup River, the width of the river in 1979 was about 92 percent of the channel width in 1860. Above the confluence with the Loup River, width reduction has occurred by progressive encroachment of vegetation and consequent vertical and horizonatal accretion on sandbars in the channel. Vegetative encroachment on sandbars has occurred becaused (1) the present hydrologic regime provides more favorable conditions for germination and growth on sandbars, and (2) since development of the basin, flood peaks are no longer capable of scouring vegetation from the sandbars. Overbank flows evidently have become more common, probably because channel narrowing and vegetative encroachment have increased the hydraulic roughness of the channels. Moreover, the magnitude of low flows has increased and the days of no flows have decreased giving the channels a more perennial character.

INTRODUCTION

The Platte River and its tributaries in Colorado, Wyoming, and Nebraska (fig. 1) are typical of many Great Plains streams that originate in the Rocky Mountains. Much of the flow in the North Platte, South Platte, and Platte Rivers is derived from spring snowmelt in the mountains. Because the plains are semiarid to subhumid, most of the flow has been appropriated for irrigation of agricultural crops, municipal use, and industrial development. These rivers have been an integral part of the economy in the Platte River basin since the middle of the 19th century.

Migratory waterfowl also use the river and adjacent farmlands in the Platte River valley of central Nebraska during their annual migration stopover in February and March. An estimated 70 to 80 percent of the world's lesser sandhill cranes and a small number of rare whooping cranes use the river valley between Overton and Grand Island, Nebraska, on their way to Canada and Siberia each year (Frith, 1974).

Concern for the habitat of sandhill cranes, whooping cranes, and other migratory-bird species prompted wildlife managers to document the changes that have occurred in the river channels since settlement of the valley and the effects of these changes on wildlife habitat. In 1979, a study was begun in the Platte River basin that included hydrologic investigations by the U.S. Geological Survey. An integral part of these investigations is this review of the history of water development in the basin and the effects of water use and land use on the hydrology and morphology of the Platte River and its major tributaries. Site-specific investigations were centered on the critical migratory-bird habitat in a 96-km (kilometer) reach of the Platte River between Overton and Grand Island, in south-central Nebraska. This paper presents an overview of the channel changes along the Platte River.

ACKNOWLEDGMENTS

The historical information in this report was excerpted from emigrant journals, expedition accounts, early photographs, and maps. The authors wish to thank the Grand Island, Nebraska Office of the U.S. Bureau of Reclamation; U.S. Geological Survey, Water Resources Division, Nebraska District; Burlington Northern Railroad; the Dawson County Historical Society; the Nebraska State Engineers Office; the Smithsonian Institution; and the Union Pacific Railroad for their assistance in locating maps, photographs, and river cross sections. Joseph Jeffrey, Norman Jeffrey, Emil Roeser, and personnel from the Colorado Historical Society, Denver Public Library, and Nebraska State Historical Society assisted in obtaining early descriptions of the Platte River valley. F. B. Shaffer provided unpublished information about reservoir capacity.

Carl F. Nordin, Jr. and Stanley A. Schumm read parts of an earlier manuscript. The manuscript was improved, both technically and editorially, by comments and suggestions in reviews by John E. Costa, Michael J. Ellis, William M. Kastner, and Garnett P. Williams. In addition, Garnett P. Williams provided many thought-provoking discussions. The sequence of tracings of maps and aerial photographs were prepared by Kenneth B. Rennick. Part of this research was conducted by the senior author while he was funded by a National Science Foundation grant.

DESCRIPTION OF THE AREA

The Platte River and its major tributaries, the North Platte and South Platte Rivers, have a drainage area of about 222,740 km^2 (square kilometers) in Colorado, Wyoming, and Nebraska. The North Platte River originates in the mountains of northern Colorado, flows northward into central Wyoming, then southeastward to Nebraska. In west-central Nebraska, the river joins the South Platte River to form the Platte River (fig. 1). The South Platte River originates in the mountains of central Colorado and flows northeastward across the eastern Colorado plains into Nebraska to meet the North Platte River (fig. 1).

Most of the flow in the Platte River system above the Loup River is derived from spring snowmelt in the Rocky Mountains. Precipitation on the Great Plains, which ranges from 330 to 635 mm (millimeters), contributes additional water to the channels. Irrigation of agricultural lands is the major water use in the basin; surface water is stored in reservoirs and diverted from channels to canals for irrigation, for municipal use, for power generation. Ground water is developed extensively in the basin.

DEVELOPMENT OF IRRIGATION IN THE PLATTE RIVER BASIN

Development of irrigation in the Platte River basin has had significant effects on the hydrology of the river. Not all of these effects have been documented owing to a lack of long-term hydrologic records. The earliest streamflow records date from 1891. Systematic flow records date from 1930. To understand the changes in hydrology that occurred prior to 1930, the history of irrigation development in the basin is reconstructed from records of canal construction and other available information.

Although irrigation development varied temporally throughout the basin, the history of development along the Platte River and tributaries followed four general stages. Each stage produced a different effect on river hydrology. The first stage represents the earliest period of irrigation. It was characterized by construction of small, crude ditches to irrigate irregular patches of land on the flood plains. The second stage was characterized by construction of larger and more sophisticted canals and ditches to irrigate lands on benches above the valley floor. The amount of water appropriated to these canals usually exceeded the summer flows of the river. Thus, canals with later water rights were unable to divert water during the irrigation season. Many canals were abandoned, and the number of new appropriations granted was reduced or eliminated.

The third stage was characterized by the construction of reservoirs to store water from snowmelt runoff. During this stage, many of the canals abandoned previously were reopened. Many new canals were constructed, and existing canals were enlarged. Summer flows were overappropriated during most of stage 3, and new claims for water each year exceeded the amount of water available in the basin. The fourth stage marked the end of canal construction in the basin. Dam construction continued, but at a slower pace, and water impounded above these structures was used to satisfy existing water rights and new municipal demands for water and power. New demands for irrigation water were satisfied with ground water; stage 4 marked the beginning of large-scale ground-water withdrawals in the basin.

Irrigation development has been documented in the reports of the State Engineers of Colorado, Nebraska, and Wyoming (State of Colorado, 1883/1884 to 1925/1926; State of Nebraska, 1913/1914 to 1917/1918; State of Nebraska, 1919/1920 to 1931/1932; State of Wyoming, 1889–1931). Early record keeping was sporadic,

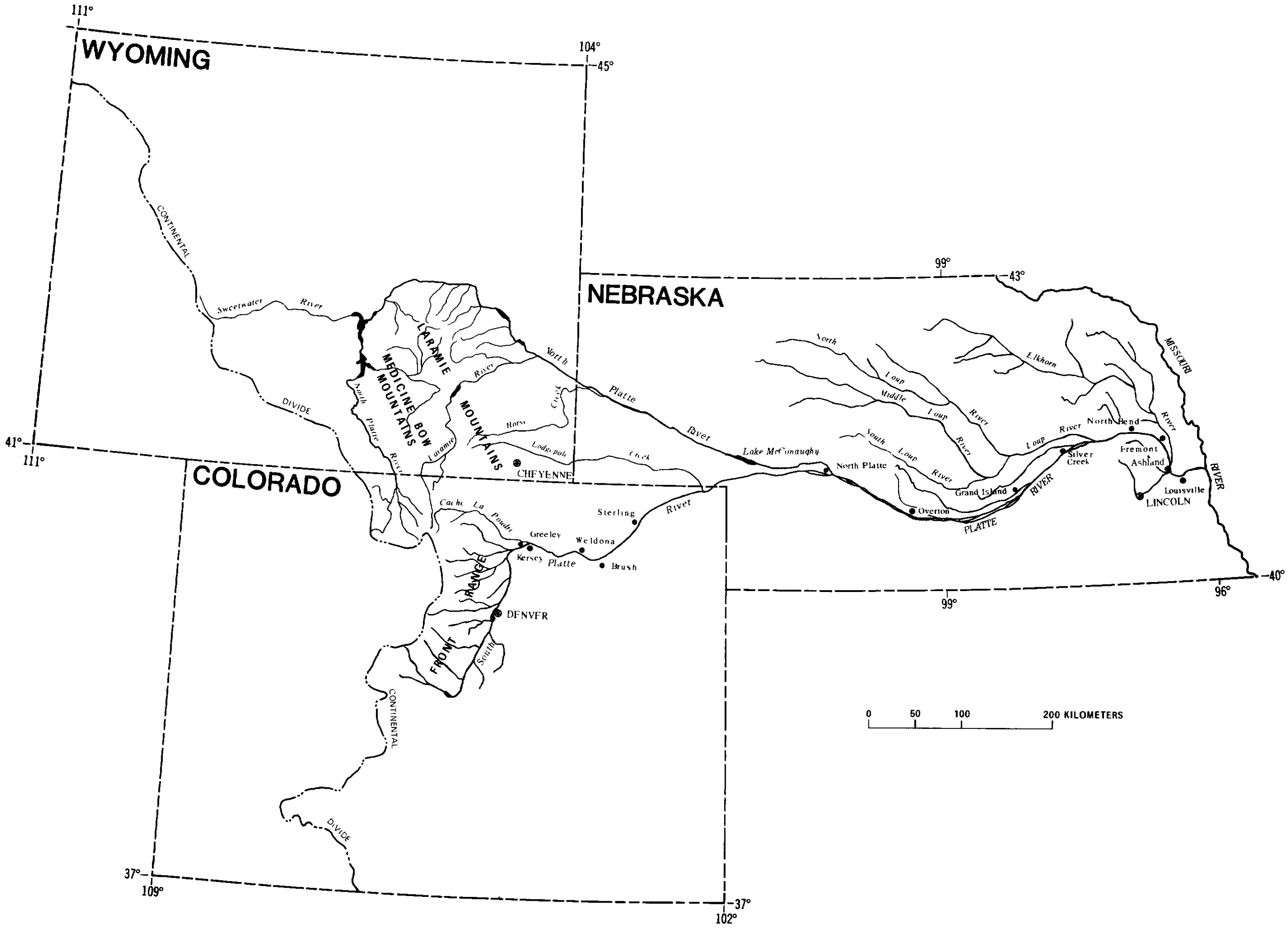


FIGURE 1.—The Platte River basin in Colorado, Wyoming, and Nebraska.

and few diversion data are available prior to 1930. Water-right adjudication records (which list the date of appropriation for each canal, usually coincident with the date of construction or enlargement) and the amount of water appropriated to each canal can be used to infer in a qualitative sense when changes in streamflow occurred. For example, during a period when hundreds of canal appropriations were granted in the basin, more consumptive use of surface water would be expected. When streamflow became overappropriated, the number of new appropriations granted should decrease. Thus, canal-appropriation records should indicate: (1) When streamflow changes caused by canal diversions began; and (2) the approximate date when summer flows were overappropriated in the basin. Comparisons of adjudication and dam-construction records with several written reports of the State Engineers suggest that canal-construction activity can be used to indicate these changes.

Similarly, few storage data exist for most of the reservoirs that were constructed in the basin prior to 1910. However, the date of closure and the usable storage capacity of each reservoir can be used to reconstruct stream flow trends. For example, the beginning of large-scale reservoir construction in the basin probably marks the date of streamflow overappropriation. This date serves as a reliable check on the overappropriation date indicated by canal-appropriation records. Moreover, certain streamflow parameters, such as peak flows, are affected by reservoir construction.

SOUTH PLATTE RIVER AND TRIBUTARIES

The South Platte River and tributaries were the focus of the earliest and most extensive irrigation development in the Platte River basin. Irrigation in the basin was first practiced by Antoine Janis, who diverted water from the Cache la Poudre River 1838 (Steinel and Working, 1926) or 1844 (Rohwer, 1953). The first ditches were small and crude; irrigated lands were confined to the flood plain. Construction of the small canals proceeded at a slow pace until about 1860. Prior to 1860, 28 appropriations were granted for canals in the South Platte River basin (table 1). The period 1840–1860 may be considered stage 1 in the development of irrigation in the South Platte River basin.

The initial impetus for large-scale development of irrigation was the influx of population at the time of the discovery of gold in the mountains west of Denver in 1858. Water-right number one in the South Platte River basin dates from 1859 on Bear Creek (table 1). In the next decade, numerous small projects were begun and irrigation was important enough by 1861 that the legislature passed a law allowing landowners access to water whether or not their land was immediately adjacent to the stream. The establishment of the Greeley Colony in 1870 marked the beginning of construction of large canals (McKinnon, 1952). This experiment demonstrated the potential value of bench or terrace land, and it may have served as a catalyst for the formation of other large canal companies. Beginning in 1874, corporations were formed to finance large-scale canal projects. A period of increased construction began that lasted until 1890. Between 1861 and 1870, 376 canals were constructed; 533 canals were constructed between 1871 and 1880, and 364 canals were constructed between 1881 and 1890 (table 1).

Appropriations granted to these canals exceeded the available water in the basin during the summer. How-

TABLE 1.—*History of canal construction in the Platte River basin, 1851–1930*[1]

River	Number of new canals constructed or existing canals enlarged[2]								Date of earliest canal[3]
	1851–1860	1861–1870	1871–1880	1881–1890	1891–1900	1901–1910	1911–1920	1921–1930	
South Platte River basin									
Cache la Poudre River and tributaries	1	37	85	37	1	46	14	7	1860
Lodgepole Creek and tributaries	0	0	31	75	28	26	10	13	1873
Big Thompson River and tributaries	0	32	29	6	0	8	3	2	1861
Bear Creek and tributaries	2	22	4	3	0	3	7	14	1859
South Platte River and tributaries below mouth of the Cache la Poudre River, except Lodgepole Creek	0	21	61	104	28	126	55	32	1868
South Platte River and minor tributaries above mouth of the Cache la Poudre	25	264	323	139	6	104	52	28	1860
Total, South Platte basin	28	376	533	364	63	313	141	96	
North Platte River basin									
Big Laramie River and tributaries	0	8	98	467	148	263	119	29	1868
Sweetwater River and tributaries	0	0	2	43	55	117	46	17	1880
North Platte River, Nebraska	0	0	0	16	36	5	7	1	1888
Tributaries to North Platte River, Nebraska	0	0	0	19	51	30	24	13	
North Platte River, Wyoming	0	0	2	32	15	47	25	17	1875
Tributaries to North Platte River, Wyoming, except Sweetwater and Big Laramie River	0	9	91	740	410	801	436	161	
North Platte River and minor tributaries, Colorado	0	0	1	310	10	128	75	11	1880
Total, North Platte basin	0	17	194	1,627	725	1,391	732	249	
Platte River basin (except North and South Platte)									
Platte River tributaries above the Loup River	0	0	0	1	3	0	6	53	
Platte River above the Loup River	0	0	0	2	7	0	3	16	1882
Total, Platte basin above the Loup River	0	0	0	3	10	0	9	69	

[1]Data compiled from Biennial Reports of the State Engineer of Colorado, 1883–1926; unpublished data from the files of the State Engineer of Colorado in Denver; Biennial Reports of the Department of Water Resources, Nebraska, 1913–1932; 2nd Annual Report of the Territorial Engineer, Wyoming, 1889; Biennial Reports of the State Engineer of Wyoming, 1893–1930; Tabulation of Adjudicated Water Rights, State of Wyoming, Water Division Number One, 1965.
[2]Numbers are based on appropriations to new canals or additional appropriations to existing canals exceeding 0.3 cubic meter per second.
[3]Based on recorded date of appropriation decree.

ever, it is difficult to pinpoint the exact year in which summer flows in the South Platte River basin were overappropriated, because development activity varied between the tributaries. For example, the earliest record of overappropriation occurred in the Cache la Poudre basin in 1876. Irrigation reports by the State Engineer of Colorado during the early 1880's indicate that most of the canals holding appropriation decrees received water during all but the driest years. By 1885, approximately 710 m^3/s (cubic meters per second) were appropriated in the South Platte River basin (State of Colorado, 1886). Although not all canals granted appropriations were diverting water, summer flows were nevertheless overappropriated. Thus, overappropriation of summer flows in the South Platte River basin occurred between 1880 and 1885, marking the end of stage 2.

Dams were built to increase available irrigation water. The earliest reservoirs impounded less than 6.2 hm^3 (cubic hectometers) in the basin in 1868. The dams were small structures built in natural depressions along or across small tributaries. Large-scale construction of dams in the basin began during the early 1880's (table 2). Canal-construction activity declined during the decade 1890–1900 (63 constructed) and increased again after 1900. Canal construction declined again after 1910. Construction of dams did not completely eliminate overappropriation of summer flows. In 1911–1912, for example, only canals with appropriation decrees of 1882 or older received water during the highest flows in June. In the same years, new claims for water totaling 784 m^3/s were made (State of Colorado, 1914).

Although present storage is double that of 1912 (fig. 2), only a minor amount of the increase has been for irrigation. Dam construction declined during the 1920's, increased slightly during the early 1930's, and declined afterward. Most of the reservoirs impounded after 1930 were for new municipal water supplies and for flood control and recreation. Little canal-construction activity occurred after 1930. New demands for irrigation water were satisfied with ground water. Thus, 1930 marks the end of stage 3 and the beginning of stage 4 in the South Platte River basin.

Diversion of surface water from the Colorado River basin and North Platte River basin provided additional water for the South Platte River basin. The earliest of these transbasin diversions was begun in the early 1890's. Importation of water increased gradually from completion of the first structures to 1947, when the Alva B. Adams Tunnel, which imports water from the Colorado River basin, was completed. The large increase in imports of water after 1947 is shown in figure 3. Average annual diversions in 1974 totaled 460 hm^3 (Gerlek, 1977).

Use of ground water for irrigation dates from 1885, from an area near Eaton, Colorado (Rohwer, 1953). Extensive development of pump irrigation did not begin until 1910. The number of irrigation wells in the South Platte River basin increased slowly to a total of about 735 by 1933. The drought years of the mid-1930's saw the number of wells almost triple, to 2,000. The use of ground water for irrigation has continued to increase in importance with time (Hurr, 1975).

NORTH PLATTE RIVER AND TRIBUTARIES

Irrigation development along the North Platte River and tributaries had an early history similar to that of the South Platte River basin. Irrigation was practiced in the vicinity of Fort Laramie as early as 1847 (McKinley, 1938). Throughout the 1850's and 1860's, small-scale irrigation projects flourished near military outposts, commonly to provide produce for emigrants.

Unlike Colorado, Wyoming did not experience a mineral-exploration boom in the late 1850's; the dominant industries in Wyoming during this period were grazing and agriculture. Although canals were built to irrigate farmland, grazing land did not require irrigation water. Thus, canal construction proceeded slowly during the 1860's and early 1870's. The period 1850–1870

TABLE 2.—*History of reservoir capacity in the Platte River basin*[1]

Basin	New usable storage, in cubic hectometers												
	1851-1860	1861-1870	1871-1880	1881-1890	1891-1900	1901-1910	1911-1920	1921-1930	1931-1940	1941-1950	1951-1960	1961-1970	1971-1980
South Platte River basin	0	0	8.7	142.2	167.5	535.3	102.6	0	186.5	118.3	76.0	0	539.0
North Platte River basin	0	0	0	0	11.6	1,408.0	97.7	79.2	1,646.8	2,402.9	969.9	0	0
Platte River above Loup River	0	0	0	0	0	0	0	0	53.9	0	0	0	0

[1]Data from Martin and Hanson, 1966; F. B. Schaffer, Conservation and Survey Division, University of Nebraska, written commun., 1979 (for reservoirs in excess of 6.2 cubic hectometers).

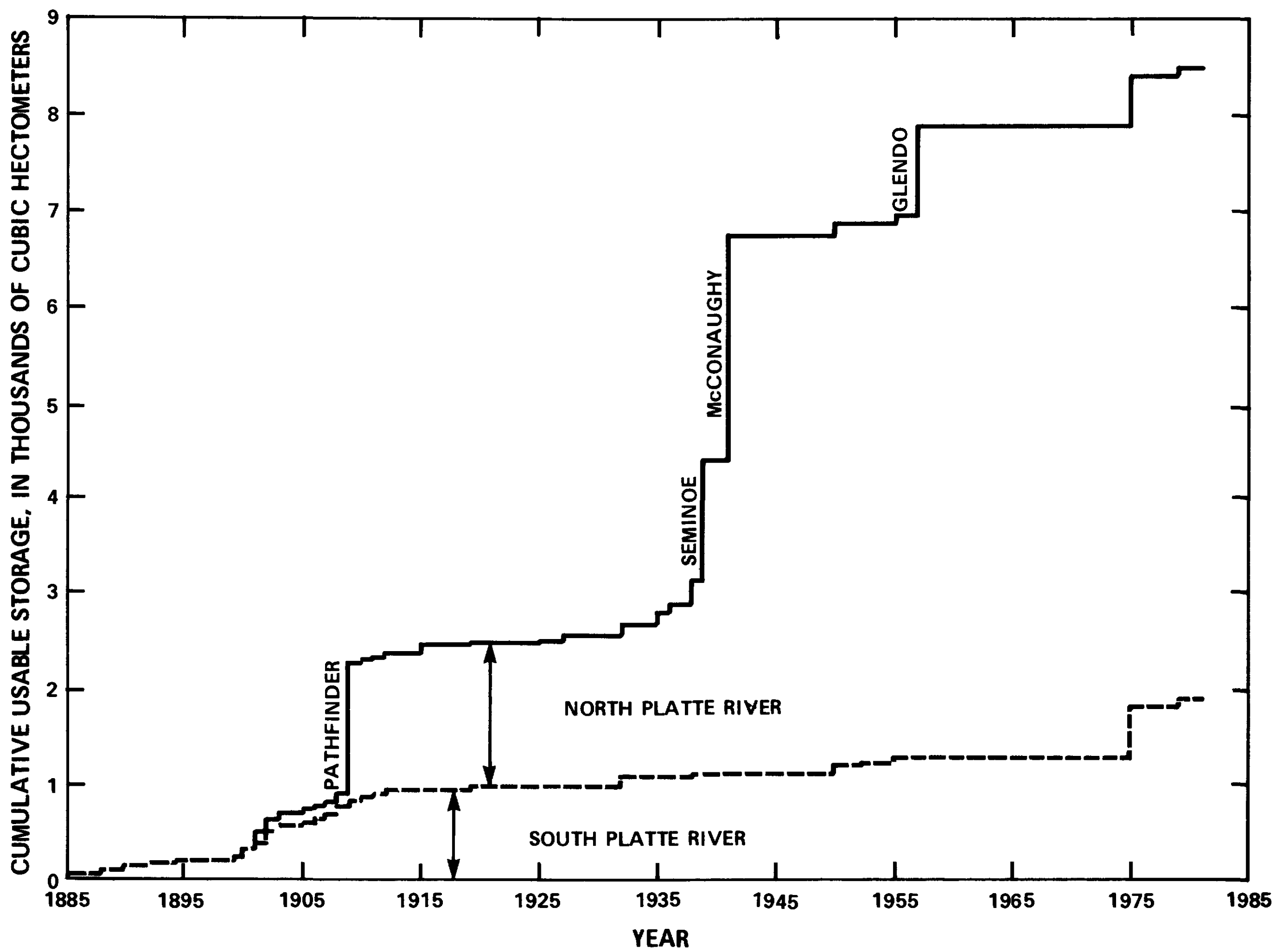


FIGURE 2.—Cumulative usable storage in reservoirs in the Platte River basin (modified from Bentall, 1975a).

may be considered stage 1 in the development of irrigation in the North Platte River basin.

The most rapid construction of canals occurred during the 1880's when cattlemen realized the benefits of irrigating grazing lands (McKinley, 1938, p. 91). In 1883, construction of the first large canals was completed on the Laramie River (Pioneer Canal) in Wyoming and the North Platte River (North Platte Canal) in Nebraska. By 1884, 22 firms, whose primary function was to supply water, existed in the North Platte River valley (McKinley, 1938). The severe winter of 1886-1887, during which the range-cattle industry experienced great losses for want of feed, provided the impetus for expansion of irrigation.

During the 1880's and early 1890's, several large canals were constructed on the North Platte River in Nebraska and on tributaries to the North Platte River in Wyoming. By 1889, Wyoming ranked third among the arid states in irrigated acreage and second in canal mileage following development in the North Platte basin above the Sweetwater River. The North Platte River in Wyoming below the mouth of the Sweetwater River was undeveloped as late as 1892 (U.S. Geolgoical Survey, 1892), primarily because of the difficulty of diverting water from the North Platte River in the reach below the Sweetwater River.

Canal construction declined in the 1890's because by 1894, most of the available land in the North Platte River basin was being irrigated. The Carey Act, enacted in 1894, provided 1 million acres to the State on the condition that it be irrigated. Under this act, the largest private irrigation development within the basin was undertaken (McKinley, 1938). A second legislative act, the Federal Reclamation Act of 1902, enabled reclamation projects to be funded from the sale of public lands in the West. As a result of these legislative acts, canal construction increased during the period 1901-1910.

Overappropriation of summer flows in the North Platte River basin varied temporally along the tributaries. By 1889, summer flows of the smaller order

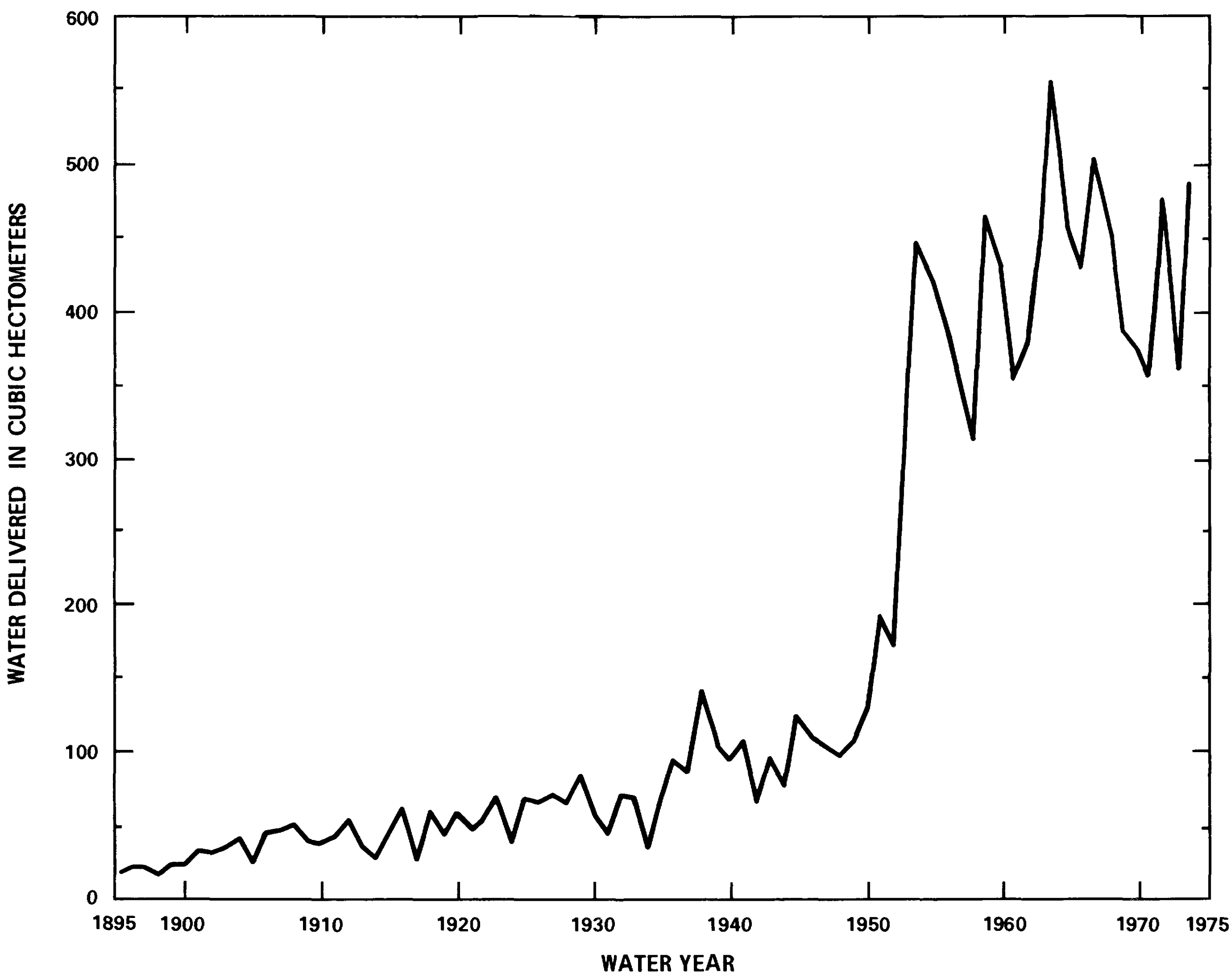


FIGURE 3.—Historical total yearly imports of water to the South Platte River basin since 1895 (modified from Gerlek, 1977).

streams in the basin were overappropriated (State of Wyoming, 1889); by 1899, flows of the Laramie River were overappropriated (State of Wyoming, 1899); by 1901, flows of Horse Creek and tributaries, Chugwater River and tributaries, Little Laramie River and tributaries, and upper North Platte River and tributaries in Colorado and Wyoming were overappropriated (State of Wyoming, 1902). Summer flows of the North Platte River in Nebraska were overappropriated sometime between 1914 and 1917 (State of Nebraska, 1914; State of Wyoming, 1918).

Flows of the North Platte River in Wyoming, below the mouth of the Sweetwater River, were not utilized until the construction of Pathfinder Dam in 1909 (fig. 2). The difficult terrain through which the river flowed offered few good sites for canal diversions, making the costs of diversion prohibitive. The Reclamation Act of 1902 provided public funds with which canals could be constructed along this section of the North Platte. Because of the lag in canal construction, overappropriation of summer flows in this section of the North Platte did not occur until much later than in the remainder of the basin. Overappropriation of summer flows in most of the North Platte River basin, however, occurred between 1900 and 1915. This period marks the end of stage 2 in the development of irrigation in the North Platte River basin.

Reservoir construction in the North Platte River basin began in 1892 (McKinley, 1938). The first reservoirs were natural lakes on the upper reaches of the tributaries that were modified to allow storage and release of water. In 1897, the Wyoming Development Company completed a reservoir on the Laramie River. By 1906, 27 small reservoirs, not listed in table 2, with combined storage capacities of 3.0 hm^3, were operating in the basin (State of Wyoming, 1906).

The impoundment of Pathfinder Reservoir marked the beginning of stage 3 in the development of irrigation in the North Platte River basin. A renewed construction of canals occurred with the construction of reservoirs. During the period 1901-1910, 1,391 canals were constructed; during the period 1911-1920, 732 canals were constructed; and during the period 1921-1930, 249 canals were constructed. Canal construction declined after 1930. Dam construction for the purpose of irrigation in the North Platte River basin ended after 1939. The year 1939 marks the close of stage 3 in the development of irrigation in the North Platte River basin.

PLATTE RIVER VALLEY

Development of irrigation along the Platte River lagged behind that of the North Platte and South Platte Rivers, partly because of the unwillingness of landowners to identify their land with more arid lands to the west (McKinley, 1938), and partly because irrigation was not essential for production of marginally profitable crops (Lugn and Wenzel, 1938).

Irrigation apparently was practiced as early as 1856 in the Platte River valley, near Wood River, about 18 km east of Fort Kearny (Carlson, 1963). Additionally, small irrigation projects were attempted during the dry years from 1859 to 1864. The project most commonly cited as the beginning of irrigation in the Platte River basin was a canal dug by John Burke in the year 1864 (Carlson, 1963) or 1866 (Willis, 1951), just east of North Platte. Little additional irrigation development occurred until 1882, when the Kearney canal was built for hydropower generation and irrigation. Further development occurred between 1891 and 1895, dry years in the Platte River valley, when six large canals were built on the Platte River between North Platte and Kearney. Between 1901 and 1930, one additional canal was constructed on the Platte River (1926), and several canals were constructed on the tributaries to the Platte River (table 1).

Construction of dams to supply canals on the Platte River did not result from overappropriation of flows on the river following canal construction. Rather, a shortage of water developed from the greater consumptive use of surface water upstream on the North Platte and South Platte Rivers. Three reservoirs, two of them offstream and Lake McConaughy on the North Platte with a combined usable storage capacity of 2,456 hm^3, were built after 1930 to supply canals and provide power.

Unreliability of streamflow in the Platte River encouraged development of ground water for irrigation. There is some historical evidence of pumping of ground water for irrigation beginning in the late 1880's (Willis, 1951), but this is not documented in the Platte River basin until 1893 (Lugn and Wenzel, 1938). Development of pump irrigation was slow initially, but it increased steadily, particularly after 1910. Between 1911 and 1920, 146 wells were constructed in the Platte River valley; between 1921 and 1930, 558 wells were constructed in the valley (Lugn and Wenzel, 1938). Most of the wells developed before 1930 were located west of Grand Island. The drought years of the 1930's hastened the development of ground-water irrigation, and its development continues to increase.

EFFECTS OF WATER DEVELOPMENT ON HYDROLOGY

PRESETTLEMENT HYDROLOGY

The Platte River valley served as a natural highway linking the eastern part of the United States with the unexplored and unsettled west. The first reliable reports of the river were written during journeys up the valley in the early 19th century. The number of reports increased during the large migrations west that began in the early 1840's, the California Gold Rush migrations in the late 1840's and early 1850's, and the Pikes Peak Gold Rush migration in the late 1850's. Between 1800 and 1860, a substantial number of observations were recorded regarding the geology, topography, geomorphology of the valley, and hydrology of the river.

Accounts written during early explorations of the Great Plains and Rocky Mountains by scientific expeditions, as discussed below, probably furnish the most reliable information about the river and valley. Location of historic sites and migration trails are shown in figure 4. In most cases, these expeditions were commissioned for the purpose of observing and reporting on the lands and rivers of the region. Later accounts of the river and valley, written during westward migrations, probably are not as reliable. These accounts were written by travelers using the valley as a means of going west; their interest in the territory was secondary to the immediate task of surviving the journey. Usually, no attempts were made at systematic observation, and the prejudices of fellow travelers and travel guidebooks often were repeated in the journals. Movement of large numbers of settlers through the Platte River valley (estimated to be 350,000 persons between 1841 and 1866 by Mattes, 1969) had a significant impact on the land. For example, timber, a scarce commodity in the valley before the first migrations, all but disappeared in many parts of the valley because of use by settlers and railroads.

The most notable expeditions that touched the Platte River valley were the Lewis and Clark Expedition in

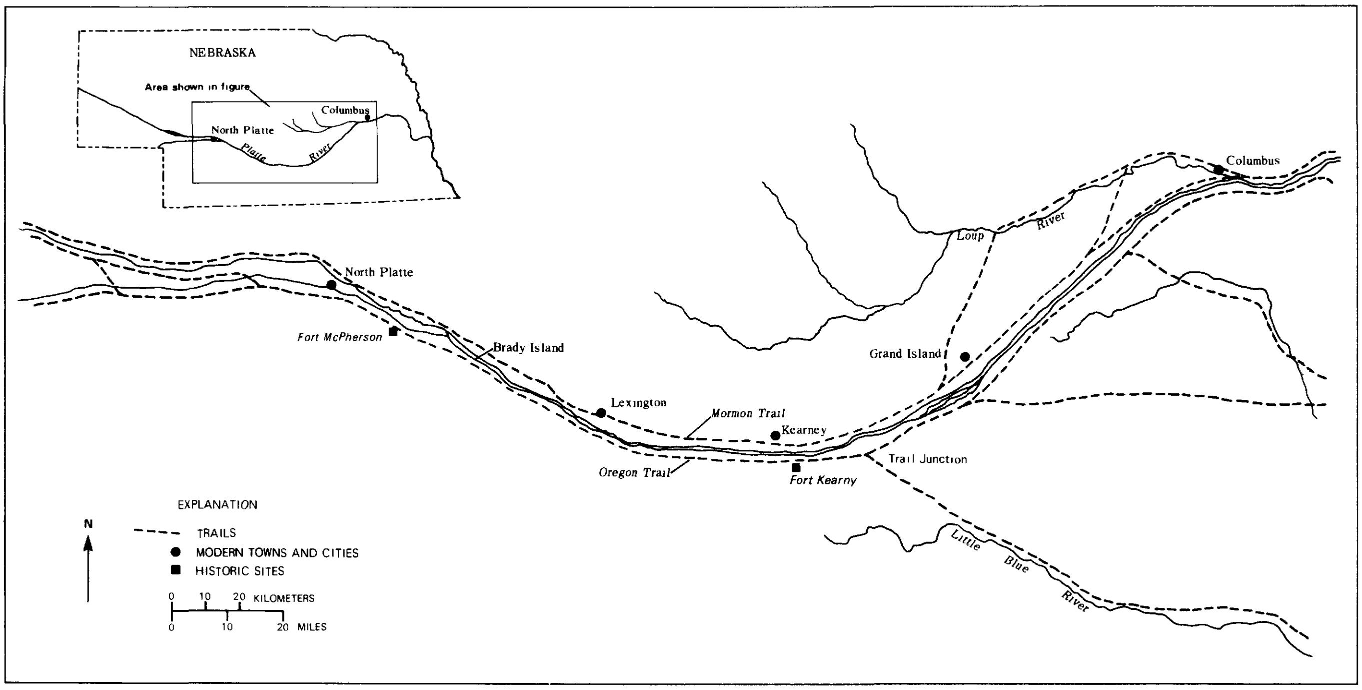


FIGURE 4.—Location of modern and historic sites in the Platte River valley.

1804, the Long Expedition in 1820, the Fremont Expedition in 1842, and the Stansbury Expedition in 1850–1851. Other notable explorations were the Stuart Exploration in 1812–1813, the Ashley-Smith Explorations in 1822–1829, and the Bonneville Exploration in 1832. These and other accounts of the river and valley written during the period 1800–1860 by missionaries, trappers, naturalists, and settlers provide the first substantial historical description of the Platte River.

FLOODS

To clear the western passes before the first snowfall, travelers had to traverse the Platte River valley in the spring, during spring floods. Thus, most observations of the river were made during high flow. In approximately 70 years of written records of early explorations of the valley, from about 1800 to the construction of railroads and the subsequent cessation of the great westward migrations in 1870, there are no accounts of overbank floods on the Platte River. In 1820, the Long Expedition (James, 1823) reported that the river was so wide and the banks so high that "the highest freshets pass off without inundating the bottoms, except in their lowest parts; the rise of the water, on such occasions, being no more than five or six feet." In 1849, Pritchard (Morgan, 1959, p. 63) wrote in his journal, that the banks of the Platte near Grand Island:

> are low at this time (the river being high) [and] do not rise more than 18 inches or two feet above the surface of the water. I judge that the bottoms at this point are rarely, if ever inundated * * *. Such is the breadth of the channel that an immense quantity of water would be required to raise it above its banks * * *.

The only observation of flooding in the Platte River basin was noted by Fremont (1845, p. 110), on the South Platte upstream of Bijou Creek, who wrote "On the evening of the 3rd (July) as we were journeying along the partially overflowed bottoms of the Platte * * *." The "bottoms" referred to in these accounts are probably the low, broken meadowlands that occur on either side of the river. These bottomlands usually contain abandoned channels, which, during high flow, may be filled with water from a rise in the ground-water table, rather than by overflow of the river. It is unclear from historical accounts, particularly the Fremont account, whether the bottomlands were inundated by overflow of the river or by a rise in the ground-water table.

LOW FLOWS

Because most of the travels along the Platte River valley occurred in the spring, few historical accounts exist of the river during low flow. Of particular interest is the behavior of the river between the junction of the North Platte and South Platte Rivers and the confluence with the Loup River (fig. 2). The Loup has a fairly constant discharge (Brice, 1964, p. 35); therefore, the Platte River below this confluence probably was a perennial stream. Little is known about low-flow behavior of the river above the confluence with the Loup prior to irrigation, about 1860. Miller (1978) concluded that prior to irrigation the Platte River above the junction of the Loup rarely, if ever, went dry in the summer. This conclusion is based primarily on indirect evidence, such as construction of canals along the Platte to divert water during the summer months.

Several observations of the Platte River during low flow are notable. Clarke (1902, p. 301) reported that "In the summer of 1863, the Platte having so nearly dried up as to make it difficult to secure water for cattle * * * We sank headless barrels in the Platte * * * to secure water from an underflow." Ware (1911, p. 41) noted that during the summer of 1864:

> From Fort Kearney, for many miles up, there was no water in the river. The water seemed to be in "the underflow". We not infrequently rode down to the river, and with shovels dug watering places in the sand of the bed * * *. We were told that 75 miles of the river were then dry, and that generally about 125 miles of it were dry in the driest season * * *

The year 1864, however, apparently was not unusually dry. In 1864, Ward (in Root and Connelley, 1901) wrote of the "unprecedented flood of 1864." McKinley (1938) also reported the river to be unusually high during the spring of 1864.

Fremont (1845, p. 77), descending the North Platte River (Sept. 3, 1845), wrote that the river was "merely a succession of sandbars, among which the channel was divided into rivulets a few inches deep." Upon reaching the Platte River, Fremont and his men constructed a bull boat which, when fully loaded with men and supplies, drew four inches of water; they attempted to navigate the river (Fremont, 1845, p. 78):

> On the morning of the 15th [September] we embarked in our hide boat, Mr. Preuss and myself, with two men. We dragged her over the sands for three or four miles, then left her on a bar and abandoned entirely all further attempts to navigate this river * * *.

If the river did not go dry every summer, the flow became relatively insignificant, a "mere trickle of water among sandy shoals" (Ghent, 1929, p. 128). Between the junction of the North Platte and South Platte Rivers and the Loup River, the Platte may have gone dry during years of low precipitation and probably was reduced to a trickle in other years.

POSTSETTLEMENT HYDROLOGY

SURFACE WATER

Diversion and storage of surface water for irrigation and hydropower generation have changed patterns of streamflow in some reaches in the Platte River basin. At some stations changes in flood peaks, annual mean discharge, and the shape of flow-duration curves have been recorded. These changes are not found uniformly throughout the Platte River basin, because development of water resources has progressed differently along the North Platte, South Platte, and Platte Rivers.

Construction of large onstream reservoirs in Wyoming and Nebraska has decreased peak flows of the North Platte River. Four gaging stations on the North Platte River with long periods of record show that peak discharge decreased progressively after the closure of each of four major dams (Williams, 1978). Kircher and Karlinger (1981) determined statistically that changes in annual peak flows on the North Plate River at North Platte, Nebraska, are better described by two regression models, one corresponding to the period prior to construction of Kingsley Dam (1895–1935) and one corresponding to the period following construction (1936–1979), than by a single model. Kircher and Karlinger did not test the significance of differences in peak flows following each period of dam construction, but peak flows from 1895 to 1935 decreased with time. There has been no significant change in peak flows since 1935.

Reservoir development has been less extensive in the South Platte River basin than in the North Platte River basin. Total reservoir storage in the South Platte River basin increased about 100 percent from 1915 to the present (fig. 2) with the majority of storage in offstream reservoirs. Kircher and Karlinger (1981) showed that peak flows of the South Platte River near Kersey and Julesburg, Colorado, have not changed significantly since 1902, the beginning of the record. However, a statistically significant decrease in peak flows with time was observed on the South Platte River at North Platte, Nebraska, probably due to surface-water diversions downstream of Julesburg.

Peak flows of the Platte River are influenced by flows from both the North Platte and South Platte Rivers. Since the reduction of flood peaks on the North Platte River, flood peaks on the South Platte River have become a more significant component of flow on the Platte River. Peak flows on the Platte River near Overton, Nebraska, have decreased over the period of record, 1915–1979, but have shown no statistically significant decrease since 1935 (Kircher and Karlinger, 1981). No long-term change is apparent in peak flows near Grand Island, Nebraska, since the record began in 1935. However, changes may have occurred prior to 1935.

If the entire period of record is considered, annual mean flows have decreased on the North Platte and Platte Rivers. However, since 1935, annual mean flows on these rivers have either not changed signficantly or have increased. Records for the North Platte River at

North Platte and the Platte River near Overton show no statistically significant change in annual mean flows for the period 1935–1979 (Kircher and Karlinger, 1981). Annual mean flows of the Platte River near Grand Island have increased significantly since 1935. No long-term change is apparent in annual mean flows of the South Platte River although changes may have occurred prior to the period of record. Importation of water into the South Platte River basin apparently has counteracted the effects of water development within the basin.

In addition to changes in streamflow characteristics that may be attributed to river regulation, one must consider the possible effects of climate. Droughts have occurred in the Great Plains roughly every 20 years (Hecht, 1981), although the distribution and intensity has been quite different for each drought period. Droughts in the Central Great Plains in 1911, 1913, and 1917 were short, severe, and spatially limited, whereas the drought of the 1930's was particularly severe in the Platte River basin (Hecht, 1981). Although flows, in general, were decreased during the 1930's drought, the maximum floods of record on the Platte River occurred in 1935 at all gaging stations (Petsch, Rennick, and Nordin, 1980). Therefore, trends in streamflow characteristics can be correlated with documentation of water development in the basin, but it is difficult to relate changes in hydrology to random climate variations.

The flow-duration curve is the frequency distribution of daily mean flows at a given site. The flow-duration curve graphically represents variability of streamflow by the shape of the curve. The position of the curve reflects the magnitude of the streamflow (Leopold, Wolman, and Miller, 1964). Curves with low slope and high minimum values generally indicate a large baseflow component of streamflow. High slope and low minimum values indicate a more ephemeral character and a quicker response to precipitation events. The flow-duration curve does not provide information about sequential relationships of flows (Hudson and Hazen, 1964). Thus, although the curve may reveal that a given flow is exceeded 50 percent of the time, it cannot indicate if the flows occurred consecutively, randomly, or in some pattern.

The shape of flow-duration curves for most stations on the North Platte, South Platte, and Platte Rivers has changed with time (Kircher and Karlinger, 1981; Eschner, 1981). In general, the curves show an increase in the magnitude of high-frequency discharges. A representative example of the type of changes that have occurred in flow duration over time is shown in figure 5. The position of the curve is dependent on the volume of water passing the gage during the period for which the flow duration is computed. However, the changes in the shape of the flow-duration curves with time reflect the cumulative effects of streamflow regulation and water use.

SURFACE-WATER – GROUND-WATER RELATIONSHIPS

Unconsolidated deposits of the Platte River valley in the study area consist of Quaternary sediments, which include Holocene alluvium. The Ogallala Formation of Tertiary age and Pierre Shale and Niobrara Formation of Cretaceous age underlie the Quaternary sediments in the Platte River valley. The Ogallala Formation thins to the east and pinches out between Kearney and Grand Island. The thickness of the Ogallala Formation is irregular due to deposition on an irregular Cretaceous surface and to subsequent erosion.

Quaternary sediments and, where present, the Ogallala Formation, are the principal aquifers in the Platte River valley. These two units act as a single aquifer in areas where the Quaternary materials overlie the Ogallala. The Quaternary sediments comprise the primary aquifer where these sediments directly overlie the Pierre Shale or Niobrara Formation. The Niobrara Formation is a source of ground water at some locations (Bentall, 1975b). Thickness of saturated alluvium varies from about 6 m to more than 122 m because of an irregular bedrock surface (Bentall, 1975a).

The Platte River is hydraulically connected with the aquifer in the valley (Lappala, Emery, and Otradovsky, 1979); water can move from the river to the ground water and from the ground water to the river. The river serves as a control on the ground-water system and can influence ground-water levels and reflect changes in those levels. A study near Grand Island indicates that ground-water levels within 0.8 km of the river in that area respond within 24 hours to changes in river stage (Hurr, 1981). It is not known if this rate of change is typical for other areas within the Platte River valley.

In general, ground-water pumping lowers ground-water levels. This reduction may result from drawdown and change in water-table gradient, rather than from appreciable loss of storage. Evapotranspiration salvage, or the reduction of evapotranspiration by lowering the water table, would offset partially the decrease in water level brought about by ground-water pumping in areas where the ground-water table is close to the surface. Ground-water withdrawals in relatively close proximity to the Platte River may influence ground-water levels in two ways: (1) By initiating drawdown, and (2) by causing river-stage decline that may induce a further reduction in ground-water levels downstream (Hurr, 1981).

Evapotranspiration also may result in considerable loss of water to the atmosphere. As vegetaton becomes established on the valley floor, transpiration increases.

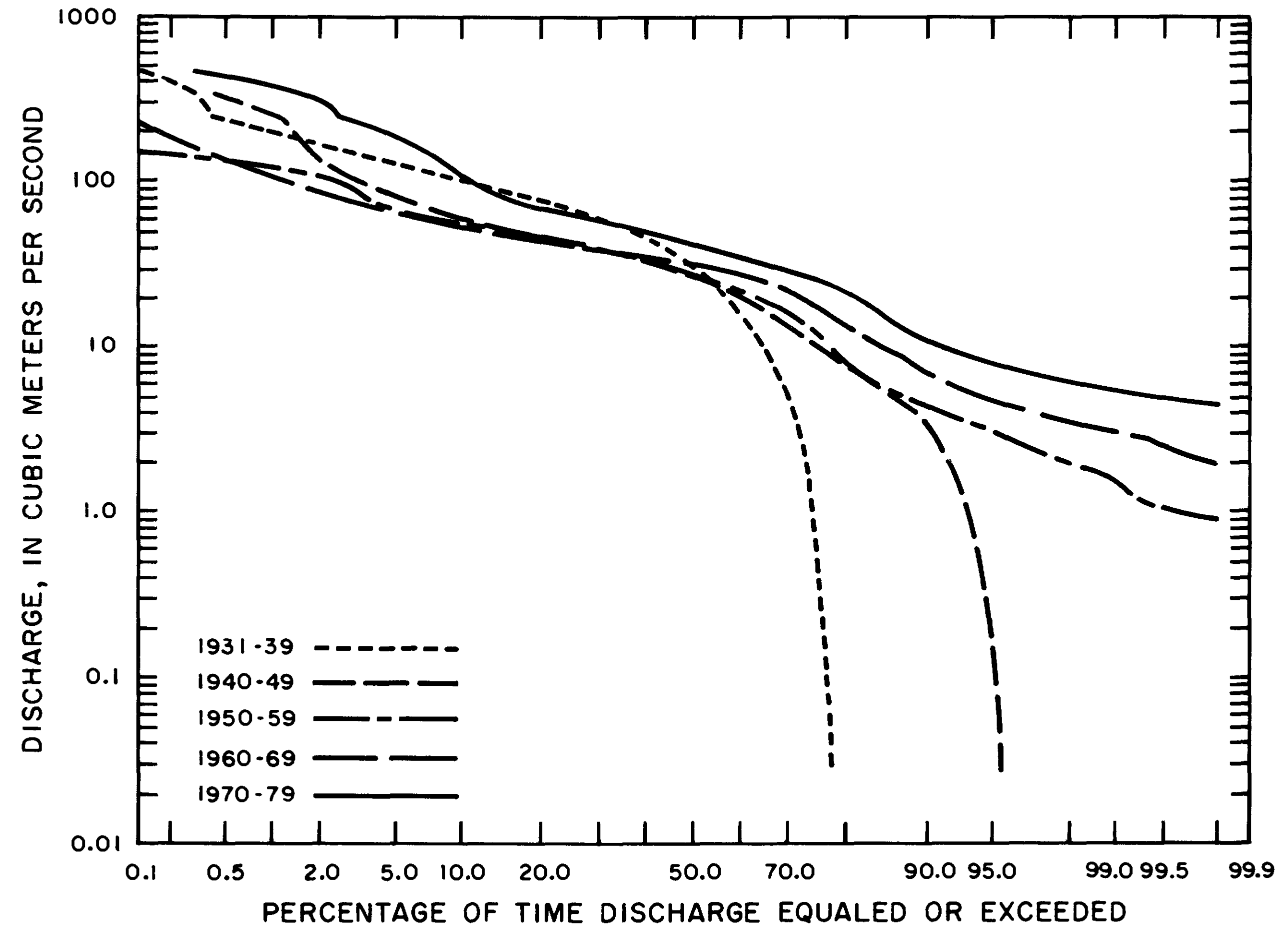


FIGURE 5.—Flow-duration curves for 10-year periods, Platte River near Overton, Nebraska (from Kircher and Karlinger, 1981).

Dirmeyer (1975) states that about 1,136 hm^3 of water are lost to the atmosphere through evapotranspiration each year between Kingsley Dam and Duncan, a distance of 386 km. This quantity was estimated by assuming that the vegetation on the valley floor is a strip 1.6 km wide, and the evapotranspiration rate is 1.8 m/yr.

An annual evapotranspiration rate of 1.8 m is probably high for central Nebraska, although this rate has been documented in more arid regions. Gatewood and others (1950) found that cottonwood trees in the Lower Safford Valley of Arizona transpire about 1.8 m annually. Average annual use of ground water by cottonwood and willow trees along the San Luis Rey River, California, was 1.6 m with the water table at 1.2 m, and 2.5 m with the water table at 0.9 m (Robinson, 1958). For Niobrara County, Wyoming, an area more similar to central Nebraska than Arizona or southern California, Whitcomb (1965) inferred that 0.9 m was a reasonable rate for annual evapotranspiration by cottonwood trees. Total lake evaporation along the Platte River ranges from 1.1 to 1.3 m/yr.

Assuming a more conservative evapotranspiration rate of 1 m/yr and a vegetation swath 1 km wide for the 386 km from Kingsley Dam to Duncan, the annual evapotranspiration loss would be 386 hm^3. This is equivalent to a flow of 12.2 m^3/s if the rate of evapotranspiration is constant throughout the year, or alternatively, it is equivalent to a flow of 24.8 m^3/s if the entire volume of water is transpired during a six-month growing season.

Net rises in ground-water level have resulted primarily from seepage water from canals and reservoirs. Lugn and Wenzel (1938) noted a rise in water level over 3 m since 1896 near Lexington, Nebraska. In general, rises of 3 m have occurred beneath the Central Nebraska Public Power and Irrigation District in Lincoln, Gosper, Dawson, Phelps, and Kearney Counties. The largest recorded rises in water levels have been 27 m for Phelps County, 19 m for Kearney County, and 25 m for Gosper County (Johnson and Pederson, 1980). Rises of more than 0.6 m were measured in those counties between October 1968 and October 1971 (Lappala, Emery, and Otradovsky, 1979).

Net declines in the water table have occurred over broad areas in the Platte River valley in response to ground-water pumping. The greatest water-table declines have occurred primarily in areas where depth to the water table prevents evapotranspiration salvage (Bentall, 1975a). Since the beginning of development declines of less than 1.5 m have occurred extensively throughout Buffalo, Hall, and Merrick Counties; declines of up to 6.4 m have been recorded in Buffalo County, mainly in upland areas along the Platte River-Loup River divide (Johnson and Pederson, 1980). Declines of more than 1.2 m have been measured for the period 1968 to 1971 for other parts of Buffalo, Hall, and Merrick Counties (Lappala, Emery, and Otradovsky, 1979).

Water-level changes in the Platte River basin in Nebraska were simulated by Lappala and others (1979) for various development schemes. Projected water-level changes ranged from rises up to 6.1 m over some areas with no further development, to net declines up to 24.4 m over the entire upper Platte subbasin, if development of ground water continues at the rate that occurred from 1960 to 1970.

EFFECTS OF CHANGES IN HYDROLOGY ON THE CHANNEL

PRESETTLEMENT CHANNEL AND VALLEY-FLOOR CHARACTERISTICS

CHANNEL WIDTH

Channel width was the most obvious characteristic of the Platte River in the 19th century. Most travelers, comparing the Platte to rivers in the Eastern United States, found the width of the river remarkable; comments on channel width were recorded in most journals. Accurately estimating distances across a wide body of water is difficult. Accordingly, estimates of channel width from historical accounts must be used with caution. In 1849, Pritchard (Morgan, 1963, p. 63) noted that it "is hardly possible to guess at the width of the river as we seldom see the whole at once, on account of the numerous islands that are scattered from shore to shore * * *." Many of the estimates of channel width included the width of the islands in the channel. In 1849 Gibbs (Settle, 1940, p. 306) noted "[the Platte] is a mile [1.6 km] in width. Where cut up by islands, as is often the case, it extends to double or treble [that distance], and in one place is seven miles [11.3 km] wide from shore to shore."

Estimates of the width of the Platte River during the period 1800–1860 vary from 1.2 to 4.8 km, with the most common estimates ranging from 1.6 to 3.2 km. There are two measured observations of channel width recorded in the the literature. In 1832, Captain Bonneville (Irving, 1837) measured the width of the Platte River 40 km below the head of Grand Island and found it "twenty-two hundred yards [2.0 km] from bank to bank." Fremont (1845, p. 21) determined the width of the Platte River below the confluence of the North Platte and South Platte Rivers to be 1.6 km.

CHANNEL DEPTH

The second most remarkable characteristic of the Platte River was its depth. The river could be forded anywhere at almost anytime of the year, except during spring floods. Observations of water depth are useful only to establish a range in flows. Most observations of depth range from 0.3 to 1.2 m, depending on river stage. Long (James, 1823) reported that the bed of the Platte "is seldom depressed more than six or eight feet [1.8 to 2.4 m] below the surface of the bottoms, and in many places even less." Jessup (James, 1823) substantiates Long's report:

> The range of the Platte, from extreme low to extreme high water is very inconsiderable, manifestly not exceeding six or eight feet [1.8 to 2.4 m]. This is about the usual height of its banks above the surface of the sand which forms its bed * * *.

Warren (1858) later reported that, "when the banks are full, it [Platte] is about six feet [1.8 m] deep throughout, having a remarkably level bed."

BED MATERIAL AND BED FORMS

In general, descriptions indicate that the bed material consisted of sand and gravel. However, James (1823), the botanist and geologist of the Long Expedition, stated, "The alluvial deposits of which the river bottoms are formed, consist of particles of mud and sand * * *," implying that the bed was finer than other accounts indicated.

Quicksand was encountered in the channels of the Platte system. In 1812, Stuart (Rollins, 1935) wrote that the bed of the Platte River, near the present day Gosper-Phelps County border, was composed "of such quicksand that it was difficult for our horse to get over, though the water was in no place more than two feet [0.6 m] deep." Farther downstream near Fort Kearny, Taylor (Williams, 1969) in 1850 noted, "The bottom is composed of a fine quicksand * * *." Fremont (1845) described the southern channel of the South Platte River near the confluence with the Platte River as being "generally quicksands."

The configuration of the channel bed and its ephemeral character were described in detail by several travelers. Bradbury (1819), recrossing the Platte, noted:

> in the same place where the day before it reached to our armpits, it did not now reach to our waists, although the river had not fallen. Such changes in the bottom of this river * * * were very frequent, as it is composed of a moving gravel, in which our feet sank to a considerable depth.

Mattes (1969) cited two descriptions of the Platte River bed near Fort Kearny. In 1849, Pritchard (Mattes, 1969) noted the composition and character of the bed: "The bed of the river is composed of sand, and this is all the time shifting its position and fresh deposits are constantly being made." Evans (Mattes, 1969) wrote in 1849 that the Platte was a wide sheet of water "running over a vast level bed of sand and mica * * * continually changing into short offsets like the shingled roof of a house * * *."

The account of the Long Expedition (James, 1823) stated of the Platte, "its bed is composed almost exclusively of sand, forming innumerable bars, which are continually changing their positions and moving downward [downstream] * * *." In their travels, members of the Long Expedition observed on the flood plain "extremely numerous natural elevations of earth, of some considerable degree of regularity * * * of a more or less oval outline" with lengths of about 30 m and heights of 0.6 to 1.5 m. These elevations were presumed to have been former sandbars, "Their existence is doubtless due to the action of water. Should the rivers Platte and Arkansas be deprived of their waters, the sand islands of their beds would probably present a somewhat similar appearance."

The water of the Platte commonly was referred to as muddy or turbid. The "turbid waters of the Platte" were noted by the Long Expedition (James, 1823). McKinstry (1975), although calling the Platte a river of sand, stated that it was "nearly as muddy" as the Missouri. Taylor (Williams, 1969) wrote that the river was, at various points, "swift and muddy ," "muddy and turbulent," and "broad swift and muddy." Kelly (1851) described the river as turbid. Ebey (Baydo, 1971) stated of the Platte: "The water is always muddy and turbid * * *." Stage coach drivers (Ghent, 1929) used to tell the story that the Platte never overflowed its banks because its flood waters carried so much mud, that as it rose, it built new banks.

ISLANDS

Islands were a ubiquitous feature in the Platte River channels. In 1852, Cole (1905, p. 29) wrote:

> Looking out upon the long stretch of river either way were islands and islands of every size whatever, from three feet in diameter to those which contained miles of area, resting here and there in the most artistic disregard of position and relation to each other, the small and the great alike wearing its own mantle of the sheerest willow-green * * *

Islands of the Platte River can be divided into two groups based on size, elevation, and vegetation. The large, well-timbered islands were described and mapped by Fremont (1845, pl. 1); these are Brady Island, Willow Island, Elm Island, Grand Island, and five other unnamed islands. Grand Island, also called the "Great Island" or "Big Island," was the largest of the islands mapped, being 84 km long and 2.8 km wide by Fremont's estimate. Although no quantitative estimates were given of the elevation of the large islands, Fremont (1845, p. 78) described Grand Island as being "sufficiently elevated to be secure from the annual flood of the river."

In addition to the large islands, there were hundreds of smaller islands too numerous to map or name. These islands were as small as a few square meters in area; most supported shrubs, young willows, and cottonwoods. A particularly dense concentration of these smaller islands occurred between Fort Kearny and Grand Island: these were named "Thousand Islands" after the Thousand Islands of the St. Lawrence River (Meline, 1966, p. 21).

VEGETATION

The valley of the Platte River supported a wide variety of plant species. The Fremont Expedition collected and cataloged over 90 plant species in the valley; the list included several species of trees, such as poplar (cottonwood), elm, hackberry, box elder, willow, and juniper. Other tree species found in the valley included cedar, dogwood, ash, and aspen.

Timber was a scarce commodity; however, it grew on the islands in the river and could be found in scattered groves between the Missouri and Loup Rivers (Fremont, 1845, p. 79). In 1820, according to Bell, the banks of the Elkhorn River and the Platte River near the Loup Fork were well-timbered (Fuller and Hafen, 1957, p. 107). The banks of the Platte River near Buffalo Creek also were timbered in 1812, according to Stuart (Rollins, 1935, p. 217). Timber also grew on the banks of the Platte River from the present site of Cozad to Brady Island (Fremont, 1845) and on the south bank of the Platte River along Brady Island (Rollins, 1935; Fremont, 1845; Palmer, 1847).

The scarcity of timber in the valley has been attributed to the effects of grazing buffalo and prairie fires (Stansbury, 1851, p. 32; Mattes, 1969). Accounts of prairie fires can be found in several reports. Wyeth (1833) noted that the ground "is covered with herbage for a few weeks of the year only, * * * owing to the Indians burning the prairies regularly twice a year." Bradbury (1819) observed near the mouth of the Platte:

the reflection of immense fires, occasioned by burning prairies. At this late season (April 28), the fires are not made by hunters to facilitate their hunting, but by war parties; and more particularly when returning unsuccessful, or after a defeat to prevent their enemies from tracing their steps * * *.

Several parties reported large areas of burned prairie along the Platte River valley. Stansbury (1851, p. 32) reported that the valley was burned for a distance of 480 km above Fort Kearny.

The influences of man and climate as regulators of tree growth in the valley have been underemphasized. The Indians used cottonwood as fodder for their horses and for firewood. Timber use by man increased during westward migrations up the valley. Fremont (1845, p. 17) noted that, near the head of Grand Island, "with the exception of a scattered fringe (of trees) along the bank, the timber * * * is confined almost entirely to the island." Burnett (1904) reported that, in 1844, "near the head of Grand Island * * * there was not a solitary tree on the south side of the river." It is likely that the few trees that grew along the banks of the Platte River were used for fodder and fuel by the Indians or settlers.

Distribution of timber in the valley was inconsistent with that expected based on the prairie-fire hypothesis. Timber grew along all the large tributaries to the Platte River, in many of the ravines in the bluffs along the valley margin, and in many hollows on the valley floor. It is unlikely that prairie fires sweeping across the valley would spare the timber along the rivers and in the ravines and hollows. A more likely explanation is that distribution of timber was controlled by availability of water; ravines, hollows, river banks, and islands are situated in topographically lower areas in close proximity to water. The conditions in these areas favor germination and growth. The remainder of the valley is topographically higher and drier. Conditions favoring the germination of seeds and growth of trees probably did not exist along most of the valley.

Aridity of the valley was observed by many travelers. In 1820, Long christened the area "The Great American Desert," a description of the valley that stuck through most the 19th century. Several writers observed saline crusts on the surface over large areas of the valley. Townsend (1833) observed that the ground near Grand Island:

is in many places encrusted with an impure salt, which by taste appears to be a combination of sulphate and muriate of soda [thenardite and halite); there were also a number of little pools, only a few inches in depth, scattered over the plain, the water of which is so bitter and pungent, that it seems to penetrate into the tongue, and almost to produce decortication of the mouth * * *.

Availability of water probably was the prime factor that determined the distribution of timber in the valley. Prairie fires and grazing buffalo may have been secondary regulators of growth and distribution.

SUMMARY OF PRESETTLEMENT CHARACTERISTICS

In the 1800's the Platte River averaged about 2 km in width; it may have been as wide as 5 km where it was cut by islands, or as narrow as 1.2 km where no islands were present in the channel. The two measured observations of width (Irving, 1837; Fremont, 1845), 2.0 and 1.6 km, fall within these average values. Flow depth varied between 0.3 and 1.2 m during most of the year; bankfull depth ranged between 1.8 and 2.4 m along most of the valley. Large sand deposits were common in the channel. The channel bed was very active; a change of bed elevation of 0.5 m was observed over a 1-day period.

The river was observed to flow at bankfull stages during the spring floods. There were no observations of overbank flow along the river. Above the confluence with the Loup, the Platte was an intermittent river. It carried little water during the late summer and dried up completely in some years.

The Platte channels contained nine large islands and hundreds of smaller islands; most supported timber. Timber grew along the banks of the Platte, along the banks of the tributary rivers, in the ravines cut in the bluffs along the margins of the river, and in hollows on the valley floor. Distribution of timber in the valley was controlled primarily by availability of water. Prairie fires and grazing buffalo probably were secondary regulators of timber growth and distribution.

CHANGES IN PLATTE RIVER MORPHOLOGY

Changes in channel morphology of the Platte River can be documented by comparison of aerial photographs taken between 1938 and 1979. In addition, General Land Office maps provide relatively accurate measurements of river width from the 1860's. Changes in the intervening years must be inferred from hydrologic data and records of canal and dam construction that indicate when changes were initiated.

The development of islands in several reaches in the study area from 1860 to 1979 is shown in figures 6 through 10; the changes are summarized in figure 11.

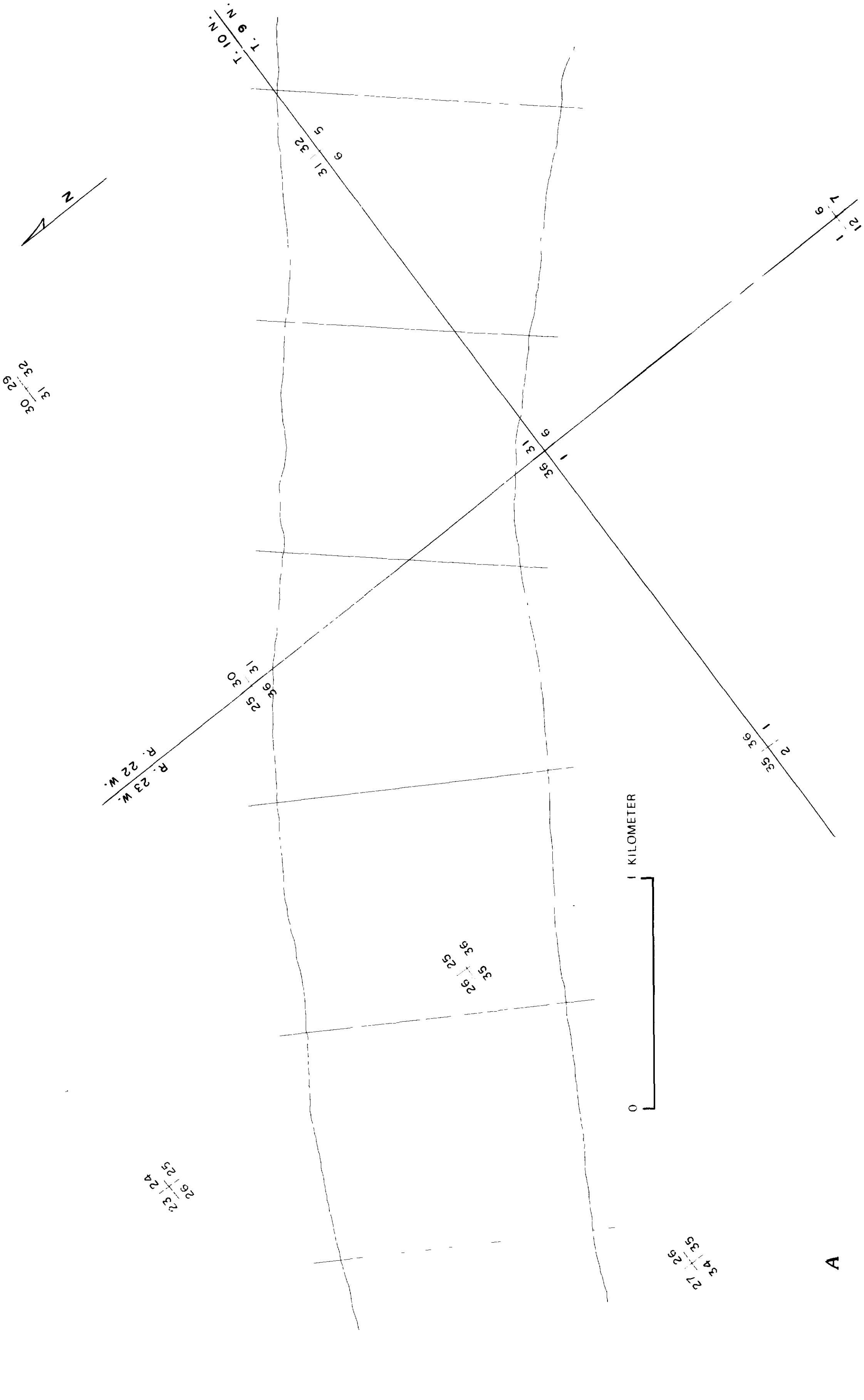


FIGURE 6.—Channel of the Platte River near Cozad, Nebraska, in sections 25, 26, 35, and 36, T. 10 N., R. 23 W., and section 31, T. 10 N., R. 22 W., and section 6, T. 9 N., R. 22 W., in (a) 1860, (b) 1938, and (c) 1979. Shaded areas are vegetated.

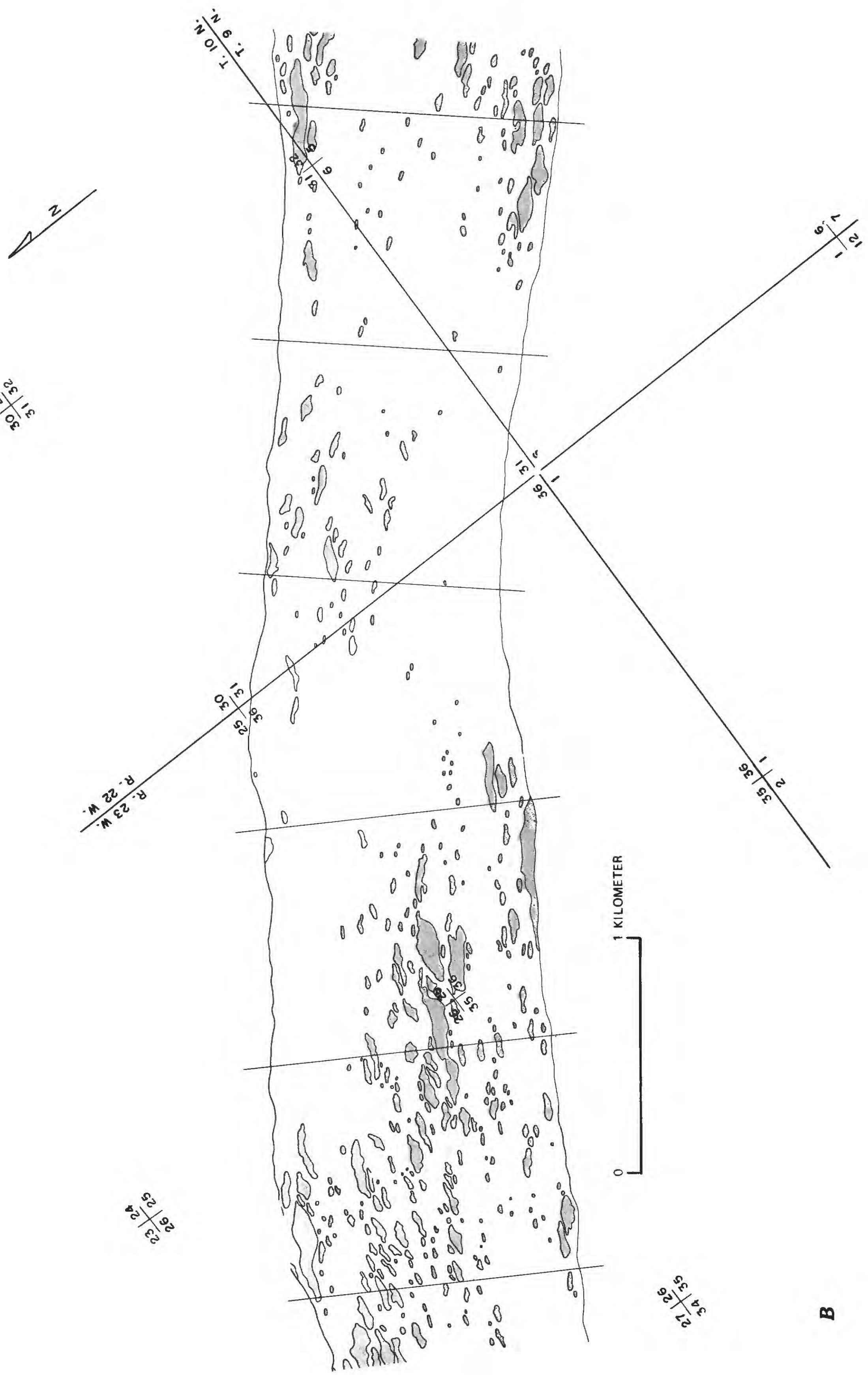


FIGURE 6.—Continued.

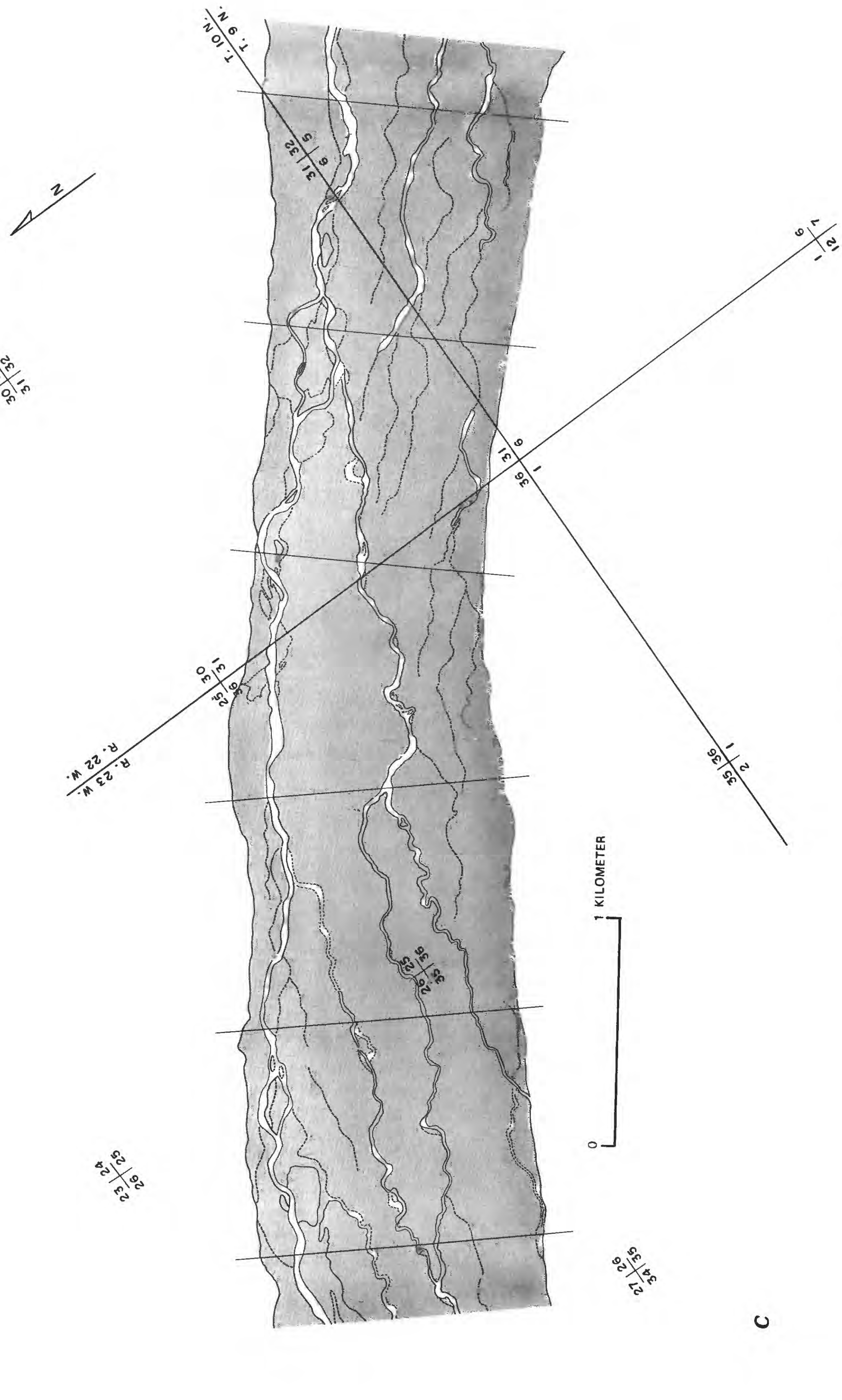


FIGURE 6.—Continued.

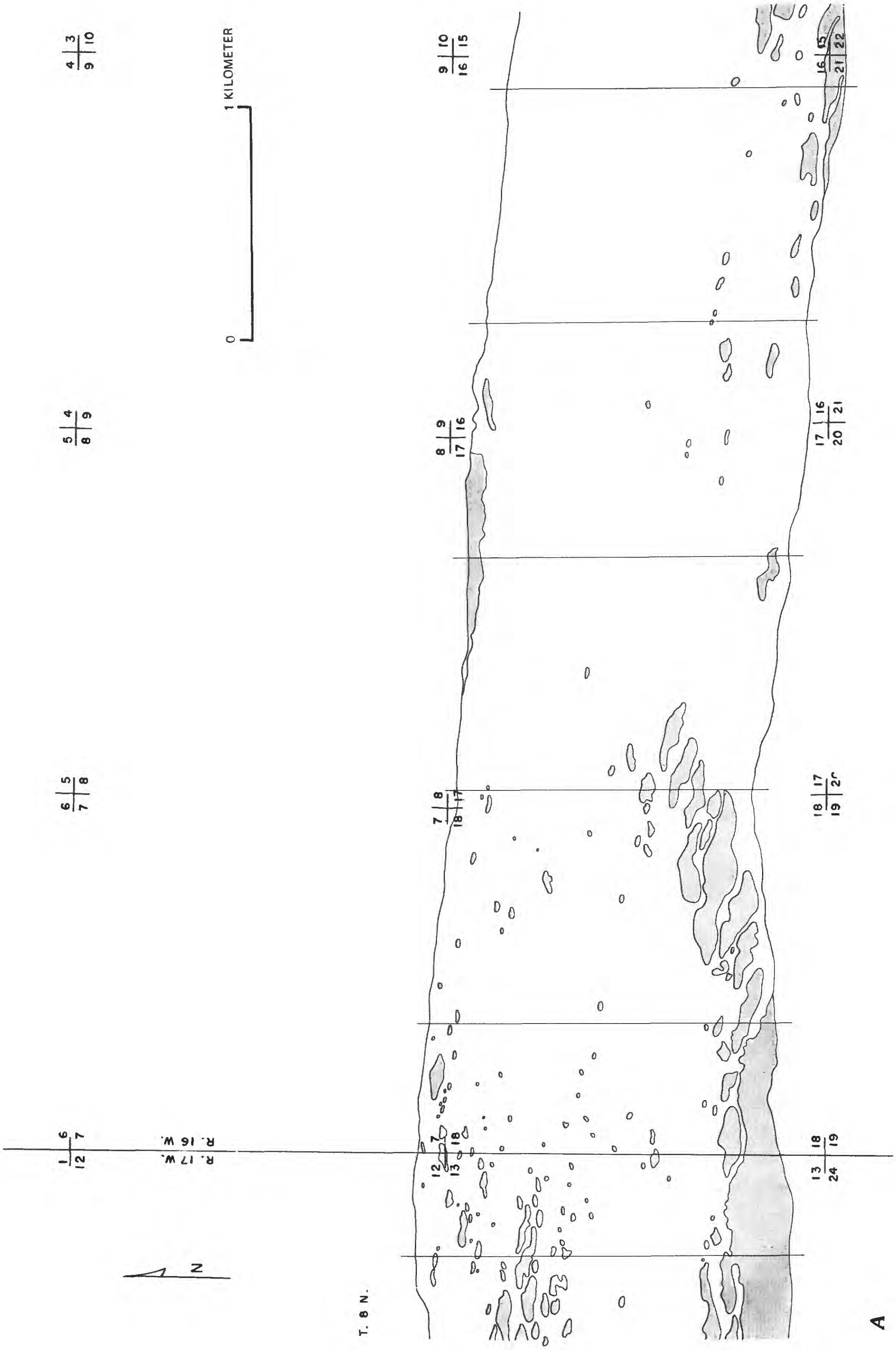


FIGURE 7.—Channel of the Platte River near Kearney, Nebraska, in sections 7, 8, 9, 16, 17, and 18, T. 8 N., R. 16 W., and sections 12 and 13, T. 8 N., R. 17 W., in (a) 1938, (b) 1957, and (c) 1979. Shaded areas are vegetated.

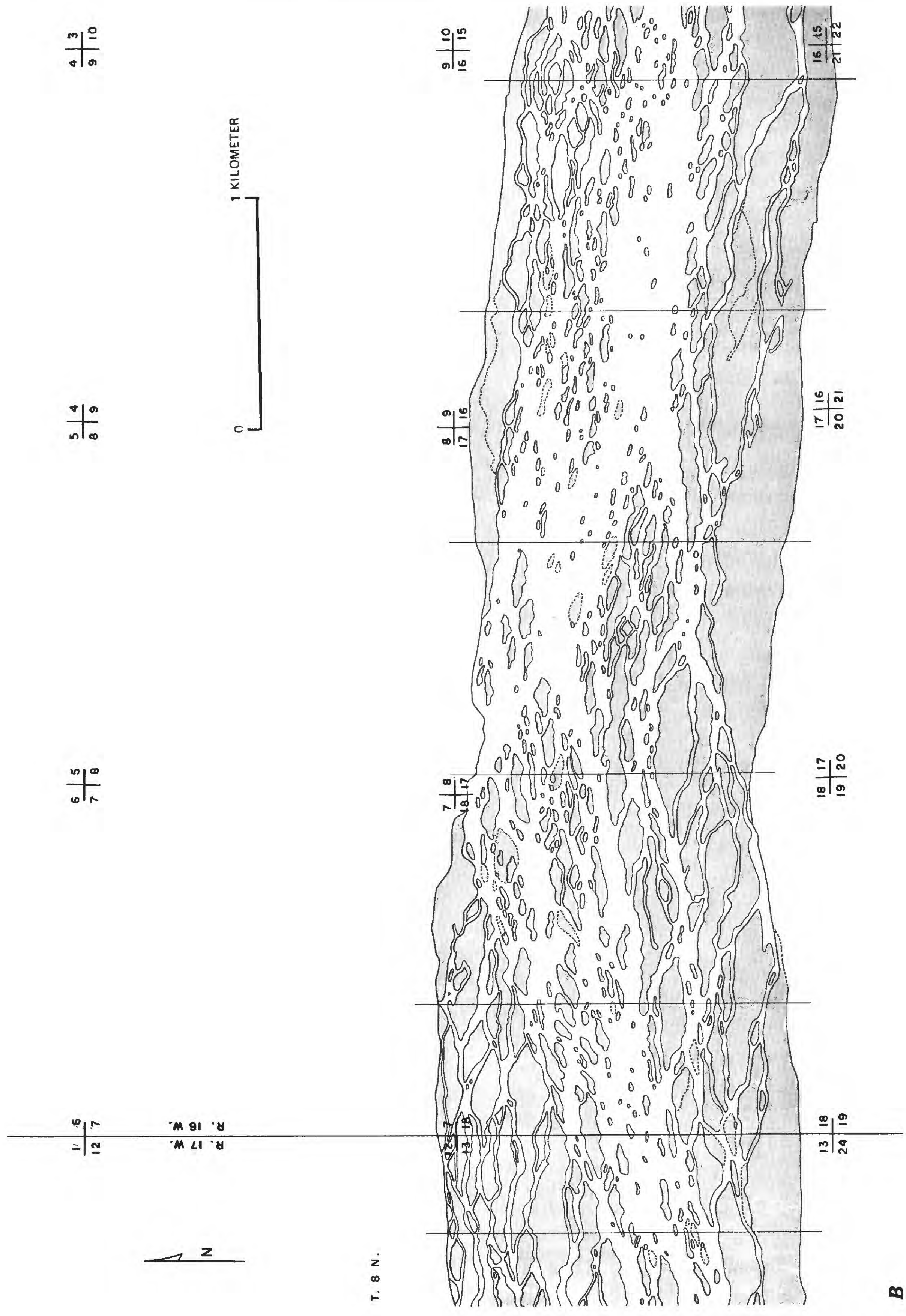


FIGURE 7.—Continued.

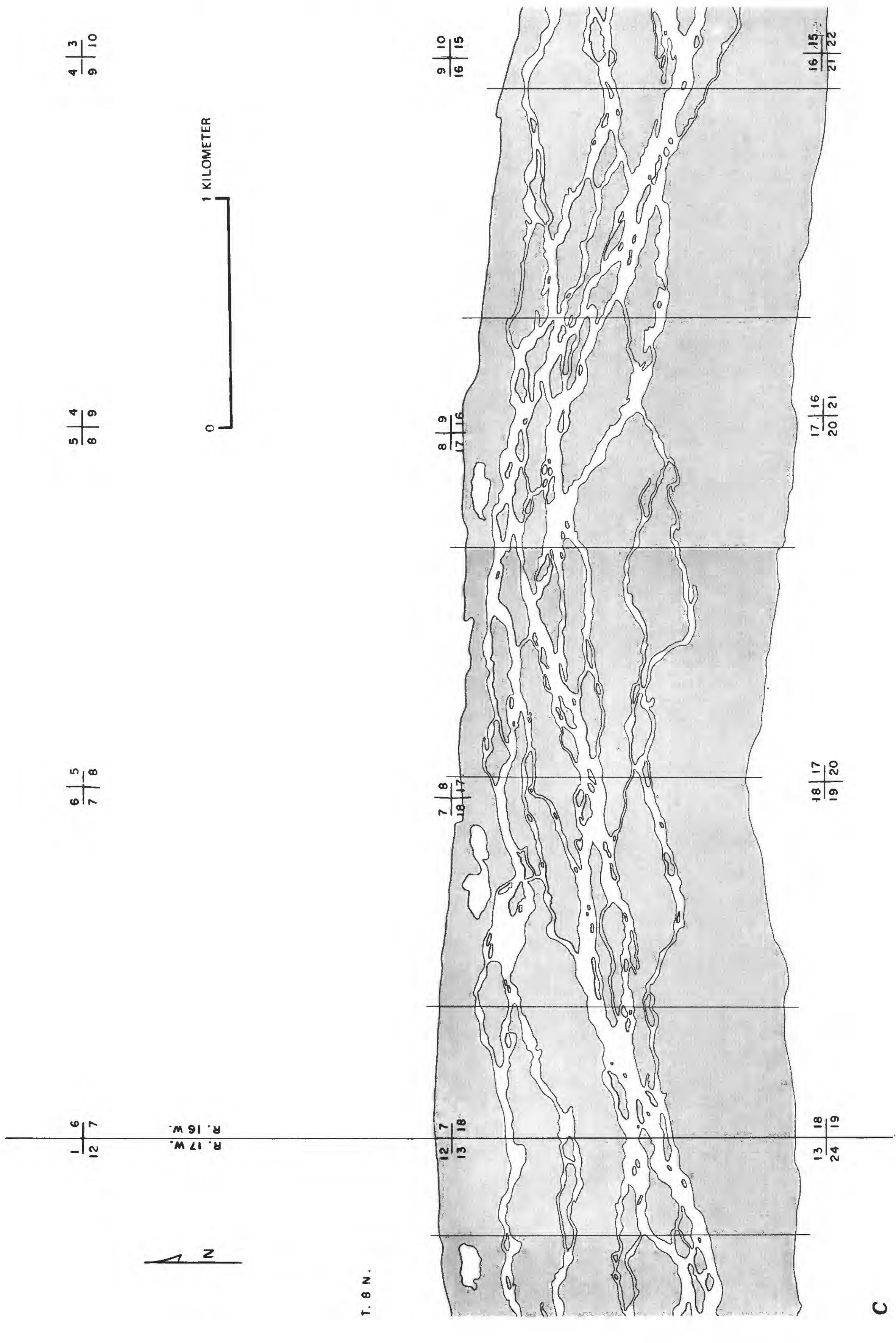


FIGURE 7.—Continued.

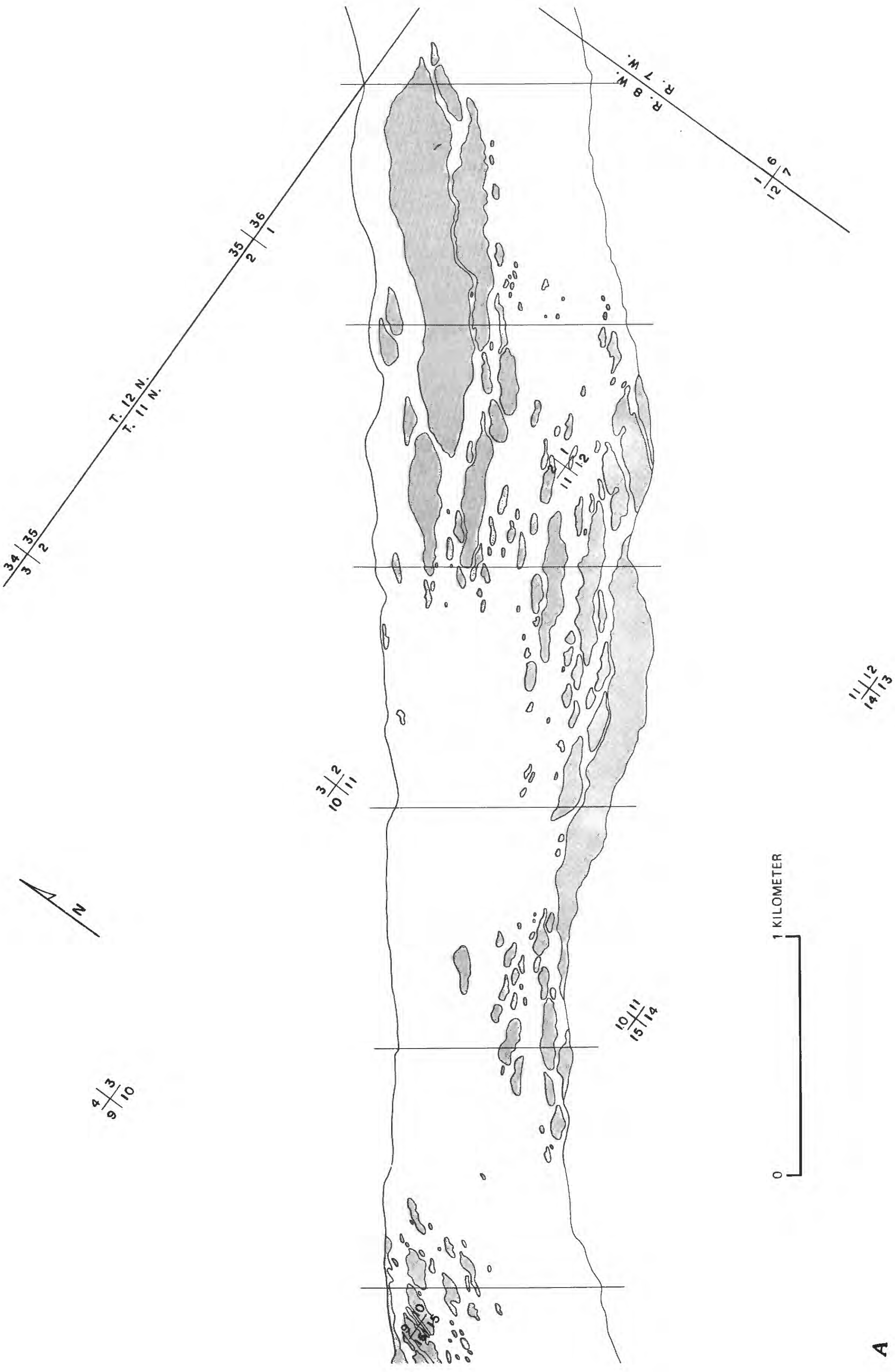


FIGURE 8.—Channel of the Platte River near Grand Island, Nebraska, in sections 1, 2, 10, 11, 12, and 15, T. 11 N., R. 8 W., and section 36, T. 12 N., R. 8 W., in (a) 1938 and (b) 1979. Shaded areas are vegetated.

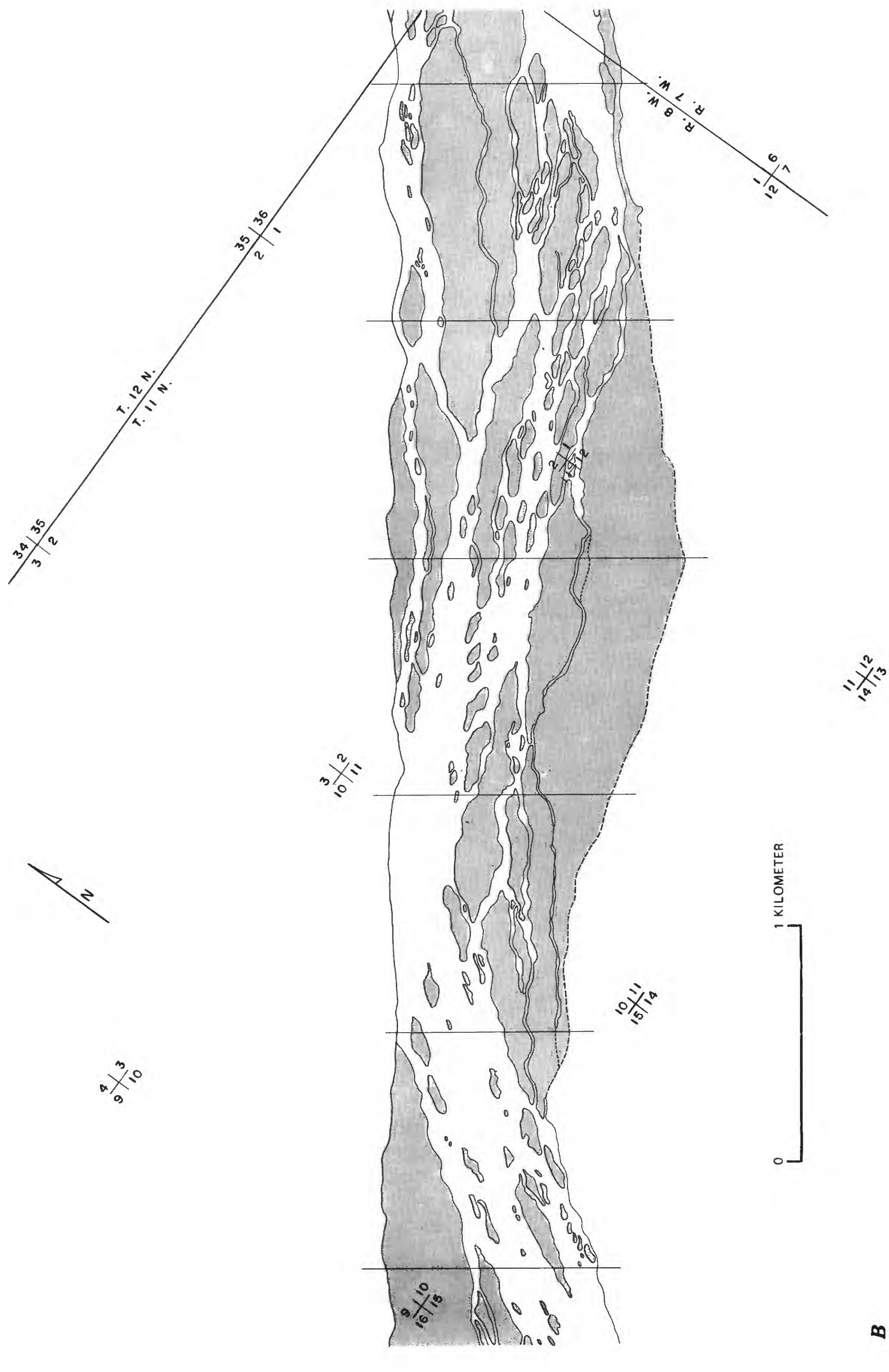


FIGURE 8.—Continued.

The same years are not shown for all the photo sets. These figures show representative island development that occurred throughout the study area.

Development of islands near Cozad, Nebraska, is shown in figure 6. The channel in 1860 was broad and open (fig. 6). By 1938, numerous islands had formed within the channel and had begun to attach to the flood plain (fig. 6). Between 1938 and 1979, significant narrowing of the channel occurred (fig. 6). Today, almost the entire channel of 1860 is covered with vegetation, and only two or three small meandering channels are present (fig. 6).

By 1938, some islands had formed and had become attached to the flood plain near Kearney (fig. 7a). A group of en echelon islands was present near the southern bank of the western edge (fig. 7a). Between 1938 and 1957, many new islands formed, and additional islands attached to the flood plain (fig. 7b). In 1957, almost the entire southern bank was lined with vegetation. In general, the islands present in 1938 are still present, but have enlarged, primarily in the downstream direction, or have coalesced with other islands. The dashed lines within the large islands in figure 7b show the locations of channels that separated islands at one time. These abandoned channels have a topographic expression on the island surface. By 1979, island attachment to the flood plain had formed a wide swath of vegetation along both banks within the former channel area (fig. 7c) and the river consisted of a series of channels braiding among large islands. This channel pattern near Kearney (in 1979) differed appreciably in appearance from both the channel at the same location in 1938 (fig. 7a) and from the channel near Cozad in 1979 (fig. 6c).

In 1938, the percentage of channel area near Grand Island occupied by islands appears to have been greater than at the other river reaches observed for this study. Islands of all sizes were present in the channel, and attachment to the flood plain had begun (fig. 8a); by 1979, new islands had formed in this reach (fig. 8b).

Only one large island existed near Duncan, Nebraska, in 1860 (fig. 9a). By 1941, several small islands were present in the channel, and attachment of islands to the flood plain had begun. The large island mapped in 1860 had decreased slightly in size (fig. 9b). Most of the islands evident in 1941 had become attached to the flood plain by 1978 (fig. 9c). Although islands continue to form, the channel is relatively open.

In 1941, the channel near Ashland, Nebraska, contained four large islands (fig. 10a). One large island along the south bank already had become attached to the bank. The remainder of the 5-km reach had a few small islands in 1941. By 1971 (fig. 10b), only one large island existed in the channel. Two of the islands had become attached to the bank and one island not present in 1941 formed and became attached to the bank during the 30-year period. The net change in average channel width at Ashland was very small when compared to sites upstream (fig. 11).

Measurements of channel width taken from the General Land Office maps surveyed in the field during the approximate period 1859–1867 and six sets of aerial photographs for six 5-km reaches of th Platte River are listed in table 3. Channel widths were measured along six cross sections, at 1-km intervals, at each of six reaches, and averaged for the entire reach. To make the comparison of various cross sections easier, the widths are plotted in figure 11 as percentages of the General Land Office map widths. For convenience the map widths are called "1860 width" in figure 11. Width changes shown in figure 11 for individual reaches are termed "at-a-station" changes, because they reflect channel width changes for a particular reach with time.

In general, the widths of the Platte channels have decreased since 1860. Width changes in the Cozad, Overton, Kearney, Grand Island, and Duncan reaches are similar in character. On the average, the magnitude of width reduction has decreased with time since 1940. The decrease in width of the Platte River near Ashland, Nebraska, has been minor, however, and channel width has increased slightly since 1941.

Width increases of a smaller scale are superimposed on the long-term width reductions. These relatively minor width increases occur between 1951 and 1957, and 1969 and 1979 for the reach near Overton; between 1950 and 1957 for the reach near Grand Island; and between 1941 and 1949, 1955 and 1959, and 1965 and 1971 for the reach near Ashland. Width decreased consistently in the reaches near Kearney and Duncan.

Williams (1978) measured river widths at 35 locations on the North Platte and Platte Rivers from the Wyoming-Nebraska State line to Grand Island. He found that channel width was about 10 to 20 percent as wide in 1965 as it was in 1860 for most of the reach. The downstream 100 km of his study reach, from Overton to Grand Island, also showed a decrease in width, but to a lesser extent than upstream, being about 60 to 70 percent as wide in 1965 as it was in 1860.

Channel widths during the periods 1938–1941, 1957–1959, 1969–1971, and 1978–1979, expressed as percentages of the 1860 channel widths, are plotted with distance downstream from the Wyoming-Nebraska State line in figure 12. The width changes with time shown in figure 12 are here termed "downstream" changes. Generally, the greatest reductions in channel widths occurred between the periods 1938–1941 and 1957–1959. At Cozad, for example, the 1938–1941 channel occupied 87 percent of the 1860 channel width, whereas the 1957–1959 channel occupied only 10

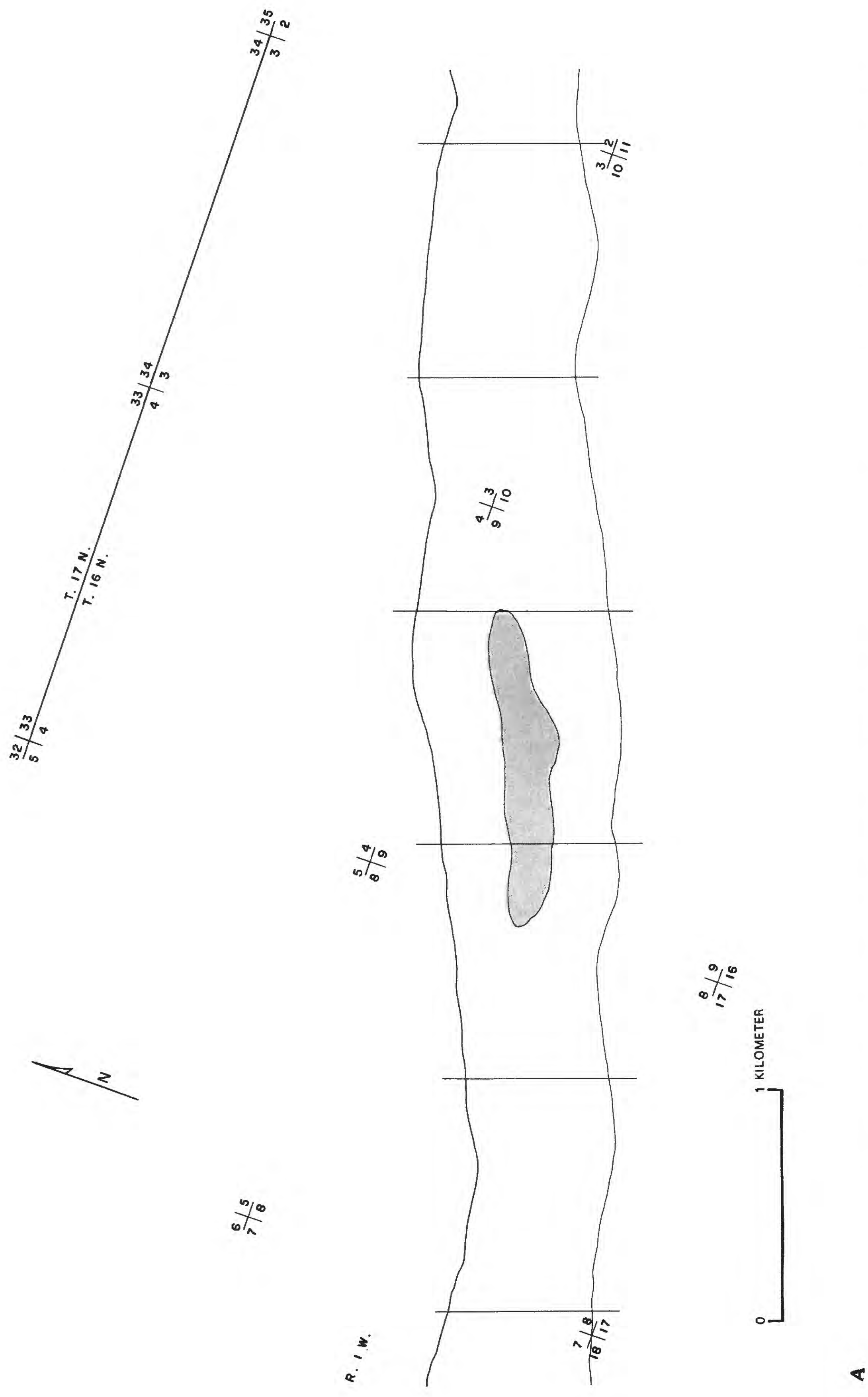


FIGURE 9.—Channel of the Platte River near Duncan, Nebraska, in sections 3, 4, 8, 9, 10, 16, and 7, T. 16 N., R. 1 W., in (a) 1860, (b) 1941, and (c) 1978. Shaded areas are vegetated.

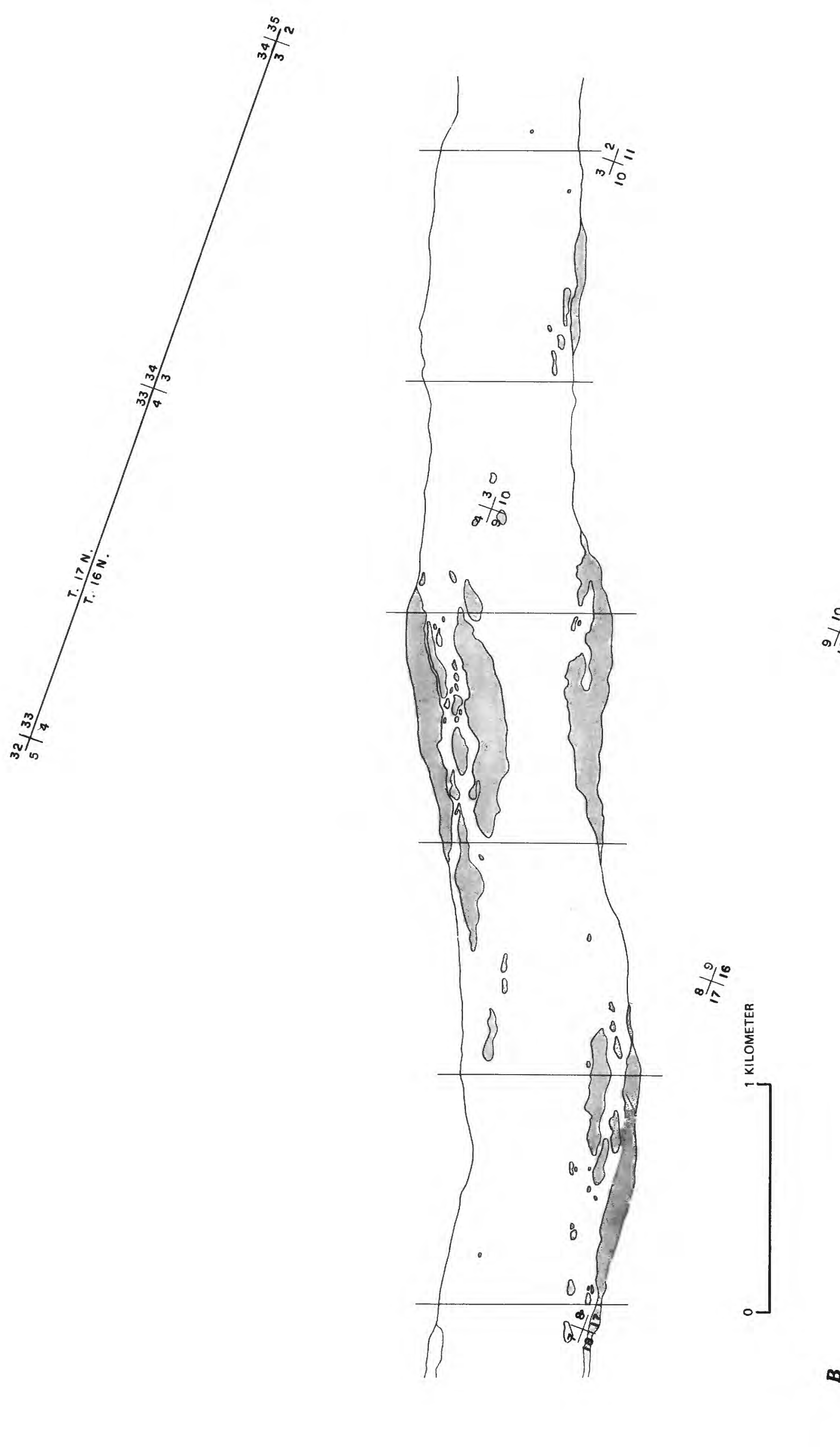


FIGURE 9.—Continued.

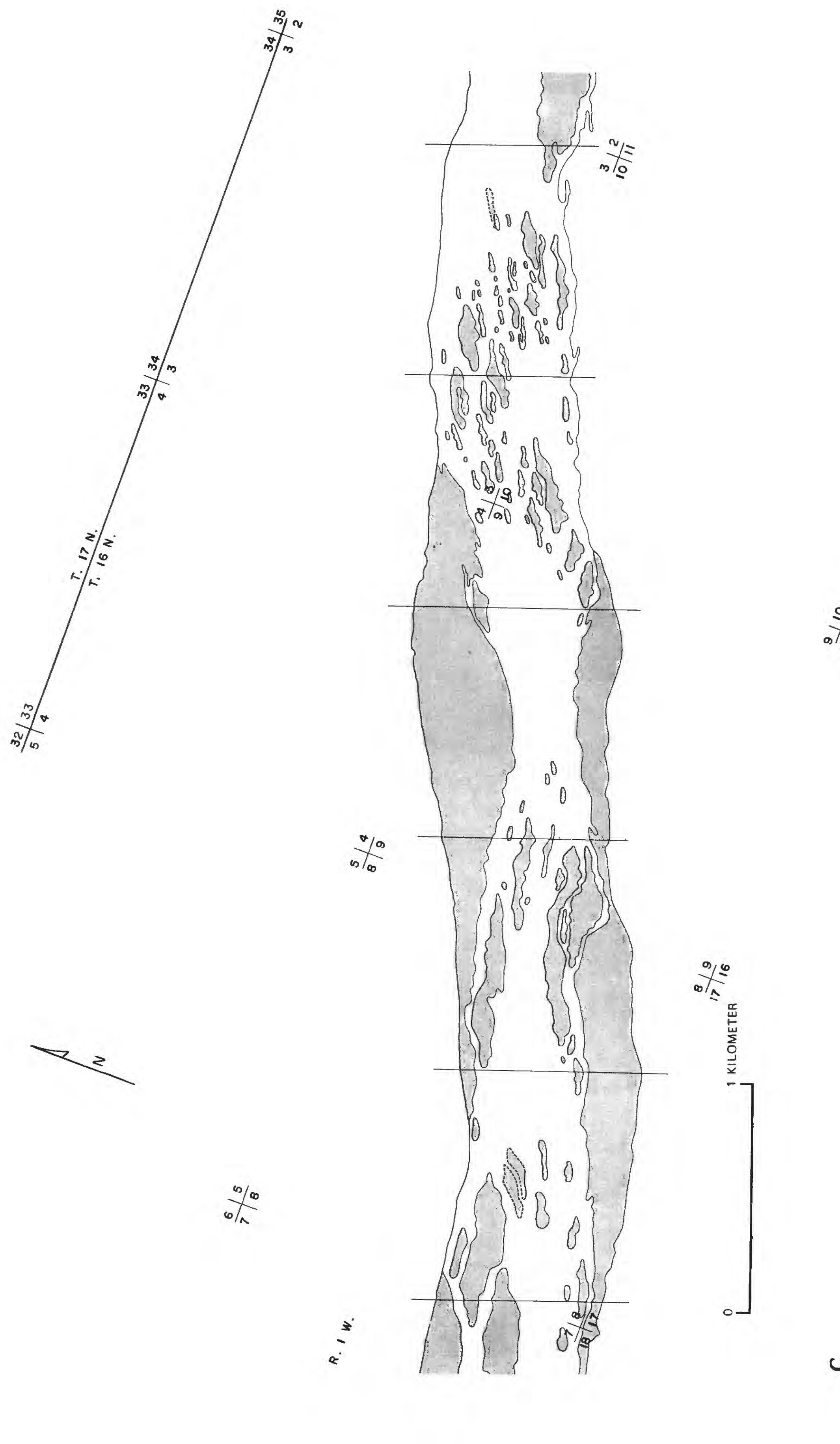


FIGURE 9.—Continued.

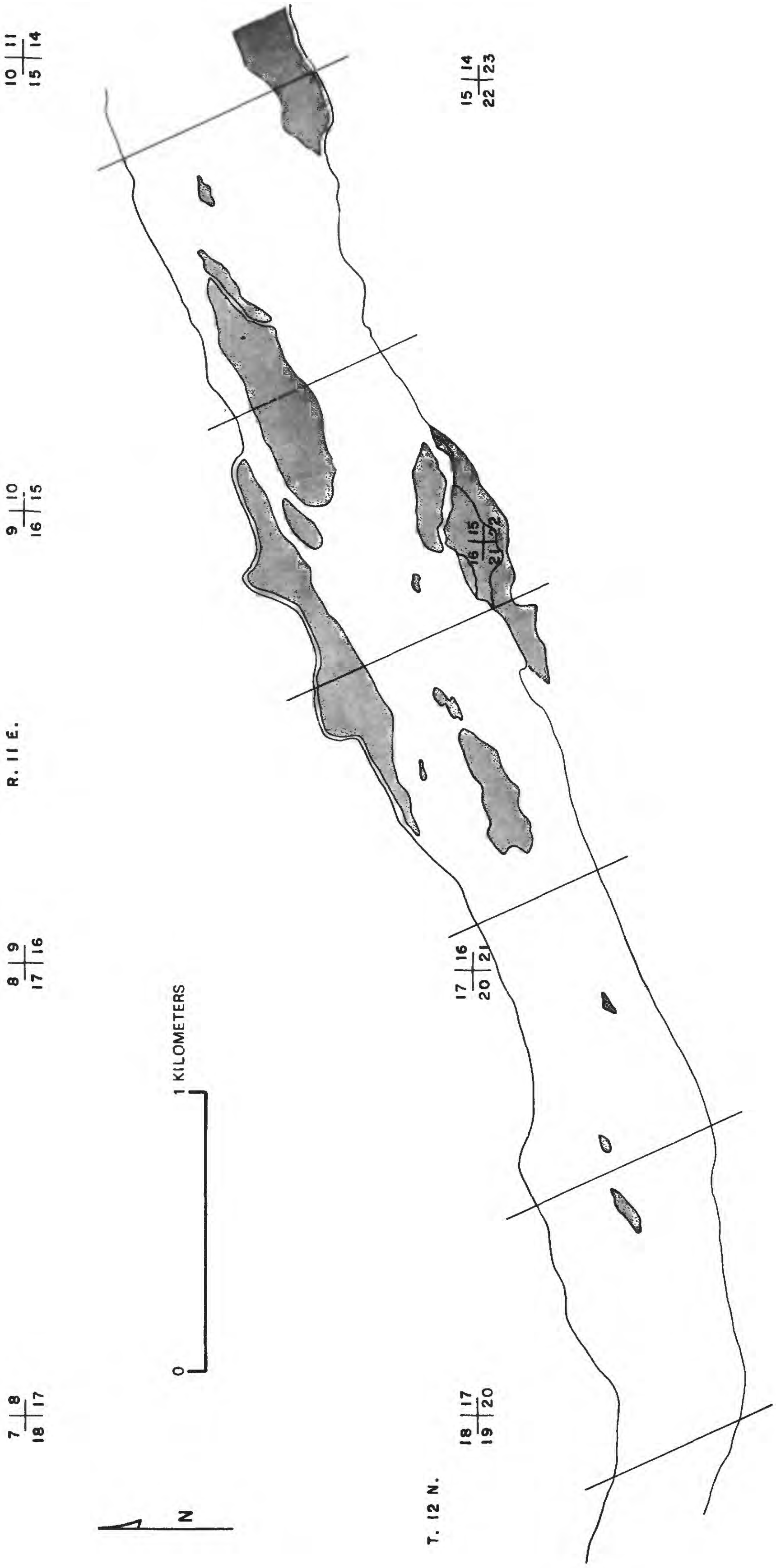


FIGURE 10.—Channel of the Platte River near Ashland, Nebraska, in sections 15, 16, 17, 18, 19, 20, and 21, T. 12 N., R. 11 E., in (a) 1941 and (b) 1971. Shaded areas are vegetated.

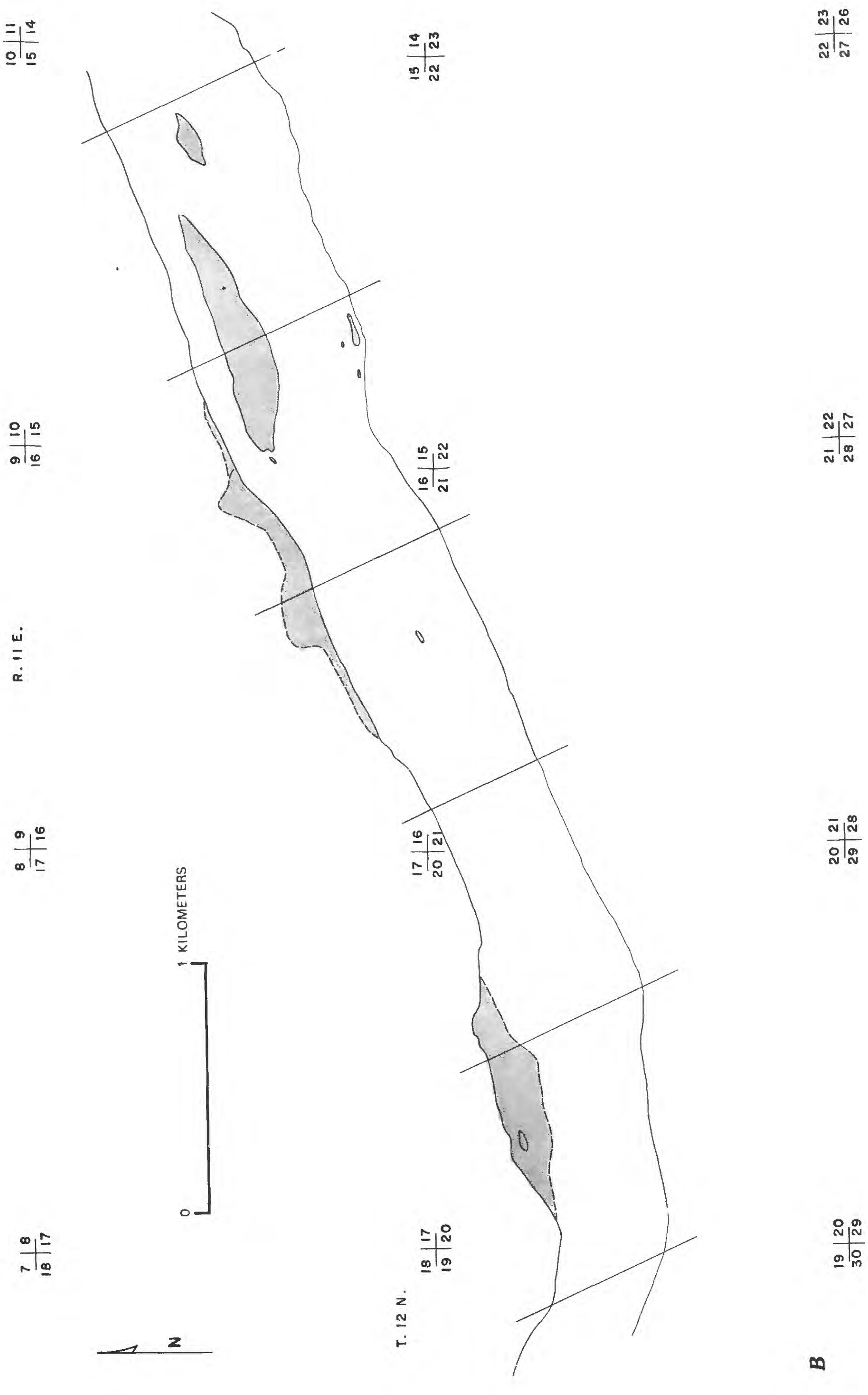


FIGURE 10.—Continued.

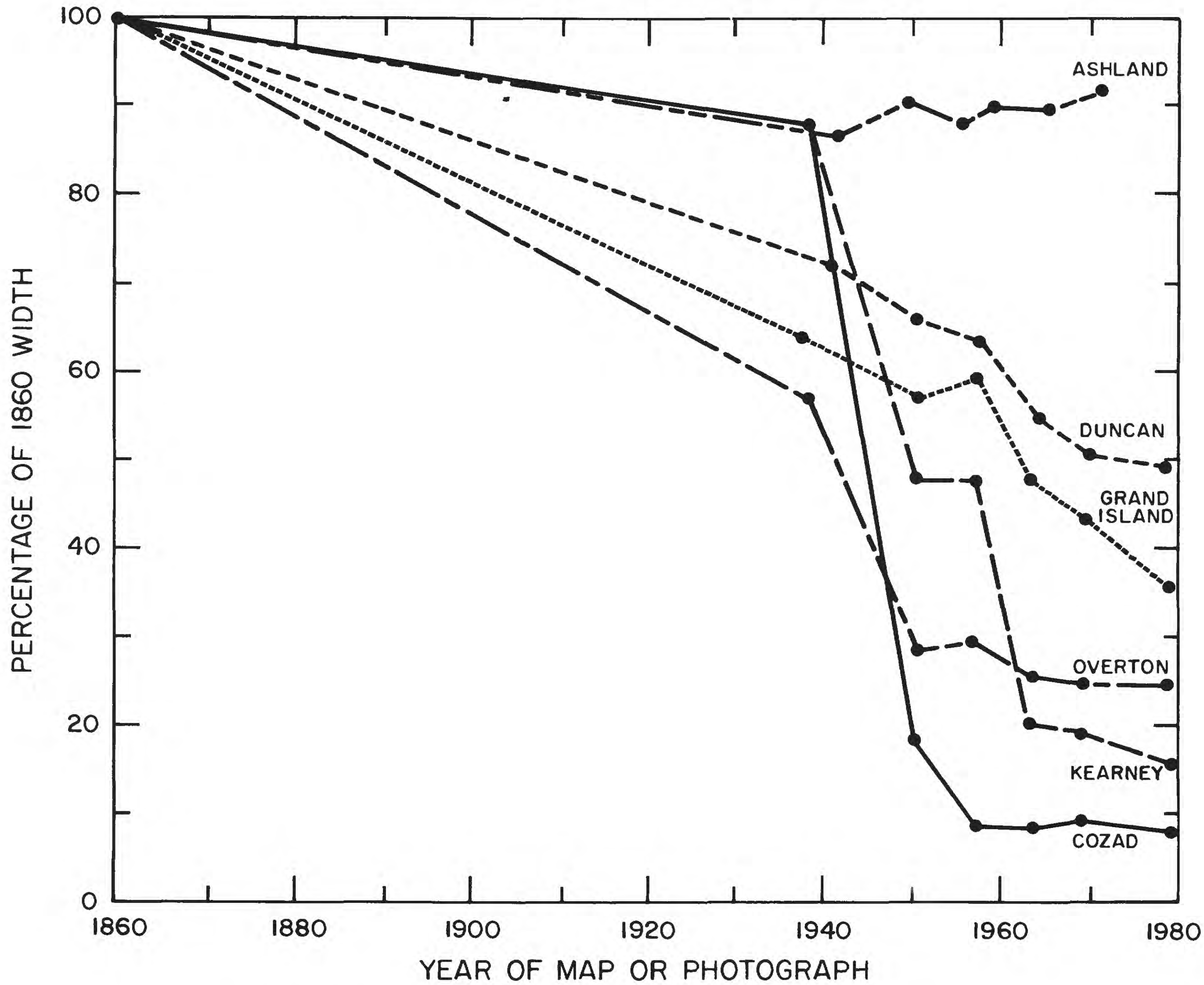


FIGURE 11.—At-a-station changes of channel width of the Platte River, Nebraska, with time.

percent of the 1860 channel width. Additionally, the magnitude of change in channel width between the periods 1938–1941 and 1957–1959 decreases downstream. The downstream-most reach, Ashland, actually shows an increase of width of 3 percent between these periods.

Channel width has decreased consistently for most of the reaches during the entire period of record (1860–1979). However, the rate of width reduction has decreased since 1957–1959. That is, there is relatively little change in channel width between 1957–1959 and 1961–1969 and almost no change between 1969–1971 and 1978–1979. During 1969–1971, the last period of complete aerial photograph coverage, channel widths ranged from 10 percent of the 1860 width at Cozad, the upstream-most reach, to 92 percent of the 1860 width at Ashland.

Reduction of channel width has been documented extensively and has been shown to coincide with a period of changing flow regime. Despite the abundance of information available from aerial photographs, channel changes in the period between the General Land Office surveys and the inception of aerial photography only can be conjectured.

Information from the gaging station formerly located south of Lexington, Nebraska, provides one precise morphologic description from this intervening period. The U.S. Geological Survey station description, prepared in 1902, states that both right and left banks were: "Low, not over four or five feet, but not subject to

TABLE 3.—*Channel widths of the Platte River, Nebraska, in downstream order, measured from General Land Office maps (1860) and aerial photographs (1938–1979)*

Year	Channel width, in meters					
	Cozad	Overton	Kearney	Grand Island	Duncan	Ashland
1860	1,161	1,545	1,484	1,100[1]	826	594
1938	1,015	890	1,298	704	---	---
1941	---	---	---	---	600	515
1949	---	---	---	---	---	539
1950	---	---	---	643	543	---
1951	204	451	698	---	---	---
1955	---	---	---	---	---	521
1957	113	460	695	664	521	---
1959	---	---	---	---	---	533
1963	110	408	308	530	---	---
1964	---	---	---	---	448	---
1965	---	---	---	---	---	530
1969	113	387	293	472	---	---
1970	---	---	---	---	424	---
1971	---	---	---	---	---	549
1978	---	---	---	---	411	---
1979	110	405	247	387	---	---

[1]From 1898 edition 30′ U.S. Geological Survey topographic map (General Land Office map incomplete).

overflow-sparingly wooded." The description further states, "Bed is composed of shifting sand. Total width is 3,720 feet [1,134 m]." The same cross section, as measured from the General Land Office maps, has a width of 1,134 m, the same width as that given in 1902. A photograph dated about 1910 of the bridge over the Platte River south of Lexington shows that the river was still wide and free of vegetation (fig. 13). A note on the back of the photo indicates the bridge was about 1,450 m long (photograph on file at the Dawson County Historical Society Museum). The 1938 aerial photograph shows the same cross section with a width about one-third of the width in 1860. Although the reduction at the gage station was largely because of fill around the bridge sections, areas of the river upstream and downstream from the bridge show that channel narrowing and island development already had occurred. Thus, morphologic change of the Platte River at this site began after 1910, but before 1938.

Further historical evidence for the change of the overall character of the channel is available from ground-level photography at several locations along the river. For example, in the reach of the river near Cozad and Kearney, the river has changed with time from a broad channel with few islands (figs. 14a and 15a) to a series of relatively narrow, well-defined channels intertwining among large islands (figs. 14b and 15b). Below the confluence with the Loup River, channel change has been far less dramatic. For example, near Ashland, a photograph taken in 1897 (fig. 16a) shows a broad, vegetation-free channel. A photograph taken from about the same location in 1982 (fig. 16b) shows that the channel changed very little. The evidence from the ground-level photography corroborates the at-a-station and downstream trends of channel width evident in figures 11 and 12.

CHANGES IN NORTH PLATTE AND SOUTH PLATTE RIVER MORPHOLOGY

Changes of North Platte River morphology have been similar to changes that occurred on the Platte River. Channel width in 1965 ranged from 5 to 40 percent of the channel width mapped in 1860 (table 4); it probably averaged about 15 percent of the 1860 channel width (Williams, 1978). Braiding and sinuosity (table 4) were determined for the channel as of 1938 and as of 1965 (Williams, 1978). In general, braiding index, defined by Williams (1978) as the sum of length of islands in a reach divided by the length of the reach, decreased, and sinuosity index, defined by Williams (1978) as the length of a reach of existing channel divided by the length of channel in the same reach in 1860, increased for the North Platte River in Nebraska.

Morphology of the South Platte River also has changed. Nadler (1978) found that channel width in 1952 averaged only about 15 percent of channel width in 1867. From 1867 to 1952, sinuosity of the South Platte River increased between 5 and 15 percent. Data from individual cross sections are listed in table 5.

RELATIONSHIP OF DISCHARGE REGULATION TO CHANNEL CHANGE

Morphologic changes of the North Platte, South Platte, and Platte Rivers have been similar despite significant differences in the hydrology of these three rivers. Construction of reservoirs and diversion of streamflow on the North Platte River have caused reductions of annual peak flows and mean annual flows of both the North Platte and Platte Rivers. In contrast, there has been no reduction of peak flows on the South Platte River upstream of Julesburg during the period of record because of a relatively small amount of reservoir construction. Transbasin diversions into the South Platte River have offset diversions of water for irrigation, resulting in no net change of mean annual flows during the period of record.

Schumm (1968) attributed decrease in size of the South Platte River channel to the decrease in the annual peak discharge. However, a decrease in the annual peak

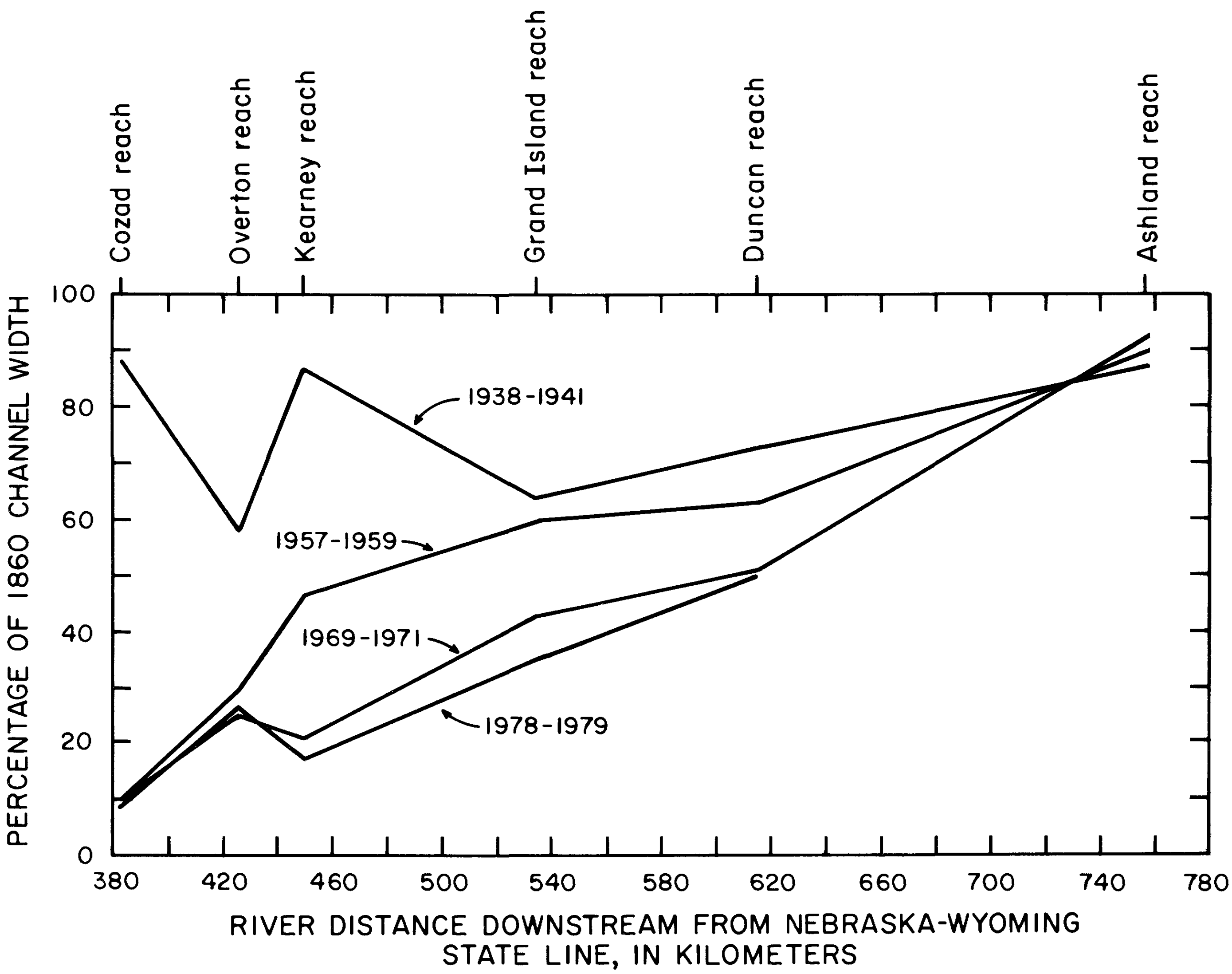


FIGURE 12.—Downstream changes in the percentage of 1860 channel width of the Platte River occupied by the channel in 1938-1941, 1957-1959, 1969-1971, and 1978-1979.

discharge of the South Platte River upstream of Julesburg, Colorado, has not occurred during the period of record (Kircher and Karlinger, 1981). Thus, morphologic change apparently has occurred in response to irrigation development in the basin prior to the period of record. Nadler (1978) proposed that irrigation development along the South Platte River changed the river from intermittent to perennial. This hydrologic change caused a change in the vegetation that stabilized the channel. The temporary reduction of discharge during the drought of the 1930's allowed vegetation to occupy and become established in areas of channel. Subsequent floods were not able to widen the channel, as they presumably might have, prior to the encroachment of vegetation.

PROCESSES OF WIDTH REDUCTION

Six sets of aerial photographs used in this report (figs. 6-10) allow documentation of channel width reductions and the processes of width reduction. These processes are island formation and subsequent attachment of islands to either the flood plain or other islands. The channel in the 1860's was broad and open (figs. 6a and 13 near Cozad, Nebraska for example) with few vegetated islands, most of which were large.

By 1938, width decreased by island formation. In addition, bank locations had shifted toward the center of the channel, as a result of island formation and attachment to the flood plain. Island attachment resulted from channel abandonment or atrophication, rather

FIGURE 13.—Photograph of the Platte River south of Lexington, Nebraska, facing toward the north, taken about 1910. (Photograph from Dawson County Historical Society Museum.)

than from a migration of the river course. Most of the small islands near these sections are wedge- or lobe-shaped; they are oriented with the pointed end downstream. Comparison of these islands with adjacent sandbars shows that they have the same form. Therefore, we conclude that the majority of the islands in the Platte River formed when vegetation established itself on these bars and stabilized them. Hydrologic changes, which began with irrigation development and were accelerated by large reservoir construction, evidently provided more favorable growing conditions on the bars, or decreased flood peaks that formerly had removed vegetation.

Once an island formed, it tended to perpetuate itself. The presence of vegetation encouraged further aggradation by increasing roughness and decreasing flood-water velocity over the bar when the island is submerged. Thus, island elevation increased until it was at or above high-water stage.

Sets of maps and photographs made after 1938 show similar, continued development of islands. However, with time, the number of islands diminished, but their size increased. Sediment was accreted at the downstream ends of islands due to decreased flow velocity at their downstream end. This sand substrate is a likely place for vegetation establishment.

The coalescence of islands occurs as the channels between islands gradually lose their water- and sediment-carrying capabilities, becoming indistinguishable, both in appearance and function, from the islands they separate. This process has been documented in other studies. Nadler (1978) proposed vertical infilling of channel braids or branch channels, as the method by which the South Platte River was transformed from a

FIGURE 14.—The Platte River near the present site of Cozad, Nebraska, from the south bank. *A*, looking approximately northwest, in the year 1866. (Courtesy of Union Pacific Railroad.) *B*, Oblique photograph, facing toward the northwest, taken in 1979.

multiple-thalweg to single thalweg stream. Branch-channel aggradation is important in the abandonment of channels and subsequent attachment of islands to the flood plain on the Cimarron River (Schumm and Lichty, 1963). The attachment of islands to the flood plain of the Loup River in Nebraska by atrophication of narrow channels carrying water at high discharges has been documented by Brice (1964).

SOME IMPLICATIONS OF FUTURE WATER DEVELOPMENT

Documented changes in the channels of the Platte River and its major tributaries that have been discussed in this report are attributed primarily to water development. Water use for irrigation in the basin and water demands from municipal, industrial, and power generation uses have significantly changed streamflow characteristics. These water uses have affected mean annual flows, peak flows, low flows, and flow distribution (Kircher and Karlinger, 1981). Also, changes in surface-water hydrology probably have affected sediment transport in major streams. New discharge and sediment-transport regimes have resulted in sand bars that are not scoured or removed each year. Vegetation has stabilized channel sand bars and transformed them into islands. These processes have been a major factor in narrowing the channels, as shown by the sequence of maps (figs. 6 to 10). All of these changes have contributed to progressive deterioration of the riverine habitat of sandhill cranes, whooping cranes, and other

FIGURE 14.—Continued.

migratory birds in the critical reach between Overton and Grand Island, Nebraska.

If the present migratory-bird habitat is to be preserved from further deterioration, further research is needed for the relationship between streamflow, sediment-transport characteristics, and channel geometry. For example, it will be useful to estimate the discharge necessary to maintain a desired channel width necessary for preservation of the habitat. This discharge must be of sufficient magnitude and duration to cause sand bar movement and removal of vegetation seedlings by scour.

REFERENCES CITED

Baydo, Gerald, 1971, Overland from Missouri to Washington territory in 1854: Nebraska History, v. 52, p. 65–87.

Bentall, Ray, 1975a, Hydrology, Nebraska mid-state division and associated areas: Lincoln, Nebr., Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska, 256 p.

_____1975b, Physiography, geology, soils, agriculture: Nebraska mid-state division: Lincoln, Nebr., Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska, 76 p.

FIGURE 15.—Platte River south of Kearney, Nebraska, from the south bank toward the north. *A*, taken between 1875 and 1880. (Photograph from Stuhr Museum of the Prairie Pioneer.) *B*, taken in 1981.

Bradbury, John, 1819, Travels in the interior of America in the years 1809, 1810, and 1911, *in* Thwaites, R. G., ed., 1905, Early western travels, v. 5: Cleveland, Ohio, A. H. Clarke Co., p. 25–320.

Brice, J. C., 1964, Channel patterns and terraces of the Loup Rivers in Nebraska: U.S. Geological Survey Professional Paper 422–D, 41 p.

Burnett, P. H., 1904, Recollections and opinions of an old pioneer: Quarterly of the Oregon Historial Society, v. 5, p. 64–99, 139–198, 272–305, 370–470.

Carlson, M. E., 1963, The development of irrigation in Nebraska, 1854–1910: A descriptive history: Ph. D. dissertation, Lincoln, Nebr., University of Nebraska, 153 p.

Clarke, H. T., 1902, Freighting—Denver and Black Hills: Proceedings and Collections of the Nebraska State Historical Society, Second Series, v. 5, p. 299–312.

Cole, G. L., 1905, In the early days along the Overland Trail in Nebraska territory, in 1852: Kansas City, Mo., Hudson Publishing Co., 125 p.

Crowley, K. D., 1981, Large-scale bedforms in the Platte River downstream from Grand Island, Nebraska: structure, process, and relationship to channel narrowing: U.S. Geological Survey Open-file Report 81–1059, 31 p.

Dirmeyer, Richard, 1975, More on protected streamflows: Nebraska Resources, v. 6, p. 3–4.

Eschner, T. R., 1981, Morphologic and hydrologic changes of the Platte River, south-central Nebraska: M.S. thesis, Fort Collins, Colo., Colorado State University, 269 p.

Fremont, (Capt.) J. C., 1845, Report of the exploring expedition to the Rocky Mountains: Washington, D. C., Gales and Seaton, 693 p.

Frith, C. R., 1974, The ecology of the Platte River as related to sandhill cranes and other waterfowl in south central Nebraska: M.S. thesis, Kearney, Nebr., Kearney State College, 115 p.

Fuller, H. M., and Hafen, L. R., 1957, The journal of Captain John R. Bell, official journalist for the Stephen H. Long expedition to the Rocky Mountains, 1820: Glendale, Calif., Arthur H. Clark Co., 349 p.

Gatewood, J. S., Robinson, T. W., Colby, B. R., and others, 1950, Use of water by bottom-land vegetation in lower Safford Valley, Arizona: U.S. Geological Survey Water-Supply Paper 1103, 210 p.

Gerlek, Stephen, 1977, Water supplies of the South Platte River basin: M.S. thesis, Fort Collins, Colo., Colorado State University, 798 p.

Ghent, W. J., 1929, The road to Oregon: New York, Longmans, Green, and Co., 274 p.

Hecht, A. D., 1981, The challenge of climate to man: EOS Transactions, American Geophysical Union V. 62, p. 1193–1197.

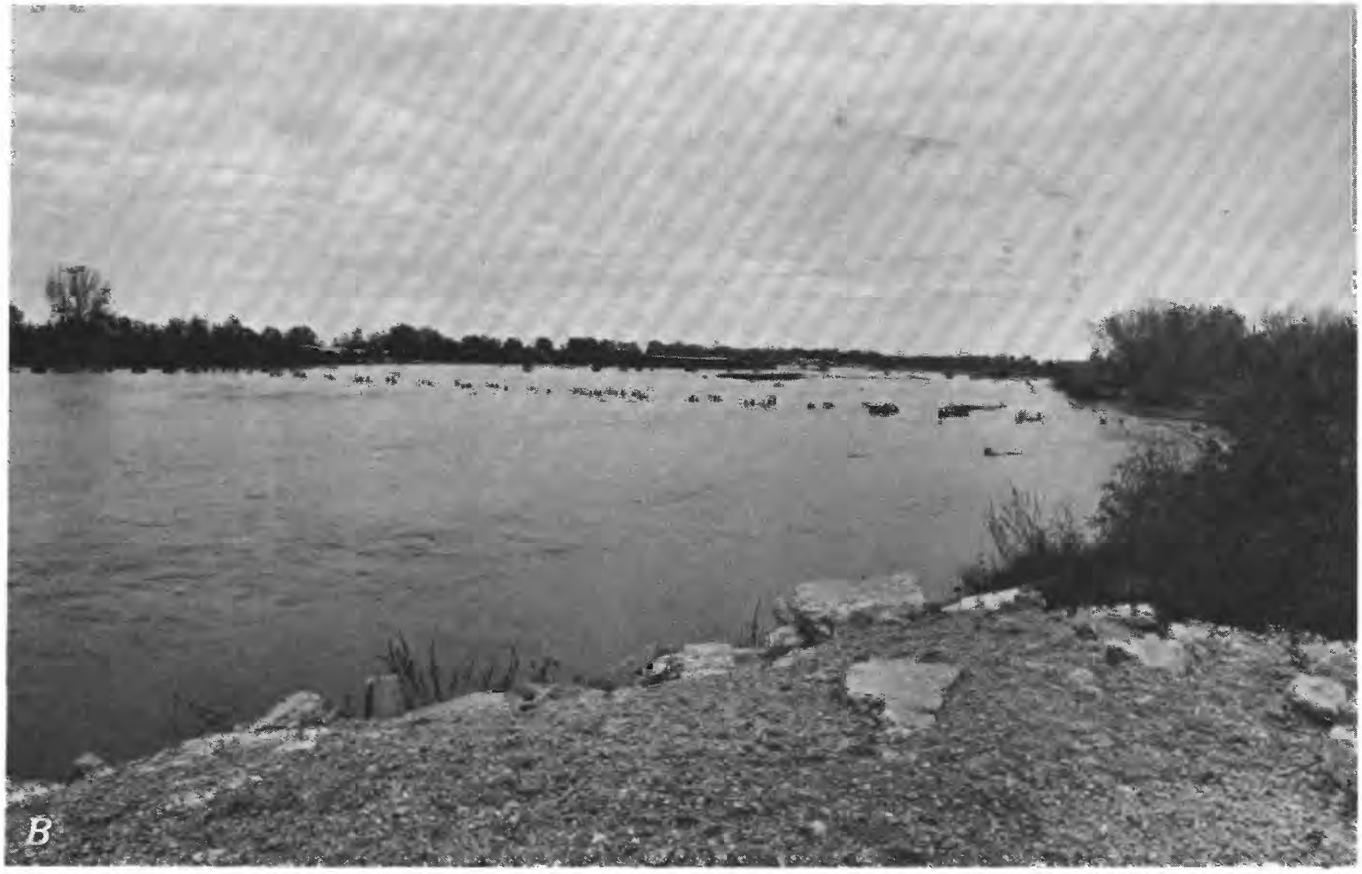


FIGURE 15.—Continued.

FIGURE 16.—Photograph of the Platte River near Ashland, Nebraska, from the south bank toward the northeast. *A*, taken in 1897. (Photograph by N. H. Darton, U.S. Geological Survey.) *B*, taken in 1982.

Hudson, H. E., and Hazen, Richard, 1964, Droughts and low streamflow, *in* Chow, V. T., ed., Handbook of applied hydrology: New York, McGraw-Hill, p. 18-1-26.

Hurr, R. T., 1975, Effects of water-management practices on the flow of the South Platte River, Colorado: International Association for Hydrological Sciences, Symposium of Tokyo, 1975, Publication no. 117, p. 611-617.

_____1981, Ground-water hydrology of the Crane Meadows wildlife area, near Grand Island, Hall County, Nebraska: U.S. Geological Survey Open-File Report 81-1109, 43 p.

TABLE 4.—*Data for channel width, braiding index, and sinuosity index for the North Platte River*[1]

Location, city name, or township and range	Total channel width (meters)				Williams' braiding index		Williams' sinuosity index	
	1865	1938	1965	Ratio of 1965 to 1865	1938	1965	1938	1965
Minatare	975	---	55	0.06	---	---	---	---
R. 52 W.	810	---	105	0.13	---	---	---	---
Bridgeport	1,140	---	120	0.11	---	---	---	---
R. 50 W.	810	---	130	0.16	---	---	---	---
R. 48 W.	1,255	---	170	0.14	---	---	---	---
Lisco	1,280	---	150	0.12	---	---	---	---
R. 46 W.	1,060	---	185	0.18	---	---	---	---
R. 44 W.	545	---	200	0.37	---	---	---	---
Lewellen	885	---	150	0.17	---	---	---	---
R. 42 W.	810	---	165	0.20	---	---	---	---
R. 40 W.	710	---	---	---	---	---	---	---
Keystone	950	---	---	---	1.21	0.00	1.06	1.00
R. 38 W.	940	200	45	0.05	1.21	0.00	1.06	1.00
R. 36 W.	850	815	45	0.05	8.13	2.50	1.00	1.11
R. 34 W.	750	325	195	0.23	2.23	0.26	1.06	1.11
Sutherland	---	410	75	---	2.13	2.20	1.05	1.30
R. 32 W.	740	460	45	0.06	3.48	1.91	1.03	1.05
North Platte	790	520	90	0.11	3.44	1.76	1.06	1.11

[1]From Williams, 1978.

TABLE 5.—*Data for channel width, braiding index, and sinuosity for the South Platte River*[1]

Location, city name, or township and range	Total channel width (meters)					Braiding index[2]		Sinuosity[3]	
	1867	1952	1977	Ratio of 1952 to 1867	Ratio of 1977 to 1867	1867	1952	1867	1952
T. 5 N., R. 65 W.	415	34	---	0.08	---	---	---	---	---
Kersey	335	52	81	0.16	0.24	0.42	0.29	1.05	1.21
Kuner	335	91	107	0.27	0.32	0.40	0.25	1.04	1.11
Hardin	435	44	61	0.10	0.14	0.17	0.21	1.05	1.12
T. 4 N., R. 63 W.	360	56	---	0.16	---	---	---	---	---
Masters	425	81	107	0.19	0.25	0.27	0.76	1.00	1.09
T. 4 N., R. 62 W.	430	39	---	0.09	---	---	---	---	---
Sublette	---	36	119	---	---	0.29	0.30	1.13	1.19
T. 4 N., R. 61 W.	610	48	---	0.08	---	---	---	---	---
Goodrich	535	80	109	0.15	0.20	0.16	0.31	1.14	1.25
T. 5 N., R. 60 W.	430	73	---	0.17	---	---	---	---	---
Weldona	440	52	91	0.12	0.21	0.21	0.50	1.02	1.12
T. 4 N., R. 59 W.	380	55	---	0.14	---	---	---	---	---
T. 4 N., R. 58 W.	605	101	---	0.17	---	---	---	---	---
Hurley	425	75	93	0.18	0.22	0.79	0.49	1.01	1.10
T. 4 N., R. 57 W.	495	51	---	0.10	---	---	---	---	---
Snyder	375	60	91	0.16	0.24	0.18	1.78	1.02	1.12
T. 4 N., R. 56 W.	535	75	---	0.14	---	---	---	---	---

[1]From Nadler, 1978.
[2]Braiding index, after Brice (1964), not equivalent to Williams' braiding index in table 4.
[3]Sinuosity defined as length of channel divided by down-valley distance.

Irving, Washington, 1837, The adventures of Captain Bonneville, Todd, E. W., ed., 1961: Norman, Okla., University of Oklahoma Press, 429 p.

James, Edwin, 1823, Account of an expedition from Pittsburgh to the Rocky Mountains: Ann Arbor, Mich., University Microfilms, Inc., 945 p. (This is a chronicle of the Long Expedition.)

Johnson, M. S., and Pederson, D. T., 1980, Groundwater levels in Nebraska, 1979: Nebraska Water Survey Paper 50, 65 p.

Kelly, William, 1851, An excursion to California, over the prairie, Rocky Mountains, and Great Sierra Nevada: New York, Arno Press, 334 p. [Reprinted 1973.]

Kircher, J. E., 1981, Sediment transport and effective discharge for the North Platte, South Platte, and Platte Rivers in Nebraska: U.S. Geological Survey Open-File Report 81-53, 26 p.

Kircher, J. E., and Karlinger, M. R., 1981, Changes in surface-water hydrology for the South Platte River in Colorado and Nebraska, the North Platte and the Platte River in Nebraska: U.S. Geological Survey Open-File Report 81-818, 77 p.

Lappala, E. G., Emery, P. A., and Otradovsky, F. J., 1979, Simulated changes in ground-water levels and streamflow resulting from future development (1970 to 2020) in the Platte River basin, Nebraska: U.S. Geological Survey Water-Resources Investigations 79-26, 82 p.

Leopold, L. B., Wolman, M. G., and Miller, J. P., 1964, Fluvial processes in geomorphology: San Francisco, Freeman, 522 p.

Lugn, A. L., and Wenzel, L. K., 1938, Geology and ground-water resources of south-central Nebraska: U.S. Geological Survey Water-Supply Paper 779, 242 p.

Martin, R. O. R., and Hanson, R. L., 1966, Reservoirs in the United States: U.S. Geological Survey Water-Supply Paper, 115 p.

Mattes, M. J., 1969, The great Platte River road: Lincoln, Nebr., Nebraska State Historical Society Publications, v. XXV, 583 p.

McKinley, J. L., 1938, The influence of the Platte River upon the history of the valley: Minneapolis, Minn., Burgess Publishing Co., 138 p.

McKinnon, J. C., 1952, Poudre Valley contributions to Colorado irrigation practice, *in* A hundred years of irrigation in Colorado: Denver, Colo., Colorado Water Conservation Board, p. 31-40.

McKinstry, B. L., 1975, The California gold rush overland diary of Byron N. McKinstry, 1850-1852: Glendale, Calif., A. H., Clark, 401 p.

Meline, J. F., 1966, Two thousand miles on horseback: Albuquerque, N. Mex., Horn and Wallace, 317 p.

Miller, Gene, 1978, History of Platte River flows: U.S. Fish and Wildlife Service, Grand Island, Nebr., unpublished manuscript, typewritten, 18 p.

Morgan D. L., ed., 1959, The overland diary of James A. Pritchard from Kentucky to California in 1849: Denver, Colo., The Old West Publishing Co., 221 p.

______1963, Overland in 1846, diaries and letters of the California-Oregon trail: Georgetown, Calif., Talisman Press, 825 p.

Nadler, C. T., Jr., 1978, River metamorphosis of the South Platte and Arkansas Rivers: M.S. thesis, Fort Collins, Colo., Colorado State University, 151 p.

Palmer, Joel, 1847, Journal of travels over the Rocky Mountains, 1845 and 1846, *in* Thwaites, R. G., ed., 1906, Early western travels, v. 30: Cleveland, Ohio, A. H. Clark Co., 311 p.

Petsch, H. E., Jr., Rennick, K. B., and Nordin, C. F., Jr., 1980, Statistical summaries of selected streamflow data—South Platte River in Colorado and Nebraska; North Platte and Platte Rivers in Nebraska: U.S. Geological Survey Open-File Report 80-679, 278 p.

Robinson, T. W., 1958, Phreatophytes: U.S. Geological Survey Water-Supply Paper 1423, 84 p.

Rohwer, Carl, 1953, History of irrigation by pumping from wells in Colorado: Text of talk presented May 25, 1953, on file in U.S. Geological Survey, Water Resources Division, Colorado District Library, Denver, Colo., 9 p.

Rollins, P. A., ed., 1935, The discovery of the Oregon trail, Robert Stuart's narratives: New York, Charles Scribner and Sons, 391 p.

Root, F. A., and Connelley, William, 1901, Overland stage of California: Topeka, Kans., by authors, 630 p.

Schumm, S. A., 1968, River adjustment to altered hydrologic regimen, Murrumbridge River and paleochannels, Australia: U.S. Geological Survey Professional Paper 598, 65 p.

Schumm, S. A., and Lichty, R. W., 1963, Channel widening and floodplain construction along Cimarron River in southwestern Kansas: U.S. Geological Survey Professional Paper 352-D, p. 71-88.

Settle, R. W., 1940, The march of the mounted riflemen: Glendale, Calif., Arthur H. Clark Co., 380 p.

Stansbury, (Capt.) Howard, 1851, Exploration and survey of the valley of the Great Salt Lake of Utah, including a reconnaissance of a new route through the Rocky Mountains: Senate Executive Document no. 3 (Serial 608), Thirty-Second Congress, Special Session of March 1851, 487 p.

State of Colorado, Biennial reports of the State engineer: nos. 2 (1883/1884) to 23 (1925/1926).

State of Nebraska, Biennial reports of the State engineer: Board of Irrigation, Highways, and Drainage, nos. 10 (1913/1914) to 12 (1917/1918).

______, Biennial reports of the State engineer: Department of Public Works, Bureau of Irrigation, Water Power, Drainage, nos. 13 (1919/1920) to 19 (1931/1932).

State of Wyoming, Biennial reports of the State engineer; nos. 1-20, 1889-1931. 1965, Tabulation of adjudicated water rights in division number one: Cheyenne, State Board of Control, 256 p.

Steinel, A. T., and Working, D. W., 1926, History of agriculture in Colorado: Fort Collins, Colo., The State Agricultural College, 659 p.

Townsend, J. K., 1833, Narrative of a journey across the Rocky Mountains, in Thwaites, R. G., ed., 1905, Early western travels, v. 21: Cleveland, Ohio, A. H. Clark Co., 369 p.

U.S. Geological Survey, 1892, Thirteenth annual report of the U.S. Geological Survey, J. W. Powell, director; Part III, Irrigation, p. 1-99.

Ware, E. F., 1911, The Indian war of 1864, ed., Walton, C. C., 1960: New York, St. Martins Press, 483 p.

Warren, (Lt.) G. K., 1858, Explorations in Nebraska; preliminary report: Annual Report of the Secretary of War, 1858 (Serial 975), p. 620-670.

Whitcomb, H. A., 1965, Ground-water resources and geology of Niobrara County, Wyoming, *with a section on* Chemical quality of the ground water: U.S. Geological Survey Water-Supply Paper 1788, 101 p.

Williams, B. J., 1969, Overland to the gold fields of California in 1850: the journal of Clavin Taylor: Nebraska History, v. 50, p. 125-148.

Williams, G. P., 1978, The case of the shrinking channels-the North Platte and Platte Rivers in Nebraska: U.S. Geological Survey Circular 781, 48 p.

Willis, R. H., 1951, Irrigation in Nebraska: Historical and informational articles, compiled by the Division of Administration of the Department of Roads and Irrigation, Lincoln, Nebr., 1950-1951, 89 p.

Wyeth, J. B., 1833, Oregon; or a short history of a long journey from the Atlantic Ocean to the region of the Pacific, by land, *in* Thwaites, R. G., ed., 1905, Early western travels, v. 21: Cleveland, Ohio, A. H. Clark Co., p. 21-106.

Effects of Water Development on Surface-Water Hydrology, Platte River Basin in Colorado, Wyoming, and Nebraska Upstream from Duncan, Nebraska

By JAMES E. KIRCHER *and* MICHAEL R. KARLINGER

HYDROLOGIC AND GEOMORPHIC STUDIES OF THE PLATTE RIVER BASIN

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1277-B

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON 1983

CONTENTS

ILLUSTRATIONS

TABLES

EFFECTS OF WATER DEVELOPMENT ON SURFACE-WATER HYDROLOGY, PLATTE RIVER BASIN IN COLORADO, WYOMING, AND NEBRASKA UPSTREAM FROM DUNCAN, NEBRASKA

By JAMES E. KIRCHER and MICHAEL R. KARLINGER

ABSTRACT

The North Platte and Platte Rivers in western and central Nebraska have undergone significant changes in surface-water hydrology since the late 19th century. The South Platte River in Colorado and Nebraska has undergone much less change during the same period. This report presents an analysis of the changes in surface-water resources in the Platte River basin in Colorado, Wyoming, and Nebraska upstream from Duncan, Nebraska, an area of 157,700 square kilometers.

Nine stream-gaging stations in the basin were selected for analysis of streamflow changes. Flow-duration curves, 1-, 3-, 7-, 14-, and 30-day mean low flows, and 1-, 3-, 7-, 15-, and 30-day mean high flows were determined for all stations. Beginning about 1950, flow-duration curves for all stations, except that of the South Platte River near Kersey, Colorado, show a change with time of the low-flow segment of the distribution curve in a downstream direction. The analyses indicate that high flows have been relatively unaffected by water development in the Platte River basin. Low flows in the North Platte River increased following the closure of Kingsley Dam during 1941. Low flows in the South Platte River at Julesburg, Colorado, increased, beginning about 1920, and at North Platte, Nebraska, about 1932. Statistical analyses of data from six selected sites were performed to determine: (1) The significance of major water developments that may have produced abrupt changes in the time series of streamflow statistics, and (2) the significance of water developments that caused a more gradual change or time trend in the streamflow statistics.

INTRODUCTION

The Plate River in Nebraska is one of the most important rivers of the Great Plains, not only because of the agricultural development within its basin, but also because it is unique as a habitat for several species of migrating waterfowl. Among these species are the sandhill cranes and the whooping cranes, which require a wide and shallow channel relatively free of vegetation for roosting and breeding. Maintaining these channel characteristics has caused concern in recent years because the Platte River channel has narrowed appreciably since the early 1950's. Before measures to prevent further narrowing can be taken, however, an examination of the hydrologic changes, which occurred along with the channel changes, is needed.

This report presents an appraisal of the changes in surface-water resources of the Platte River basin. In the appraisal, the following aspects were considered: (1) The present use of the surface-water supplies, (2) the historical flow characteristics of the streams, and (3) the effects of environmental factors on streamflow.

PHYSICAL SETTING

The South Platte and North Platte Rivers originate primarily as snowmelt streams in the Rocky Mountains of Colorado. They flow across the Great Plains to form the Platte River at their confluence at North Platte, Nebraska (fig. 1).

The South Platte originates in the central part of Colorado, flows southeastward to a point about 100 km (kilometers) southwest of Denver, flows northeastward, leaves the mountains about 50 km southwest of Denver, flows through Denver, and continues northeastward to the confluence with the North Platte River. Total drainage area of the South Platte River is about 62,900 km^2 (square kilometers), and the river is about 720 river km long (Bentall, 1975, p. 6). The reach of the South Platte River studied extends from Kersey, Colorado, to the confluence with the North Platte River, a distance of about 380 river km.

From its origin in north-central Colorado, the North Platte River flows northward into east-central Wyoming near Casper, and then flows southeastward to its confluence with the South Platte River. The North Platte River drains about 80,000 km^2 and is about 1,050 river km long. The reach of the North Platte River studied is from Lake McConaughy near

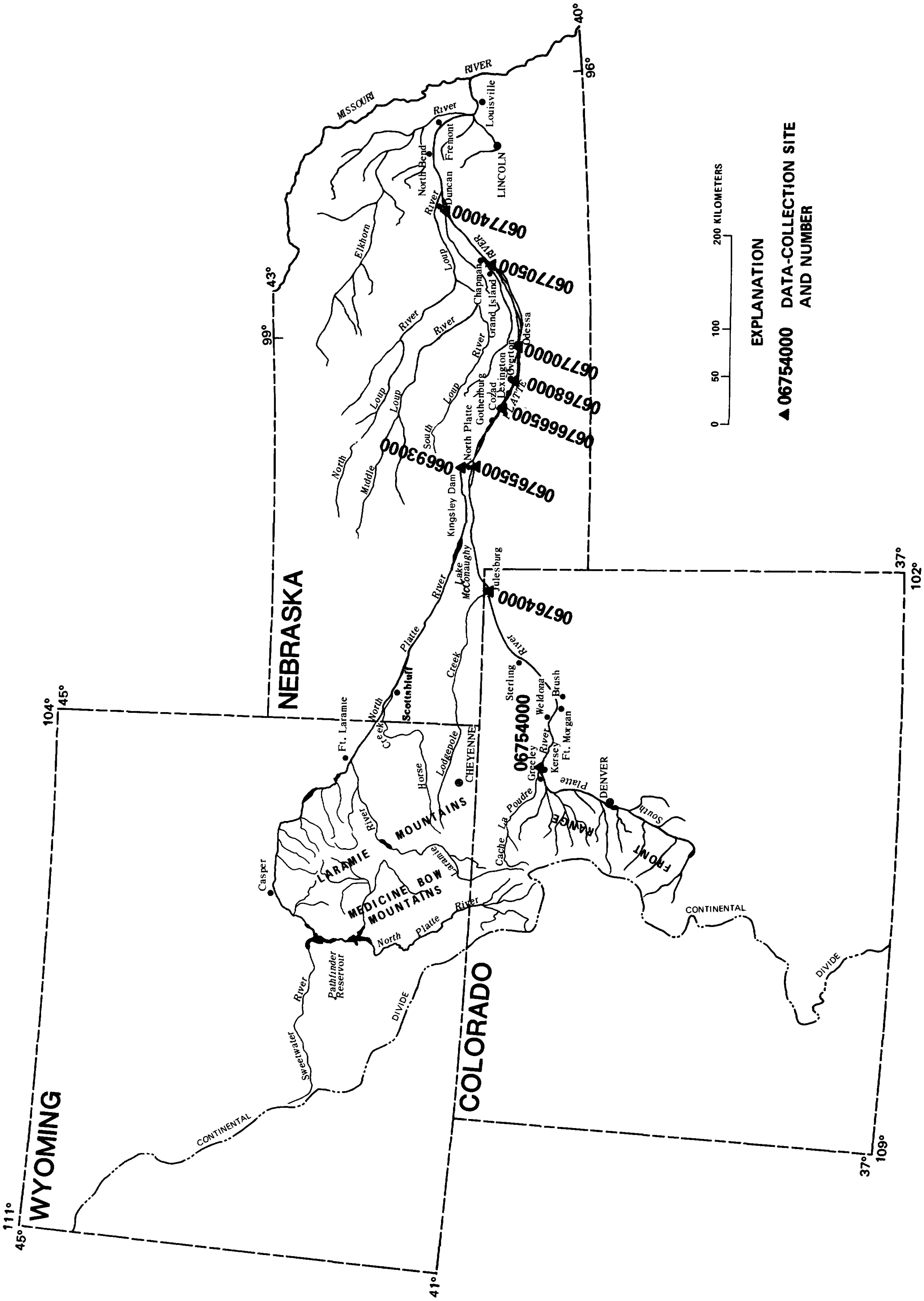


FIGURE 1.—Platte River basin and location of data-collection sites.

Ogallala, Nebraska, to the confluence with the South Platte River, a distance of about 86 river km.

The Platte River is formed at the confluence of the North Platte and South Platte Rivers. The Platte flows eastward through Nebraska to the Missouri River at the eastern edge of the State. The reach of the Platte River studied extends from North Platte to Duncan, Nebraska, a distance of about 460 river km.

CLIMATE

Climate in the basin is affected by altitude, latitude, and topography. The Platte River basin has a continental-type climate, characterized by a large range of temperature and irregular annual and seasonal precipitation.

The mountainous region of the South Platte River basin has long winters, significant snowfall, and a short growing season. Precipitation varies in the mountains according to altitude; high mountainous areas along the Continental Divide average about 1,000 mm (millimeters) of precipitation annually.

Annual precipitation in the foothills averages about 400 to 500 mm. Snowfall constitutes a smaller percentage of precipitation here than in the mountains. Summer and winter temperatures in the foothills are more moderate than in either the mountains or the plains.

The plains region just east of the foothills has low humidity, warm summers, cold winters, and considerable year-to-year variation in precipitation. Average annual precipitation ranges from approximately 300 to 460 mm. Most of the precipitation occurs from April through September.

The climate of the North Platte River basin is about the same as that for the South Platte River basin. The climate generally can be characterized as semiarid with large fluctuations in temperature. Annual precipitation on most of the plains area ranges from 230 to 400 mm; in mountainous areas from about 500 to 1,000 mm.

The climate of the eastern plains of Nebraska is different, however, from the climate of the plains nearer the mountains. Precipitation across Nebraska is variable both geographically and seasonally. Average annual precipitation ranges from about 380 mm at the western end of Nebraska to about 790 mm at the eastern end.

Mean annual precipitation at several locations within the basin is shown in table 1. Total annual precipitation for each year of record for four precipitation stations in the basin is shown in figures 2 through 5.

The average annual evaporation from the basin as estimated by Meyers (1962) is tabulated in table 2. The entire basin as of 1962 had an annual evaporation of 1,447 hm^3 (cubic hectometers) (table 2). There have been reservoirs, ponds, and canals added since 1962 that will increase this amount.

PRESENT USE OF SURFACE WATER

STORAGE RESERVOIRS

The Platte River basin has 194 reservoirs that have useable-storage capacities greater than 0.6 hm^3. These reservoirs are listed in table 3. The combined useable-storage capacity of the reservoirs is 8,829 hm^3. In addition to the reservoirs shown in table 3, numerous small lakes and stock ponds are scattered throughout the study area.

TRANSMOUNTAIN DIVERSIONS

The major transmountain diversions are located in Colorado and import water to the South Platte River. This imported water is collected from the Colorado River basin and the North Platte River basin and

TABLE 1.—*Mean annual precipitation at selected sites*

Weather station location[1]	Mean annual precipitation (millimeters)	Period of record	Weather station location[1]	Mean annual precipitation (millimeters)	Period of record
Pathfinder, Wyoming	253	1900–1978	Sterling, Colorado	377	1910–1978
Casper, Wyoming	347	1911–1978	Julesburg, Colorado	427	1888–1978
Ft. Laramie, Wyoming	349	1886–1978	Scottsbluff, Nebraska	389	1889–1978
Cheyenne, Wyoming	367	1871–1978	North Platte, Nebraska	471	1875–1978
Denver, Colorado	345	1873–1978	Gothenburg, Nebraska	542	1895–1978
Greeley, Colorado	315	1888–1978	Grand Island, Nebraska	629	1890–1978
Ft. Morgan, Colorado	335	1889–1978			

[1]See figure 1.

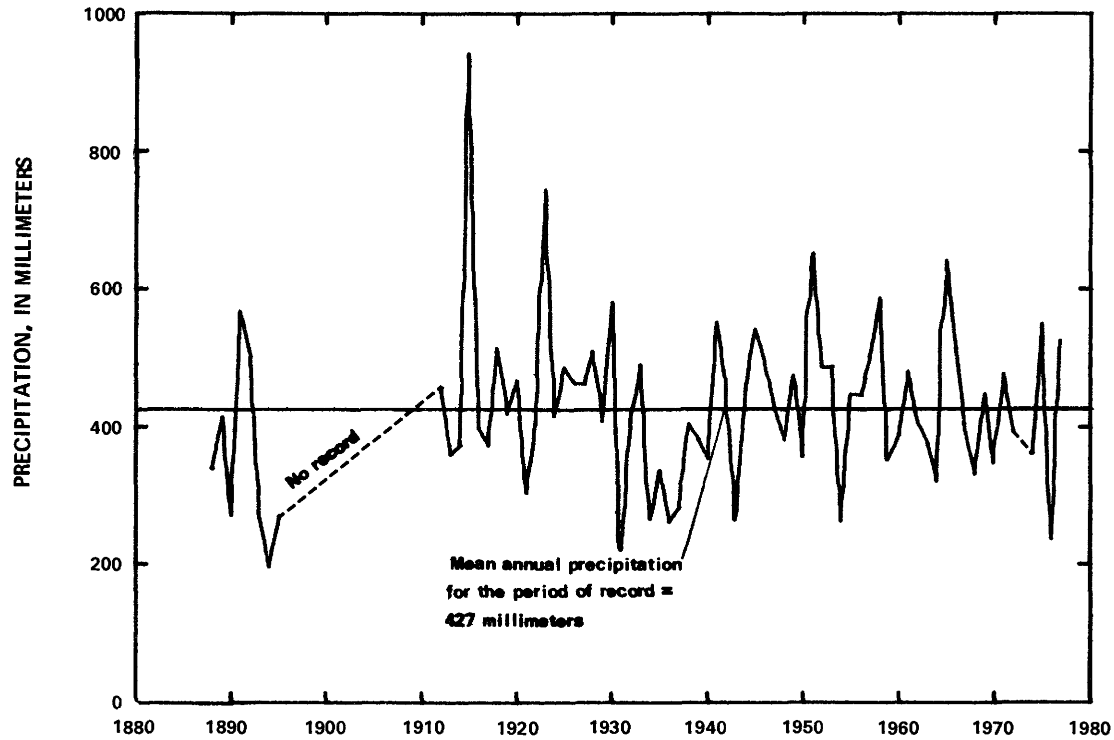


FIGURE 2.—Annual precipitation at Julesburg, Colorado (1888–1978)

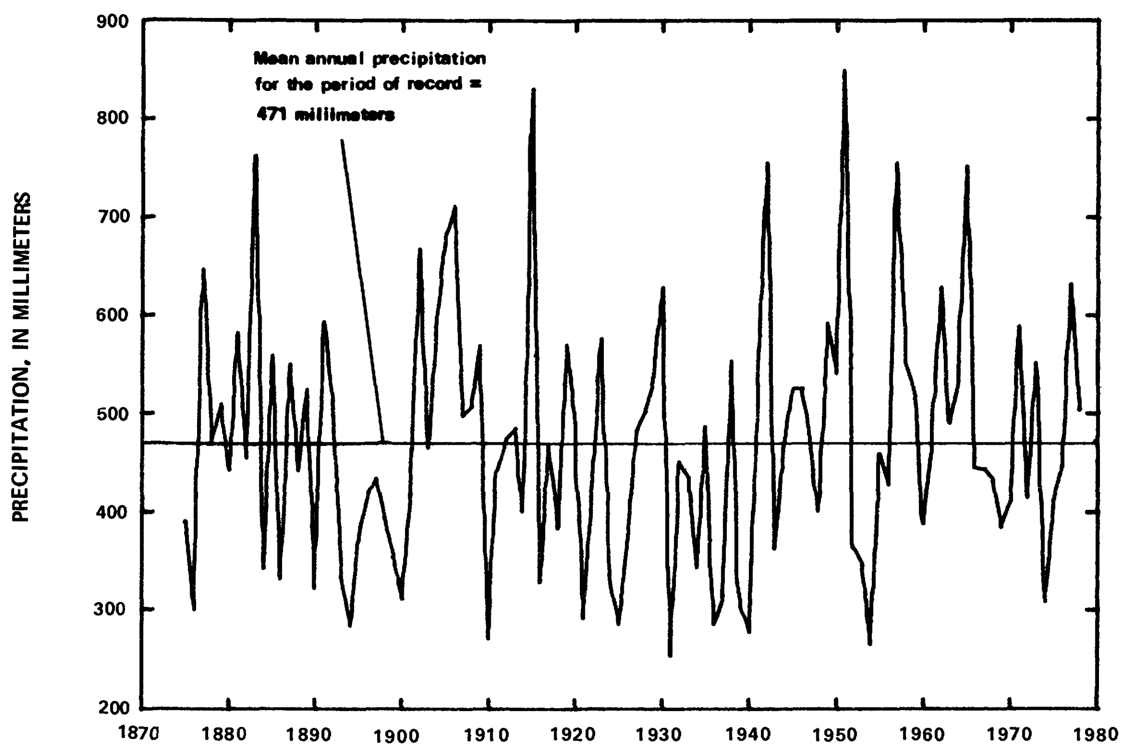


FIGURE 3.—Annual precipitation at North Platte, Nebraska (1875–1978).

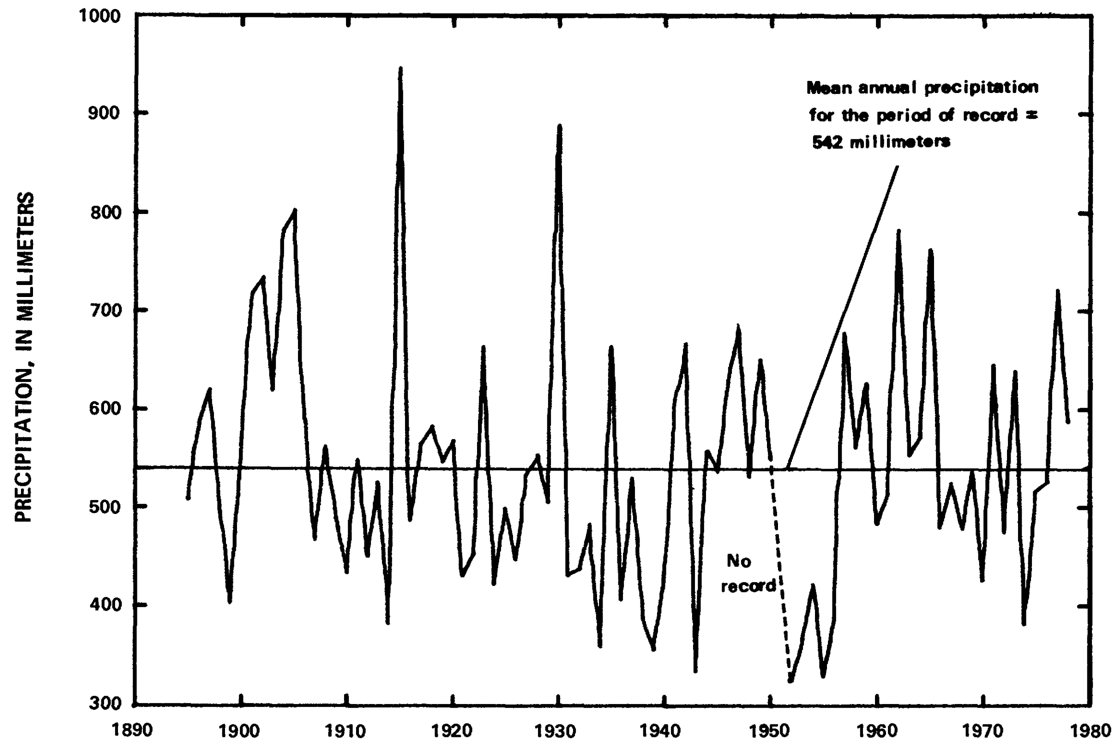


FIGURE 4.—Annual precipitation at Gothenburg, Nebraska (1895–1978).

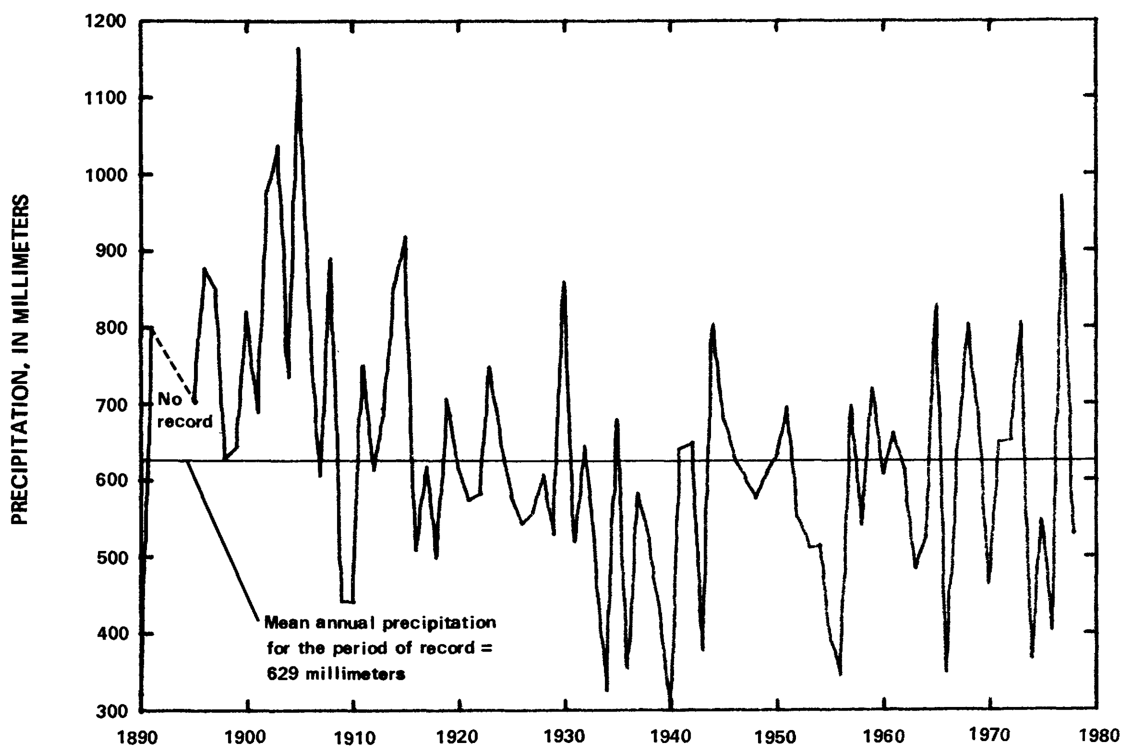


FIGURE 5.—Annual precipitation at Grand Island, Nebraska (1890–1978).

TABLE 2.—*Surface-water areas of 1962 and evaporation from reservoirs, lakes, streams, and canals (from Meyers, 1962)*

[hm^2 = square hectometers; hm^3 = cubic hectometers]

River basin	State and boundary	Principal reservoirs and regulated lakes		Other lakes with areas greater than 0.6 square hectometer		Principal streams and canals		Small ponds and reservoirs		Small streams		Total for all classes	
		Effective area (hm^2)	Annual evaporation (hm^3)	Effective area (hm^2)	Annual evaporation (hm^3)	Effective area (hm^2)	Annual evaporation (hm^3)	Effective area (hm^2)	Annual evaporation (hm^3)	Effective area (hm^2)	Annual evaporation (hm^3)	Effective area (hm^2)	Annual evaporation (hm^3)
North Platte River	Wyoming	13,558	147	3,642	40.7	3,495	38.2	2,520	25.9	1,808	18.9	25,023	271
	Colorado	10.93	.09	0	0	69.6	.60	455	3.88	103	.87	639	5.44
	Nebraska	13,986	167	0	0	9,031	107.6	12,368	147.2	627	7.32	36,012	429
	Total of N. Platte	27,554.93	314.09	3,642	40.7	12,595.6	146.4	15,343	176.98	2,538	27.09	61,674	705.44
South Platte River	Wyoming	25.5	.24	0	0	0	0	258	2.57	307	3.16	590	6.0
	Colorado	11,999	120	91.9	.89	1,741	19.2	5,530	54.7	1,779	18.63	21,140	214
	Nebraska	0	0	0	0	1,919	23.1	3,211	38.35	111	1.30	5,241	62.7
	Total of S. Platte	12,024.5	120.24	91.9	.89	3,660	42.3	8,999	95.62	2,197	23.09	26,971	282.7
Platte River downstream from confluence of North and South Platte Rivers	Nebraska	1,856	22.6	0	0	24,819	273	8,930	99.1	5,820	64.2	41,423	459

diverted to the South Platte River basin for municipal, industrial, and irrigation uses. The average annual water diverted from western Colorado is 414 hm^3 (Gerlek, 1977). Development of conditional water rights may yield an additional 271 to 308 hm^3 per year of water from western-slope diversions.

IRRIGATION

Irrigation in the Platte River basin began during the early 1800's with the construction of small, wide ditches to small irrigated tracts of land on the flood plain adjacent to the river. Since that time, there have been many reservoirs built to store water and many elaborate canal and ditch systems built to more efficiently use surface water. The earliest development occurred on the Colorado and Wyoming plains where the climate necessitated having irrigation projects store water for use during the dry summer months.

Since the earliest irrigation projects, when only the land next to the rivers was used for agriculture, the irrigated land has increased to about 1.4 million hm (hectometers) in the entire basin. The area now is irrigated by means of direct diversions, reservoirs, and ground-water systems, and encompasses land several kilometers from the river.

DOMESTIC AND MUNICIPAL USES

Several cities and industrial plants within the basin obtain water supplies from the river or from aquifers that are recharged mainly from the river. The municipalities continue to grow at a rapid rate, especially along the Front Range of Colorado and coal-rich eastern Wyoming. This growth has been accompanied by increased water demands.

HYDROLOGY

GENERAL

When the Platte River and its tributaries were virtually unregulated, spring runoff flowed unchecked down the mountain stream channels and onto the plains. During the summer after the snowpack melted, flow in these streams became very low. In the plains many of the rivers and tributaries were ephemeral, as most of the low flow infiltrated into the stream bed.

Today, after more than 100 years of irrigation and water-resource development in the basin, the Platte River and its major tributaries, the North and South Platte Rivers, have changed from ephemeral streams to perennial streams. Spring runoff from the mountains now is diverted and stored in offstream reservoirs or retained by onstream reservoirs, to be used later in the year as needed. Through irrigation, much of the water is used on large tracts of agricultural land. The basin water balance also has been changed further by imported water from adjacent river basins.

The hundreds of reservoirs and the thousands of kilometers of unlined canals, ditches, feeders, and laterals have large seepage losses. As a result of this and of the irrigation practices used, the water tables have risen over the years making the plains' streams effluent; in other words, they gain water from irrigation return flows. These flows then are rediverted farther downstream leaving the channel dry downstream from the point of diversion. This pattern of use and reuse extends along the length of the plains' reaches of the South Platte, North Platte, and Platte Rivers.

The balance between diversions and return flows has been affected in recent years by extensive pumping from the riparian aquifer. This has been a serious effect on the surface-water users who are dependent on these ground water seeps. Therefore, the practice of irrigation may have affected and overridden natural factors that normally define the hydrology of the Platte River.

Because of these changes in the hydrology during the last 40 years, the Platte River channel has decreased in cross sectional area and the island areas has increased (figs. 6–9). As a result, the channel has undergone considerable narrowing (fig. 10). Measurements made from aerial photographs were used in developing figures 6 through 10. These changes in the Platte River have caused concern among wildlife managers interested in maintaining a suitable habitat for the thousands of migrating waterfowl that use the Platte in central Nebraska. The reach of river concern extends from Lexington, Nebraska, to near Grand Island, Nebraska. This reach will be referred to throughout the remainder of the report as the critical habitat reach.

One of the potential consequences of the hydrologic changes is a change in vegetation growth along and within the river channel. If channel bars are exposed for a sufficient period of time, vegetation may become established, causing island formation and channel narrowing. Currier and Van Der Valk (1980) found that cottonwood and willow seeds begin falling about mid-May and continue to fall through mid-July. They state that after germination these seedlings could be viable until the end of August. If seed germination and seedling establishment is to occur, mud flats with significant soil moisture would have to be exposed for at least 1 to 2 weeks. Therefore, the investigation of hydrologic changes require special attention to the period from mid-May to the end of August, defined as the critical growth period for vegetation.

SITE SELECTION

Nine sites along the North Platte, South Platte, and Platte Rivers were chosen for evaluation of flow changes. These sites are listed in table 4. Flow-duration curves and average 1-, 3-, 7-, 15-, and 30-day mean high and 1-, 3-, 7-, 14-, and 30-day mean low flows were defined for all sites. For six of the nine sites, statistical analyses were performed on the records of annual mean flow and annual peak discharge. The six sites chosen were the North Platte River at North Platte, Nebraska; the South Platte River near Kersey, Colorado; the South Platte River near Julesburg, Colorado; the South Platte River at North Platte, Nebraska; the Platte River near Overton, Nebraska; and the Platte River near Grand Island, Nebraska. These sites were chosen because the spatial and temporal coverage of flow data best represents the hydrology in the critical reach, as well as the reaches of the North Platte and South Platte Rivers that show the effect of the extensive development along these rivers that have had an effect on the critical reach. The results of the statistical analyses will be discussed later in the report.

FLOW-DURATION CURVES

Flow-duration curves for 10-year intervals within the period of record at each of the nine selected stations, which show the percentage of time that water discharges of various magnitude have been equaled or exceeded, are presented in figures 11 through 19. The flow-duration curves shown illustrate the progression of hydrologic change that has occurred within the basin. Although flow-duration curves for longer periods of record may have less time variability, it was believed that the longer-period flow duration curves might mask the nature of progressive change in the flow characteristics. For a discussion of defining the period or periods selected for computation of flow duration for a given station, see Riggs (1972).

The only station showing any major change in the upper end of the flow-duration is the North Platte River at North Platte (fig. 11). All the 10-year periods following the 1931–39 period were smaller in magnitude and had a flatter slope except for 1970–79, which had several years of very high flow that may have caused the increase. This flattening indicates a decrease in the magnitude of high flows resulting from flow regulation occurring along the North Platte River. The remainder of the stations show very little change in the high flow section of the flow-duration curves, indicating no or very little change in the high flows.

The South Platte River near Kersey, Colorado, is the only station that shows very little change in the entire flow-duration curve sequence. This can be attributed partly to an increase in transmountain diversions of surface water. These diversions have been used to meet 1980 municipal, industrial, and agricultural demands thereby resulting in very little change in the native water supply. As water use continues to increase along the Front Range, however, the flow characteristics for the Kersey station also may change.

The changes in the flow-duration curve sequences are indicative of the reduction in flow variability as one

TABLE 3.—*Reservoirs with capacities greater than 0.6 cubic hectometer*

RIVER BASIN	RESERVOIR NAME	RESERVOIR CAPACITY (CUBIC HECTOMETERS)
NORTH PLATTE	ALCOVA RESERVOIR	233.0
NORTH PLATTE	AQUA FRIA	0.9
NORTH PLATTE	ARNOLD RESERVOIR	1.4
NORTH PLATTE	BATIS RESERVOIR	3.8
NORTH PLATTE	BENNETT RESERVOIR	1.2
NORTH PLATTE	BIG CREEK	8.5
NORTH PLATTE	BOETTCHER	0.8
NORTH PLATTE	BOSLER	2.0
NORTH PLATTE	BUCKLIN	0.9
NORTH PLATTE	BUTTE	1.2
NORTH PLATTE	CARLSTROM	0.8
NORTH PLATTE	CARROL LAKE RESERVOIR	0.7
NORTH PLATTE	CASE BIER	1.8
NORTH PLATTE	CAVENDAR	0.7
NORTH PLATTE	COALMONT	39.1
NORTH PLATTE	COW CREEK LAKE RESERVOIR	0.6
NORTH PLATTE	CRYSTAL LAKE	5.6
NORTH PLATTE	DARCY	0.9
NORTH PLATTE	DENTION DAM 8-2	0.8
NORTH PLATTE	DUTTON CREEK RESERVOIR	3.2
NORTH PLATTE	GLENDO RESERVOIR	980.5
NORTH PLATTE	GLOWMILL RESERVOIR	1.0
NORTH PLATTE	GOSHEN HOLE	6.1
NORTH PLATTE	GOSHEN NO. 2 RESERVOIR	1.1
NORTH PLATTE	GRANITE SPRINGS	9.1
NORTH PLATTE	GRAY REEF	2.2
NORTH PLATTE	GUERNSEY RESERVOIR	55.8
NORTH PLATTE	HAMILTON RESERVOIR	1.2
NORTH PLATTE	HAWK SPRINGS	20.6
NORTH PLATTE	HOG PARK	3.8
NORTH PLATTE	HUGHES RESERVOIR	0.8
NORTH PLATTE	HUTTON LAKE	3.1
NORTH PLATTE	HYANNIS	2.6
NORTH PLATTE	J. FRANK WALKER	0.7
NORTH PLATTE	KING NO. 1	2.7
NORTH PLATTE	KORTESRESERVOIR	5.7
NORTH PLATTE	LA PRELE RESERVOIR	2.5
NORTH PLATTE	LAKE OWEN BERG	1.7
NORTH PLATTE	LAKE JOHN	8.0
NORTH PLATTE	LAKE HATTIE	84.5
NORTH PLATTE	LAKE ALICE	14.1
NORTH PLATTE	LAKE MINATARE	76.7
NORTH PLATTE	LAKE MCCONAUGHY	2401.9
NORTH PLATTE	LAKE OGALLALA	16.0
NORTH PLATTE	LAUNE	3.7
NORTH PLATTE	LEE'S RESERVOIR	0.6
NORTH PLATTE	MCFARLANE	8.0
NORTH PLATTE	MEADOW CREEK	6.2
NORTH PLATTE	NORTH SPRING CREEK RESERVOIR	0.9
NORTH PLATTE	NORTH MICHIGAN	1.6
NORTH PLATTE	OLIVE RESERVOIR	9.2
NORTH PLATTE	PATHFINDER RESERVOIR	1319.3
NORTH PLATTE	PIERCE RESERVOIR	4.0
NORTH PLATTE	PINE RIDGE	2.7
NORTH PLATTE	POLARIS RESERVOIR	0.7
NORTH PLATTE	POLE MOUNTAIN	2.3
NORTH PLATTE	RAINER RESERVOIR	0.7
NORTH PLATTE	RAWLINS RESERVOIR	0.8
NORTH PLATTE	ROLE ROY	11.0
NORTH PLATTE	SABIN	3.9
NORTH PLATTE	SADDLEBACK RESERVOIR	0.8
NORTH PLATTE	SAGE CREEK RESERVOIR	0.7
NORTH PLATTE	SAND LAKE	1.4
NORTH PLATTE	SARATOGA RESERVOIR	1.0
NORTH PLATTE	SEMINOE	1246.3
NORTH PLATTE	SEPERATION LAKE RESERVOIR	0.7

TABLE 3.—*Reservoirs with capacities greater than 0.6 cubic hectometer—Continued*

RIVER BASIN	RESERVOIR NAME	RESERVOIR CAPACITY (CUBIC HECTOMETERS)
NORTH PLATTE	SEYMOUR	0.6
NORTH PLATTE	SIRNARD RESERVOIR	1.9
NORTH PLATTE	SOUTH SPRINGS CREEK RESERVOIR	0.8
NORTH PLATTE	SPECTACLE LAKE	1.8
NORTH PLATTE	TURPIN PEAK RESERVOIR	1.6
NORTH PLATTE	UPPER VAN TASSEL RESERVOIR	2.3
NORTH PLATTE	UPPER ROCK CREEK	3.5
NORTH PLATTE	WALDEN RESERVOIR NO 1	4.4
NORTH PLATTE	WALDEN RESERVOIR NO 2	0.9
NORTH PLATTE	WHR RESERVOIR NO I	1.1
NORTH PLATTE	WHR RESERVOIR NO 1	1.1
NORTH PLATTE	WILLOW CREEK RESERVOIR	0.9
NORTH PLATTE	WYOMING DEVELOPMENT CO. RESERVOIR NO 1	18.9
NORTH PLATTE	WYOMING DEVELPMENT CO. RESERVOIR NO. 2	121.2
SOUTH PLATTE	AGATE	12.9
SOUTH PLATTE	ALBION LAKE	1.3
SOUTH PLATTE	ALTURA (DUCK LAKE)	5.4
SOUTH PLATTE	ANTERO	19.6
SOUTH PLATTE	BADGER	12.2
SOUTH PLATTE	BARKER MEADOWS	15.0
SOUTH PLATTE	BARR LAKE	39.6
SOUTH PLATTE	BASE LINE RESERVOIR	6.5
SOUTH PLATTE	BILLINGS, ARBUCKLE	1.2
SOUTH PLATTE	BOOTLEG	7.6
SOUTH PLATTE	BOULDER	21.5
SOUTH PLATTE	BOULDER	9.4
SOUTH PLATTE	BUTTON ROCK	19.1
SOUTH PLATTE	CABIN CREEK	2.3
SOUTH PLATTE	CASTLEWOOD	4.2
SOUTH PLATTE	CHERRY CREEK	303.4
SOUTH PLATTE	CLARK COUNTY NO. 2	1.4
SOUTH PLATTE	CLOVER BASIN	0.7
SOUTH PLATTE	COALBANK WATERSHED	2.6
SOUTH PLATTE	D.A. LORD NO. 4	4.3
SOUTH PLATTE	ELEVENMILE CANYON	120.6
SOUTH PLATTE	EMPIRE	46.5
SOUTH PLATTE	ENGLEWOOD	7.4
SOUTH PLATTE	FALL RIVER RESERVOIR	1.1
SOUTH PLATTE	FOOTHILLS	5.2
SOUTH PLATTE	FRANKTOWN PARKER	0.8
SOUTH PLATTE	GEORGETOWN	0.9
SOUTH PLATTE	GOLD LAKE RESERVOIR	1.7
SOUTH PLATTE	GROSS RESERVOIR	53.1
SOUTH PLATTE	HAYDEN	0.6
SOUTH PLATTE	HIDDEN LAKE	4.0
SOUTH PLATTE	HIGHLAND NO. 2	4.6
SOUTH PLATTE	HILLCREST	2.2
SOUTH PLATTE	HORSE CREEK	36.2
SOUTH PLATTE	HUDSON	14.6
SOUTH PLATTE	JACKSON LAKE	44.0
SOUTH PLATTE	JULESBURG RESERVOIR	34.7
SOUTH PLATTE	JUMBO RESERVOIR	3.1
SOUTH PLATTE	KENWOOD	12.3
SOUTH PLATTE	KIOWA	10.3
SOUTH PLATTE	KLUG NO. 3	0.9
SOUTH PLATTE	LAKE CHEESMAN	97.5
SOUTH PLATTE	LAKE MALONEY	7.4
SOUTH PLATTE	LEFT HAND VALLEY	13.0
SOUTH PLATTE	LEFT HAND PARK	1.9
SOUTH PLATTE	LEGGET	1.2
SOUTH PLATTE	LIDDERDALE LAKE	0.9
SOUTH PLATTE	LOCH LOMAND	10.8
SOUTH PLATTE	LOST PARK	56.6
SOUTH PLATTE	LOVELLA	8.3
SOUTH PLATTE	LOWER LATHAM	7.1
SOUTH PLATTE	MARSHALL LAKE	12.9

progresses downstream. The North Platte River at North Platte, Nebraska, the South Platte River at Julesburg, Colorado, and North Platte, Nebraska, and the Platte River near Overton, Nebraska, show a flattening in the lower end of flow-duration curves beginning about 1950 and continuing to 1979. This flattening usually is due to an increase of inflows caused by irrigation return flows or controlled release from reservoirs that maintain streamflow during low-flow periods. The period of record for the Platte River near Cozad, Nebraska, is too short to detect any obvious flattening of the flow-duration curves from those prior to 1940. The flow-duration curves for the gaging stations at Platte River near Odessa, Grand Island, and Duncan, Nebraska, are progressively flattening at the low-flow end. Changes in the shapes of the flow-

TABLE 3.—*Reservoirs with capacities greater than 0.6 cubic hectometer—Continued*

RIVER BASIN	RESERVOIR NAME	RESERVOIR CAPACITY (CUBIC HECTOMETERS)
SOUTH PLATTE	MCINTIRE NO. 1	1.1
SOUTH PLATTE	MESA	1.2
SOUTH PLATTE	MILTON LAKE	53.2
SOUTH PLATTE	MONTGOMERY	6.3
SOUTH PLATTE	NOONAN NO. 2	3.3
SOUTH PLATTE	NORTH STERLING	91.2
SOUTH PLATTE	OLIVER	9.2
SOUTH PLATTE	PANAMA	0.8
SOUTH PLATTE	PANHANDLE	1.3
SOUTH PLATTE	PARK CREEK DAM	9.1
SOUTH PLATTE	PETERSON LAKE	1.1
SOUTH PLATTE	PETERSON LAKE	1.5
SOUTH PLATTE	PLATTE CANYON	1.2
SOUTH PLATTE	PLEASANT VALLEY	3.1
SOUTH PLATTE	POINT OF ROCK	99.4
SOUTH PLATTE	PREWITT	40.1
SOUTH PLATTE	PROSPECT	9.4
SOUTH PLATTE	QUINCY	3.5
SOUTH PLATTE	RATTLESNAKE	2.7
SOUTH PLATTE	RESERVOIR NO. 22	51.7
SOUTH PLATTE	RESERVOIR NO. 8	13.0
SOUTH PLATTE	RESERVOIR NO. 4	1.6
SOUTH PLATTE	RIVERSIDE	70.9
SOUTH PLATTE	SHEEP CREEK	2.2
SOUTH PLATTE	SIX MILE	13.4
SOUTH PLATTE	SILVER LAKE	4.9
SOUTH PLATTE	SOUTH GRAY	1.4
SOUTH PLATTE	SUTHERLAND RESERVOIR	9.9
SOUTH PLATTE	TARRYALL	16.2
SOUTH PLATTE	TERMINAL	4.2
SOUTH PLATTE	TERRY LAKE	10.0
SOUTH PLATTE	TIMNATH	12.5
SOUTH PLATTE	TWIN LAKES	21.1
SOUTH PLATTE	UNION	15.7
SOUTH PLATTE	UPPER URAD	0.9
SOUTH PLATTE	VALMONT	17.2
SOUTH PLATTE	WARREN LAKE	2.8
SOUTH PLATTE	WASSON	1.0
SOUTH PLATTE	WATER SUPPLY NO. 4	1.2
SOUTH PLATTE	WATER SUPPLY NO. 3	5.9
SOUTH PLATTE	WILD HORSE	1.0
SOUTH PLATTE	WILLAMS MCCREERY	21.7
SOUTH PLATTE	WINDSOR	19.3
SOUTH PLATTE	WORSTER (EATON)	2.5
PLATTE	BLUE STEM	3.7
PLATTE	BRANCHED OAK	32.0
PLATTE	CONESTOGA	3.2
PLATTE	ERICSON	2.0
PLATTE	GALLAGER CANYON LAKE	3.7
PLATTE	HOLMES LAKE	1.5
PLATTE	JEFFERY RESERVOIR	14.2
PLATTE	JOHNSON RESERVOIR	66.6
PLATTE	LAKE BABCOCK AND LAKE NORTH	5.5
PLATTE	MIDWAY CANYONS LAKE SYSTEM	11.6
PLATTE	OLIVE CREEK	1.8
PLATTE	PAWNEE	10.5
PLATTE	PLUM CREEK LAKE	5.7
PLATTE	SHERMAN RESERVOIR	85.2
PLATTE	STAGE COACH	2.4
PLATTE	TWIN LAKES	3.5
PLATTE	WAGON TRAIN	3.1
PLATTE	YANKEE HILL	2.5

TOTAL RESERVOIRS = 194 TOTAL CAPACITY = 8829.4

duration curves can be related to the channel width and area changes already shown in figures 6 through 10.

It should be emphasized that a distinction be made between change in shape of flow-duration curves and shift in flow-duration curves for different periods of record. A change in the shape of a flow-duration curve indicates change in the characteristics of flow distribution. This is the basis of the preceding analysis. A shift in a flow-duration curve, however, indicates a change in flow volume, but not distribution shape. A change in shape from 1940–49 to 1950–59 and a change in volume from 1960–69 to 1970–79 are shown in figure 16.

Further interpretation of the flow-duration curves may be made using periods of records longer than 10 years. Again using figure 16 as an illustration, an analysis could have been made using two periods, 1931–49 and 1950–79. It is apparent that the resulting flow-duration curves would lie somewhere between the respective 10-year period curves as plotted. The resulting two curves would allow one to relate the changes in water use and environmental factors to flow characteristics between the two periods.

HIGH FLOWS

High flows, as used in this section, are defined as the largest mean flows occurring for durations of 1, 3, 7, 15, or 30 consecutive days for any given year. Changes in the mean high flows in the study reach are presented in figures 20 through 28. The North Platte River at North Platte, Nebraska, shows a general decrease in the high mean flows coinciding with the establishment of Lake McConaughy during 1941. During 1971 and 1973, however, a unique combination of large holdovers in the reservoirs and large inflows into the reservoirs, because of rapid snowmelt along with simultaneous heavy rains on the Nebraska part of the drainage basin, resulted in higher than normal releases from the reservoir (Shaffer, 1976). The two peaks on the high-flow graphs are not believed to indicate a sustained upward trend in mean high flows. This also was shown in the flow-duration curves with a flattening of the curves. The remainder of the stations, however, show little change in high flows.

LOW FLOWS

Low flows, as used in this section, are defined as the smallest mean flows occurring for durations of 1, 3, 7, 14, or 30 consecutive days for any given year. The 1-, 3-, 7-, 14-, and 30-day low flows for each of the nine stations are presented in figures 29 through 37. The North Platte River at North Platte, the South Platte River at North Platte, and the Platte River near Cozad and Overton, show an increase in the minimum level of low flows since about 1940, while the South Platte River at Julesburg, Colorado, shows an increase, starting about 1920. The South Platte River near Kersey,

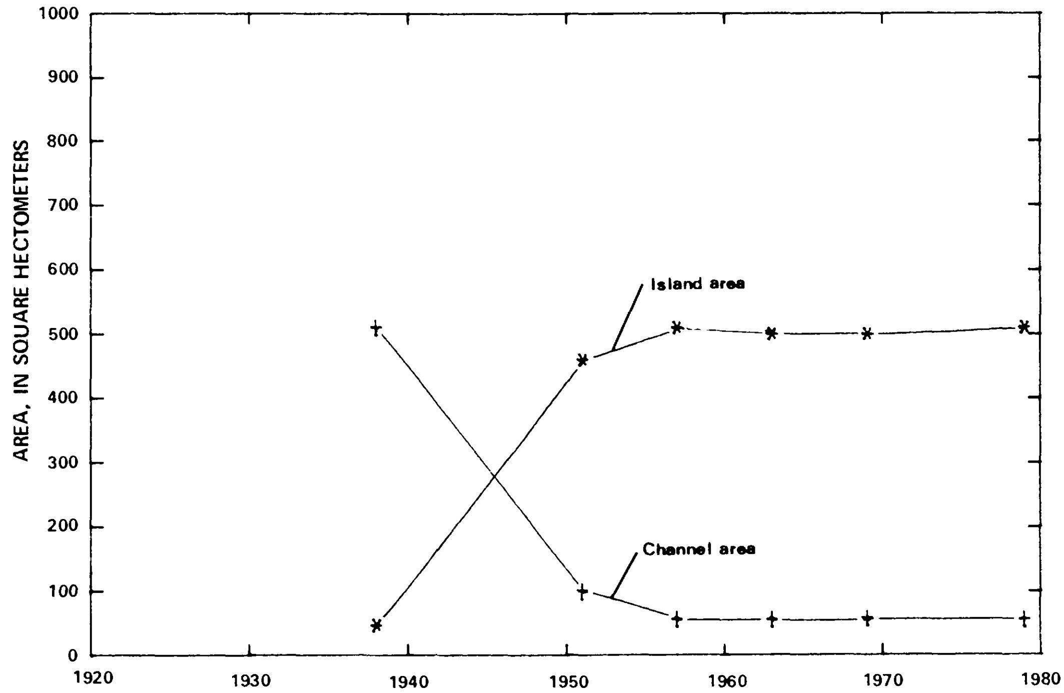


FIGURE 6.—Change in channel area and island area near Cozad, Nebraska.

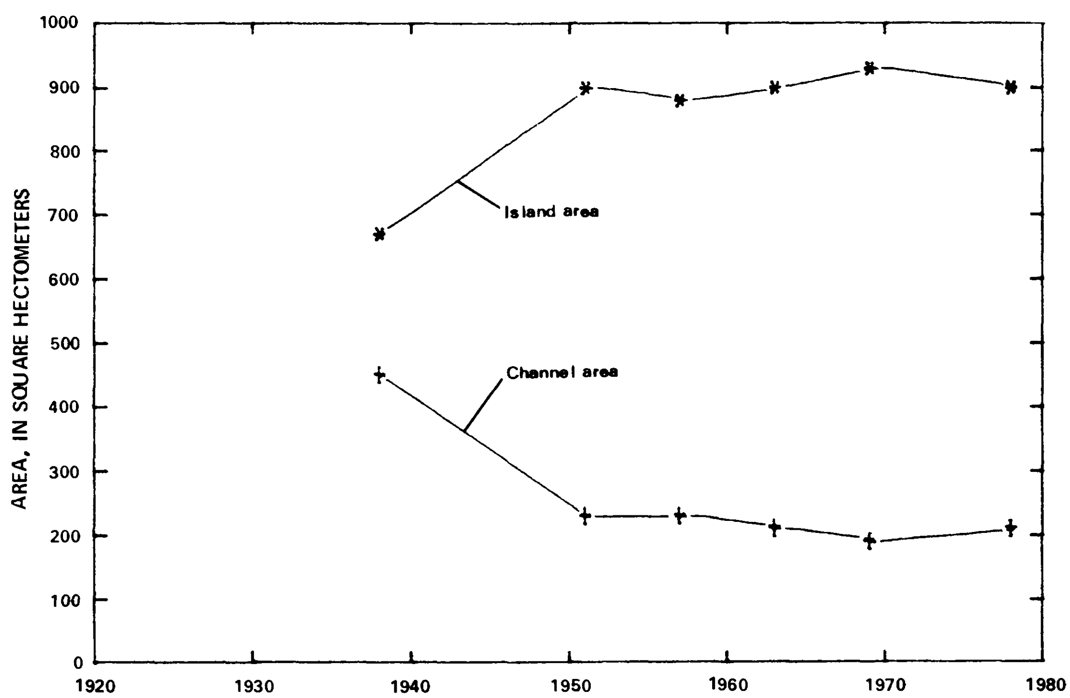


FIGURE 7.—Change in channel area and island area near Overton, Nebraska.

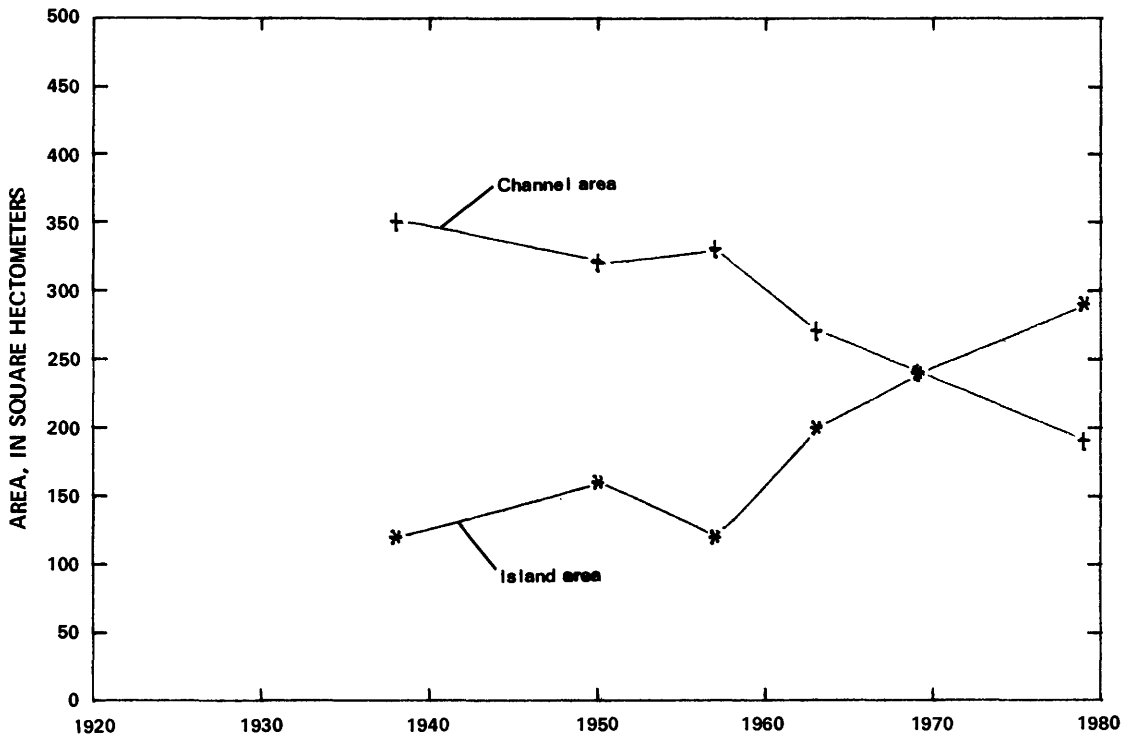


FIGURE 8.—Change in channel area and island area near Grand Island, Nebraska.

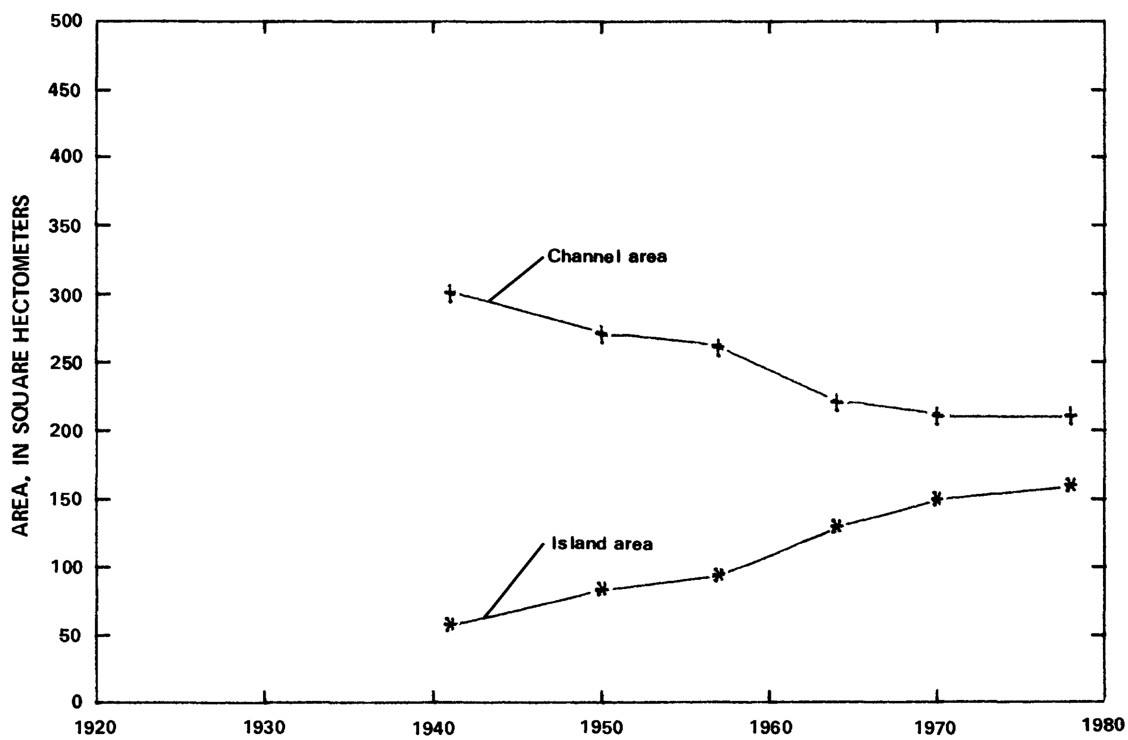


FIGURE 9.—Change in channel area and island area near Duncan, Nebraska.

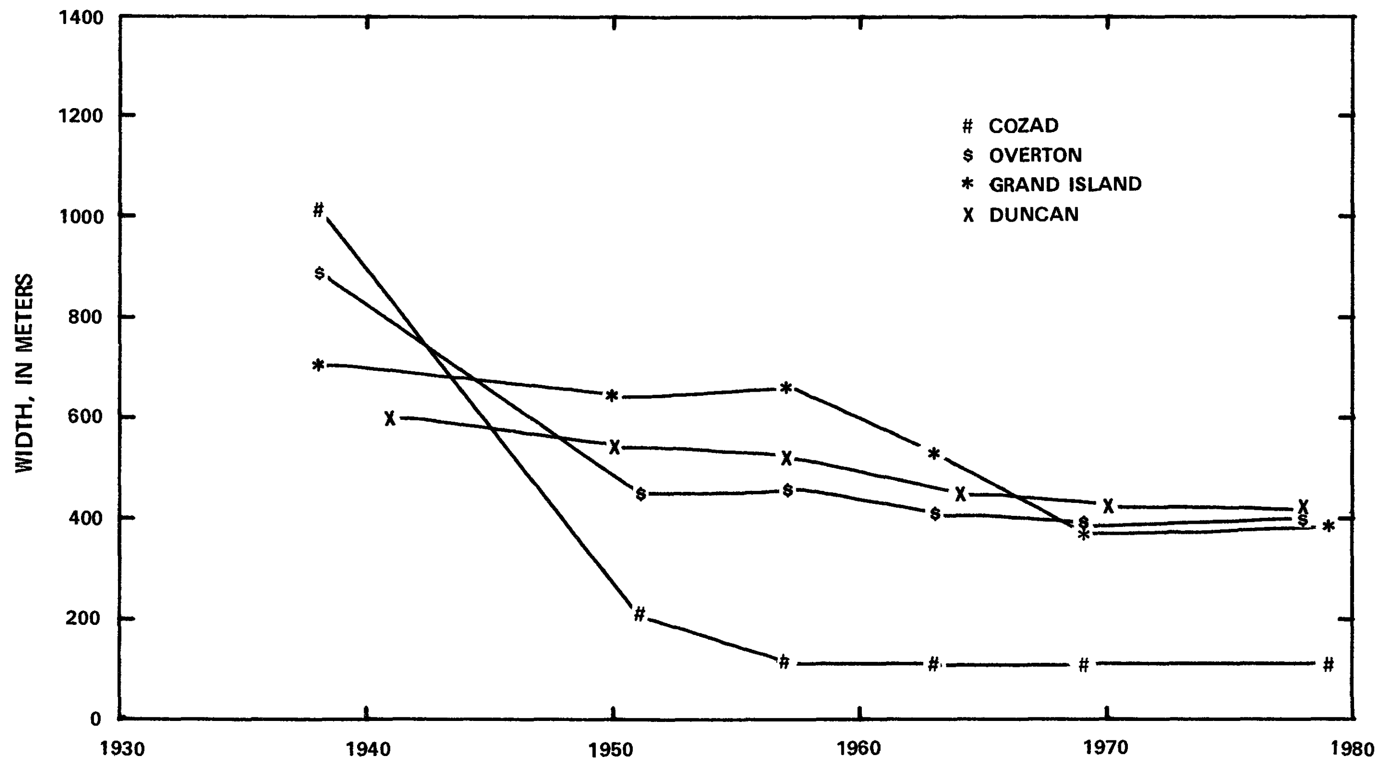


FIGURE 10.—Change in channel width at four sites along the Platte River.

TABLE 4.—*Streamflow characteristics of primary data sites*

[km² = square kilometers; m³/s = cubic meters per second]

Station name	Station number	Period of streamflow record (water years)	Drainage area (km²)	Mean annual discharge (m³/s)
North Platte River at North Platte, Nebraska.	06693000	1895–1979	80,000	23.5
South Platte River near Kersey, Colorado.	06754000	1902–03, 1905–79	24,859	22
South Platte River near Julesburg, Colorado.	06764000	1903–06, 1909–12, 1914–21, 1925–79	59,927	13.5
South Platte River at North Platte, Nebraska.	06765500	1897, 1914–15, 1917–79	62,900	9.5
Platte River near Cozad, Nebraska.	06766500	1932, 1937–79	146,300	14.2
Platte River near Overton, Nebraska.	06768000	1915–79	149,400	39
Platte River near Odessa, Nebraska.	06770000	1937–79	150,500	35.9
Platte River near Grand Island, Nebraska.	06770500	1934–79	152,300	35.6
Platte River near Duncan, Nebraska.	06774000	1895–1910, 1910–11, 1912–15, 1928–79	157,700	41.2

Colorado, shows no change in low flows. The Platte River near Odessa, Grand Island, and Duncan, Nebraska, shows a slight increase in low flows, but the change is not as pronounced as at the upstream stations.

STATISTICAL ANALYSES

Statistical analyses were performed on annual mean flow and peak flow for the previously mentioned six sites to make the following determinations:

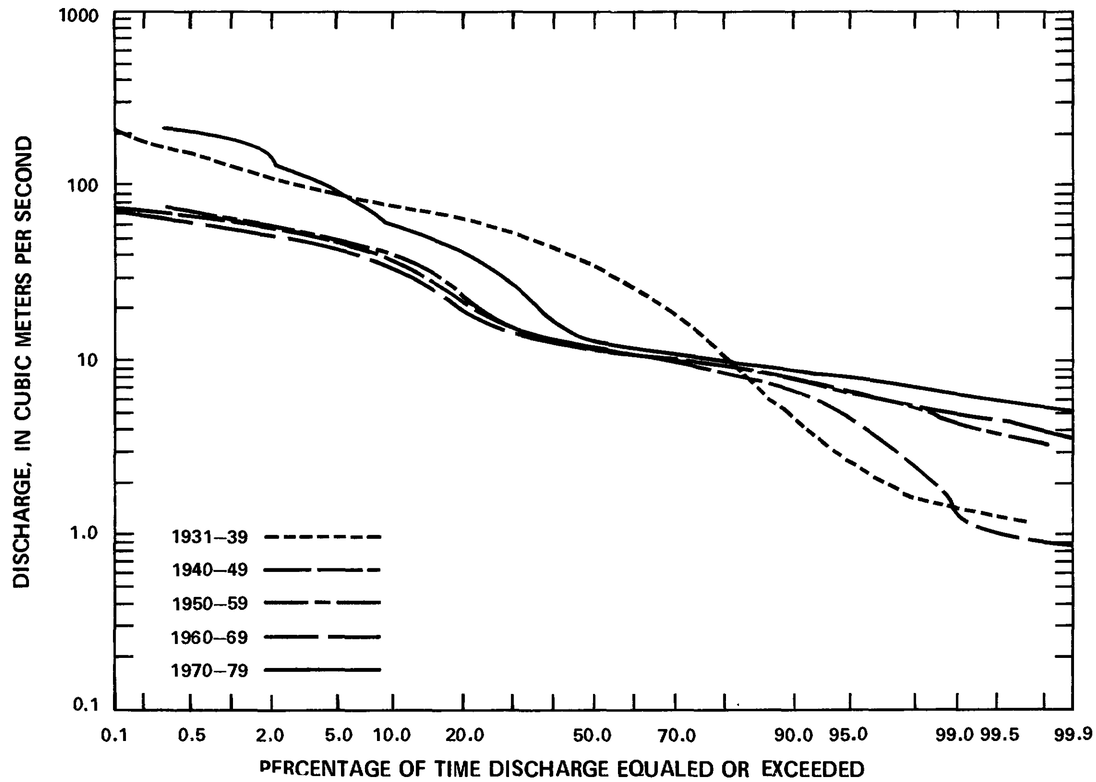


FIGURE 11.—Selected flow-duration curves at Station 06693000, North Platte River at North Platte, Nebraska (water years 1931–79).

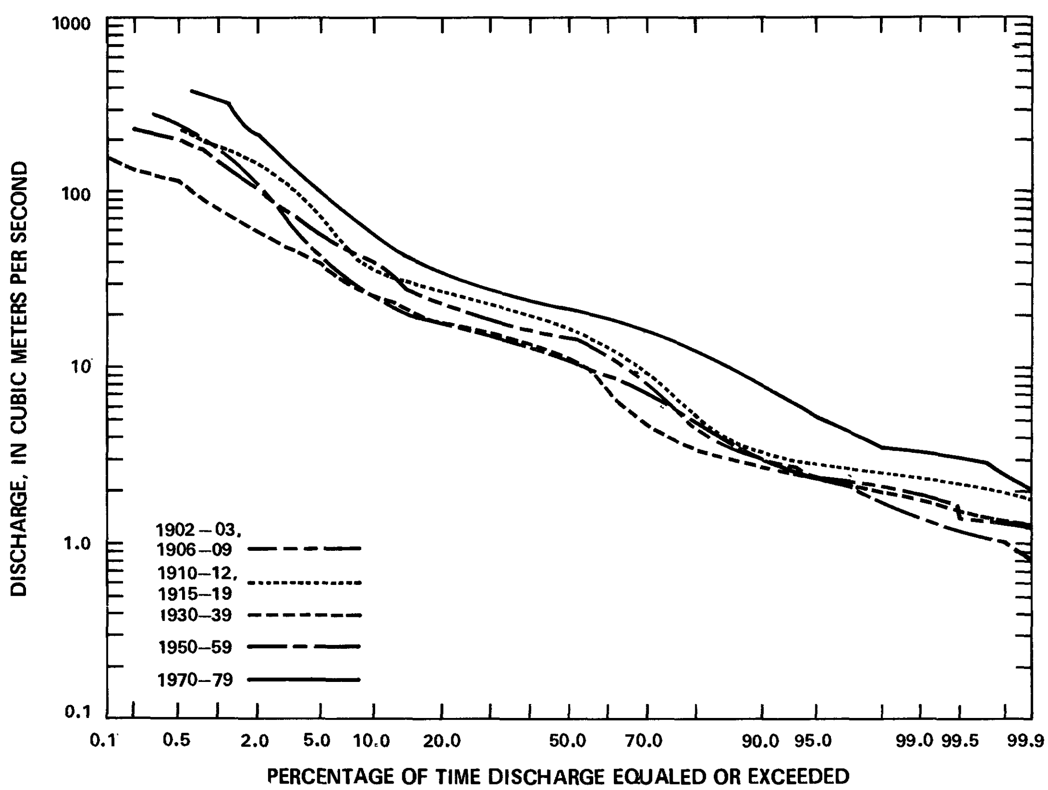


FIGURE 12.—Selected flow-duration curves at Station 06754000, South Platte River near Kersey, Colorado (water years 1902, 1903, 1906–12, 1915–79).

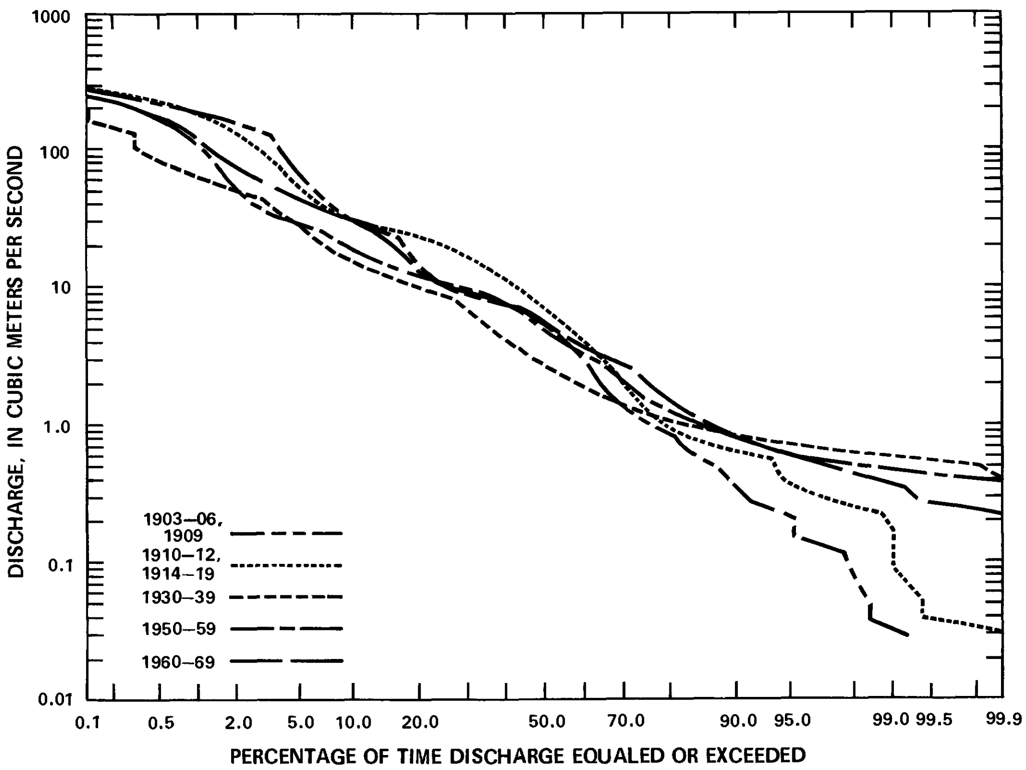


FIGURE 13.—Selected flow-duration curves at Station 06764000, South Platte River at Julesburg, Colorado (water years 1903-79).

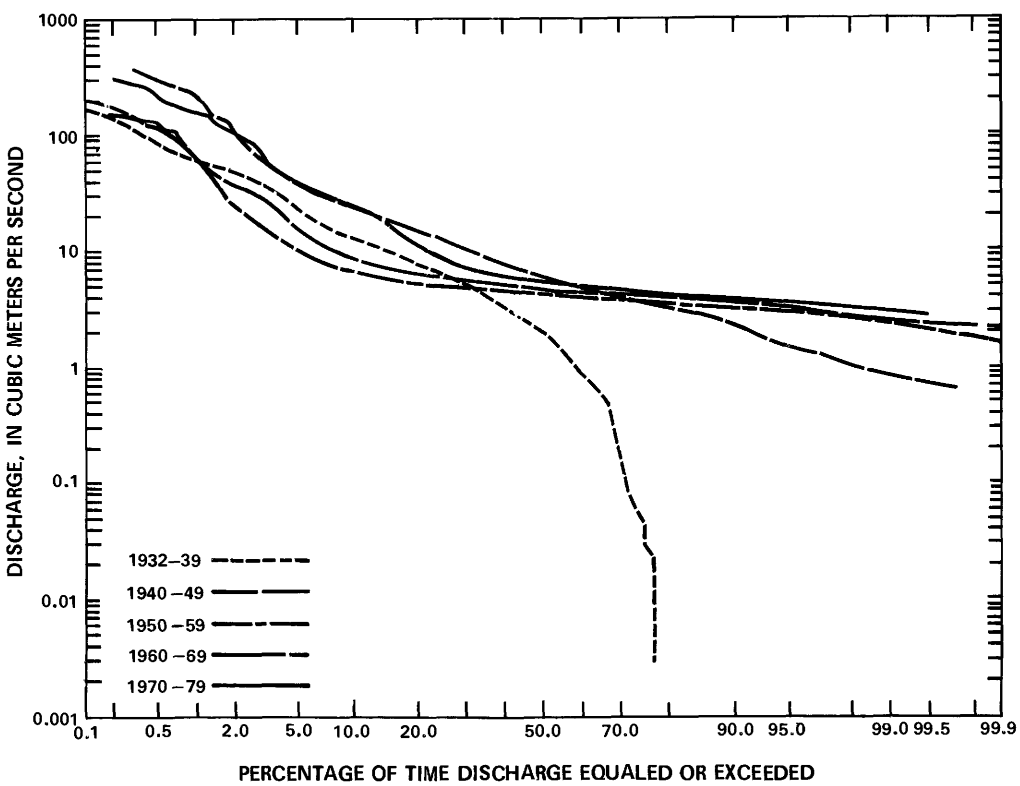


FIGURE 14.—Selected flow-duration curves at Station 06765500, South Platte River at North Platte, Nebraska (water years 1932-79).

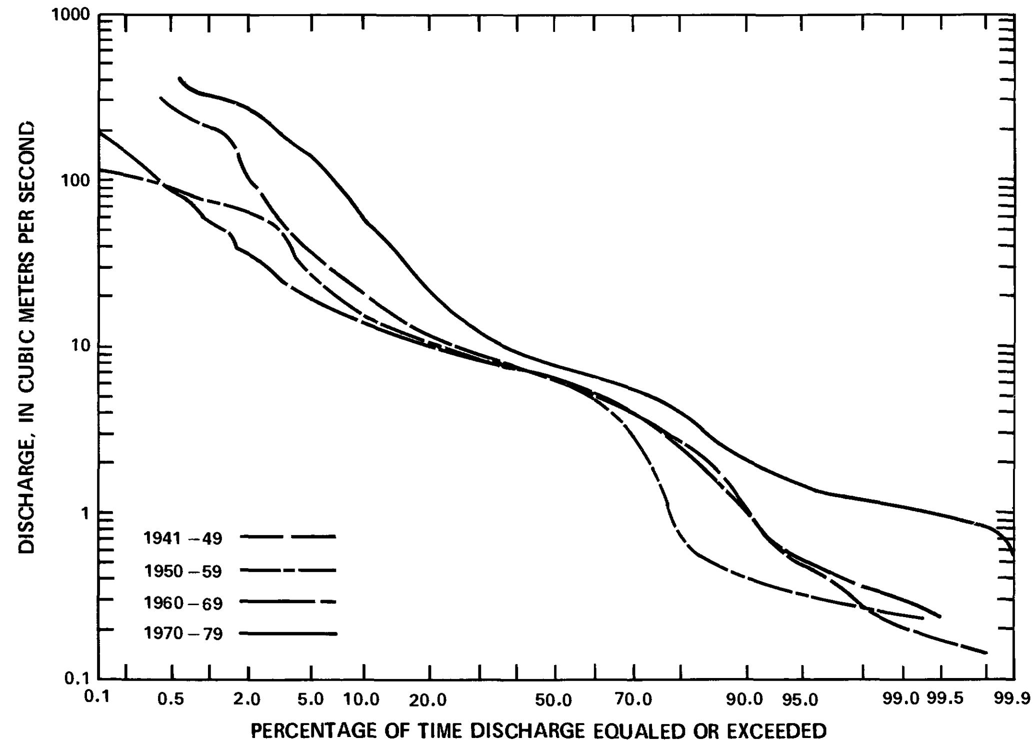


FIGURE 15.—Selected flow-duration curves at Station 06766500, Platte River near Cozad, Nebraska (water years 1941–79).

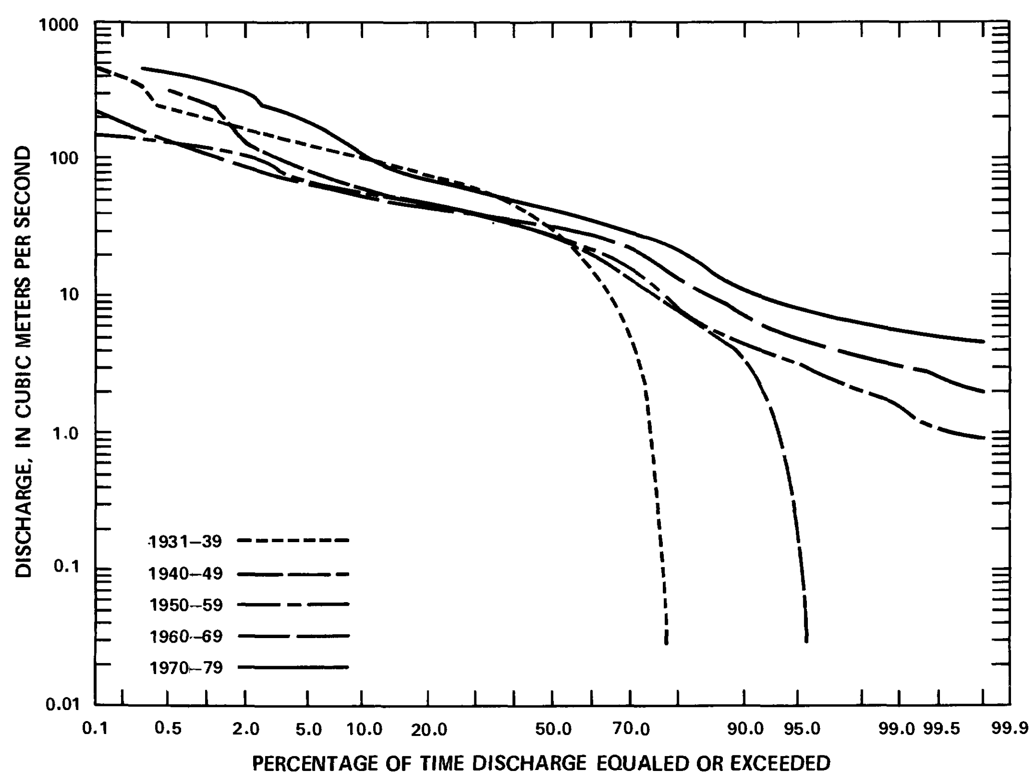


FIGURE 16.—Selected flow-duration curves at Station 06768000, Platte River near Overton, Nebraska (water years 1931–79).

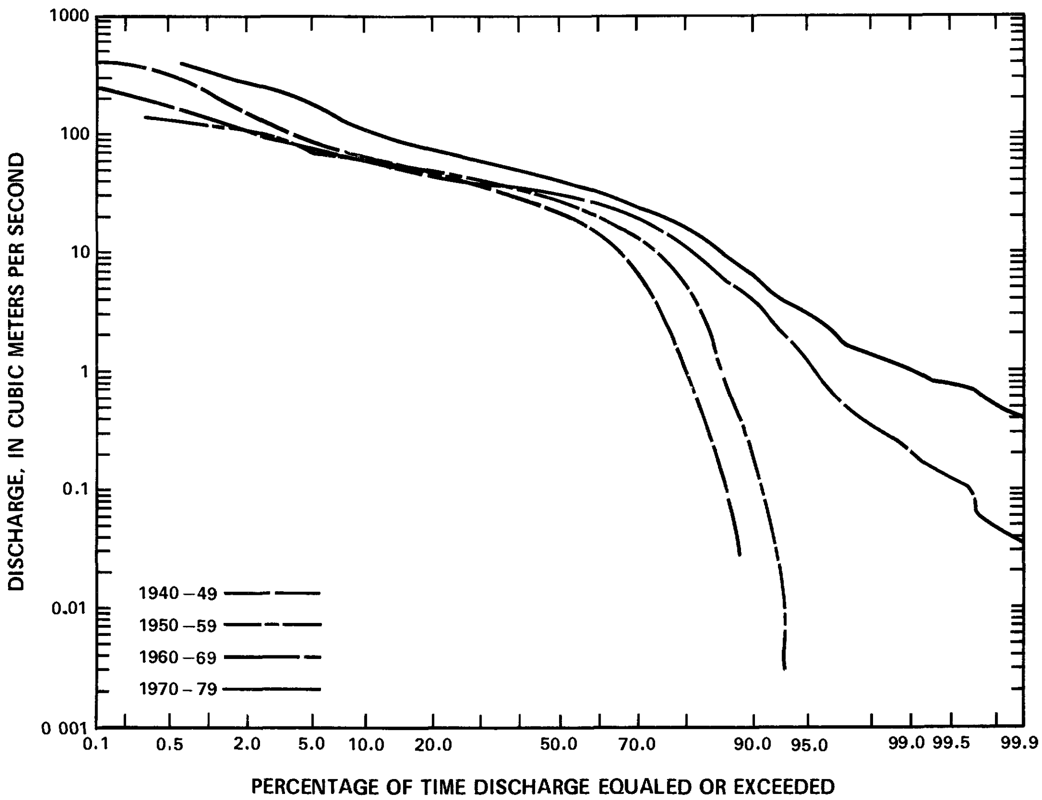


FIGURE 17.—Selected flow-duration curves at Station 06770000, Platte River Near Odessa, Nebraska (water years 1940–79).

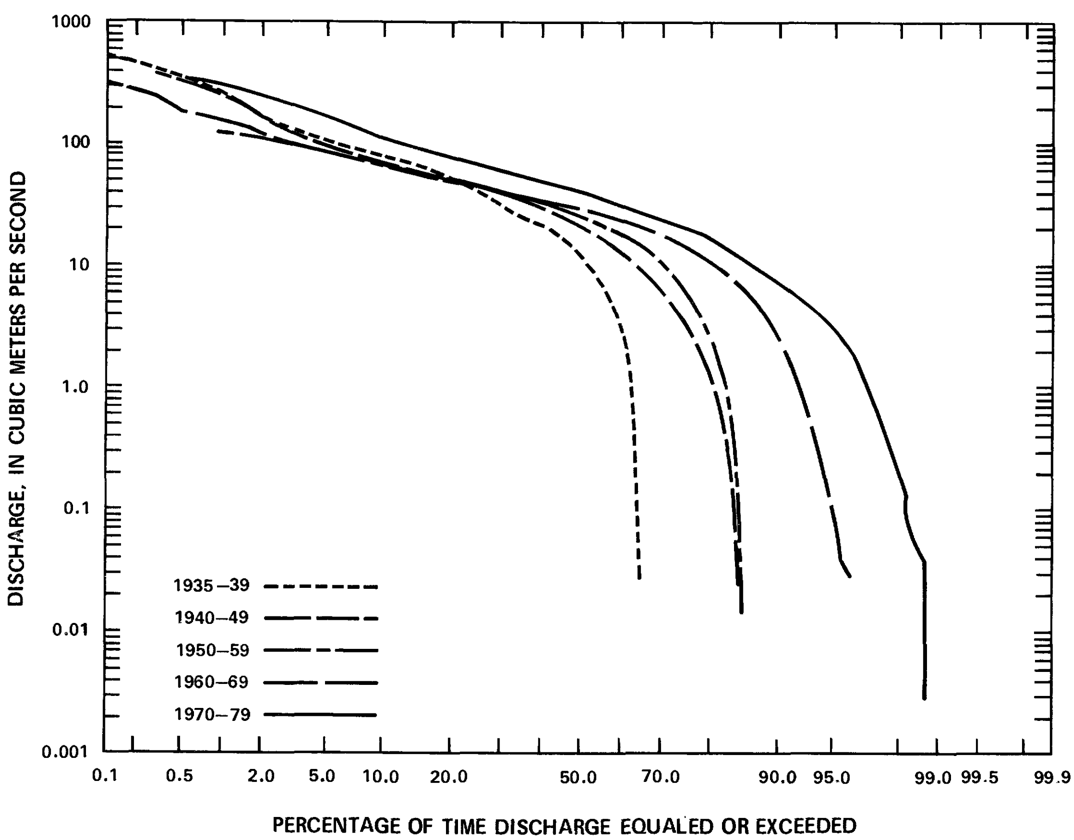


FIGURE 18.—Selected flow-duration curves at Station 06770500, Platte River near Grand Island, Nebraska (water years 1935–79).

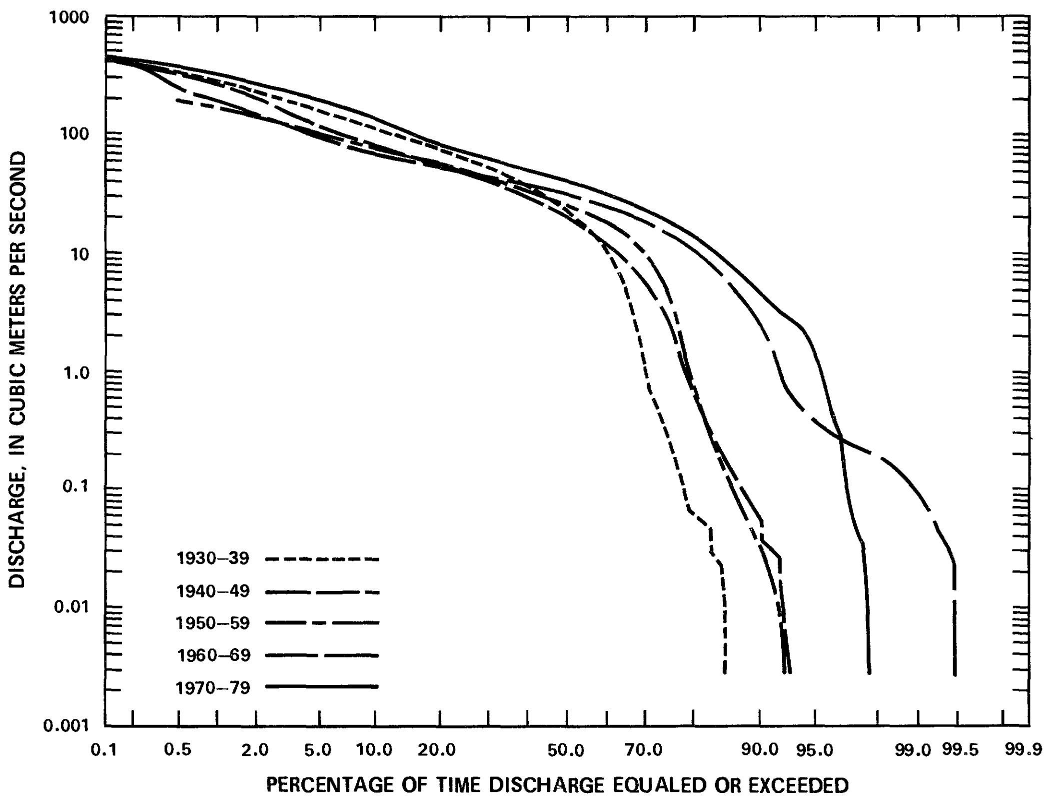


FIGURE 19.—Selected flow-duration curves at Station 06774000, Platte River near Duncan, Nebraska (water years 1930–79).

1. The significance of major developments along the rivers that would cause abrupt changes in the time series of annual mean flow and annual peak flow and,
2. The significance of developments that would show a more gradual change or time trend in annual peak flow and annual mean flow.

The only major development along the Platte River system that was suspected to cause a drastic modification in the time series of the flow statistic was the construction of Kingsley Dam and subsequent formation of Lake McConaughy. Construction of coffer dams, diversions, and off-stream storage for Kingsley Dam was begun about 1935 (Shaffer, 1976), so the period of record for all sites was divided into two time frames, when available, of pre-1935 and post-1935. Water year 1935 was included in the post-1935 time frame.

The significance of any major development causing abrupt changes in the time series of the flow variables, was determined by an analysis of covariance (Riggs, 1969; Kleinbaum and Kupper, 1978). In this analysis, logarithms of the flow variable were regressed against time with dummy variables as additional independent variables. The dummy variable was given a value of 1 for the pre-1935 period and a value of 0 for the post-1935 period. If the partial F-statistics of the regression indicated that the inclusion of the dummy variables was statistically significant to the regression, then the regression was analyzed considering the separate periods for time trend analyses. The level of significance used was the 5-percent level.

The trend analysis was performed to determine any gradual change of the flow variable with time. The trend analysis was simply a regression of the logarithm of the flow variable against time, for either the total period or for each individual period. Whether one or two time periods were analyzed was determined from the results of the analysis of covariance. If the hypothesis that the construction of Kingsley Dam had no effect on the respective flow variable is not rejected (corresponding to the F-statistics of the analysis of covariance being insignificant at the 5-percent level), then a single trend line would be obtained for the entire period of record. If, however, this same hypothesis is rejected then a trend line would be determined for the period before 1935 in addition to one for the period after 1935.

It is important to note that the determination of the trends is made only for comparative purposes, and not for estimations of the particular flow variable to be made at any site. A statistical summary of the covariance analyses is shown in table 5. The values in the table are applicable only for comparing the signifi-

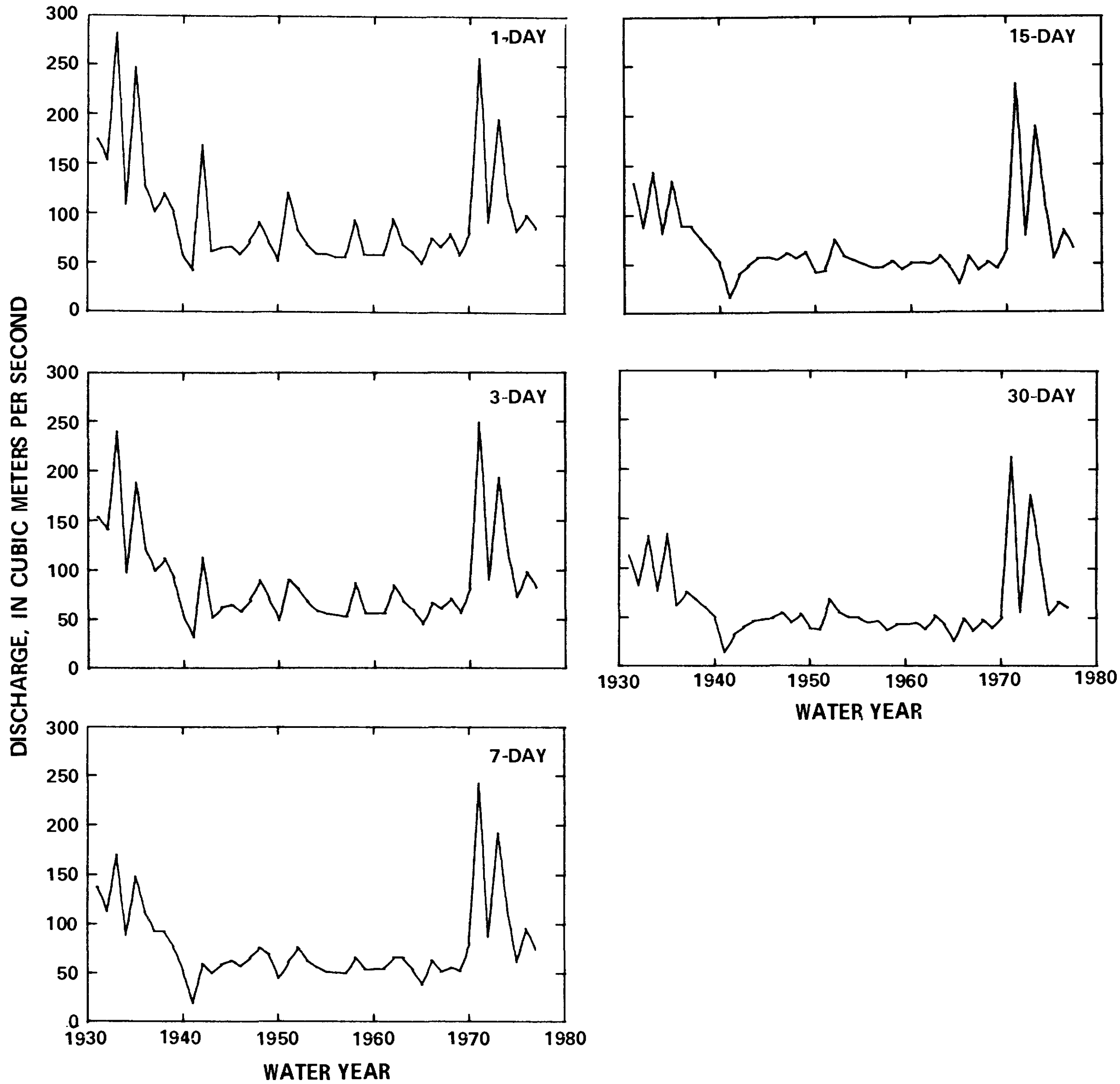


FIGURE 20.—Mean 1-, 3-, 7-, 15-, and 30-day high flows at Station 06693000, North Platte River at North Platte, Nebraska (water years 1931–79).

cant changes in hydrology between sites or between periods or to notice any overall trend in flow variables for any site.

MEAN FLOWS

Annual mean flows for the six sites are shown in figures 38 through 43. The North Platte River at North Platte, Nebraska (fig. 38), had a decrease in annual mean flows during the mid-1930's. From the analysis of covariance results of table 5, it can be seen that there is a definite shift in the time series for mean flows in the North Platte around 1935. The large F-statistic indicates that a model of mean flow versus time should be broken into the pre-1935 and post-1935 time periods. However, the slope for each time period is not significantly different from zero; therefore, there was no significant trend in mean flow at this station during the period before 1935 or during the period after 1935. Because regressions of mean discharge versus time for the pre- and post-1935 periods show no change in mean flow with time for each period, an alternative test for indicating the difference in the respective

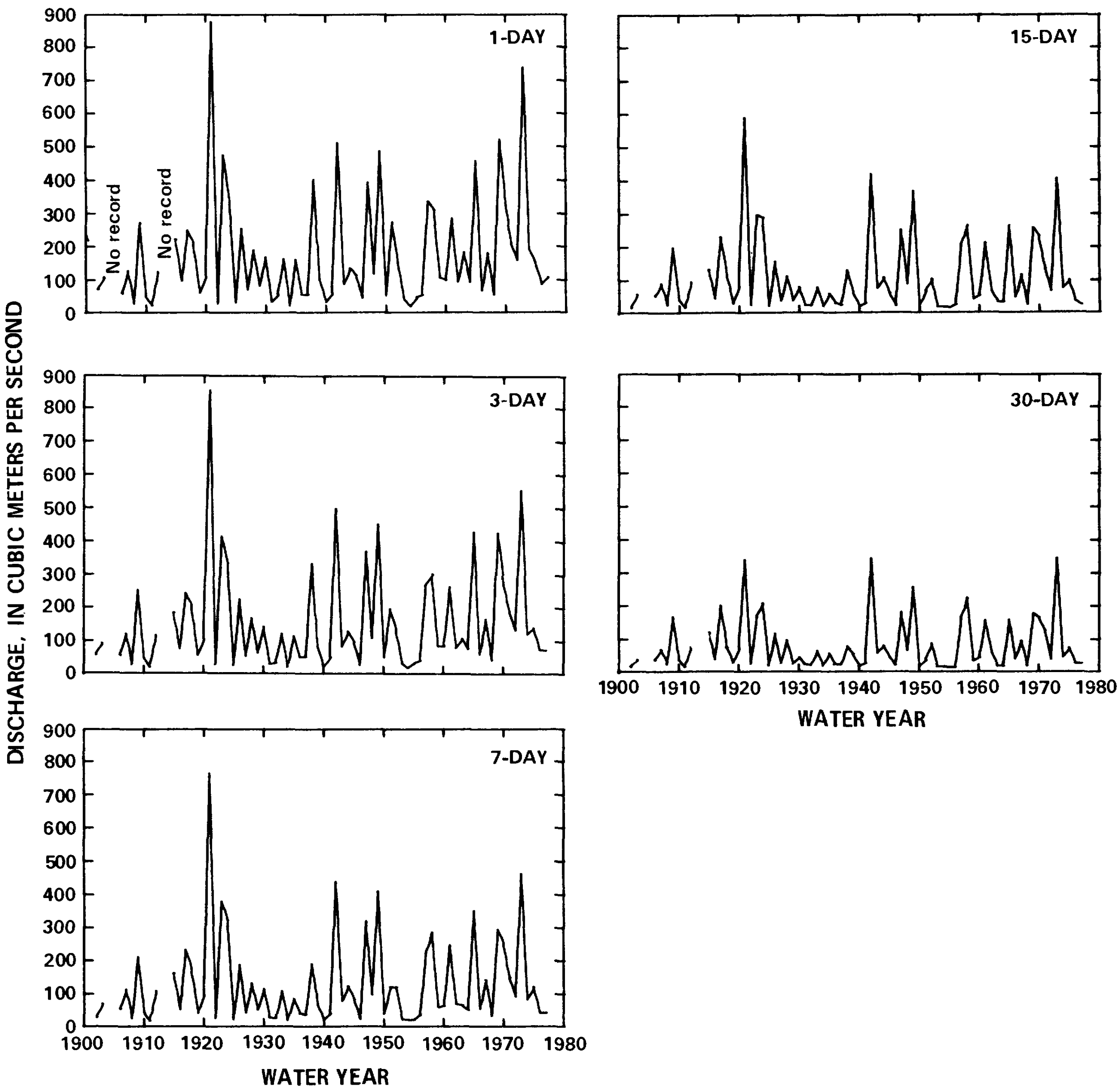


FIGURE 21.—Mean 1-, 3-, 5-, 15-, and 30-day high flows at Station 06754000, South Platte River near Kersey, Colorado (water years 1902, 1903, 1906-12, 1915-79).

populations would be a simple t-test on the means for each period.

The South Platte River stations (figs. 39 through 41) indicate very little change in the annual mean flow with time, even with the extensive development upstream. The absence of change indicated by visual inspection of the records from the South Platte River stations is verified by the analysis of covariance. The F-statistics indicate that there has been no statistically significant shift in logarithms of mean flows between the two periods, and the total period t-statistics on the regression slope parameter indicate that there was no significant trend over the entire period.

The annual mean flows for the Platte River near Overton (fig. 42) decreased abruptly during the mid-1930's. The statistical results of table 5 support this significant trend by indicating that a regression model of the logarithms of mean flow versus time for Overton need to be divided into the two specified periods. Slope parameters of the individual regressions are not significantly different from zero.

The logarithms of the mean flows for the Platte

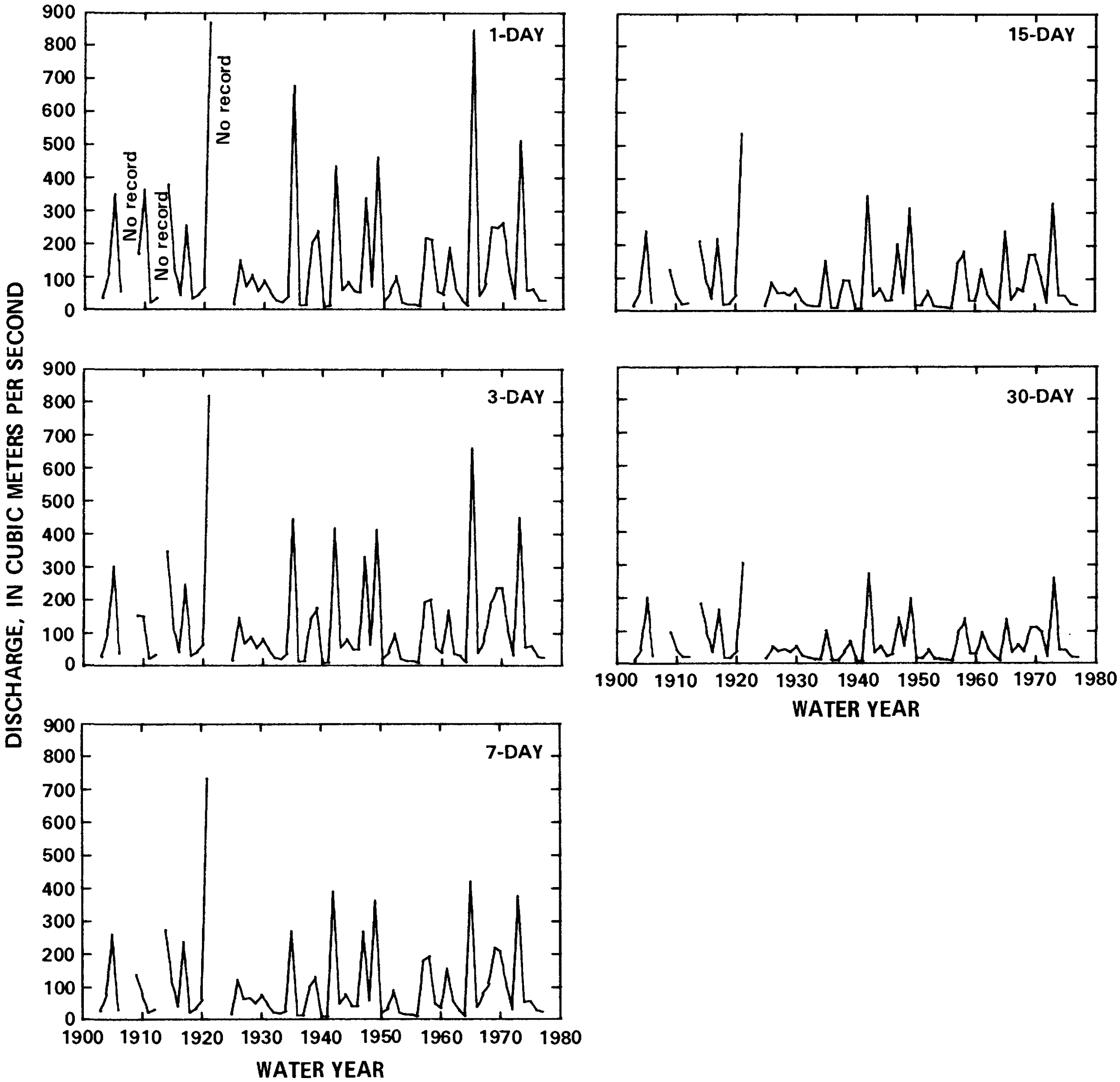


FIGURE 22.—Mean 1-, 3-, 7-, 15-, and 30-day flows at Station 06764000, South Platte River at Julesburg, Colorado (water years 1903–79).

River near Grand Island (fig. 43) show an increasing trend for the entire period of record, which began after 1935. This increase probably was unduly affected by the high flow water years 1971–74.

Monthly mean flows for the period of record for April through September are shown in figures 44 through 47. These months were chosen because they encompass the critical growth period for vegetation as defined by the U.S. Fish and Wildlife Service. The months also include the major runoff period and irrigation season. Only four stations were used in this analysis to show the changes on the North Platte River, South Platte River, and the Platte River in and near the critical reach.

The monthly mean flows during July and August for the North Platte River (fig. 44) indicate a marked increase beginning about 1945. These are two of the peak irrigation months and the increases are the result of releases from Lake McConaughy. April and May are the months of spring runoff and the North Platte River at North Platte shows a decrease in these flows following the construction of Lake McConaughy, which now holds back the higher flows.

The South Platte River at North Platte (fig. 45) had

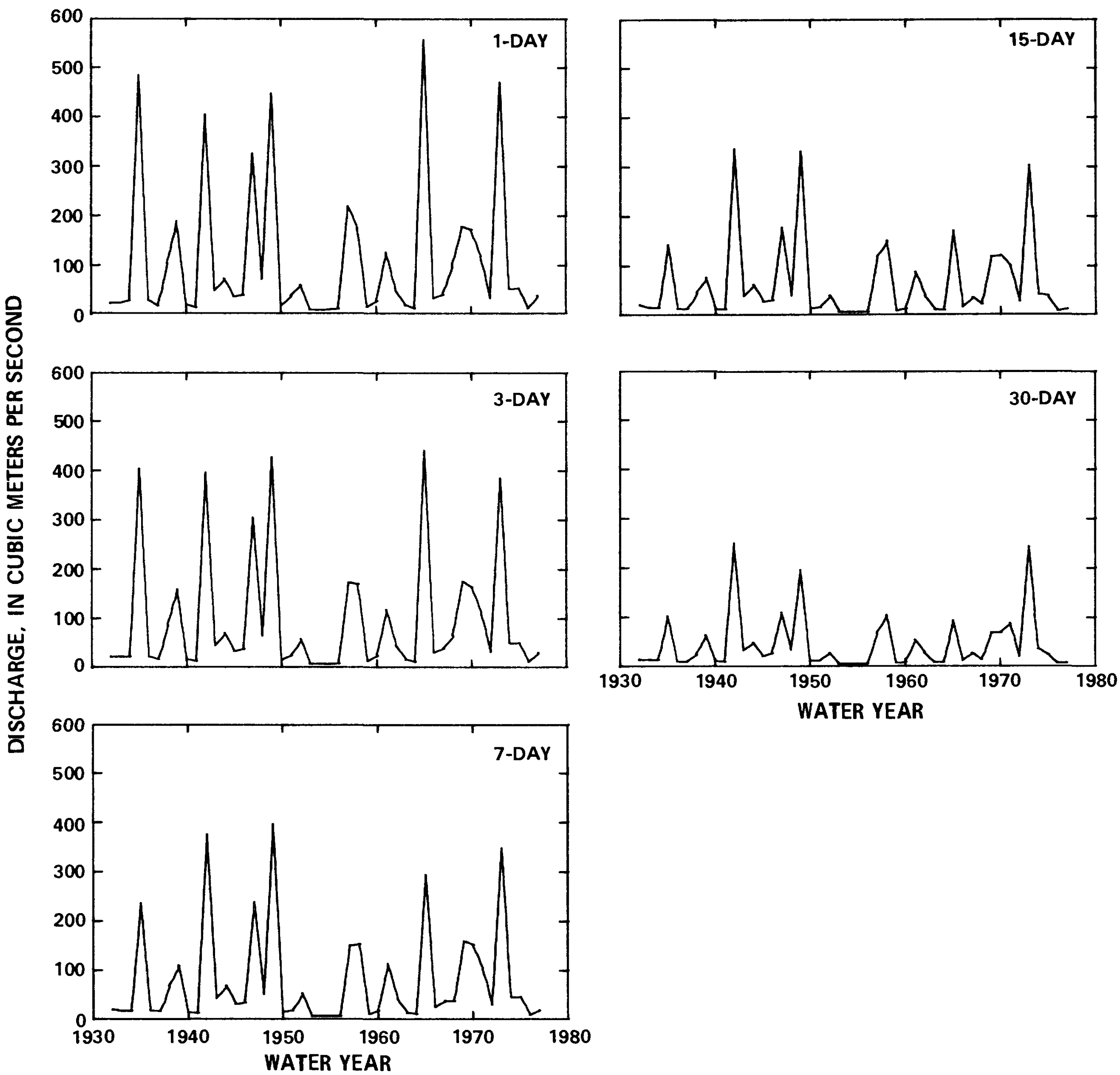


FIGURE 23.—Mean 1-, 3-, 7-, 15-, and 30-day flows at Station 06765500, South Platte River at North Platte, Nebraska (water years 1932–79).

little change in the monthly mean flows. The records for the Platte River near Overton and Grand Island (figs. 46 and 47) do not indicate the large change that occurred in the North Platte River, but do show a small increase in the monthly mean flows during July and August. The change in monthly mean flows possibly is damped out by the South Platte River, which has had little change in the mean flows.

INSTANTANEOUS PEAK FLOWS

The yearly instantaneous peak flows for six stations in the study reach are given in figures 48 through 53. The North Platte River at North Platte (fig. 48) indicates the largest change in peak flows of the six stations; this is most likely a result of the on-stream construction of Kingsley Dam, which holds back the peak flows that once continued downstream. The statistical analysis (table 6) indicates that a regression model of the logarithms of annual peak flow versus time needs to be divided into two models corresponding to pre-1935 and post-1935 time periods. This first model indicates a decrease in peak flows to 1935; following 1935 there is no significant change in the peak flows with time.

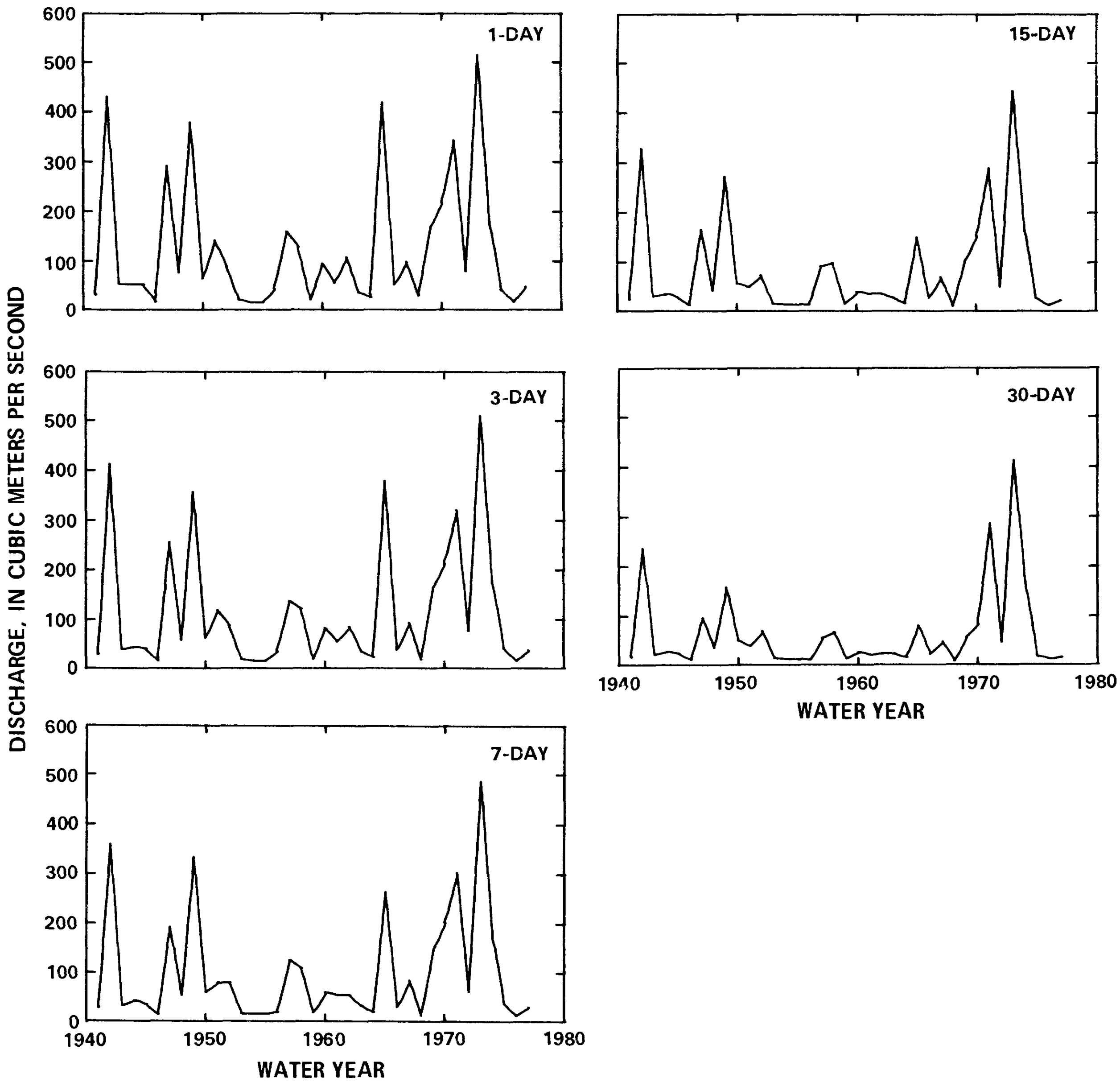


FIGURE 24.—Mean 1-, 3-, 7-, 15-, and 30-day flows at Station 06766500. Platte River near Cozad, Nebraska (water years 1941–79).

For the South Platte River near Kersey, Colorado, and the South Platte River at Julesburg, Colorado, the regression results indicate no shift in time series for the logarithms of peak flows as well as no significant trend with time. The F-test for the South Platte River at North Platte (fig. 51) indicates a homogeneity in the data set for the entire period, and there is a gradual decrease in annual peak flows throughout the entire period of record. The 1935 data point may have an inordinate effect on the trend of the regression.

The Platte River near Overton (fig. 52) indicates a single regression of the logarithms of annual peak flow versus time with a negative trend for the period of record, while statistically the 1935–present data set of peak flows at Grand Island (fig. 53) shows no appreciable trend. The similarity of the peak flows at Overton compared to the South Platte River near North Platte, shown by both statistical results and visual inspection, is indicative of the important contribution of the South Platte peak flows to the Platte River major peak flows. The overlaid plots of peak flows for the South Platte River at North Platte, Nebraska, and the Platte River near Overton, Nebraska, are shown in figure 54. This is substantiated by Williams (1978) who stated that the North Platte River upstream from Lake McConaughy showed a decrease in peak flow after the construction of each of the major reservoirs in Wyoming, and the Platte River

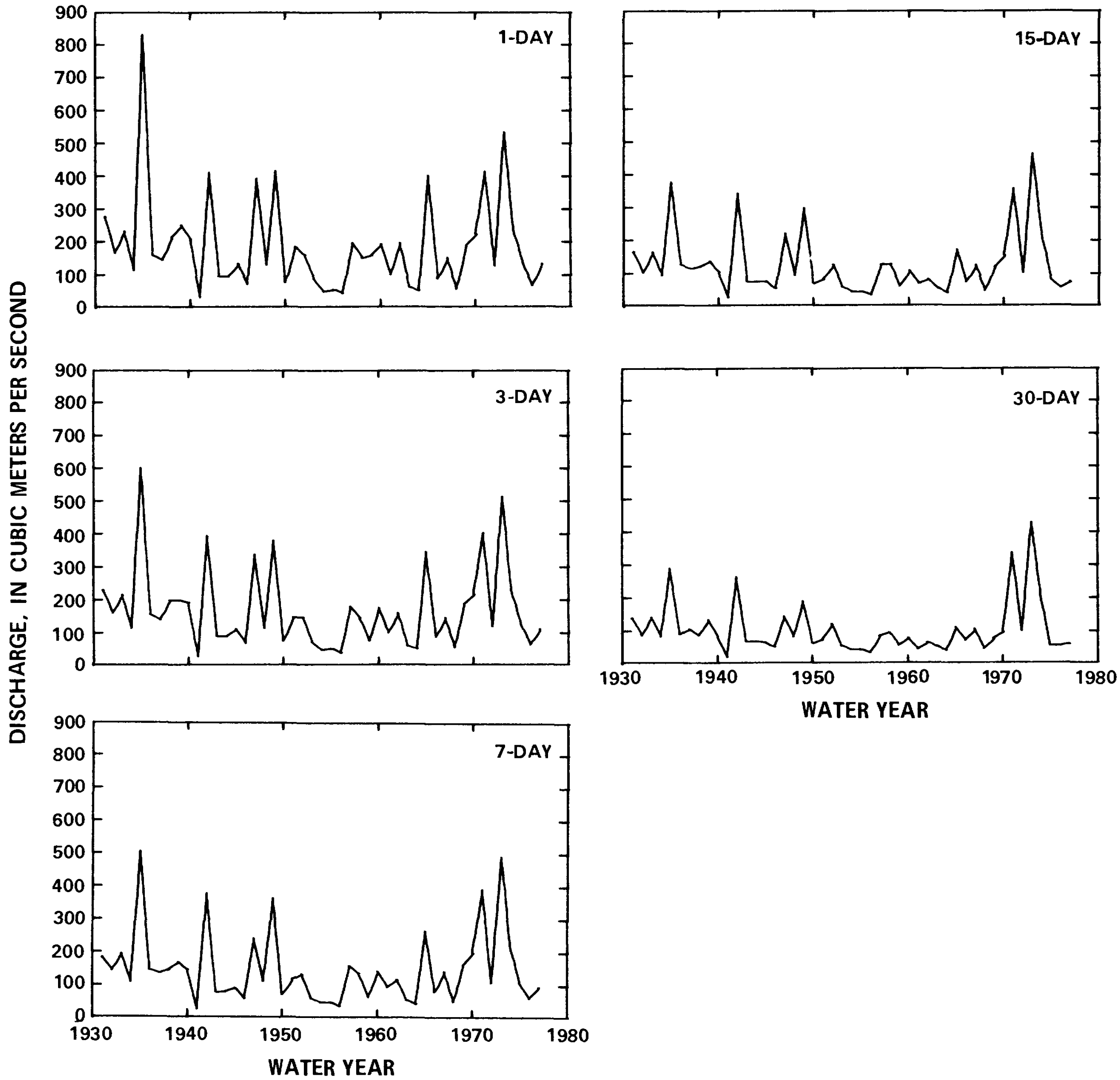


FIGURE 25.—Mean 1-, 3-, 7-, 15-, and 30-day high flows at Station 06768000, Platte River near Overton, Nebraska (water years 1931–79).

near Grand Island, Nebraska, shows similarity of peak-flow occurrences (fig. 54).

In order to illustrate the effect of the peak flows and mean flows of the South Platte and North Platte Rivers on the peak flows and mean flows for the Platte River near Overton, regression analyses were performed relating the logarithms of these flow variables, and the results are listed in table 7. Because the time-trend analyses previously discussed for both peak and mean flows of the North Platte River at North Platte indicate that two separate time periods need to be considered in making statistical determinations regarding this site, the interstation regressions were performed for each time period.

The difference in the magnitudes of the slope coefficients of the respective North Platte River and South Platte River flow variables are not legitimate measures of the relative importance of one independent variable compared to another in affecting the flow variables at Overton. This is true because the size of a coefficient would change as a result of merely changing the scale of the measurements of the variable. However, by adjusting the ordinary least-squares regression-slope coefficient estimates by the ratio of the standard deviations of the independent and dependent variables, an objective measure of importance of the independent variables can be determined. These adjusted coefficients are called "beta coefficients"

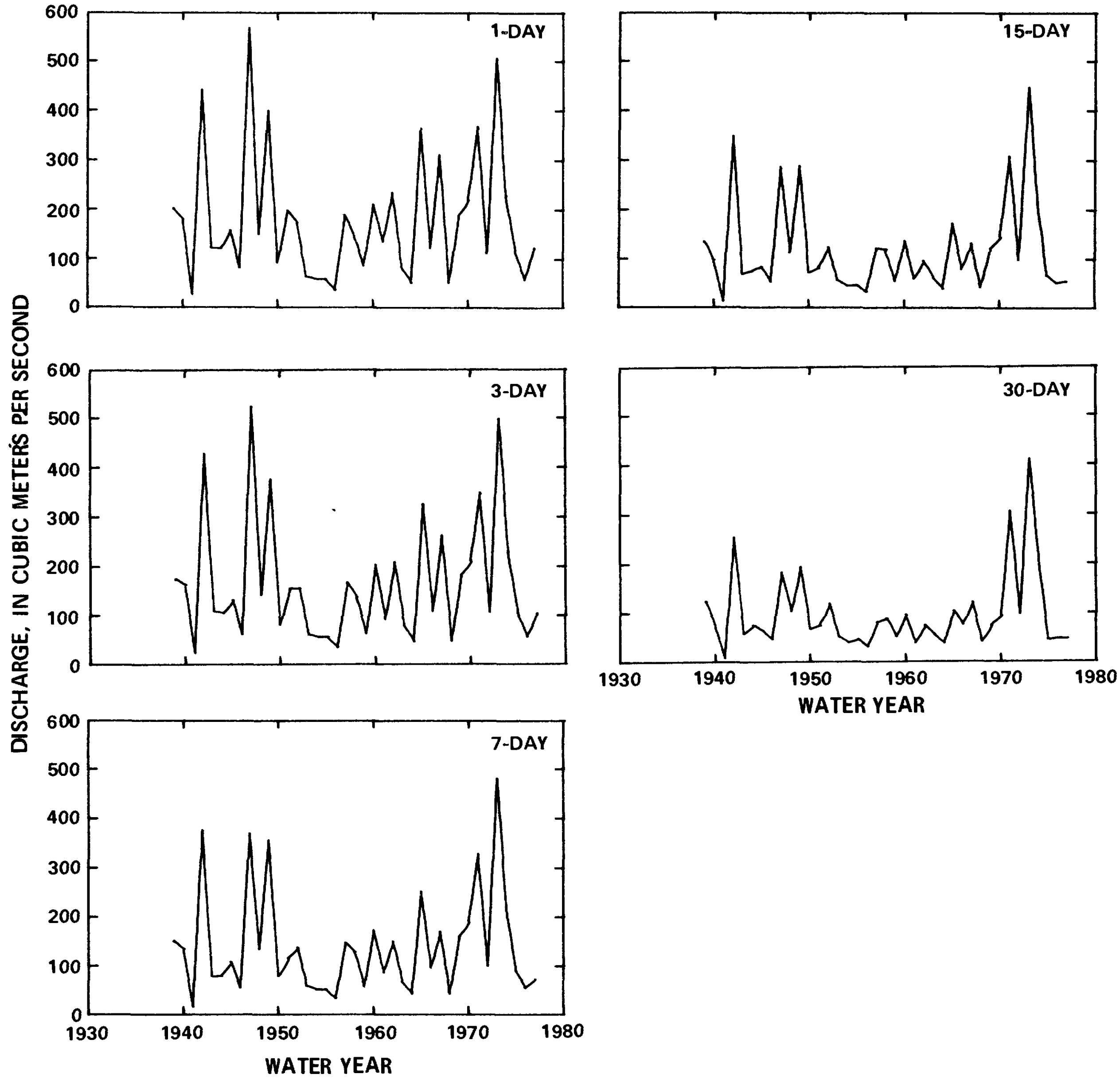


FIGURE 26.—Mean 1-, 3-, 7-, 15-, and 30-day high flows at Station 06770000, Platte River near Odessa, Nebraska (water years 1940–79).

(Goldberger, 1964). The beta coefficients calculated from the slope coefficients in table 7 are listed in table 8.

The pre-1935 beta coefficients from table 8 indicate that the mean flow variable from the North Platte River at North Platte is the more important contributor to the mean flow variable at Overton. Similarly, the pre-1935 peak flow variable beta coefficients show the North Platte River peaks to be slightly more dominant then the peak flow variable from the South Platte River in affecting the peak flow variable at Overton. However, the post-1935 beta coefficient from the mean flow analysis indicate that the South Platte River has equalized its effect on the mean flow variable at Overton relative to the North Platte River's effect. The regression analysis of the post-1935 peak flow variable shows that the roles of the more important contributor for this flow variable have reversed. This role reversal can be explained by the fact that the South Platte peak flows account for the majority of the significant peaks at Overton. Although the North Platte River is a major contributor to most annual peak flows at Overton, most large peaks are derived from the South Platte basin.

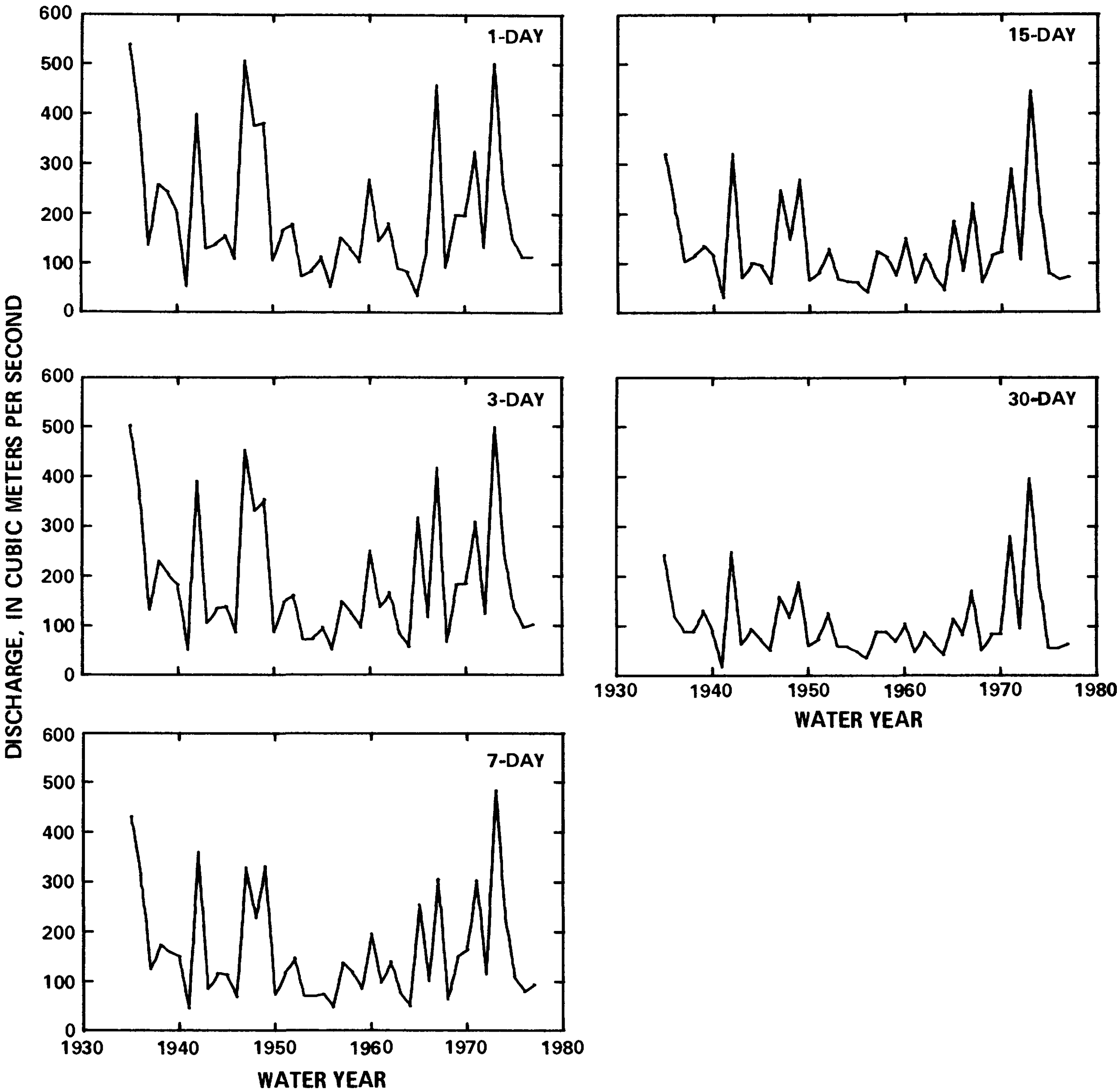


FIGURE 27.—Mean 1-, 3-, 7-, 15-, and 30-day high flows at Station 06770500 Platte River near Grand Island, Nebraska (water years 1935–79).

SUMMARY

Flow in the Platte River basin is affected by transmountain diversions in the headwaters, dams that create on-stream reservoirs, structures that divert water to off-stream reservoirs, ground-water pumpage from lands bordering rivers, return of water to channels from irrigation and hydropower releases, possible gain or loss of water by seepage, water demands of an increasing population, and the requirements of more vegetation that now grows in the river valley. These effects of man in the Platte River basin are the most logical explanation for the observed changes in flow.

Changes in surface-water hydrology and channel size have occurred at different times throughout the basin. The hydrologic changes are identified by shifts in levels of low flows and high flows, and the flattening of flow-duration curves. These changes also are illustrated in the time series of annual mean and peak flows. Changes in channel morphology are exhibited in the plots of width and area of the Platte River channels through time.

The hydrologic and channel changes have occurred

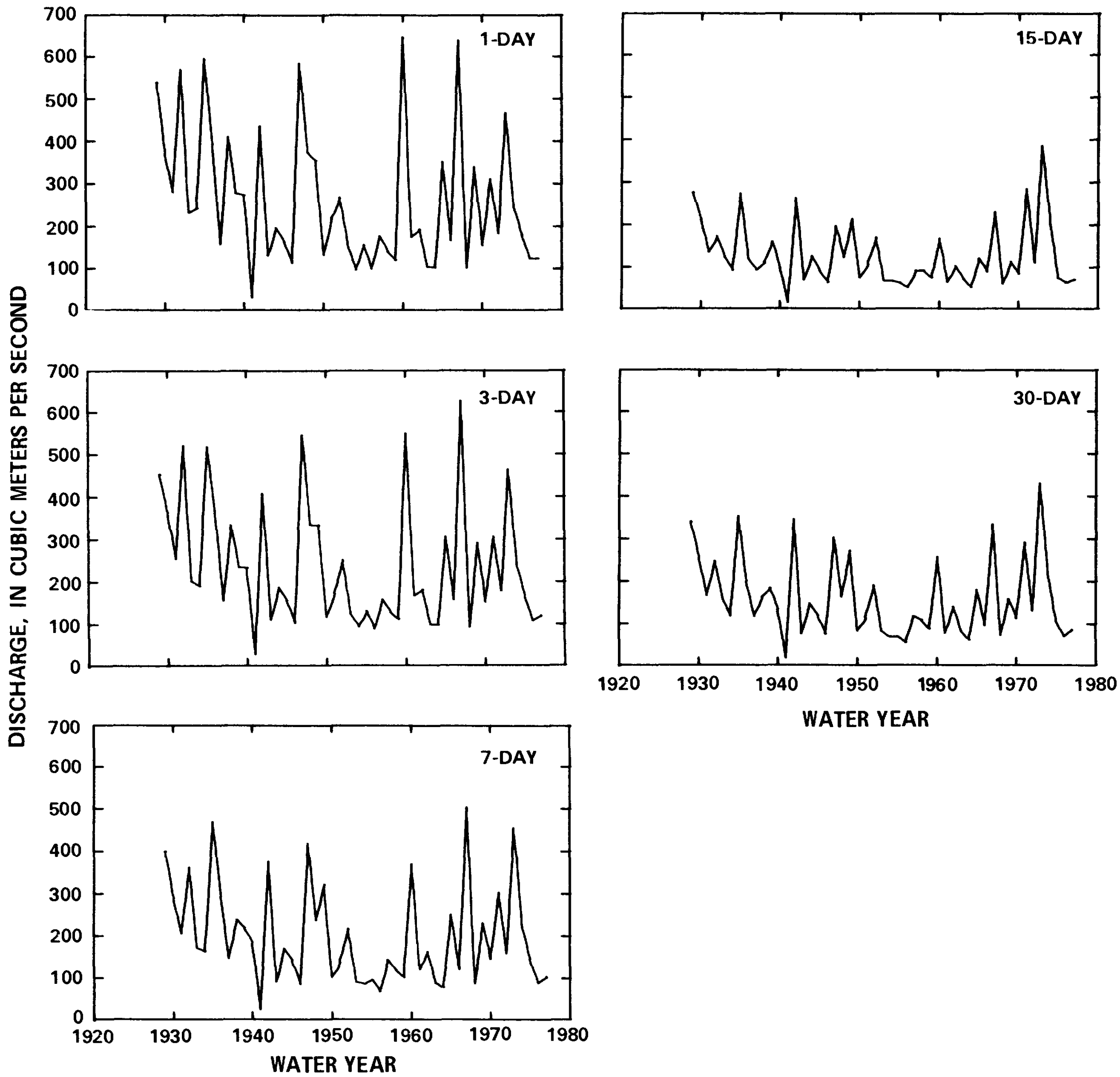


FIGURE 28.—Mean 1-, 3-, 7-, 15-, and 30-day high flows at Station 06774000, Platte River near Duncan, Nebraska (water years 1930–79).

in such a manner that the upstream reaches were affected earliest in the period of record. Observing the 10-year flow-duration curves and low flows at the sites studied indicate the stations upstream of the Platte River near Overton are maintaining relative stability, while those sites downstream of Overton still are adjusting to the changes in the hydrologic system upstream. This relative stability reached at each of the sites is as follows: The North Platte River at North Platte, Nebraska, about 1941; the South Platte River at Julesburg, Colorado, about 1920; the South Platte River at North Platte, Nebraska, about 1937; and the Platte River near Cozad and Overton, Nebraska, about 1950. The Platte River near Odessa, Grand Island, and Duncan, Nebraska, still is adjusting toward stability, while the South Platte River near Kersey, Colorado, has not shown any significant change for the period of record investigated. Therefore, in hydrologic analysis, caution needs to be taken in defining the period of record used because of the changing hydrologic system.

At each site, statistical analyses were performed on records prior to and following the construction of Kingsley Dam, to determine the effect on the peak and annual mean flows. The South Platte River in Colorado shows no trend in either the peak or annual mean

TABLE 5.—*Summary of regression and covariance analysis for the logarithms of annual mean flows*

Site	F-statistic	Number of regression equation	Pre-1935 population		Post-1935 population		Total record	
			Slope	t-statistic	Slope	t-statistic	Slope	t-statistic
North Platte River at North Platte, Nebraska	73.9*	2	−0.006	−1.13	0.000	0.03	—	—
South Platte River near Kersey, Colorado	2.26	1	−.005	—	.015	—	0.003	0.85
South Platte River at Julesburg, Colorado	1.28	1	−.006	—	.011	—	−.001	−.26
South Platte River at North Platte, Nebraska	2.50	1	−.064	—	.003	—	−.006	−1.16
Platte River near Overton, Nebraska	20.2*	2	−.031	−1.82	.010	1.99	—	—
Platte River near Grand Island, Nebraska	—	1	—	—	.013	—	.013	2.30*

*Indicates statistic is significant at the 5-percent level.

TABLE 6.—*Summary of regression and covariance analysis for the logarithms of annual peak flows*

Site	F-statistic	Number of regression equation	Pre-1935 population		Post-1935 population		Total record	
			Slope	t-statistic	Slope	t-statistic	Slope	t-statistic
North Platte River at North Platte, Nebraska	156.4*	2	−0.021	−3.15*	0.001	0.24	—	—
South Platte River near Kersey, Colorado	0.570	1	−.004	—	.016	—	0.007	1.63
South Platte River at Julesburg, Colorado	2.40	1	−.010	—	.004	—	-.004	−.62
South Platte River at North Platte, Nebraska	1.31	1	−.067	—	.077	—	-.018	−2.22*
Platte River near Overton, Nebraska	1.93	1	−.037	—	-.007	—	-.019	−4.23*
Platte River near Grand Island, Nebraska	—	1	—	—	-.007	—	-.007	−.99

*Indicates statistic is significant at the 5-percent level.

TABLE 7.—*Summary of regression results relating the logarithms of mean annual and peak flows of the South Platte River and North Platte River to the logarithms of mean annual and peak flows of the Platte River.*

	Variable	Slope regression coefficient	t-statistic*	Slope regression coefficient	t-statistic*
Pre-1935	Logarithms of mean flow Platte River near Overton, Nebraska.	0.984	7.99	0.166	2.85
	Logarithms of peak flow Platte River near Overton, Nebraska.	.674	5.17	.260	4.45
Post-1935	Logarithms of mean flow Platte River near Overton, Nebraska.	.725	7.09	.376	6.57
	Logarithms of peak flow Platte River near Overton, Nebraska.	.288	2.07	.353	6.88

*All t values are significant at the 5 percent level.

TABLE 8.—*Summary of beta coefficients relating the logarithms of mean annual and peak flows of the North Platte River and South Platte River to the logarithms of mean annual and peak flows of the Platte River*

	Variable	Beta coefficient (North Platte)	Beta coefficient (South Platte)
Pre-1935	Logarithms of mean flow Platte River near Overton, Nebraska.	0.756	0.269
	Logarithms of peak flow Platte River near Overton, Nebraska.	.576	.495
Post-1935	Logarithms of mean flow Platte River near Overton, Nebraska.	.571	.529
	Logarithms of peak flow Platte River near Overton, Nebraska.	.211	.702

flows. The South Platte River at North Platte, Nebraska, shows no trend in annual mean flows, but a decrease in peak flows for the period of record. The North Platte River at North Platte, Nebraska, and the Platte River near Overton, Nebraska, show a decrease in both the peak and annual mean flows, while the Platte River near Grand Island, Nebraska, shows no trend in the peak flows, but a slight increase in annual mean flows.

REFERENCES

Bentall, Ray, 1975, Hydrology, Nebraska Mid-State Division and associated areas: Nebraska University Conservation and Survey Division, Institute of Agriculture and Natural Resources Report, 256 p.

Bentall, Ray, and Shaffer, F. B., 1975, Availability and use of water in Nebraska, 1975: Nebraska University Conservation and Survey Division, Institute of Agriculture and Natural Resources Report, no. 48, 121 p.

Currier, P. J., and Van Der Valk, A. G., 1980, The vegetation of the Platte River, in Phytosociology, forest development, and seedling establishment: U.S. Fish and Wildlife Service, Northern Prairie Wildlife Research Center, Jamestown, North Dakota, 40 p.

Gerlek, Steve, 1977, Water supply management analysis and alternative development for the South Platte River basin, v. 2: U.S. Army Corps of Engineers, 354 p.

Goldberger, A. S., 1964, Econometric theory: New York, John Wiley and Sons, 399 p.

Kleinbaum, D. G., and Kupper, L. L., 1978, Applied regression analyses and other multivariate methods: Belmont, California, Wadsworth Publishing, p. 209-226.

Meyers, J. S., 1962, Evaporation from the seventeen western States: U.S. Geological Survey Professional Paper 272-D, p. 71- 100.

Riggs, H. C., 1969, Some statistical tools in hydrology: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 4, Chapter A1, 39 p.

_____1972, Low-flow investigations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 4, Chapter B1, p. 15.

Shaffer, F. B., 1976, History of irrigation and characteristics of streamflow in Nebraska part of the North and South Platte River basins: U.S. Geological Survey Open-File Report 76-167, 98 p.

Williams, G. P., 1978, The case of the shrinking channels-The North Platte and Platte Rivers in Nebraska: U.S. Geological Survey Circular 781, 48 p.

FIGURES 29-54

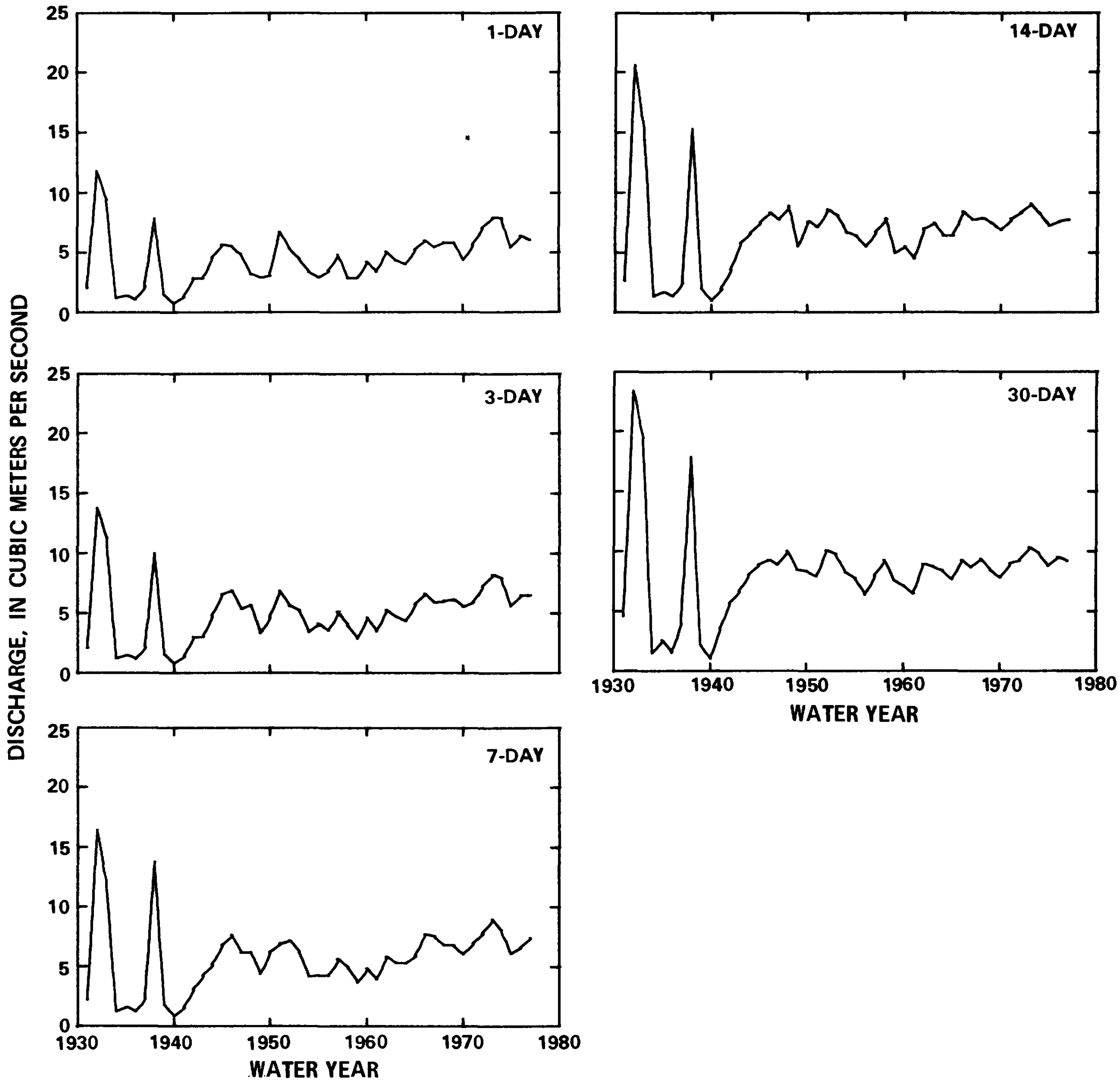


FIGURE 29.—Mean 1-, 3-, 7-, 14-, and 30-day low flows at Station 06693000, North Platte River at North Platte, Nebraska (water years 1931–79).

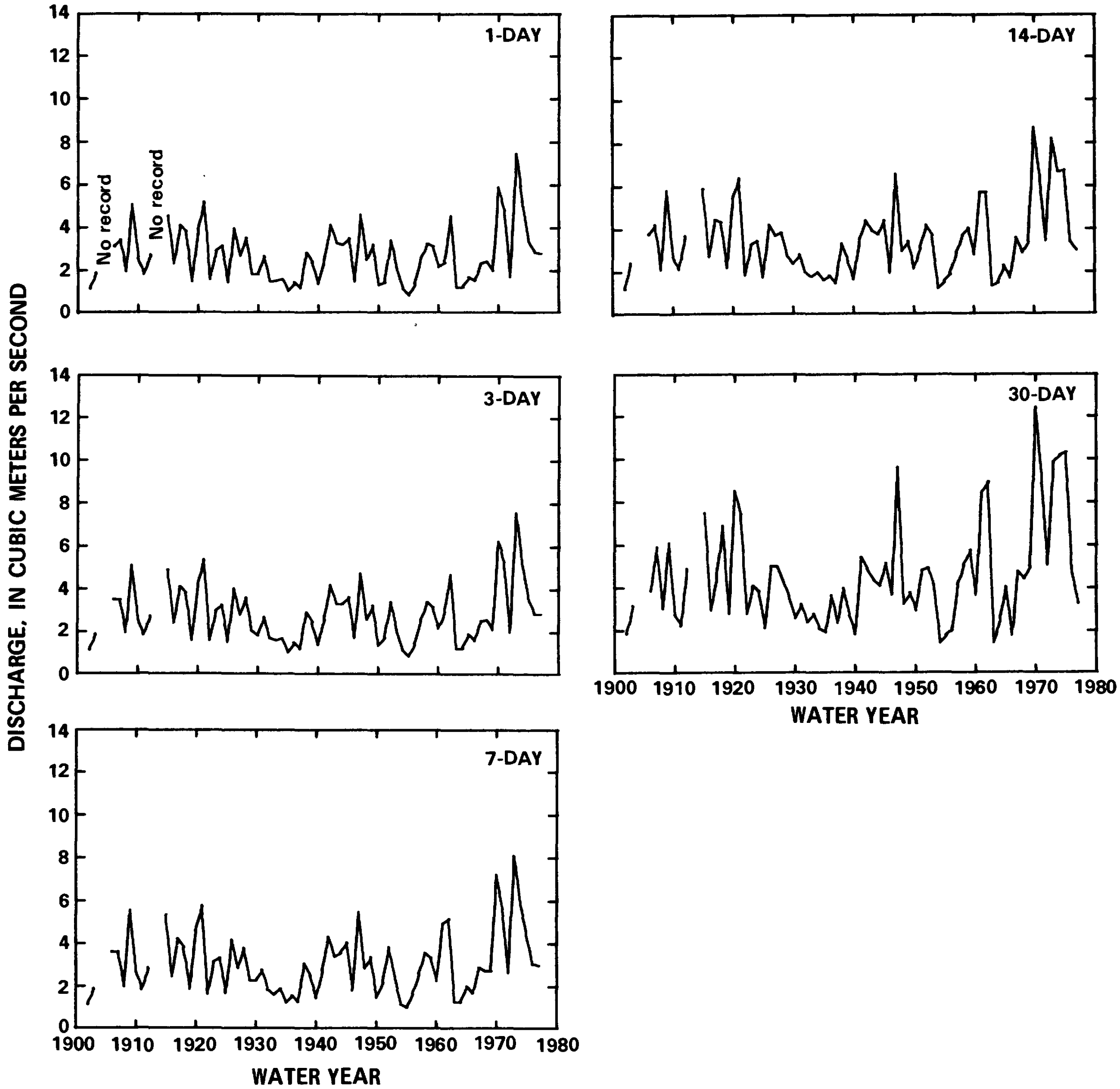


FIGURE 30.—Mean 1-, 3-, 7-, 14-, and 30-day flows at Station 067754000, South Platte River near Kersey, Colorado (water years 1902, 1903, 1906-12, 1915-79).

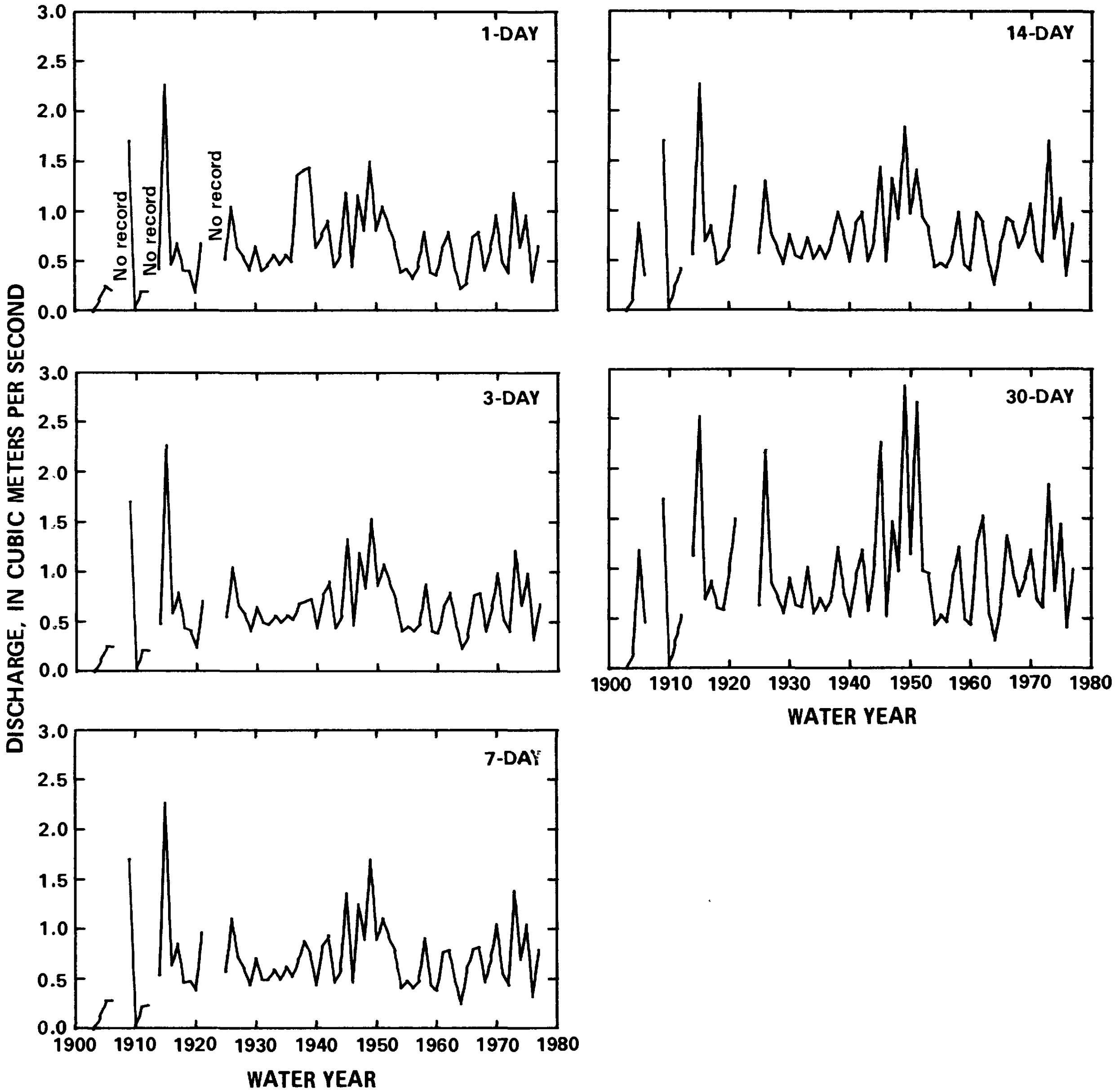


FIGURE 31.—Mean 1-, 3-, 7-, 14-, and 30-day flows at Station 06764000, South Platte River at Julesburg, Colorado (water years 1903–79).

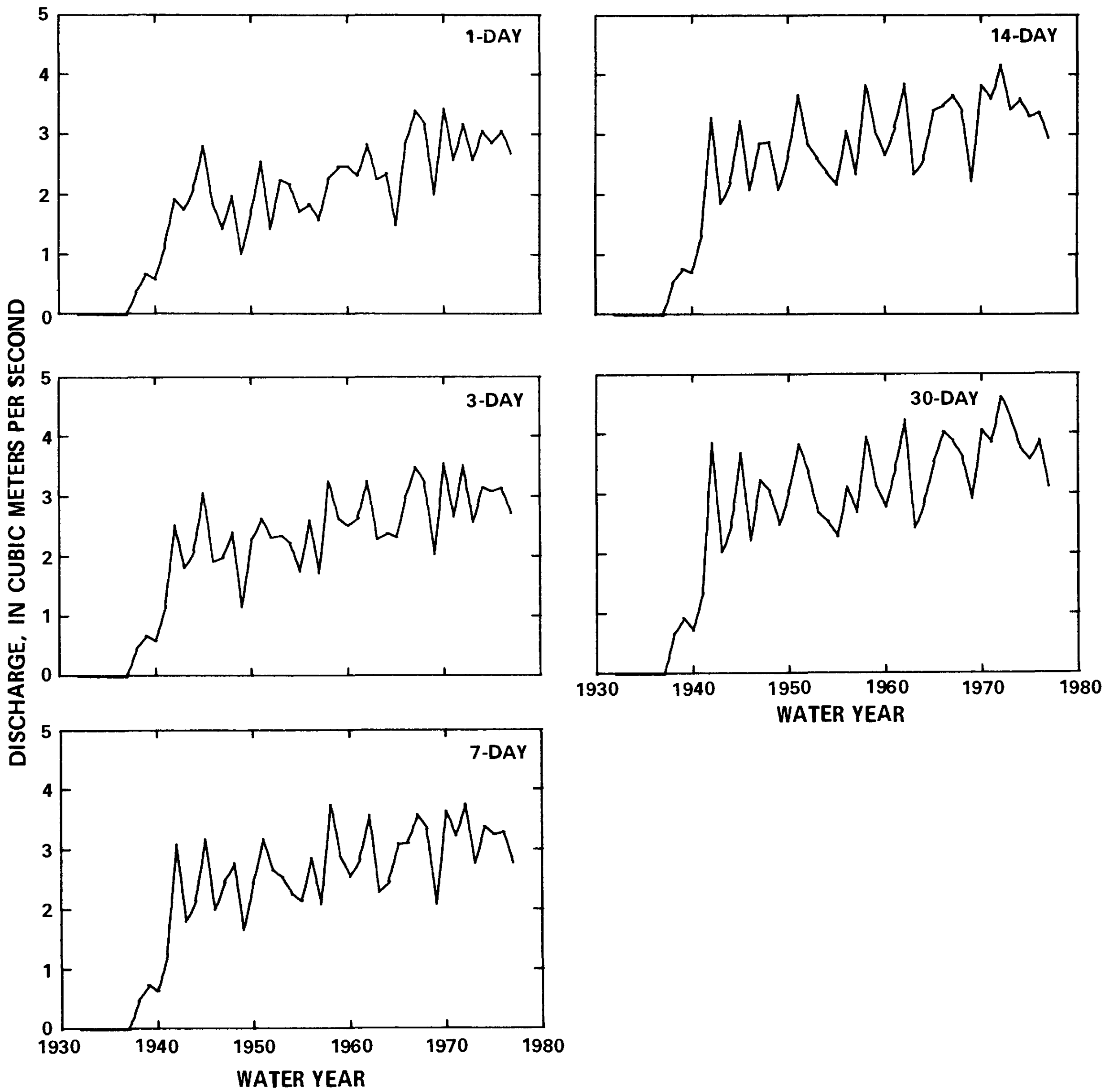


FIGURE 32.—Mean 1-, 3-, 7-, 14-, and 30-day low flows at Station 06765500, South Platte River at North Platte, Nebraska (water years 1932-79).

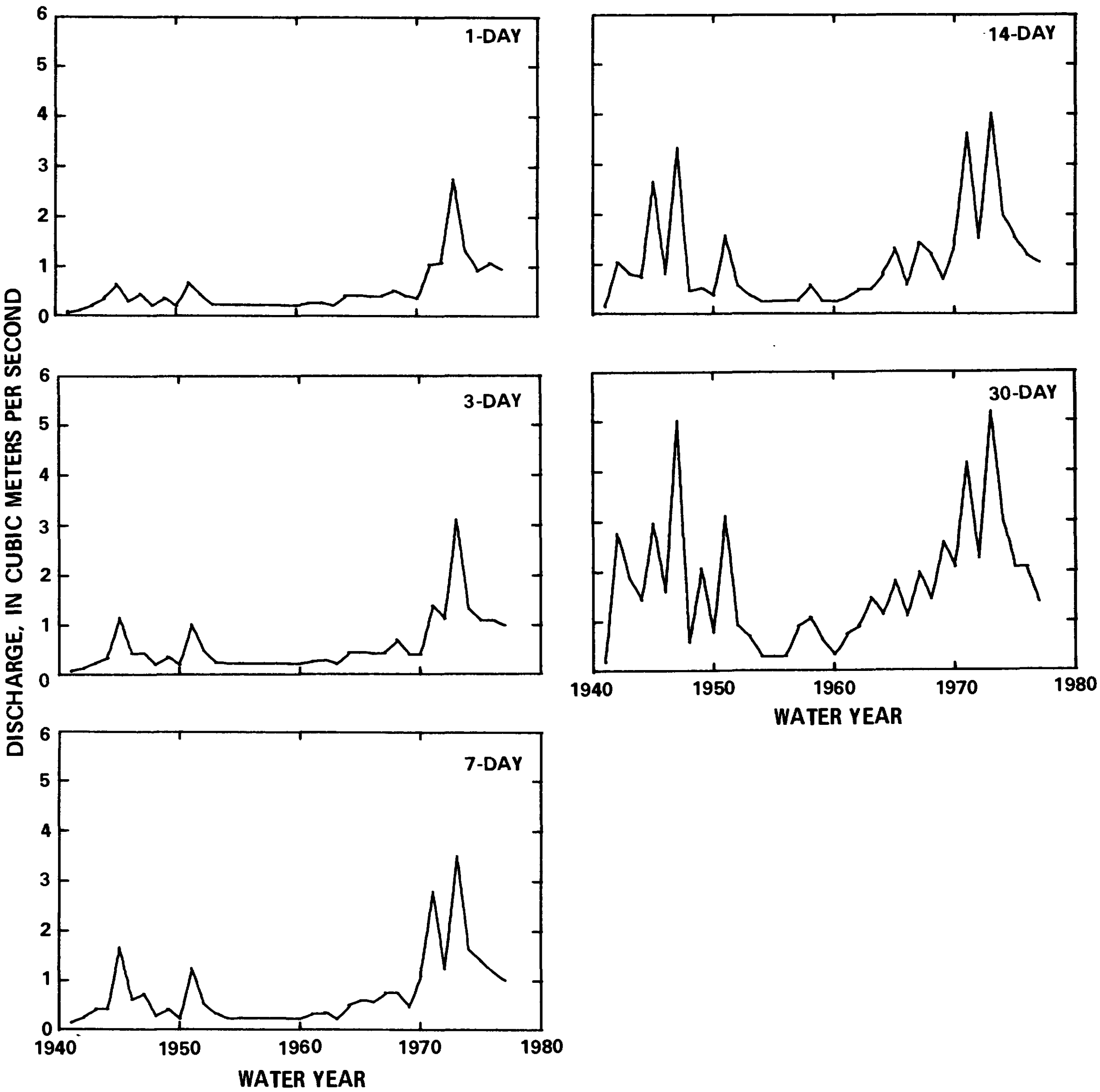


FIGURE 33.—Mean 1-, 3-, 7-, 14-, and 30-day low flows at Station 06766500, Platte River near Cozad, Nebraska (water years 1941–79).

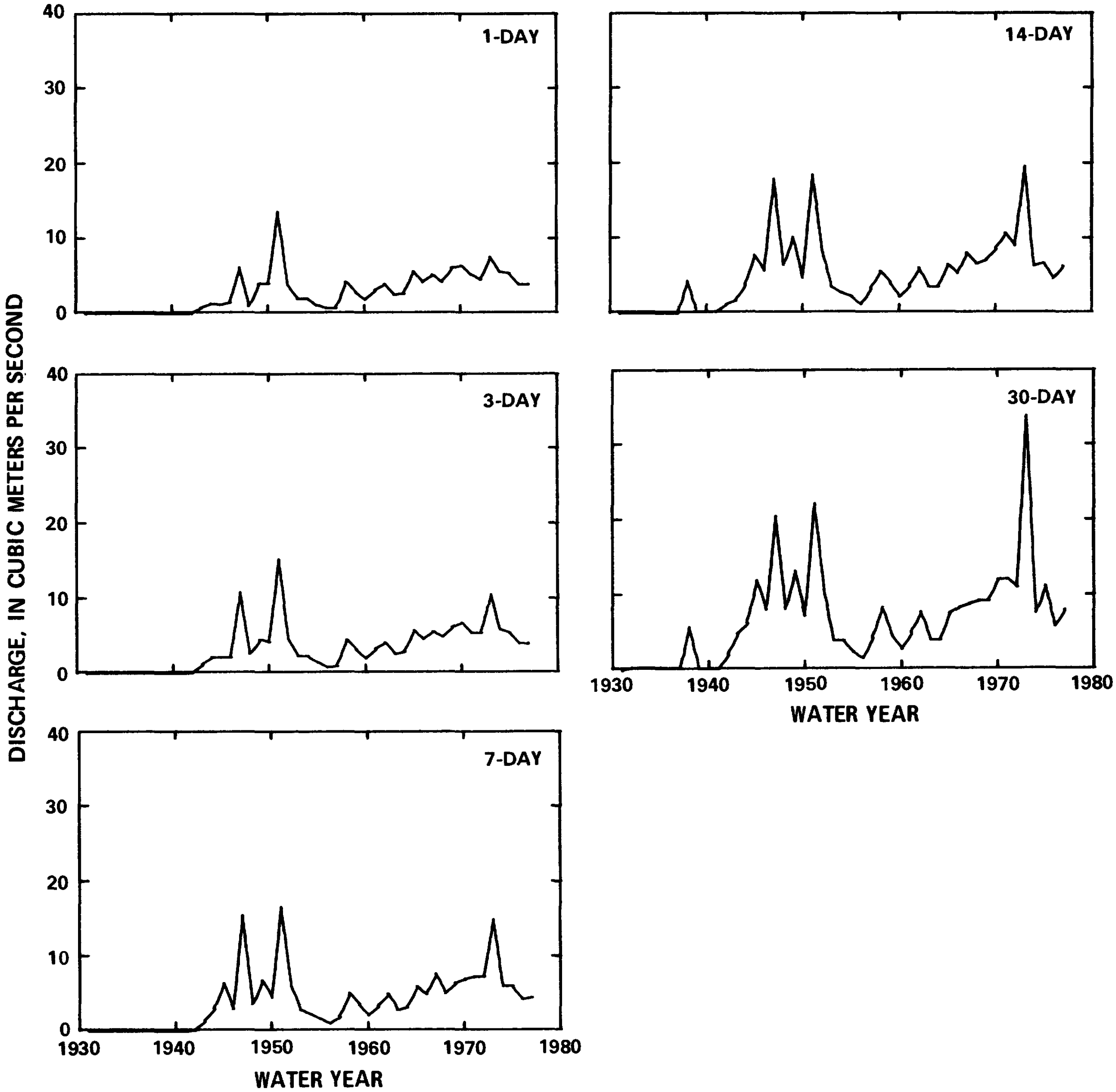


FIGURE 34.—Mean 1-, 3-, 7-, 14-, and 30-day low flows at Station 06768000, Platte River near Overton, Nebraska (water years 1931–79).

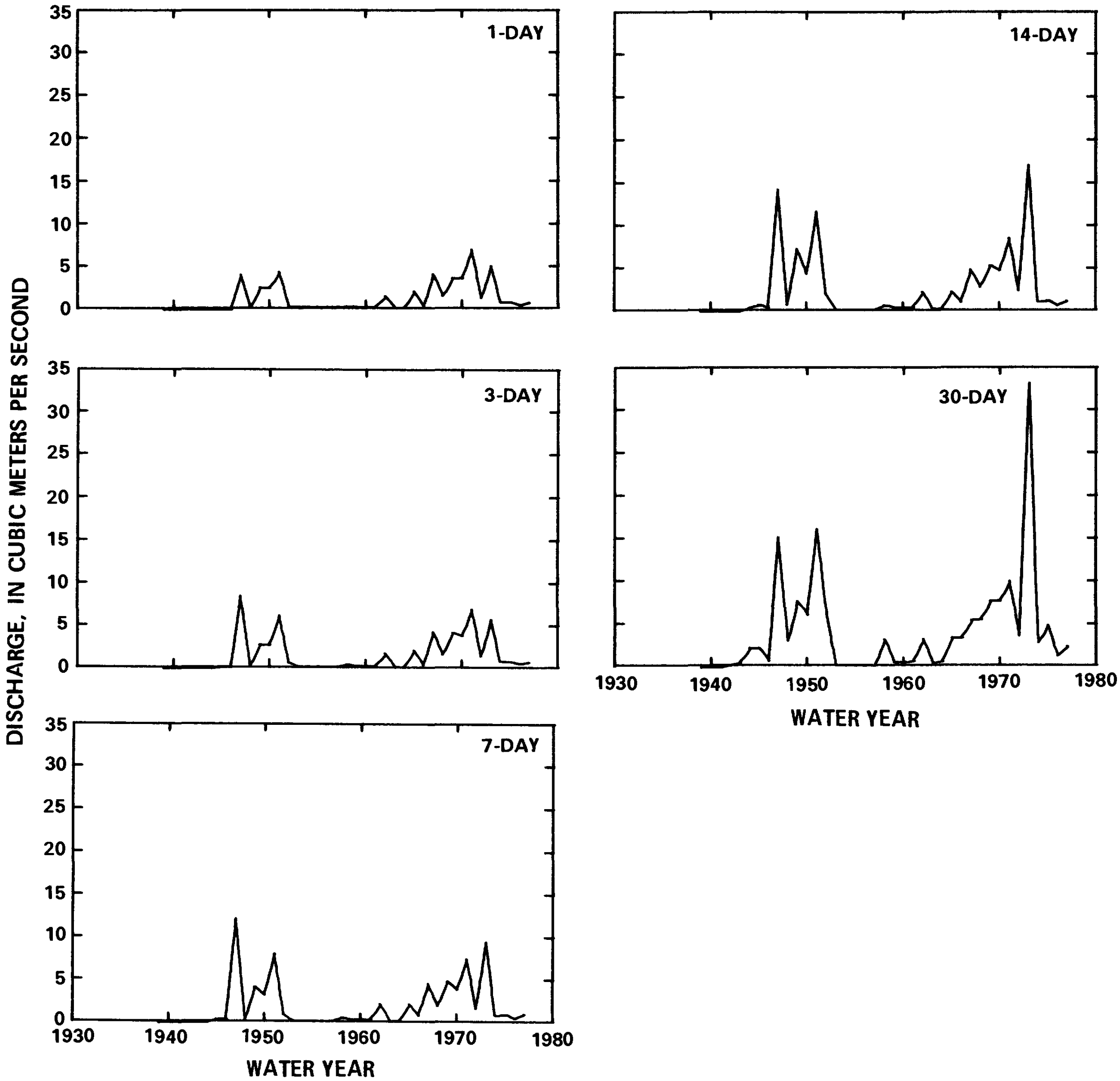


FIGURE 35.—Mean 1-, 3-, 7-, 14-, and 30-day low flows at Station 06770000, Platte River near Odessa, Nebraska (water years 1940–79).

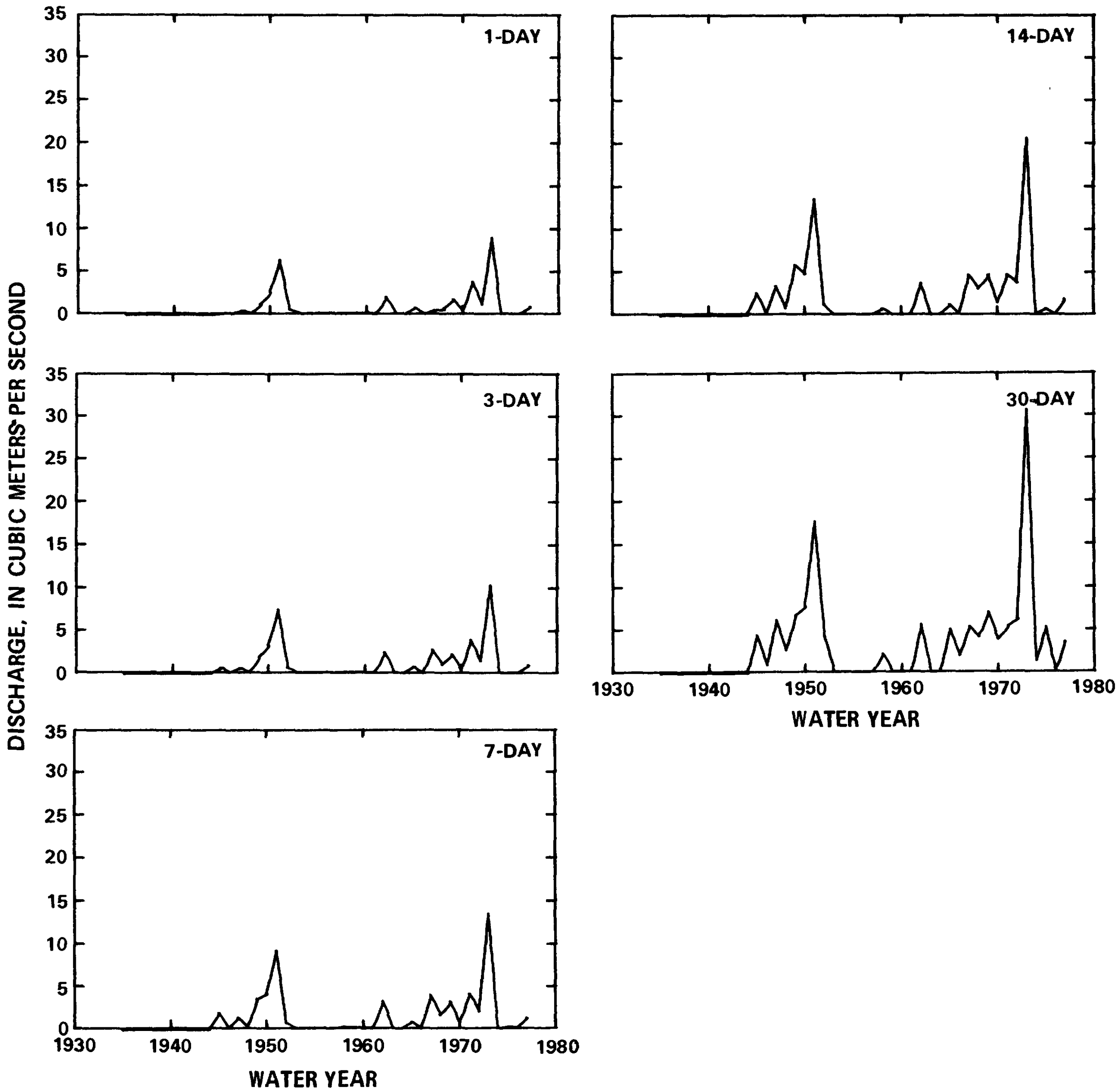


FIGURE 36.—Mean 1-, 3-, 7-, 14-, and 30-day low flows at Station 06770500, Platte River near Grand Island, Nebraska (water years 1935–79).

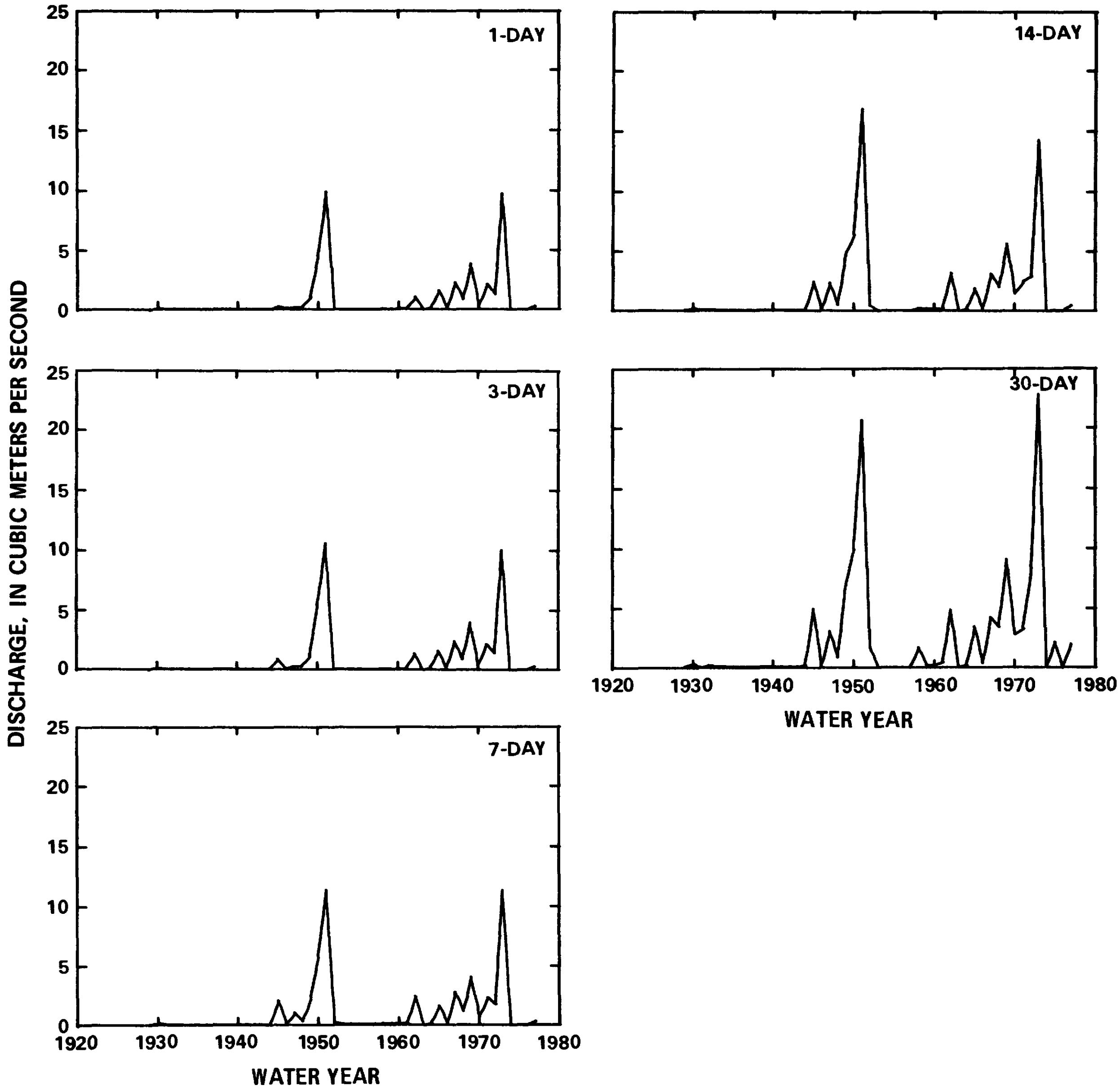


FIGURE 37.—Mean 1-, 3-, 7-, 14-, and 30-day low flows at Station 06774000, Platte River near Duncan, Nebraska (water years 1930–79).

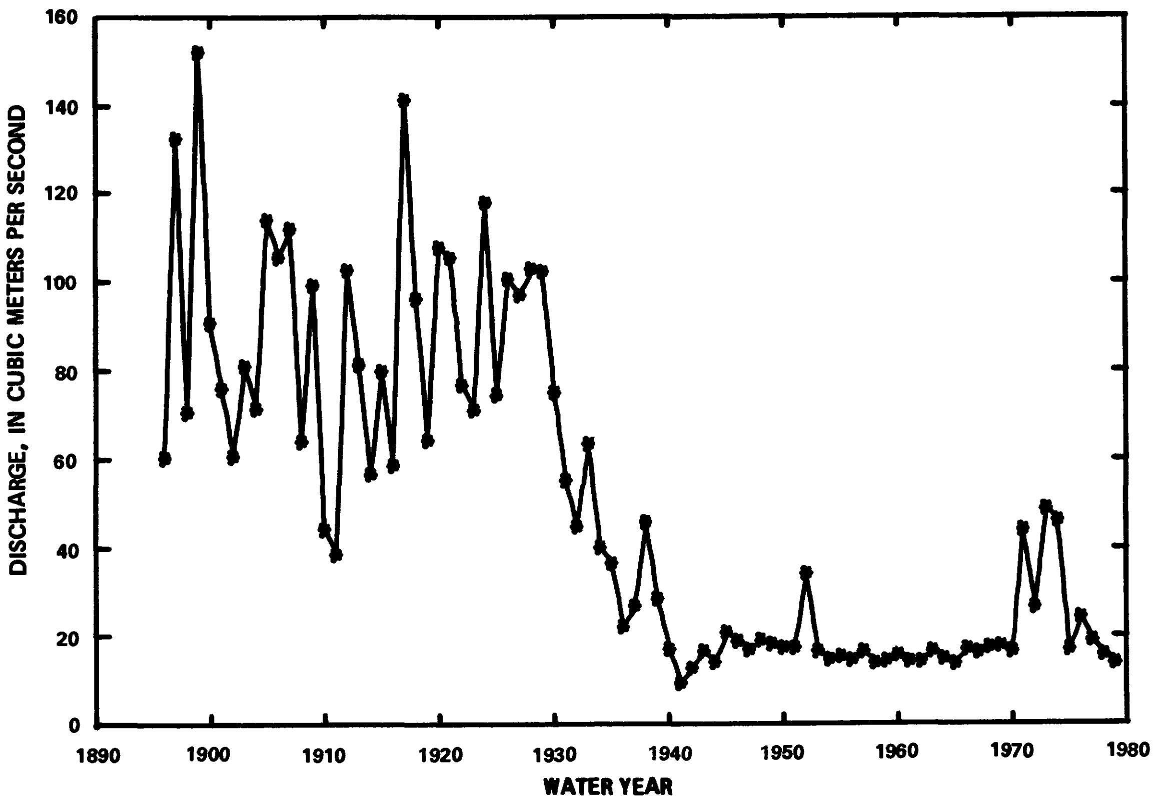


FIGURE 38.—Annual mean discharges at Station 06693000, North Platte River at North Platte, Nebraska (water years 1895-1979).

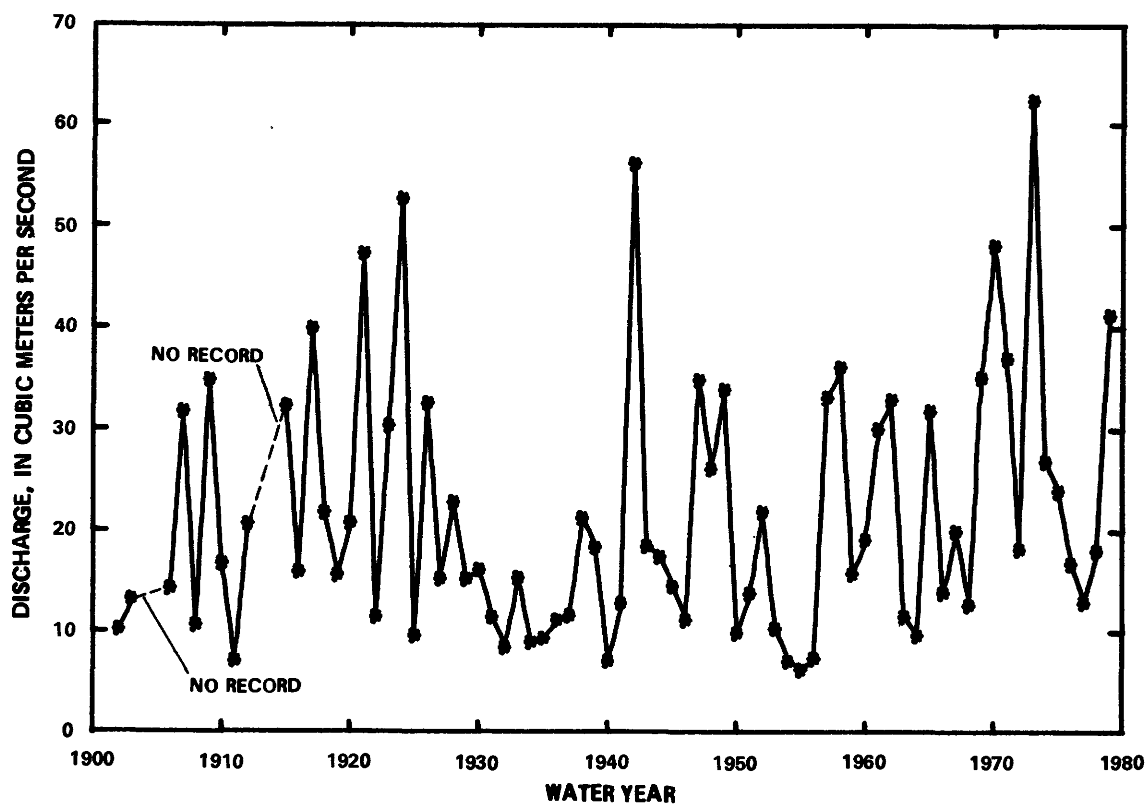


FIGURE 39.—Annual Mean discharges at Station 06754000, South Platte River Near Kersey, Colorado (water years 1902, 1903, 1906-12, 1915-79).

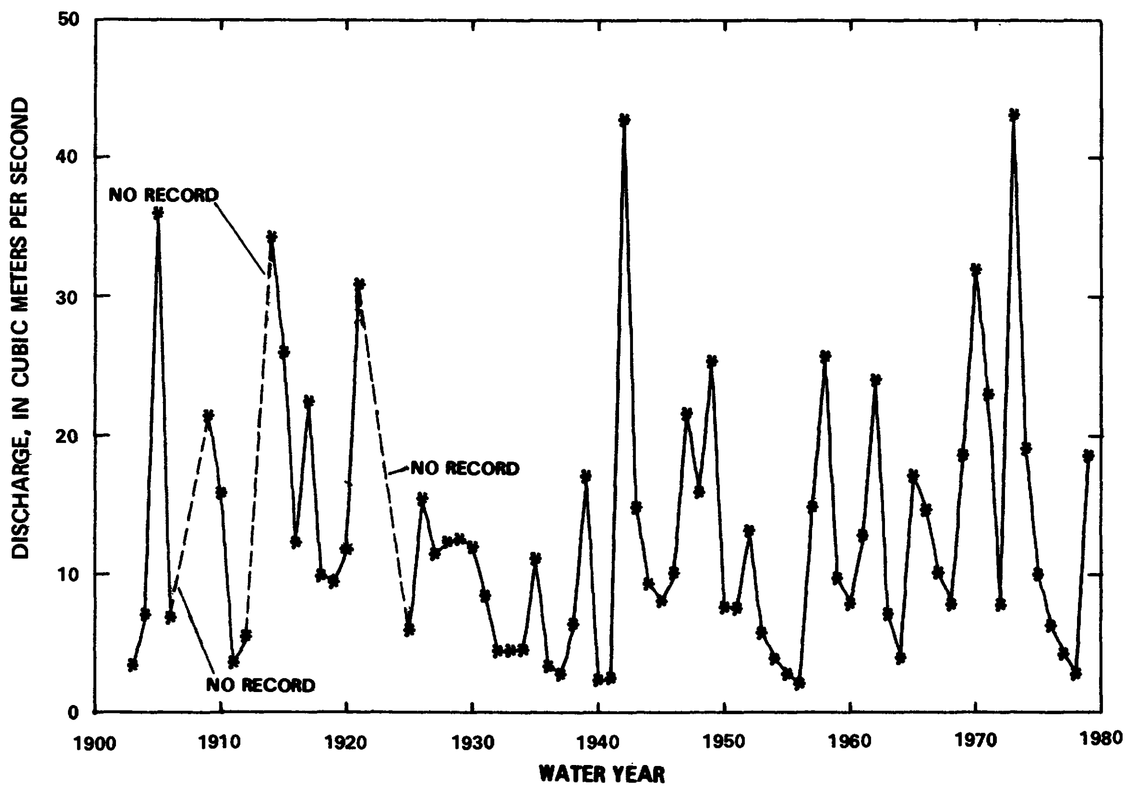


FIGURE 40.—Annual mean discharges at Station 06764000, South Platte River at Julesburg, Colorado (water years 1903–79).

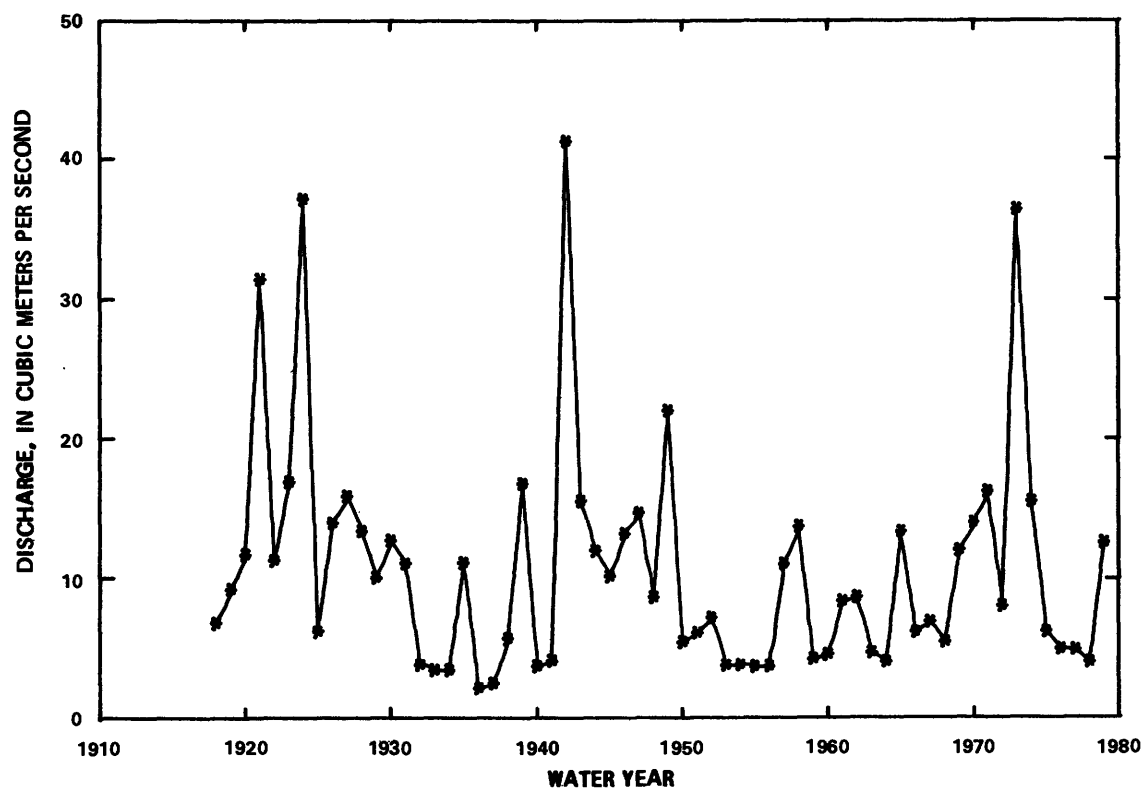


FIGURE 41.—Annual mean discharges at Station 06765500, South Platte River at North Platte, Nebraska (water years 1918–79).

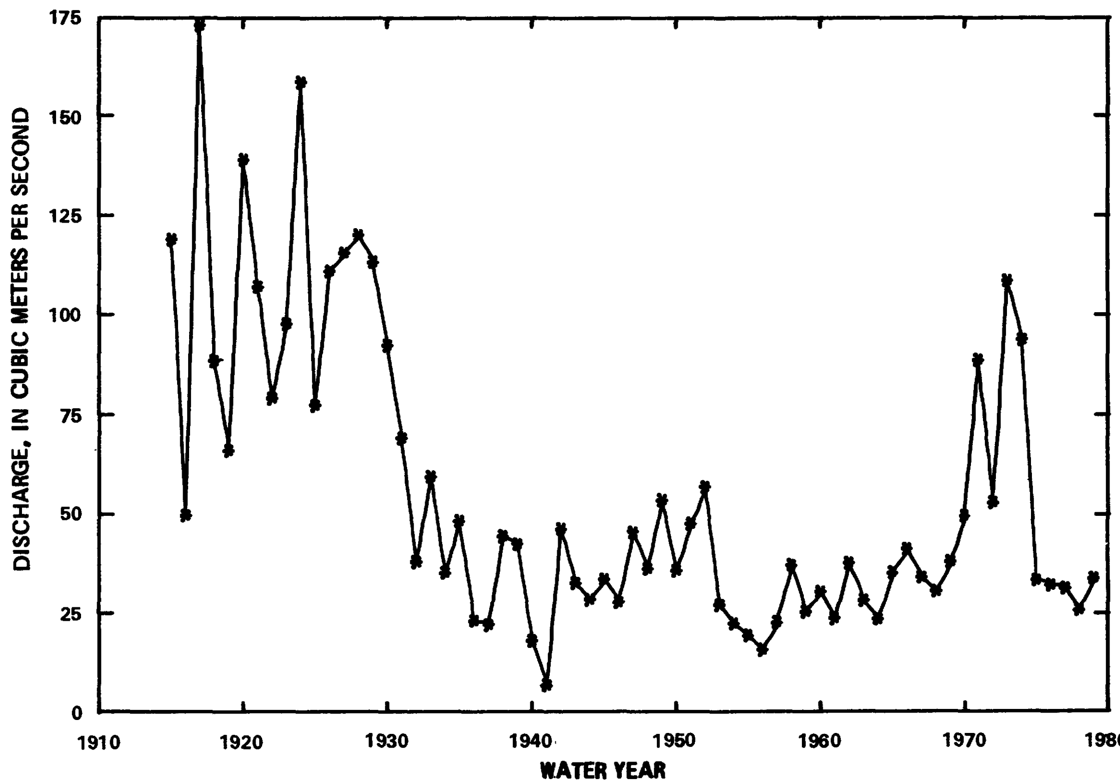


FIGURE 42.—Annual mean discharges at Station 06768000, Platte River near Overton, Nebraska (water years 1915–79).

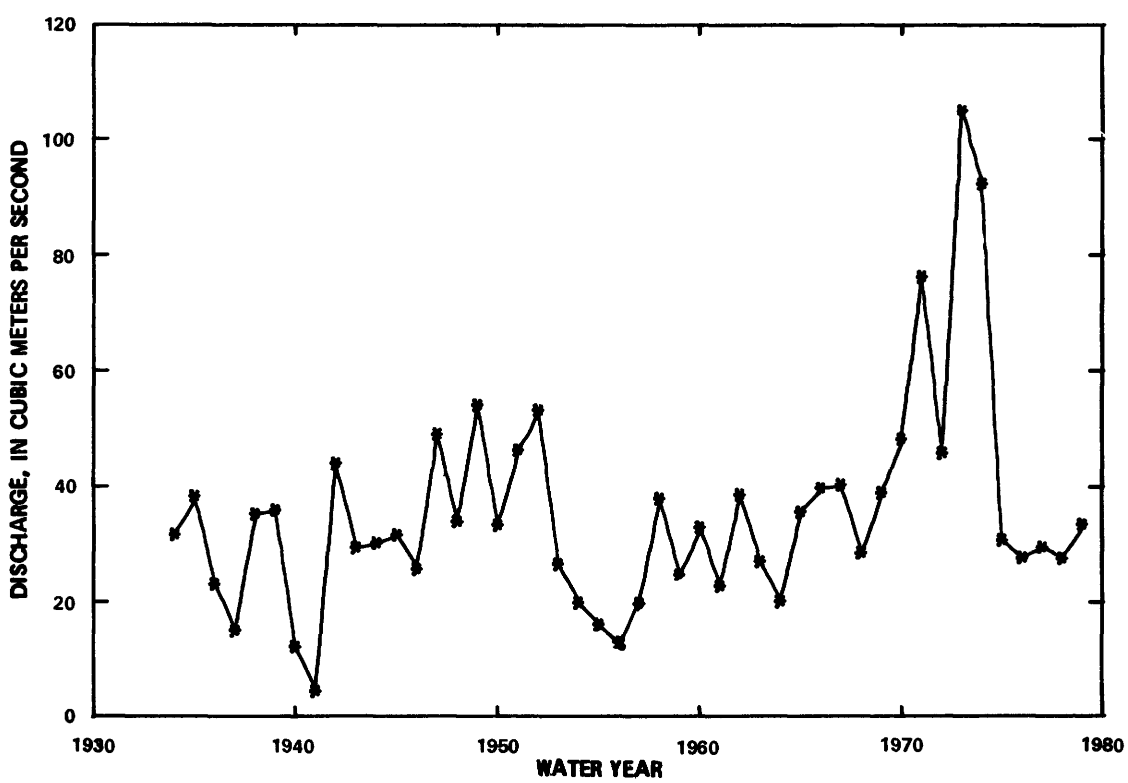


FIGURE 43.—Annual mean discharges at Station 06770500, Platte River near Grand Island, Nebraska (water years 1934–79).

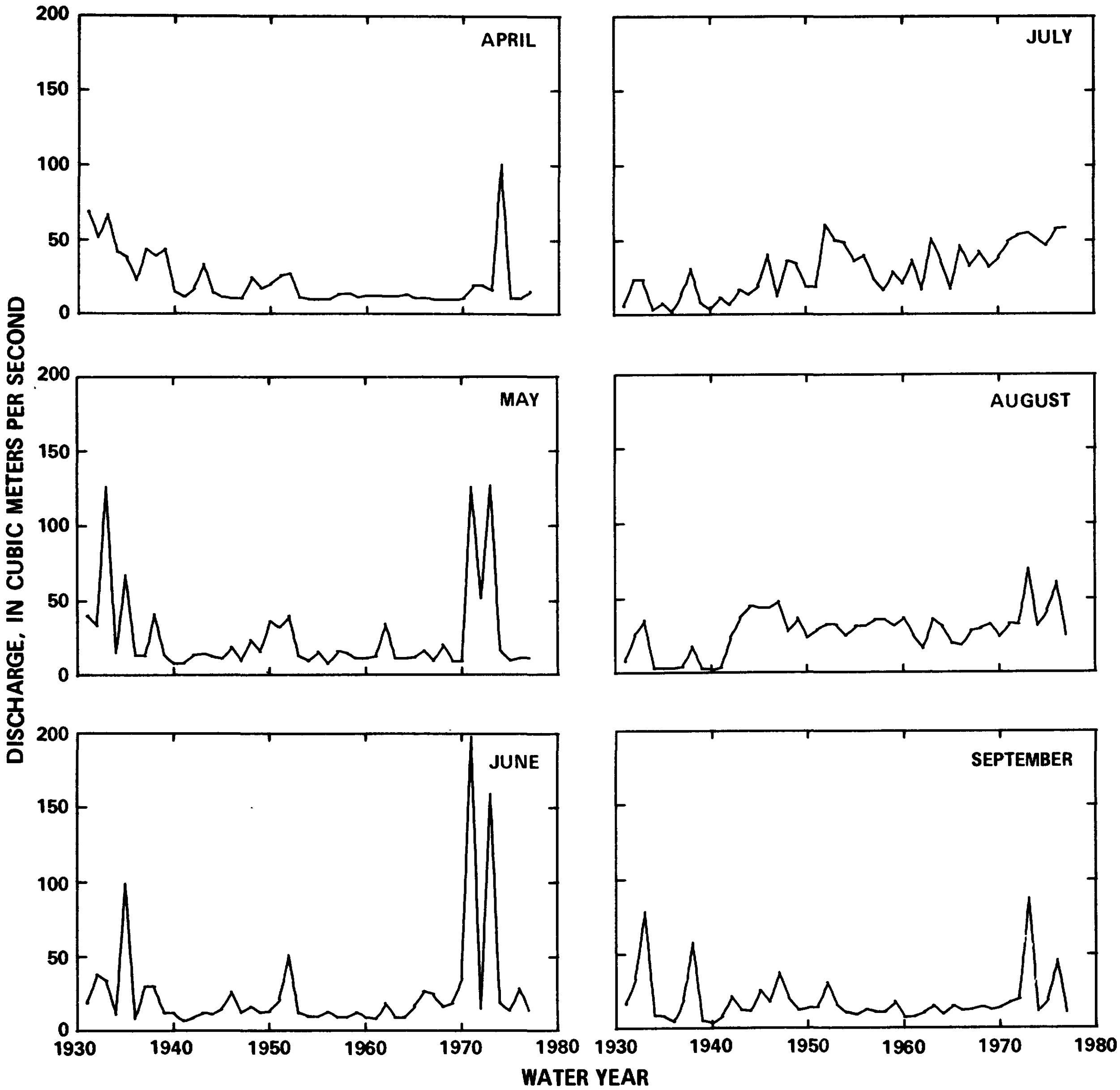


FIGURE 44.—Monthly mean discharges for April through September at Station 06693000, North Platte River at North Platte, Nebraska (water years 1931–78).

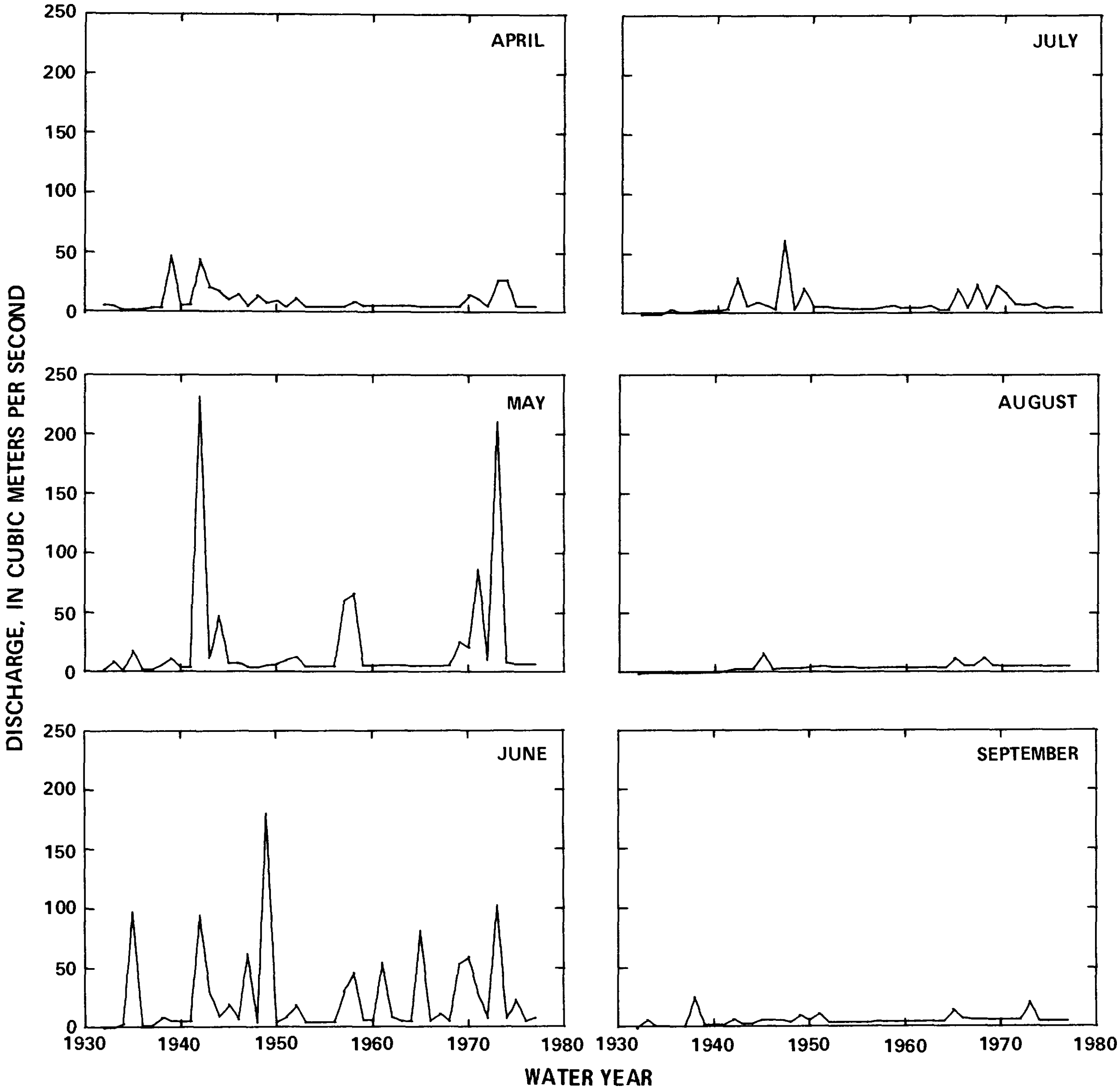


FIGURE 45.—Monthly mean discharges for April through September at Station 06765500, South Platte River at North Platte, Nebraska (water years 1932–78).

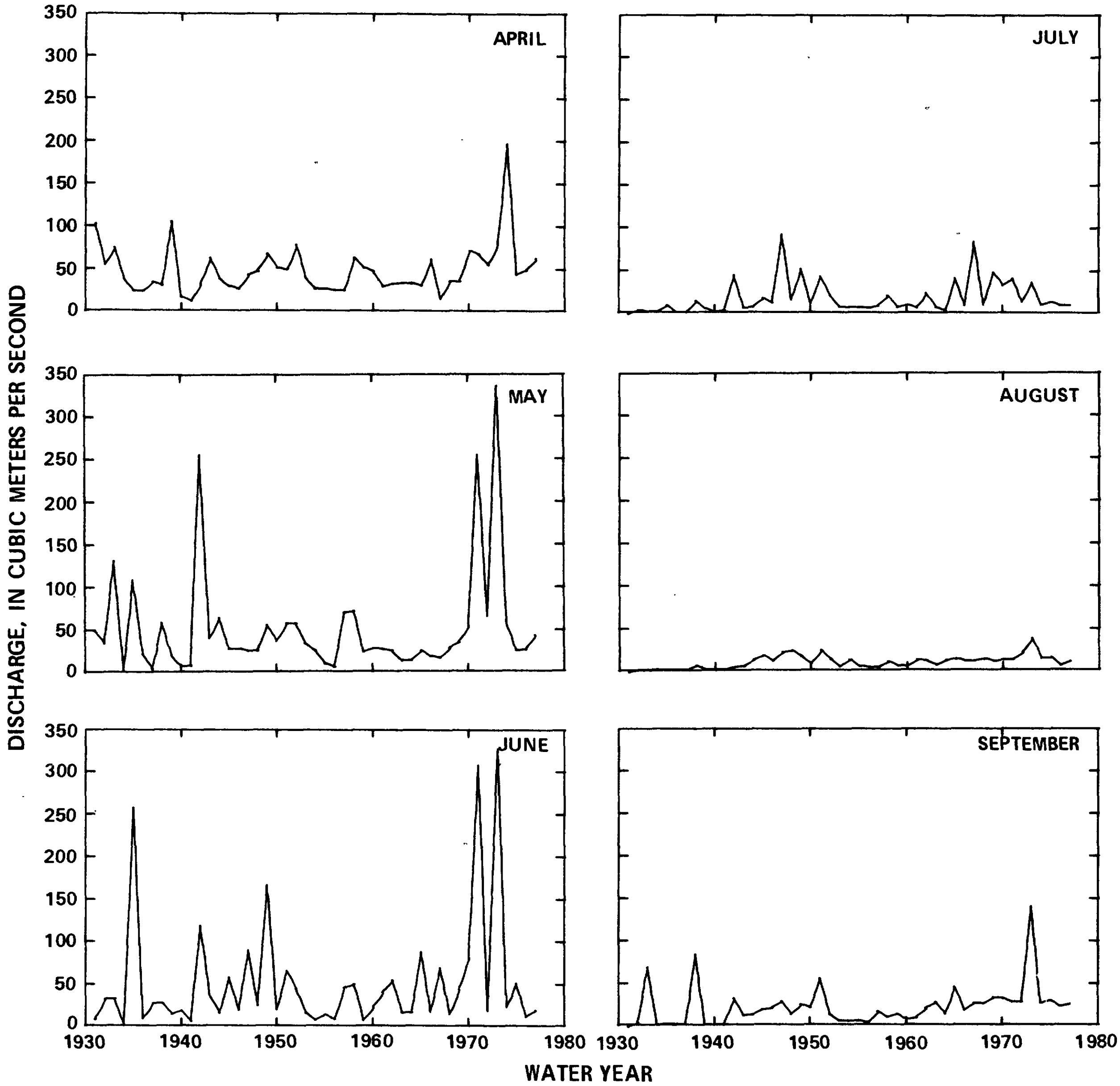


FIGURE 46.—Monthly mean discharges for April through September at Station 06768000, Platte River near Overton, Nebraska (water years 1931–78).

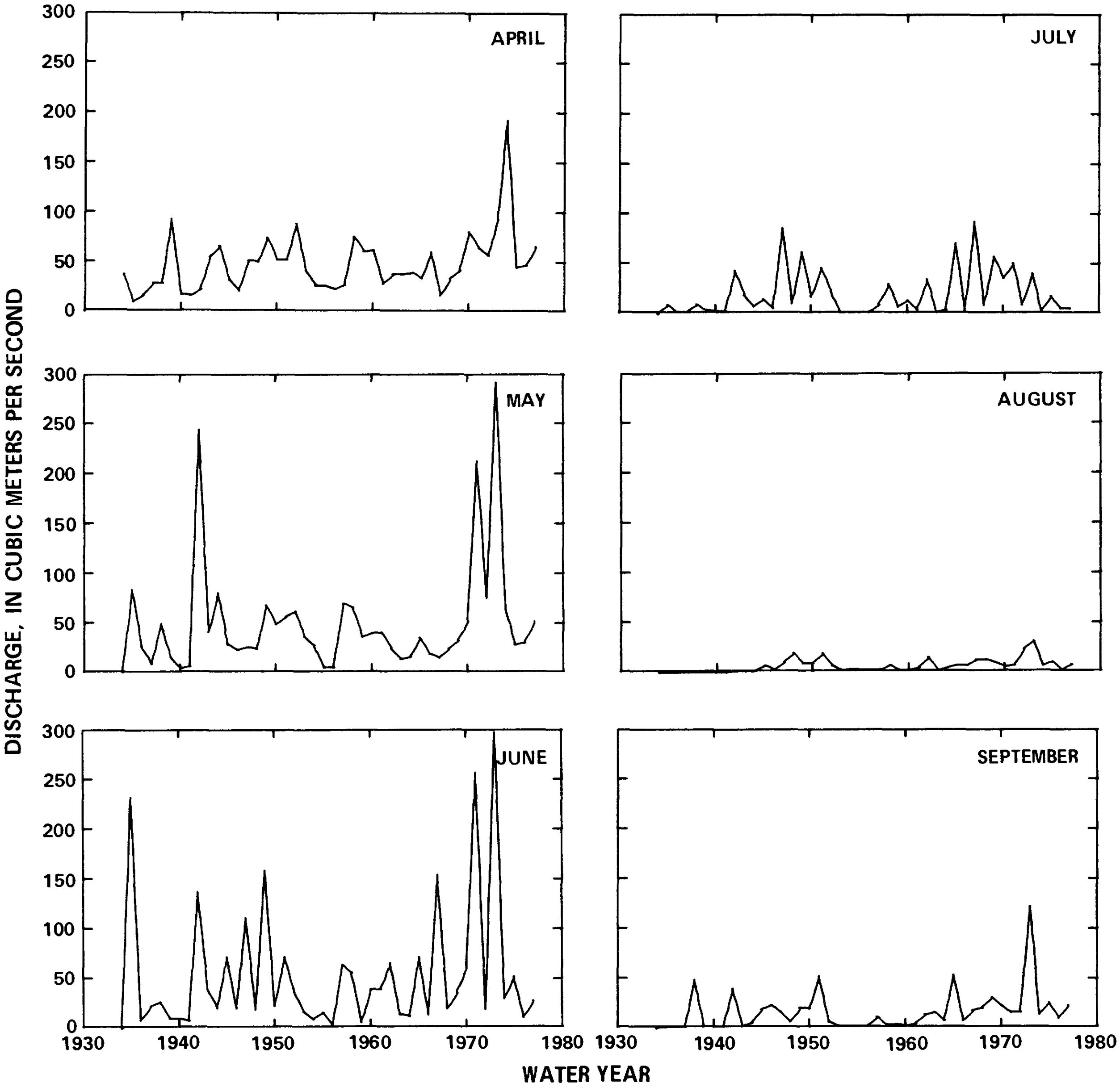


FIGURE 47.—Monthly mean discharges for April through September at Station 06770500, Platte River near Grand Island, Nebraska (water years 1935–78).

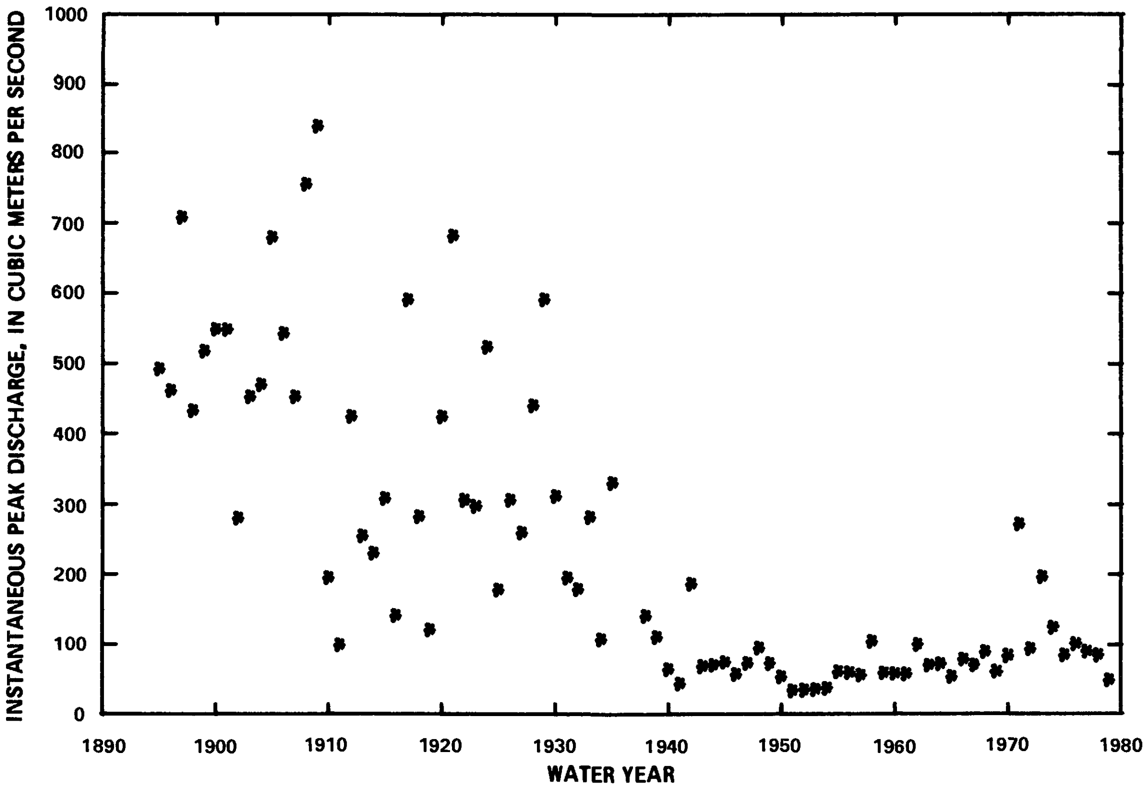


FIGURE 48.—Annual instantaneous peak discharges at Station 06693000, North Platte River at North Platte, Nebraska (water years 1895–1979).

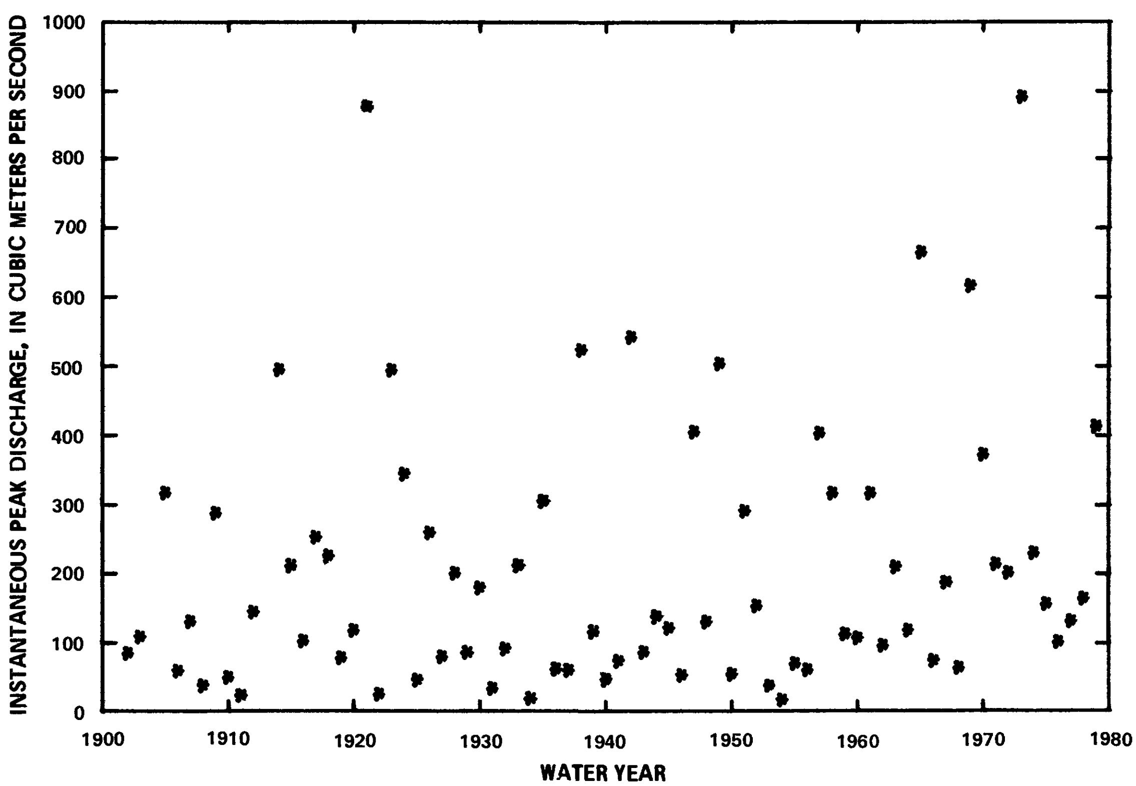


FIGURE 49.—Annual instantaneous peak discharges at Station 06754000, South Platte River near Kersey, Colorado (water years 1902, 1903, 1905–12, 1914–79).

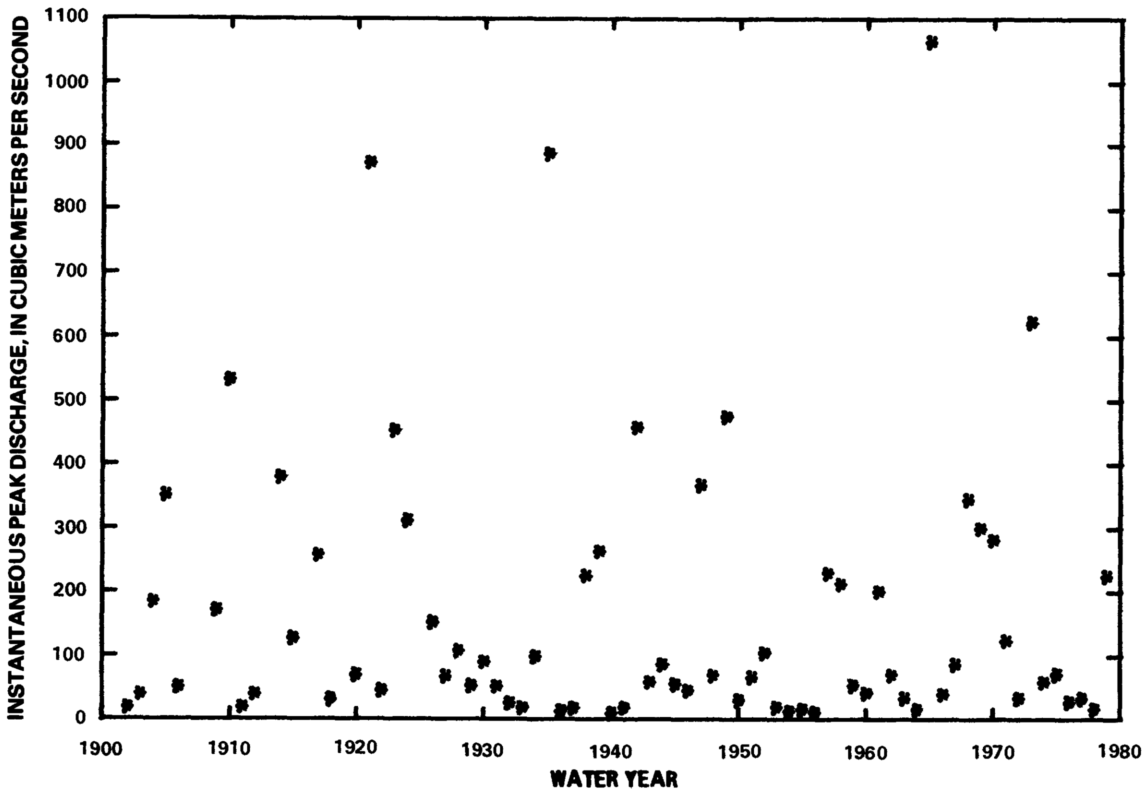


FIGURE 50.—Annual instantaneous peak discharges at Station 06764000, South Platte River at Julesburg, Colorado (water years 1902-06, 1909-12, 1914-15, 1917-18, 1920-24, 1926-79).

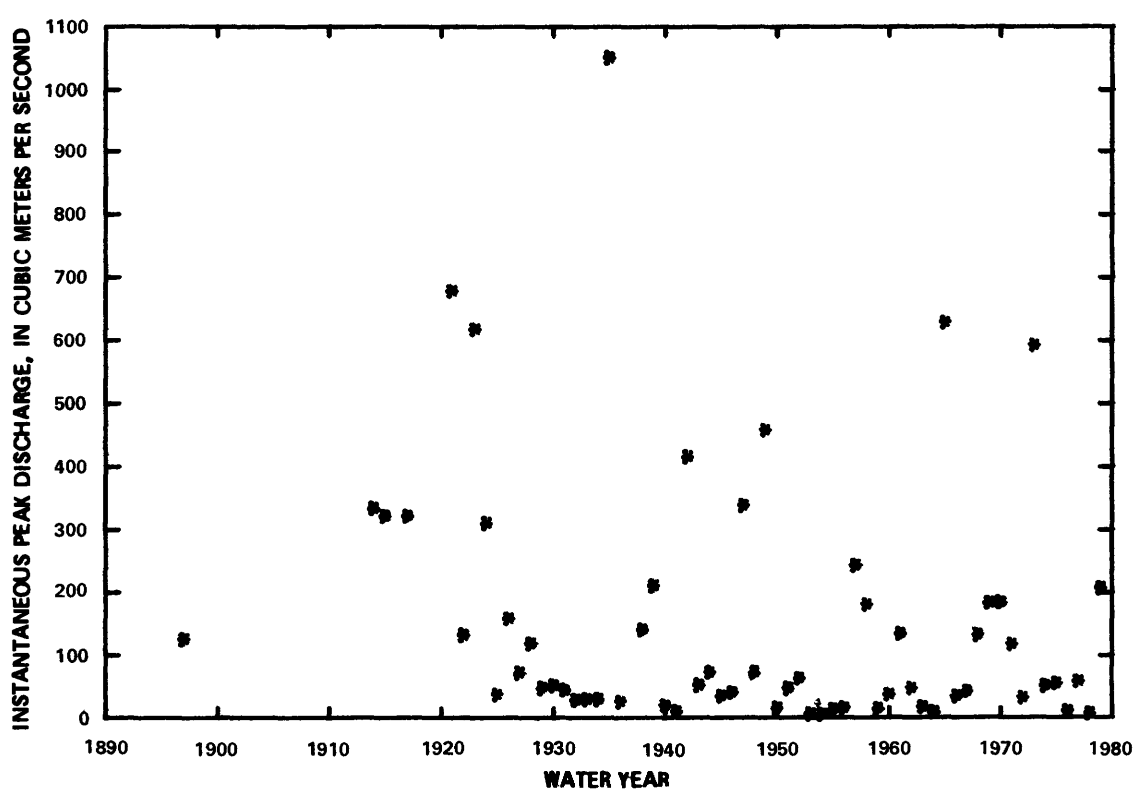


FIGURE 51.—Annual instantaneous peak discharges at Station 06765500, South Platte River at North Platte, Nebraska (water years 1897, 1914-15, 1917, 1921-79).

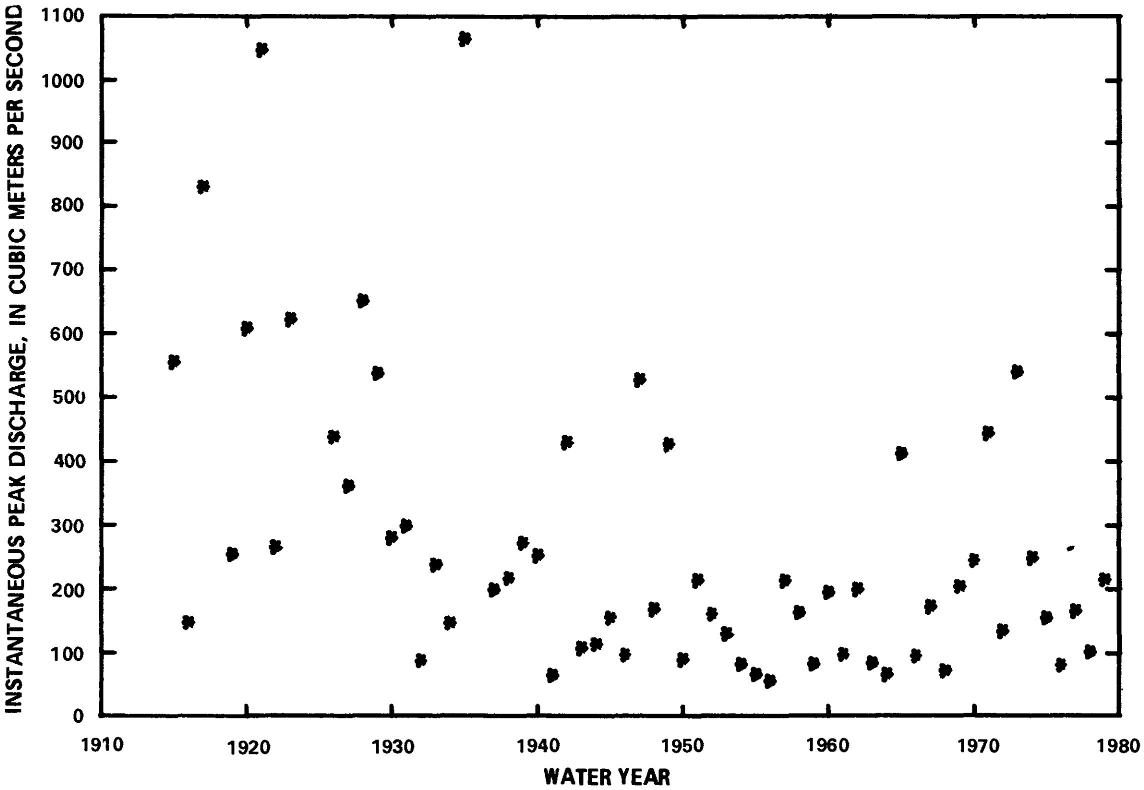


FIGURE 52.—Annual instantaneous peak discharges at Station 06768000, Platte River near Overton, Nebraska (water years 1915-17, 1919-23, 1926-79).

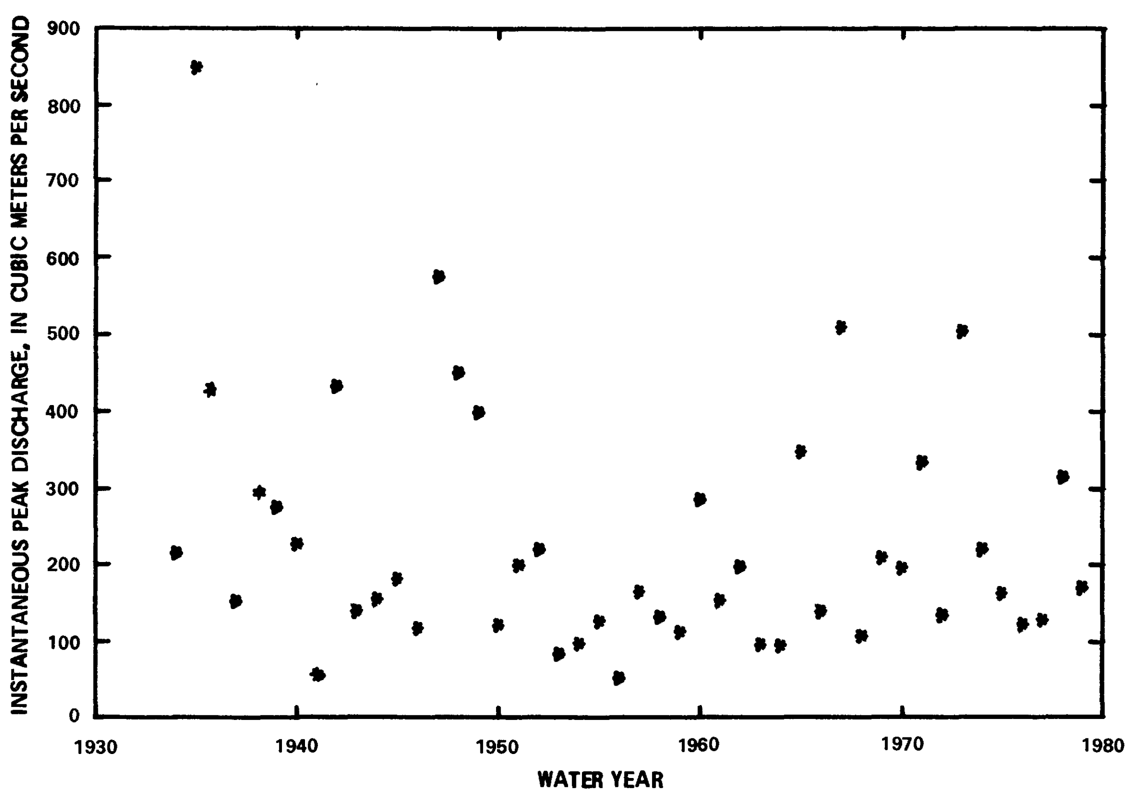


FIGURE 53.—Annual instantaneous peak discharges at Station 06770500, Platte River near Grand Island, Nebraska (water years 1934-79).

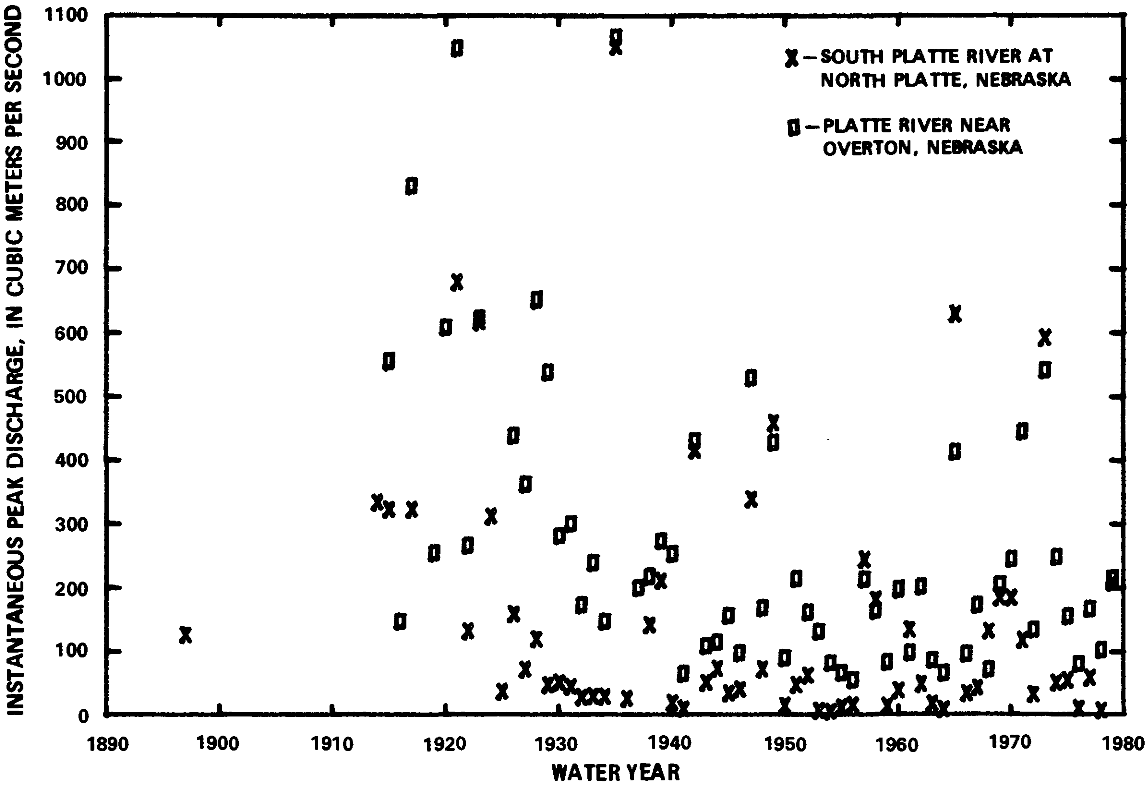


FIGURE 54.—Comparison of instantaneous peak flows on the South Platte River at North Platte, Nebraska, and the Platte River near Overton, Nebraska.

Hydraulic Geometry of the Platte River Near Overton, South-Central Nebraska

By THOMAS R. ESCHNER

HYDROLOGIC AND GEOMORPHIC STUDIES OF THE PLATTE RIVER BASIN

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1277-C

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1983

CONTENTS

ILLUSTRATIONS

TABLES

HYDRAULIC GEOMETRY OF THE PLATTE RIVER NEAR OVERTON, SOUTH-CENTRAL NEBRASKA

By THOMAS R. ESCHNER

ABSTRACT

At-a-station hydraulic-geometry relations were computed for a reach of the Platte River in south-central Nebraska containing habitat for sandhill and whooping cranes. The range of exponents of log-linear relations is large between different reaches of the river, and among different sections within a given reach. In general, simple linear regression of the logarithms of width, depth, and velocity on the logarithm of discharge yielded large proportionate reductions in the variances of the dependent variables. Examination of plots of the data indicates that, in many instances, the relations are log-linear, or power functions (Leopold and Maddock, 1953).

Use of the *b-f-m* diagram, a graphical representation of at-a-station hydraulic-geometry exponents (Rhodes, 1977), allows responses of width, depth, and velocity to changing discharge to be interpreted from physical consideratons. In general, based on simple power functions, with increasing discharge for the Platte River in the study area: (1) Width-depth ratio increases; (2) velocity increases more slowly than channel cross-sectional area; and (3) roughness increases. The b-f-m diagram also allows the systematic variation of the hydraulic-geometry exponents with time to be assessed. In general, the width exponent has decreased with time. Trends in the velocity and depth exponents are less apparent.

For some sections, power functions do not appear to describe adequately the observed at-a-station relations. For these sections, breaks in the slopes of the hydraulic geometry relations serve to partition the data sets. Power functions fit separately to the partitioned data described the width-, depth-, and velocity-discharge relations more accurately than did a single power function. Plotting positions of the exponents from hydraulic geometry relations of partitioned data sets on *b-f-m* diagrams indicate that much of the apparent variation of plotting positions of single power functions results because the single power functions compromise both subsets of partitioned data. Although there is for some sections a suggestion of a decrease in the width exponent through time even for partitioned data, in general the differences in plotting positions between the subsets of partitioned data for a given time interval are at least as great as the differences in plotting positions between successive time intervals for non-partitioned data.

The shape of the complex at-a-station relations may have at least three causes: (1) Changes in bed roughness with discharge may not be linear (Richards, 1973); (2) channel shape may preclude constant rates of increase in water width and depth with increasing discharge; and (3) an insufficient range of data values may account for apparent complex behavior. Complex hydraulic-geometry relations have significance for channel maintenance and preservation of sandhill- and whooping-crane habitat. Nearly the entire channel bed of sections exhibiting complex hydraulic-geometry relations can be covered with low-magnitude discharges. Vegetation encroachment may be inhibited, preventing further channel narrowing, where non-log-linear relations apply. Discharges required to cover the channel bed are lower than discharges estimated as necessary for channel maintenance by other methods, but the former may serve as minimum values for channel maintenance.

INTRODUCTION

The Platte River in south-central Nebraska in the mid-1800s exceeded 1 km (kilometer) in width. Descriptions of its appearance and its treacherous fords today seem exaggerations, because the present river width rarely exceeds 300 m (meters). Sandbars and islands have become vegetated, as have the banks and adjacent bottomlands. These morphologic and vegetative changes have resulted from continuous changes in the hydrology of the river. Annual discharge and annual peak discharge have decreased in many locations since the development of irrigation in the Platte River basin (Kircher and Karlinger, 1981). These changes in streamflow characteristics have decreased the capability of the river to shift sandbars and scour encroaching vegetation (Eschner, Hadley, and Crowley, 1981). Equally as important, irrigation practices apparently have changed the Platte River from an intermittent stream to a perennial stream in many locations.

Changes in hydrology and channel morphology of the Platte River have reduced its value as a wildlife habitat for some species and increased its value for others. The river presently is used by a wide variety of waterfowl, including ducks, geese, bald eagles, and sandhill and whooping cranes. Sandhill cranes (*Grus canadensis*) and the endangered whooping crane (*Grus americana*) use the Platte River as a staging area and stopover point. In March, these birds spend several weeks in the Platte River valley prior to completing their northward migration to breeding grounds in Canada. In the fall, the river is used as a stopover point when the birds return to wintering grounds in the southern United States (U.S. Fish and Wildlife Service, 1981).

Two features of the Platte River especially are desirable as crane habitat. Unvegetated sandbars in broad, shoal reaches of the river provide ideal night-roosting sites; the open character of these sites decreases the likelihood of predation. Wet meadows adjacent to the river provide important nutrients, in the form of invertebrates, for the cranes.

In general, changes in the hydrology and channel morphology of the Platte River have been detrimental to crane habitat (U.S. Fish and Wildlife Service, 1981). As vegetation increases in height and channel width decreases, the river loses its suitability as a night-roosting area. Changes in river water level affect the quality of the wet meadows. If these meadows are not subirrigated adequately, they may be converted to pasture or cropland, and, therefore, will be lost as feeding grounds.

Not all of the Platte River valley in south-central Nebraska is presently prime habitat. Frith (1974) classified crane habitat along the Platte River and found a broad range of habitat quality. The U.S. Fish and Wildlife Service (1978) determined that the 100-km reach of the Platte River downstream from Lexington, Nebraska was critical habitat for the whooping crane; maintaining the crane habitat along this reach of the river is essential for the preservation of the whooping crane.

Studies of channel changes of the Platte River basin have been undertaken, at least at a preliminary level. Schumm (1968) described the reduction in channel width of the North Platte River and attributed it to the decrease in annual peak flows of the river. Nadler (1978) showed that the South Platte River had decreased in width and increased in sinuosity, the ratio of channel length to valley distance, since the beginning of irrigation. Changes in channel width, channel pattern, and vegetation encroachment on the North Platte and Platte Rivers were described by Williams (1978b). The processes of width reduction of the Platte River were documented by Eschner and others (1981).

The primary objective of this study were to compute at-a-station hydraulic-geometry relations at selected sites, to examine how the relations have changed with time, and to determine the significance of the relations for channel maintenance.

DESCRIPTION OF THE STUDY AREA

The Platte River is formed by the confluence of the North Platte and South Platte Rivers, about 6 km east of the city of North Platte, Nebraska. From this confluence, the Platte River flows generally toward the east. Initially the river arcs to the north to Duncan, then it arcs south to Ashland. From Ashland, the Platte River flows 80 km east to its confluence with the Missouri River (fig. 1). The total area drained by the Platte River is about 233,000 km^2 (square kilometers). The Loup River, the primary tributary to the Platte River, drains 39,400 km^2.

FIELD STUDY AREA

The field study area is a 72-km reach of the Platte River in south-central Nebraska, extending from the town of Cozad to the town of Odessa (fig. 2). The entire area lies within the High Plains Section of the Great Plains Province of the Interior Plains (Fenneman, 1931).

Annual precipitation decreases to the west across the study area, ranging from about 560 mm (millimeters) at Kearney to about 510 mm at Cozad. Most of the precipitation falls as spring and summer rains, and the largest amount falls in June. Total lake evaporation is about 1,270 mm per year throughout the area.

The Platte River in the study area is affected by man to varying degrees. Gravel pits, both active and abandoned, dot the river bottom. Water is diverted for the Dawson County Canal immediately upstream of the study area. Water from the Tri-County Supply Canal that has been used for hydropower generation and for cooling is returned to the South Channel of the river through the Johnson-2 power return at a point about midway between Lexington and Overton. The amount of water returned depends on irrigation demand and power generation at hydropower plants. About 3 km east of the town of Elm Creek, water is diverted by the Kearney Canal for irrigation and hydropower. The banks of the river have been riprapped at various locations to reduce the erosive effect of the river against the banks.

Three gaging stations, operated by the U.S. Geological Survey and the Nebraska Department of Water Resources, are within the study reach. The river at the gage near Cozad, at the western edge of the study area, has a drainage area of approximately 146,300 km^2. Two channels are present at Cozad, and each channel is gaged separately. Only the north channel is considered in the discussion of at-a-station hydraulic geometry in this report. These gages produced records from April 1939, with irrigation-season records for 1932, and 1937 to 1938. The gage near Overton, although not occupying the same site for the period of record, produced records from October 1914 to the present, and gage heights from the period July to September 1914. The drainage area of the Platte River at this gaging station

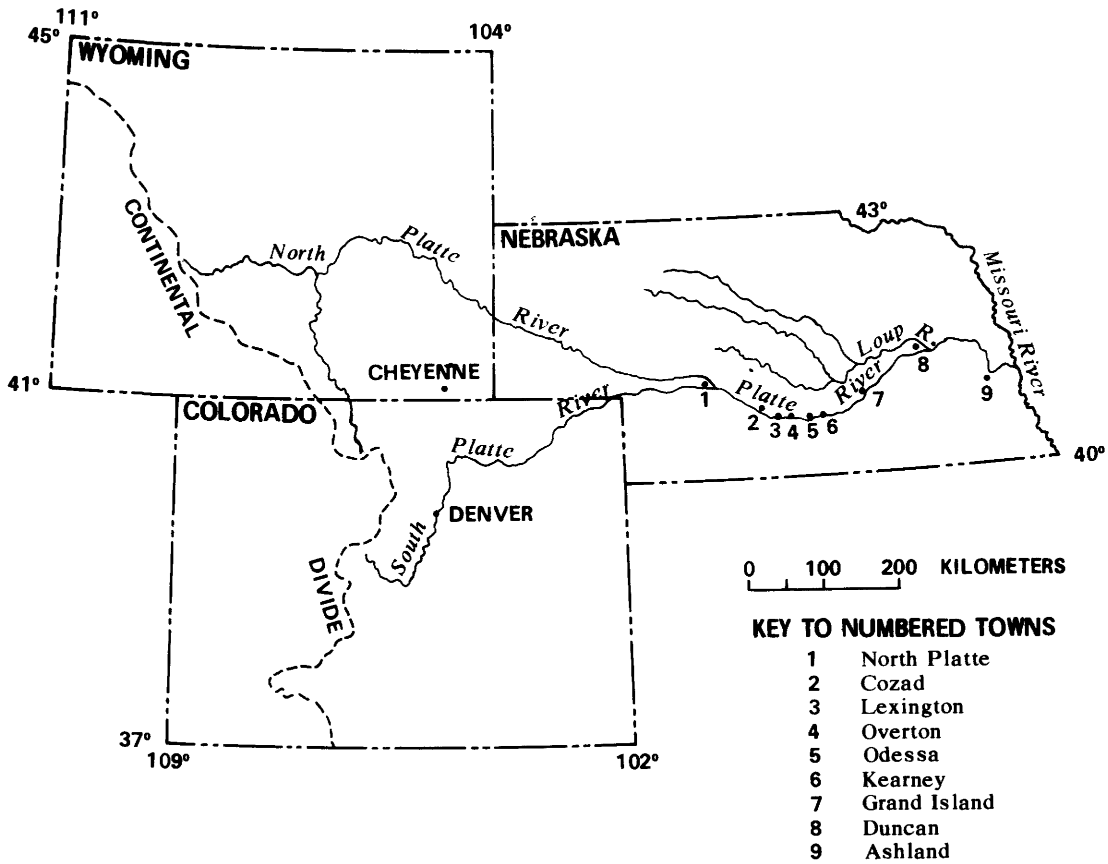


FIGURE 1.—Index map of the Platte River basin.

is about 149,400 km². The gaging staton near Odessa, at the eastern end of the study area, has had a recording gage since October 1938. The basin area at this gage is approximately 150,500 km².

CROSS-SECTION LOCATIONS

Six river cross sections have been established within the study reach for field observations (fig. 2). These sections will be referred to as Cozad (section 1), Lexington (section 2), Johnson 2 (section 3), Overton (section 4), Elm Creek (section 5), and Odessa (section 6), in downstream order. The location of the Johnson-2 power return also is indicated in figure 2.

CHANNEL CHARACTERISTICS

The channel of the Platte River in the study area ranges in width from about 120 m to over 500 m. Water depth varies from a few millimeters over bars at low flow to over 2 m in the thalweg at high flow.

Vegetated sandbars occur throughout the river at average flows (near mean annual); the width of these bars approaches two-thirds of the channel width; their length approaches twice the channel width. Vegetation comprises low weeds and grasses, with willow or cottonwood seedlings at various stages of development; these seedlings, if not destroyed by flood, become firmly established and cause the sandbar eventually to become an island. Permanent islands also occur.

Vegetation along the river bank consists of grasses, shrubs, and trees. The trees most commonly found are species of willow, cottonwood, and ash. Russian olive and red cedar trees grow in areas not frequently inundated. Tamerisk has been seen infrequently, and only within the last decade (Joe Jeffrey, rancher, oral commun., 1979).

The Platte River channel is braided at low flows, with threads of water intertwining among ripples, dunes, and sandbars. At the highest flows, water extends from bank to bank and flows straight through the channel. At many locations, the channel pattern appears to be meandering or anastomosing, that is, consisting of branches that separate and rejoin around islands.

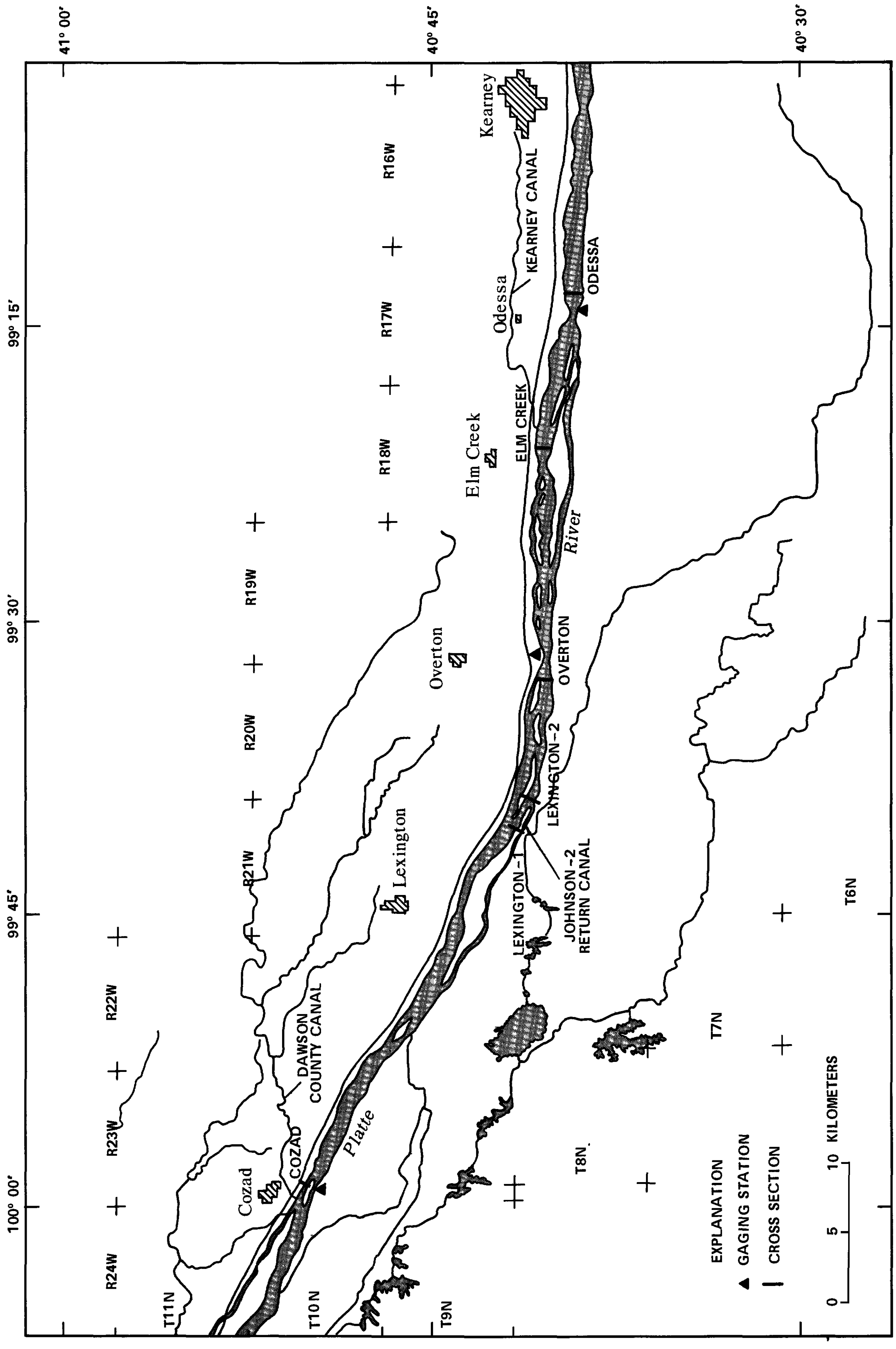


FIGURE 2.—Location of the study area in south-central Nebraska.

THE CONCEPT OF HYDRAULIC GEOMETRY

The term hydraulic geometry was introduced by Leopold and Maddock (1953) to describe the way in which channel characteristics vary with discharge. In essence, hydraulic geometry is an empirical model expressing the changes in channel and hydraulic variables as simple power functions of discharge. The resulting equations have the form:

$$w=aQ^b \quad (1)$$

$$d=cQ^f \quad (2)$$

$$v=kQ^m \quad (3)$$

where

w = width,
d = mean depth,
v = mean velocity,
Q = instantaneous discharge,
b, f, and m = the exponents of the equations, and
a, c, and k = the coefficients.

For continuity, the product of width, mean depth, and mean velocity must be the discharge:

$$Q=wdv. \quad (4)$$

Then the product of the hydraulic-geometry coefficients and the sum of the exponents must be:

$$Q=ack\ Q^{b+f+m} \quad (5)$$

Hydraulic-geometry relations can be defined for both specific cross sections on a river (at-a-station hydraulic geometry) and different cross sections on a river at a constant frequency of discharge (downstream hydraulic geometry), although not necessarily in downstream order. The exponents of both the at-a-station and downstream relations have been studied in various physiographic and climatic regions. In addition, expected exponents under ideal conditions have been derived theoretically for both downstream and at-a-station geometry.

AT-A-STATION HYDRAULIC GEOMETRY

Exponents for at-a-station hydraulic geometry, reported in the literature, range at least from 0.0 to 0.84 for the width exponent, b; 0.01 to 0.84 for the depth exponent, f; and 0.03 to 0.99 for the velocity exponent, m (Rhodes, 1978). Park (1977) calculated modal class values for 139 at-a-station data sets for streams in proglacial, humid temperature, semiarid, tropical, and "unspecified" regions. Park found that exponent values for width fell within the class 0.0 to 0.1, for depth within the class 0.3 to 0.4, and for velocity within the class (0.4 to 0.5. Knighton (1975) reported average exponents for 206 cross sections in the United States as 0.16 for width, 0.43 for depth, and 0.42 for velocity. Perhaps the most commonly cited average exponent values are those computed by Leopold and Maddock (1953) for "a large variety of rivers* * *." The values are b=0.26, f=0.40, and m=0.34.

Computed exponent values have been compared to theoretically derived at-a-station values. Theoretical at-a-station exponent values will vary with the channel shape assumed for their derivation. The "most probable values" as generally cited (Park, 1978; Rhodes, 1978) are b=0.23, f=0.42, and m=0.35 (Langbein, 1964). Wolman and Brush (1961) derived theoretical at-a-station cross-section area (A), and width exponents based on flume studies of coarse noncohesive sands. For channels at or above the critical velocity of incipient motion, $A=Q^{0.9}$ and b=0.90. For channels below the point of incipient motion, $A=Q^{0.9}$ and b=0.75. Wolman and Brush (1961) cited the Platte River near Grand Island, Nebraska at moderate stages as an example of a river in coarse noncohesive sands that behaves according to their derivation.

DOWNSTREAM HYDRAULIC GEOMETRY

Computed downstream exponents range at least from 0.03 to 0.89 for width, 0.09 to 0.70 for depth, and −0.51 to 0.75 for velocity. These values are those reported by Park (1978) for 72 observations. The modal classes of these observations are 0.4 to 0.5 for width, 0.3 to 0.4 for depth, and 0.1 to 0.2 for velocity. Leopold and Maddock (1953) listed the average exponents calculated for their classic study as b=0.5, f=0.4, and m=0.1. Carlston (1969) computed least-square solutions for Leopold and Maddock's data and found the mean of the exponents to be 0.461 for width, 0.383 for depth, and 0.155 for velocity.

Theoretical exponents have been derived for downstream hydraulic geometry. Leopold and Langbein (1962) obtained values of b=0.55, f=0.36, and m=0.09. Langbein (1964) calculated the exponents as b=0.53, f=0.36, and m=0.10. Using a different method, Smith (1974) obtained average downstream exponent values of b=0.6, f=0.3, and m=0.1.

The use of average hydraulic-geometry exponents, even for rivers within one basin, has led to the theory that rivers have similar geometries despite different physiographic and climatic settings. Recently, however, the validity and usefulness of average hydraulic-geometry exponents have been questioned (Knighton, 1975; Rhodes, 1977; Park, 1978). The large range of all three exponent values suggests that mean geometry may be an attractive, but more or less meaningless, concept.

ASSUMPTIONS

The concept of hydraulic geometry is based on assumptions, which may include the following (Thornes, 1977; Knighton, 1977):

1. A direct causal relationship exists in the system, with discharge as the primary independent variable.
2. A change in the independent variable will cause a specific change to occur in the dependent variables.
3. The changes are continuous and reversible.
4. Mean-stream characteristics are represented by the relations at a particular site.
5. Simple log-linear relationships accurately describe the observed changes.

Although channel width is determined largely by discharge, at-a-station hydraulic geometry is a function of channel shape for low flows (Richards, 1976). Channel shape is (in turn) determined by physical properties of channel-perimeter sediment (Schumm, 1960) and past flow events (Pickup and Rieger, 1979). Thus, despite, the ultimate cause of channel size, the channel yields an at-a-station hydraulic geometry that is a relic of larger flows.

Hydraulic geometry relations describe observed changes in a channel with changing discharge; the relations are best-fit lines for the data used and do not necessarily represent unique values. A given change in discharge need not always produce the same response in the channel; width may adjust slightly more than depth on one occasion, but the reverse may occur on another occasion. In the same manner, channel response may not be reversible in a strict sense. This fact was documented by Leopold and Maddock (1953) with their example of the passage of a single flood on the San Juan River in Utah. Hydraulic-geometry plots from this flood show hysteresis, that is, channel depth, mean velocity, suspended-sediment load, streambed elevation, and water surface all responded differently to the same discharge on the rising and falling stage.

Knighton (1977) has studied the theory that mean stream characteristics are represented by at-a-station relations. He concluded that four factors were responsible for short-term variation at a given site. Measurement error is present in all discharge measurements; mean depth and velocity particularly are susceptible to error because they are computed from point measurements. Random error is also a source of variation in all discharge observations. Hysteresis is a random variation. Systematic variation, or variation resulting from progressive change of the channel, in hydraulic geometry is a third source of short-term variation at a site. Knighton suggests that systematic variation can be examined by looking at discrete time phases of the sample from a given site. The final source of short-term variation in at-a-station hydraulic geometry lies in analytical error.

The existence of analytical error would be a refutation of the assumption that simple log-linear relations adequately describe channel changes with discharge. Richards (1973) pointed out that, because depth and velocity are functions of roughness, they also should be functions of bed sediment and channel geometry. He suggested that higher-order equations, specifically log-quadratic equations, may express more accurately hydraulic-geometry relations.

Log-quadratic or log-polynomial equations are appropriate for use in hydraulic geometry because they allow use of the continuity relationship. For example, the width-discharge power-function relation (equation 1) can be rewritten as:

$$(\log w)=\log a+b_1\,(\log Q)\,. \qquad (6)$$

Generalization to a log-quadratic equation yields:

$$(\log w)=\log a+b_1\,(\log Q)\,b_2\,(\log Q)^2 \qquad (7)$$

By analogy to equation 6, the first derivative of equation 7 with respect to log Q,

$$\frac{d(\log w)}{d(\log Q)}=b_1+2b_2\,(\log Q) \qquad (8)$$

is the instantaneous slope of the curve. The continuity equation using first derivatives of log-quadratic functions becomes:

$$(b_1+f_1+m_1)+2(b_2+f_2+m_2)\log Q=1 \qquad (9)$$

(Richards, 1973). The first derivative, therefore, is analogous to the exponent of the power function.

THE *B-F-M* DIAGRAM

Two methods of graphically representing hydraulic-geometry exponents have been proposed. Park (1978) presented tri-axial graphs of both at-a-station and downstream hydraulic-geometry exponents to allow consideration of the simultaneous variations in the three exponents. Park concluded that there is not a tendency within an area or environment to establish a unique hydraulic-geometry relation or series of relations, either at-à-station or downstream.

Rhodes (1977) graphically represented hydraulic-geometry exponents by plotting them on a triangular-coordinate system, which he termed a *b-f-m* diagram. The arrangement of the *b-f-m* diagram was different from the tri-axial graphs proposed by Park. Rhodes' research indicated that comparison of channels through assessing the similarity of exponents was inadequate. He proposed a series of subdivisions of the *b-f-m* diagram based on hydraulic and morphologic considerations (fig. 3). The ten fields of the diagram are created with five lines, as follows:

1. $b=f$: This line represents no change in the width-depth ratio with changing discharge. To the right of this line, width-depth ratios decrease with discharge, and to the left of this line, width-depth ratios increase with discharge. Location of a point relative to this line may provide information about channel shape and stability, and bedload transport.
2. $m=f$. Rhodes (1977) suggested that the competence of channels plotting above this line should increase with discharge. This statement was based on an analysis of competence and the rates of change of velocity and depth by Wilcock (1971), and on work by Leopold and Maddock (1953), associating the ratio of the rates of change in velocity to depth with the rate of change of suspended load.
3. $m=f/2$: This division is based on Froude number and represents a constant value. The Froude number, defined as:

$$F=\frac{v}{\sqrt{gd}} \quad (10)$$

where

v =velocity,
g =gravitational constant, and
d =water depth,

can be expressed as a proportion between m and f, because both velocity and depth can be expressed in terms of discharge. If the constants are eliminated, the proportion of $Q^{f/2} \propto Q^{m}$ results. Thus, a constant Froude number is expressed by $m=f/2$. Froude number increases above this line with increasing discharge and decreases below the line with increasing discharge.
4. $m=b+f$, or $m=0.50$: Channels plotting above this line show rapid increase in velocity with discharge. If the velocity (m) increases more rapidly than cross-sectional area ($b+f$), resistance must decrease rapidly. Rhodes (1977) indicated that this division provided information about channel stability.
5. $m/f=2/3$: This line is related to the Manning roughness coefficient, n, in the Manning equation (metric form):

$$v=\frac{R^{2/3}S^{1/2}}{n} \quad (11)$$

where R=hydraulic radius, the ratio of the cross-sectional area to the wetted perimeter, and S=slope. Mean depth is assumed to be approximately equal to hydraulic radius for wide, shallow channels, such as those of the Platte River.

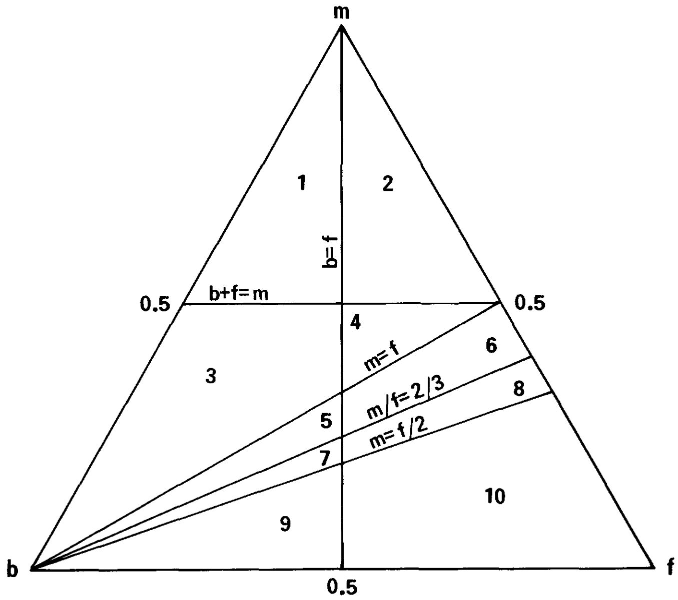


FIGURE 3.—Divided *b-f-m* diagram, showing fields that represent different channel types. (After Rhodes, 1977).

Expressing slope, $S\propto Q^{z}$, and roughness, $n\propto Q^{y}$, as functions of discharge, Manning's equation may be rewritten as:

$$Q^{m}\propto Q^{(2/3)f}\times\frac{Q(1/2)^{z}}{Q^{y}} \quad (12)$$

If $m=2/3\ f$, the ratio $S^{1/2}/n$ is constant with changing discharge. Rhodes assumed (from data from several sources) that slope varies little with discharge; thus, roughness may change appreciably. This assumption, although true for limited ranges of discharge, is probably not true for the full range of flows. Points below the line $m/f=2/3$ on the b-f-m diagram represent channels in which roughness increases with discharge.

AT-A-STATION HYDRAULIC GEOMETRY

Hydraulic-geometry relations were computed both for the six field-study sections and for several cross sections near the Cozad, Overton, and Odessa gages. The exponents were calculated using linear regression techniques on log-transformations of the data. Initially, first-order log equations (power functions) were assumed to represent the hydraulic-geometry relations. In addition, log-quadratic equations were fitted to the data sets, and separate power functions were fitted to discrete segments of the data sets for these purposes: (1) To decrease the residual error of the regressions; (2) to approximate more closely the apparent trend of the data; and (3) to meet physical constraints observed in the field. For the purpose of discussion, the data are grouped as: (1) Summarized data, those data obtained from discharge measurement summary sheets; and (2) field data, those data collected from field measurements.

SUMMARIZED DATA

These values of water width, depth, velocity, and discharge were summarized from discharge-measurement sheets and summary sheets in the Nebraska District Office of the Water Resources Division of the U.S. Geological Survey. The range of summarized data is relatively small, but the data set is large. High-flow discharge observations are missing from the summarized data; such measurements usually are made from bridges and do not represent natural sections. At lower discharges, measurements were made at specified distances from the gage or bridge. In contrast to the method employed by Leopold and Maddock (1953), discharge measurements for this study were grouped by specific location, as recorded on the individual discharge notes. For example, discharge measurements made at a given cross section were not grouped with measurements made 20 m upstream or downstream from that cross section. These data groupings should reduce the scatter introduced by the use of different sections.

Hydraulic-geometry exponents that apply for the at-a-station case, for the period of record and for shorter time periods, are listed in table 1 for data from sections near the Cozad, Overton, and Odessa gages. Exponents for power functions based on whole data sets and partitioned data sets are listed in table 1; corresponding significance levels and corresponding correlation coefficients are listed in the summary of statistical data at the end of the report (table 2).

The range of exponents for the sections near Cozad, Overton, and Odessa is relatively large for each of the hydraulic-geometry relations computed from simple linear regression. The width exponent varies from 0.22 to 0.80, the depth exponent varies from 0.11 to 0.63, and the velocity exponent varies from 0.09 to 0.44. The amount of variation of the exponent varies from area to area. For example, the width exponent ranges from 0.21 to 0.66 for the sections near Cozad, but the width exponent ranges only from 0.48 to 0.68 for the sections near Odessa. Variability of all three exponents is least for the three sections near Odessa.

For the period of record, simple linear regression of the logarithms of width, depth, and velocity on the logarithm of discharge yielded large reductions in the variances of the dependent variables relative to the variances of the logarithms of width, depth, and velocity alone. Similar reductions were found for the period since 1969 in most instances.

The reduction of variances of the dependent variables does not necessarily indicate that the relations between discharge and width, depth, and velocity are power functions, because the correlation coefficient is not a measure of the appropriateness of the straight-line model. However, examination of representative plots of the data (figs. 4–12) indicates that some of the relations are log-linear, or plot as straight lines on log-log plots.

For some sections, however, power functions do not appear to be the correct model for the data, although simple linear regression did reduce significantly the variances of the dependent variables (figs. 5, 6, 7, 9, and 10). In general, for the period of record and for the period since 1969 for the sections where power functions do not appear to describe hydraulic-geometry relations, the addition of a second-order discharge term results in a significant proportionate reduction of the variance of the dependent variable relative to the variance of the dependent variable without the second-order discharge term. This is particularly true for the data sets from the period of record, probably because of the size of the data sets. The significance of higher-order terms tends to decrease as the order of the term increases. Statistics on the second-order terms are not included in table 1 because although the improved fit of regression lines obtained from second-order discharge terms is statistically significant in some instances, it has no physical meaning.

On many of the hydraulic geometry plots, breaks in the slopes of the width, depth, and velocity-discharge relations are evident at a certain discharge (fig. 10). These breaks in slope can serve to partition the data sets. Power functions fitted separately to the low range of discharge and to the high range of discharge generally yielded large proportionate reductions in the variances of the dependent variables relative to the vari-

TABLE 1.—*At-a-station hydraulic-geometry exponents for summarized data, expressed as coefficients of power functions of the form: (log w)=log a+b(log Q)*

Platte River near:	Distance downstream from gage (meters)	Period of record	Coefficients *b*	*f*[1]	*m*
Cozad	30	1961–1979	0.5282	0.2939	0.1778
		1961–1963	.5560	.2804	.1636
		1964–1969	.492	.2169	.2913
		1970–1979	.4893	.3405	.1702
Cozad	45	1954–1979	.5082	.3537	.1381
		Low	.795	.127	.078
		High	.3741	.4905	.1354
		1954–1969	.5492	.297	.153
		Low	.755	.245	.015
		High	.5998	.4002	.1521
		1970–1979	.2782	.6274	.0944
		High	.2351	.6847	.0801
Cozad	60	1953–1979	.5339	.2720	.1941
		Low	.6788	.1273	.1939
		High	.3576	.4503	.1921
		1953–1957	.6610	.1637	.1753
		1958–1963	.4944	.3473	.1583
		1953–1963	.5728	.2450	.1822
		Low	.6801	.1395	.1805
		High	.435	.4359	.1295
Cozad	60	1964–1969	0.4468	0.2831	0.2701
		Low	.772	−.101	.329
		High	.3738	.4071	.2190
		1970–1979	.3809	.4551	.1640
		Low	.997	−.0161	.0192
		High	.1772	.5717	.2511
Cozad	75	1961–1979	.4345	.3625	.2030
		Low	.5848	.0414	.3739
		High	.5188	.3560	.1252
		1961–1963	.4999	.3580	.1421
		Low	.510	.2106	.2798
		High	.6425	.2859	.0717
		1964–1969	.5086	.2832	.2082
		Low	.752	−.111	.3599
		High	.5435	.3543	.1023
		1970–1979	.2155	.5151	.2694
		High	.2553	.4705	.2742
Cozad	120	1951–1979	.4998	.3131	.1871
		Low	.6224	.2067	.1709
		High	.2281	.5790	.1930
Cozad	120	1951–1963	0.6168	0.2198	0.1634
		Low	.6585	.1863	.1551
		1964–1969	.2345	.5147	.2508
		Low	.4669	.3629	.1702
		High	.1636	.6166	.2198
		1970–1979	.3184	.5334	.1482
		Low	.4380	.5240	.0380
		High	.2165	.5833	.2024
Overton, north channel	30	1968–1976	.4294	.3497	.2210
Overton, north channel	45	1968–1976	.3850	.3608	.2543
		Low	.305	.307	.388
		High	.2139	.5465	.2396
Overton, north channel	60	1968–1976	.4100	.3658	.2242
		Low	.5226	.2684	.2090
		High	.0474	.7883	.1643
Overton, north channel	75	1968–1978	.0813	.4815	.4372
		Low	.770	.139	.091
		High	.4161	.2456	.3383
Overton, north channel	90	1968–1978	0.3154	0.4331	0.2514
		Low	.654	.1923	.1538
		High	.1665	.4806	.3529

TABLE 1.—*At-a-station hydraulic-geometry exponents for summarized data, expressed as coefficients of power functions of the form: (log w)=log a+b(log Q)*—Continued

Platte River near:	Distance downstream from gage (meters)	Period of record	Coefficients *b*	*f*[1]	*m*
Overton, south channel	30	1968–1978	.5332	.3974	.0694
Overton, south channel	90	1968–1978	.3870	.3229	.2901
Overton	30	1961–1967	.8011	.1165	.0824
Overton	45	1961–1963	.914	−.048	.134
Overton	60	1954–1967	.6523	.1984	.1493
		Low	.462	.503	.034
		High	.4637	.3150	.2213
		1954–1963	.7303	.1384	.131
		Low	.948	−.114	.166
		High	.5152	.2705	.2143
		1964–1967	.6047	.247	.1484
		Low	.251	.721	.028
		High	.4550	.3435	.2014
Overton	75	1962–1967	0.4878	0.2386	0.2736
		Low	.770	.139	.091
		High	.4161	.2456	.3383
		1962–1963	.386	.347	.267
		1964–1967	.4973	.2264	.276
		Low	.768	.177	.0552
		High	.4282	.2227	.3491
Overton	90	1962–1967	.4729	.3207	.2064
		Low	.7072	.1686	.1242
		High	.1961	.5819	.2219
		1962–1963	.5092	.3010	.1898
		Low	.8478	.0432	.1090
		High	.1283	.5905	.2812
		1964–1967	.4602	.327	.2123
		Low	.6402	.2307	.1292
		High	.2157	.5787	.2056
Odessa	60	1962–1979	.6286	.2218	.1496
		Low	.6508	.1805	.1687
		High	.3701	.548	.082
Odessa	60	1962–1963	0.6807	0.1362	0.1832
		Low	.7100	.0994	.1906
		High	.320	.383	.297
		1964–1969	.5868	.2940	.1193
		1970	.4829	.4028	.1143
Odessa	75	1961–1979	.6018	.2033	.1949
		Low	.6138	.1718	.2144
		High	.256	.551	.193
		1961–1963	.5963	.1615	.2922
		1964–1969	.5869	.2691	.1442
		Low	.6224	.2258	.1519
		High	.254	.600	.146
		1970–1979	.5692	.3084	.1224
Odessa	90	1953–1979	.6183	.2074	.1743
		Low	.6804	.1540	.1656
		High	.3077	.4817	.2106
		1953–1963	.6343	.1974	.1683
		Low	.6562	.1623	.1814
		High	.2662	.565	.169
Odessa	90	1964–1969	0.5514	0.2521	0.1966
		Low	.7244	.1233	.1523
		High	.2719	.4782	.2499
		1970–1979	.5077	.3295	.1698

[1]Negative values for the depth exponent occur only in the low range of discharges for partitioned data sets. The values result as discharge increases; spreading flow over previously unwetted streambed, and they reflect the fact that mean depth may decrease as width increases rapidly.

ances of the variables alone (table 2, at the end of the report).

Regressions based on partitioned data sets indicate

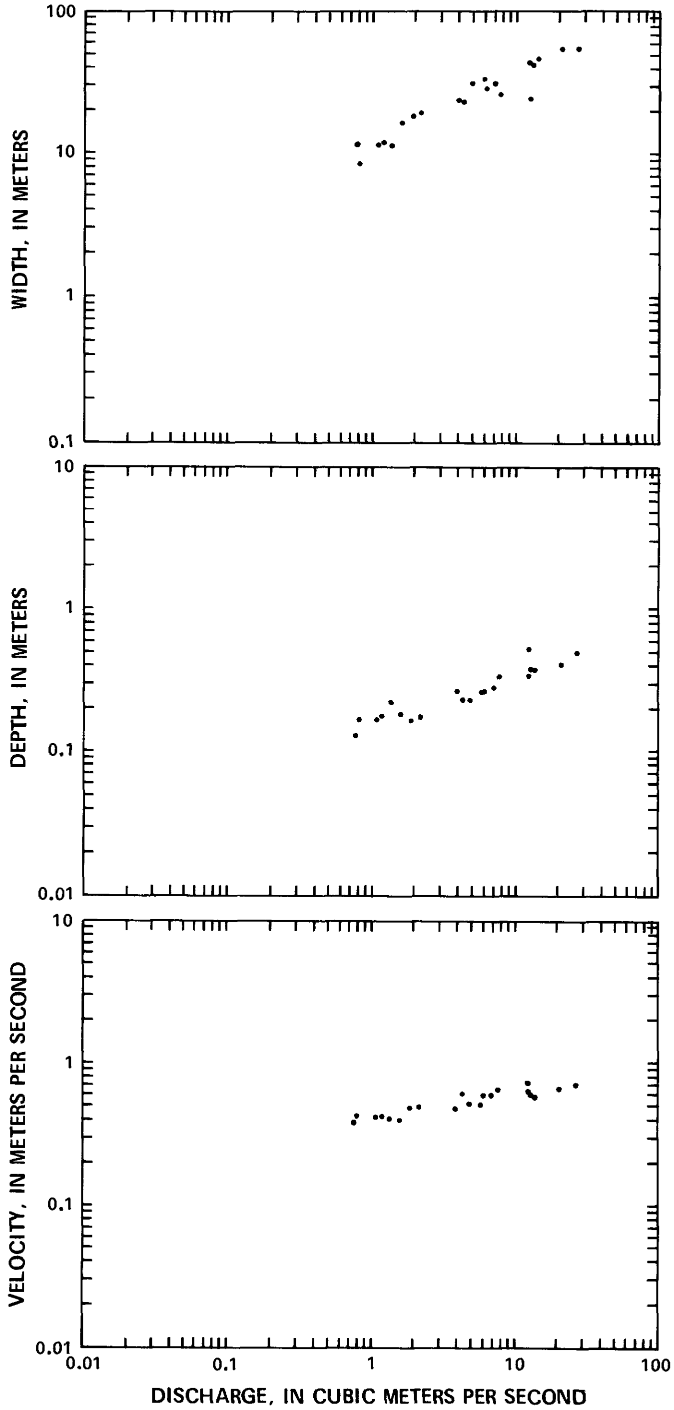


FIGURE 4.—Relation of width, depth, and velocity to discharge, Platte River 30 meters downstream from gage near Cozad, Nebraska, post-1969 record.

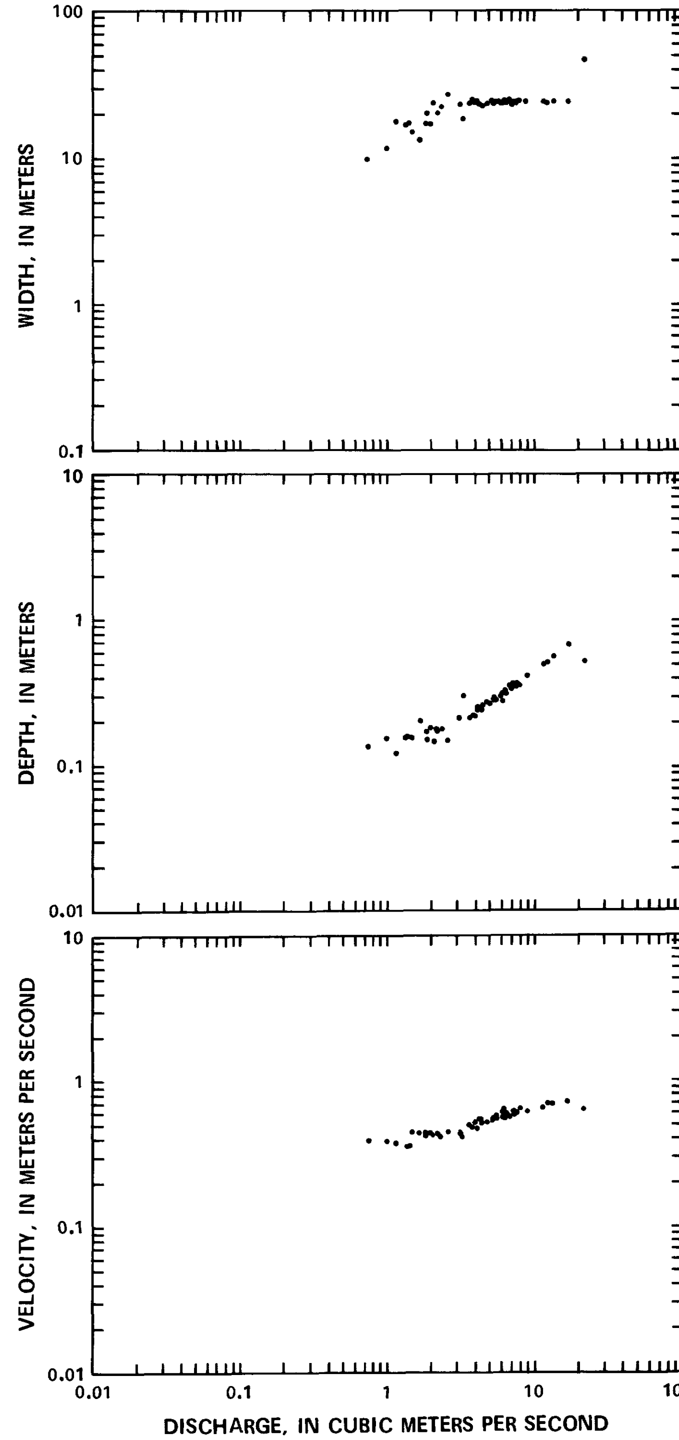


FIGURE 5.—Relation of width, depth, and velocity to discharge, Platte River 120 meters downstream from gage near Cozad, Nebraska, 1964-1969.

the effect of the range of data values. For example, the exponent of the width-discharge power function for the period of record from the section 45 m downstream of the gage near Cozad is 0.5082 (table 1). For the same station and period of record, the width-discharge power function exponents are 0.795 for discharge values less than 1.1 cubic meters per second (m^3/s), and 0.3741 for discharge values greater than or equal to 1.1 m^3/s. The data points for this station from 1970 to 1979

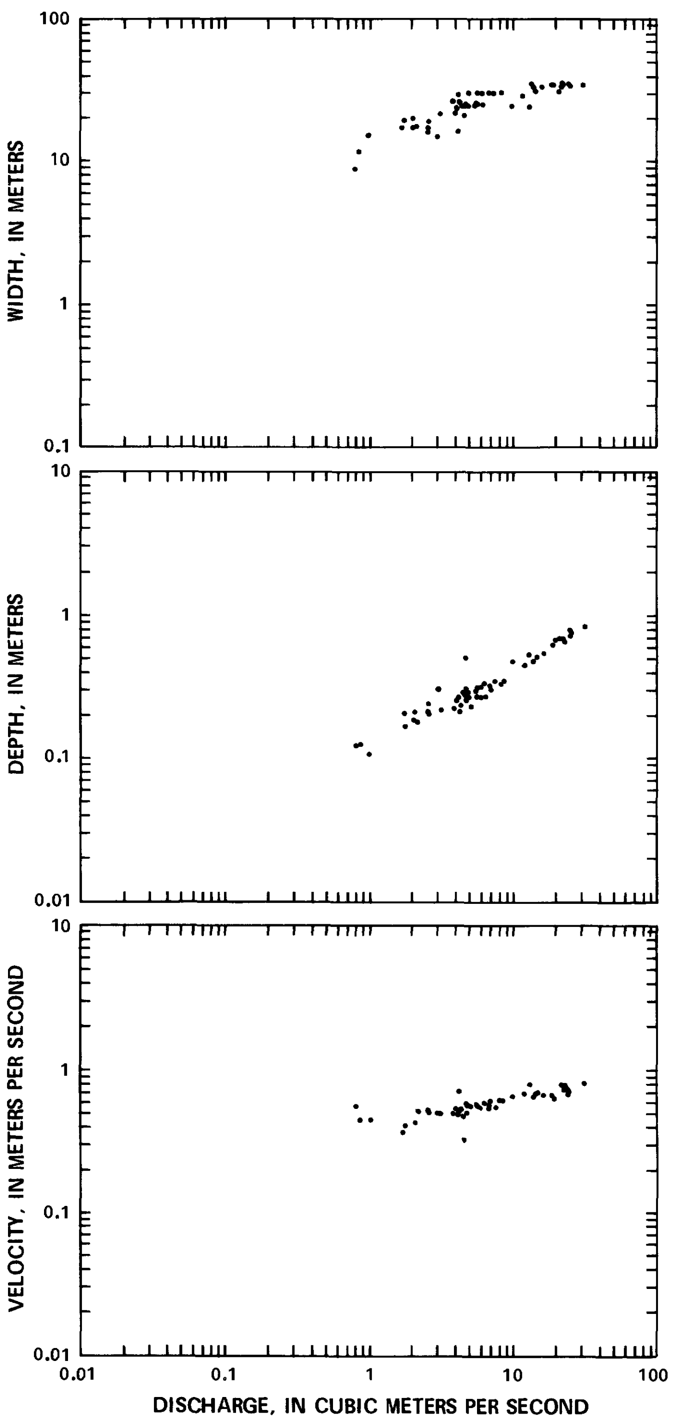


FIGURE 6.—Relation of width, depth, and velocity to discharge, Platte River 120 meters downstream from gage near Cozad, Nebraska, post-1969 record.

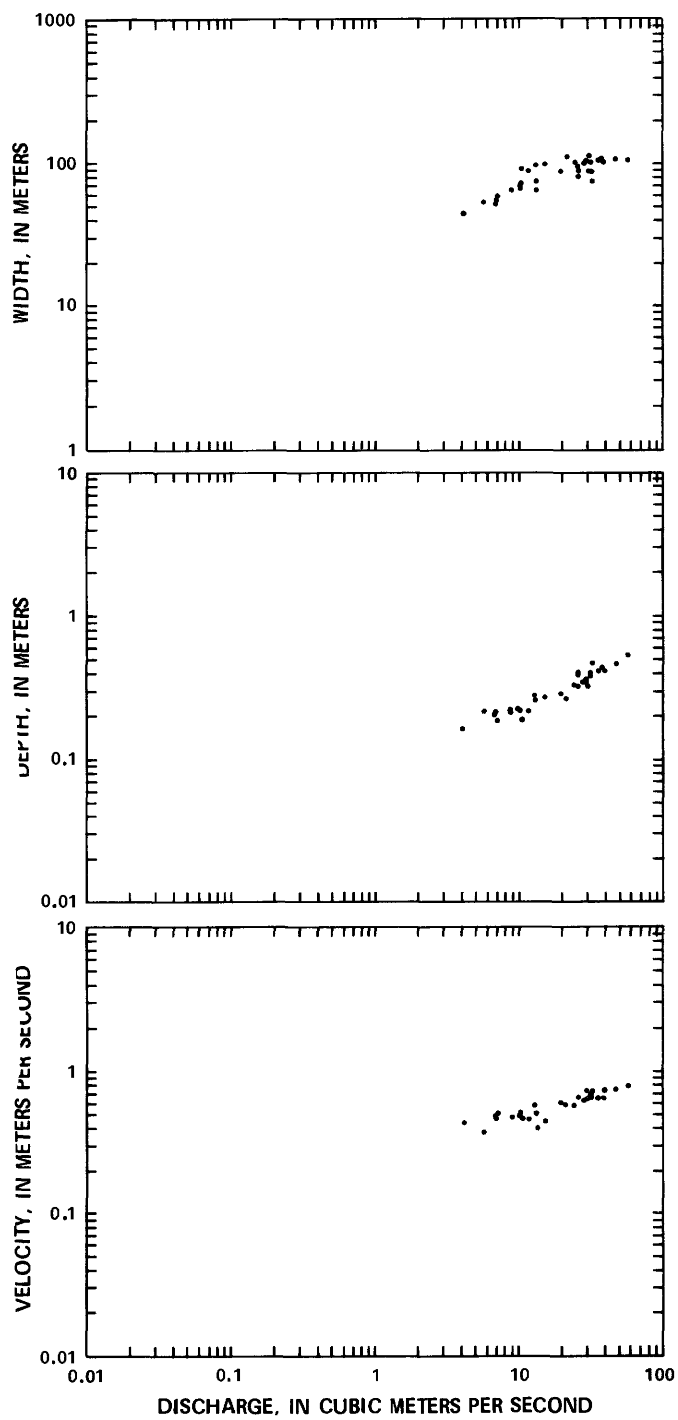


FIGURE 7.—Relation of width, depth, and velocity to discharge, north channel of the Platte River 90 meters downstream from gage near Overton, Nebraska, post-1969 record.

almost all have discharge values greater than 1.1 m³/s; thus, the width-discharge power function cannot be established for discharge values less than 1.1 m³/s. As would be expected from the range of discharges, the exponent for the width-discharge power function for discharges of 1.1 m³/s or greater is quite similar to the exponent for the width-discharge power function for all data from 1970 to 1979 (table 1).

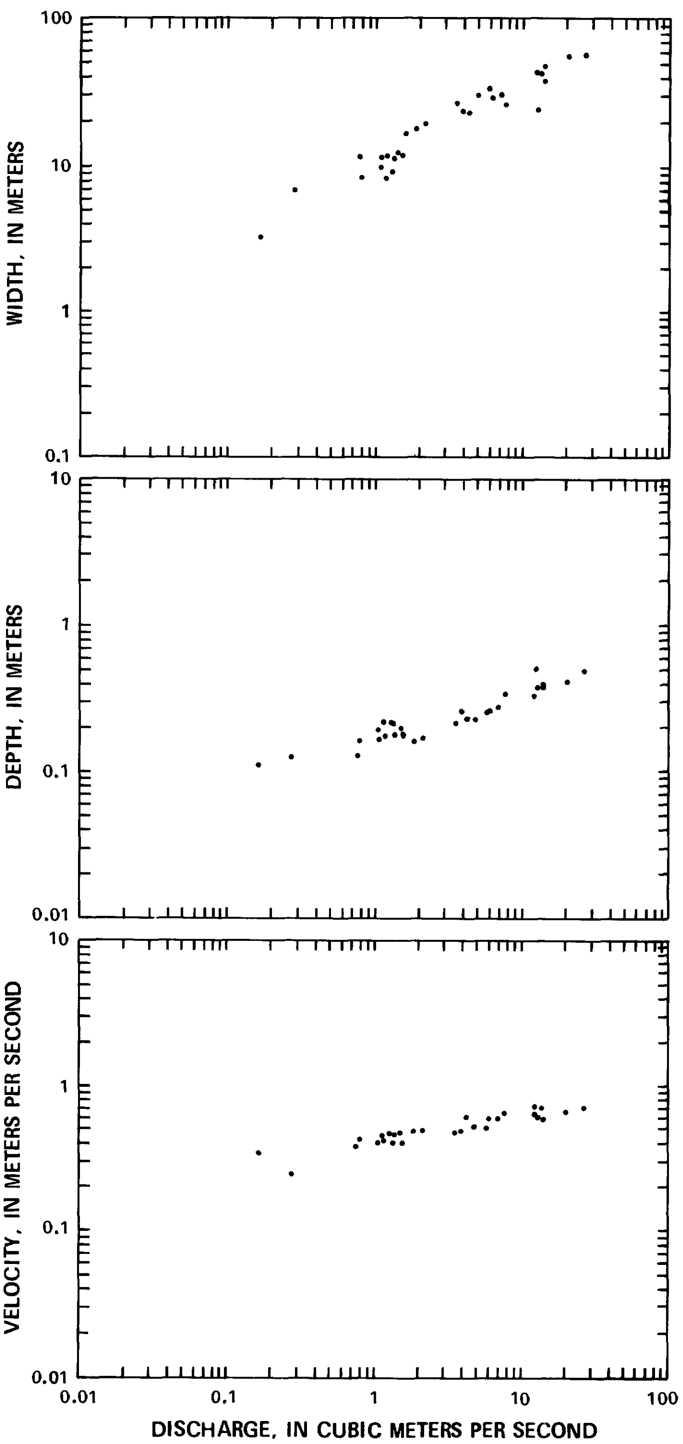


FIGURE 8.—Relation of width, depth, and velocity to discharge, Platte River 30 meters downstream from gage near Cozad, Nebraska, for the period of record.

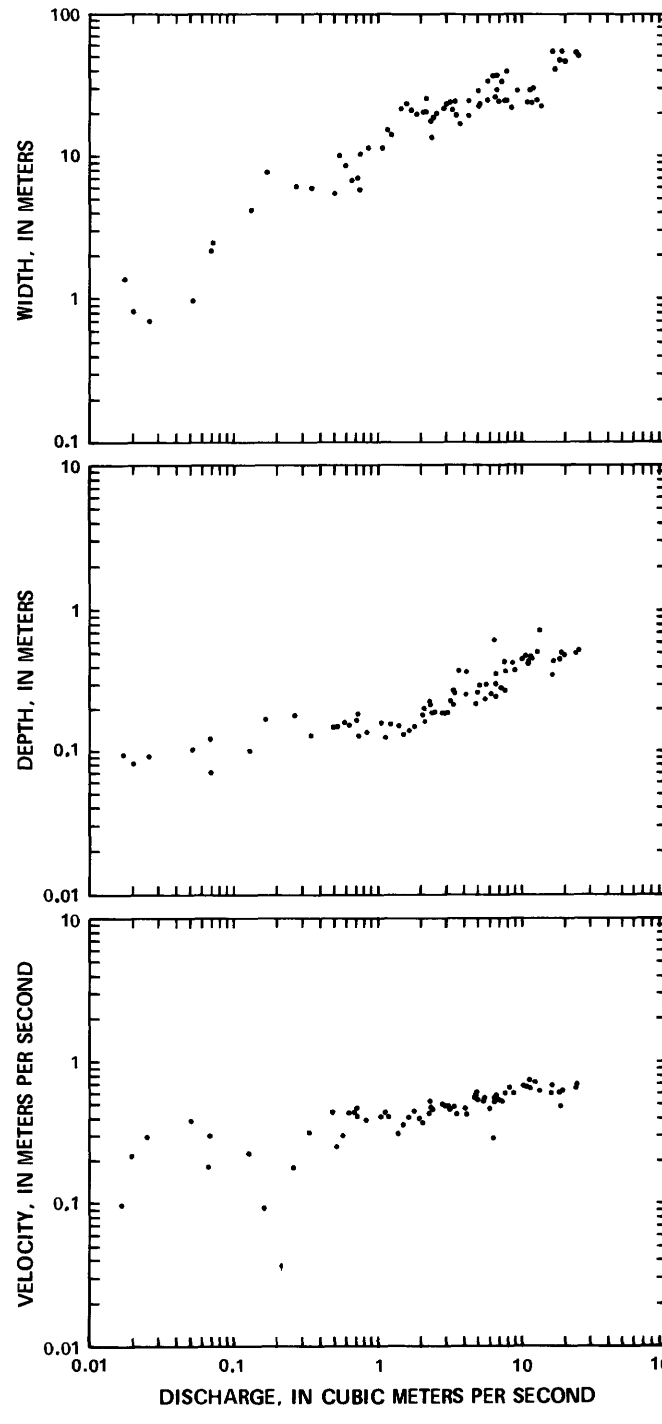


FIGURE 9.—Relation of width, depth, and velocity to discharge, Platte River 60 meters downstream from gage near Cozad, Nebraska, for the period of record.

FIELD DATA

Field data were collected at the six cross sections established for this study. Discharges were obtained by gaging for the Lexington, Johnson-2, and Elm Creek sections. At the remaining three sites (Cozad, Overton, and Odessa), rating curves were used to estimate discharge; therefore, channel depth and velocity were not measured at all six sections. The range of observed discharges is larger than the range of summarized dis-

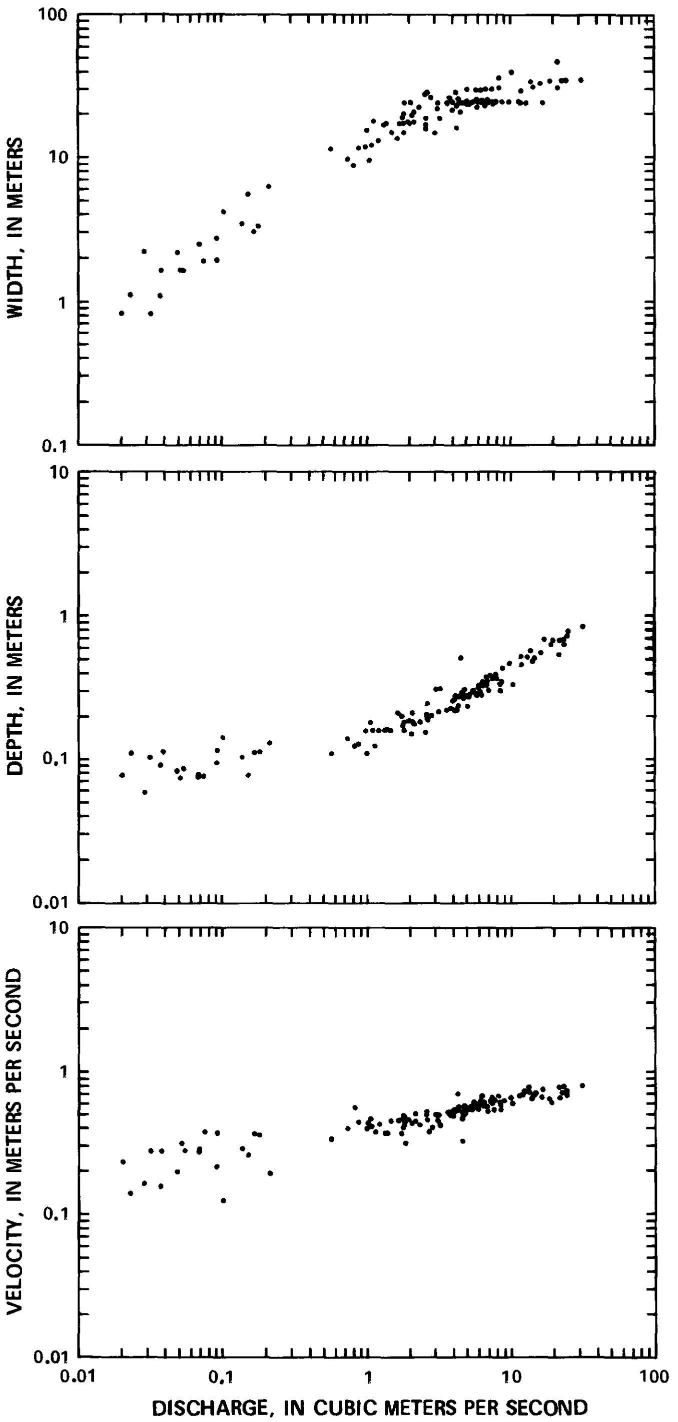


FIGURE 10.—Relation of width, depth, and velocity to discharge, Platte River 120 meters downstream from gage near Cozad, Nebraska, for the period of record.

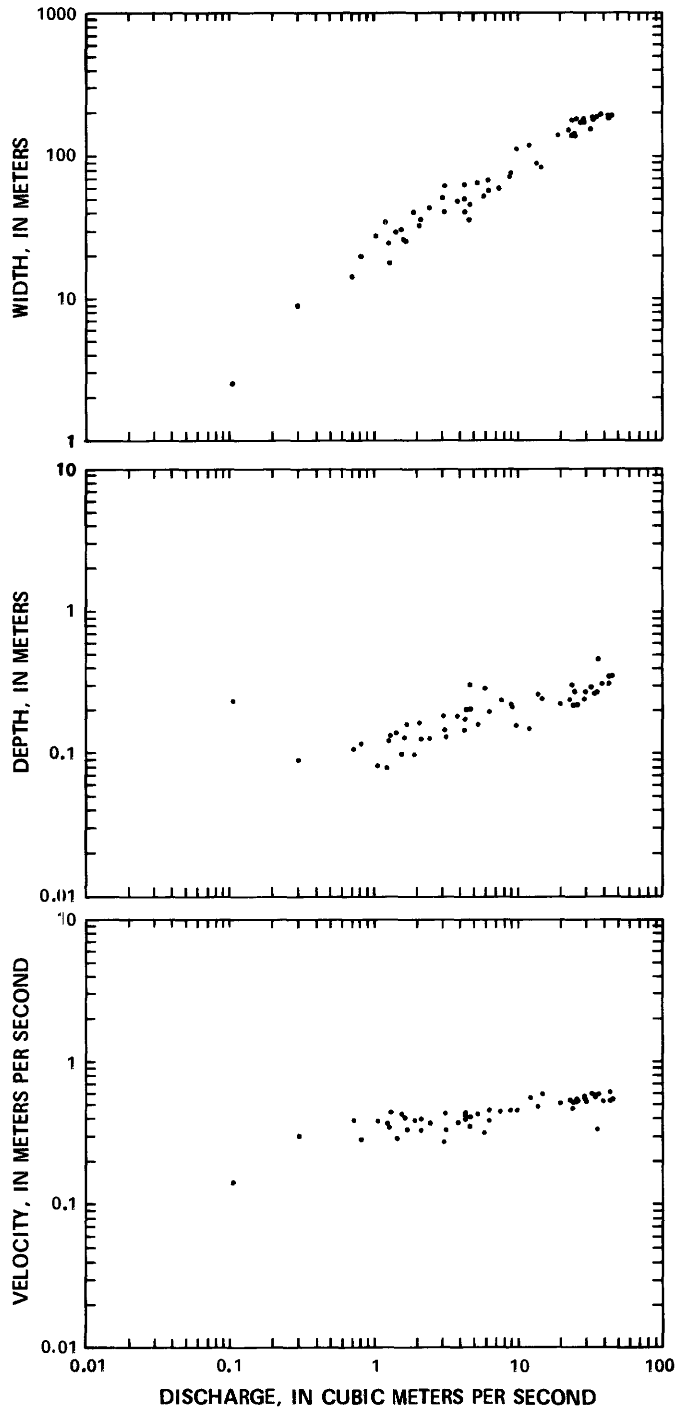


FIGURE 11.—Relation of width, depth, and velocity to discharge, Platte River 60 meters downstream from gage near Odessa, Nebraska, for the period of record.

charges, but the data are deficient toward the middle of the discharge range. In addition, the number of discharge observations is low.

Width-discharge relations were plotted for the six field sections. At the Cozad, Lexington, and Johnson-2 sections, sufficient data were collected to permit plotting of depth-discharge and velocity-discharge relations also. Plots of some of the field data are presented as figures 13 to 15.

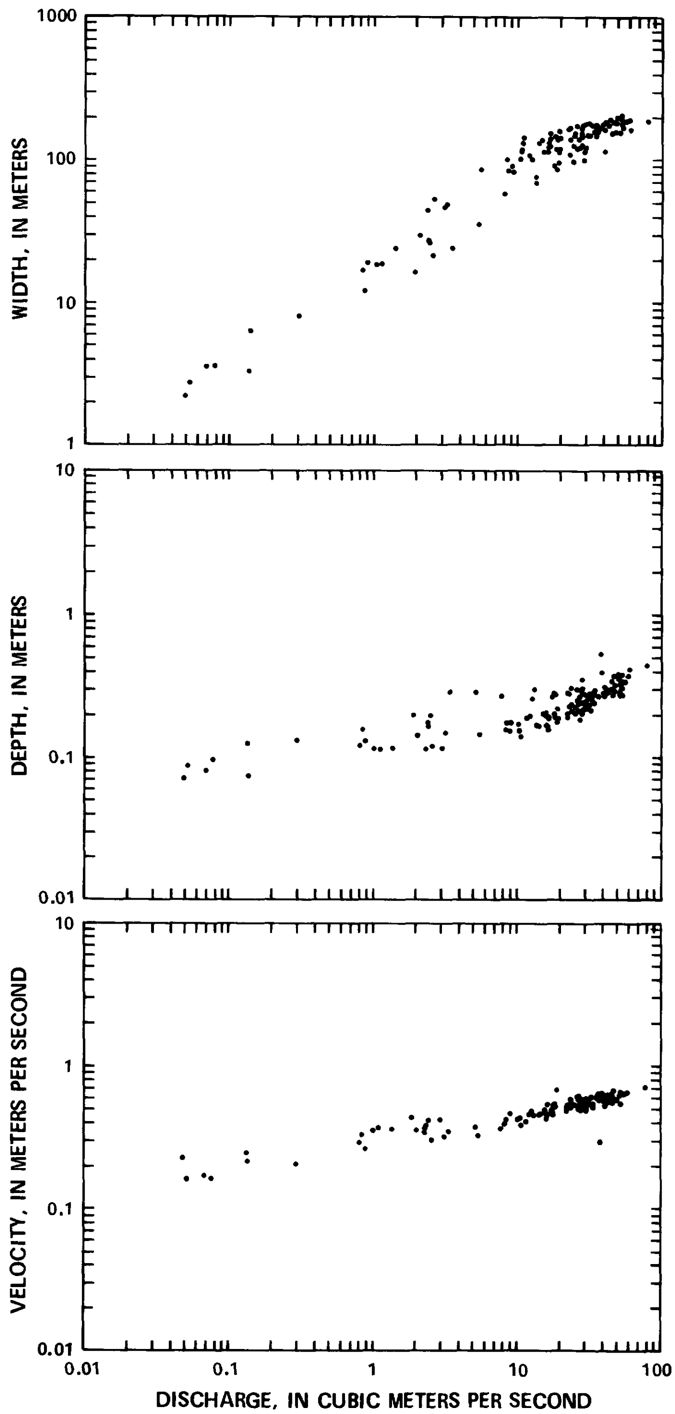


FIGURE 12.—Relation of width, depth, and velocity to discharge, Platte River 90 meters downstream from gage near Odessa, Nebraska, for the period of record.

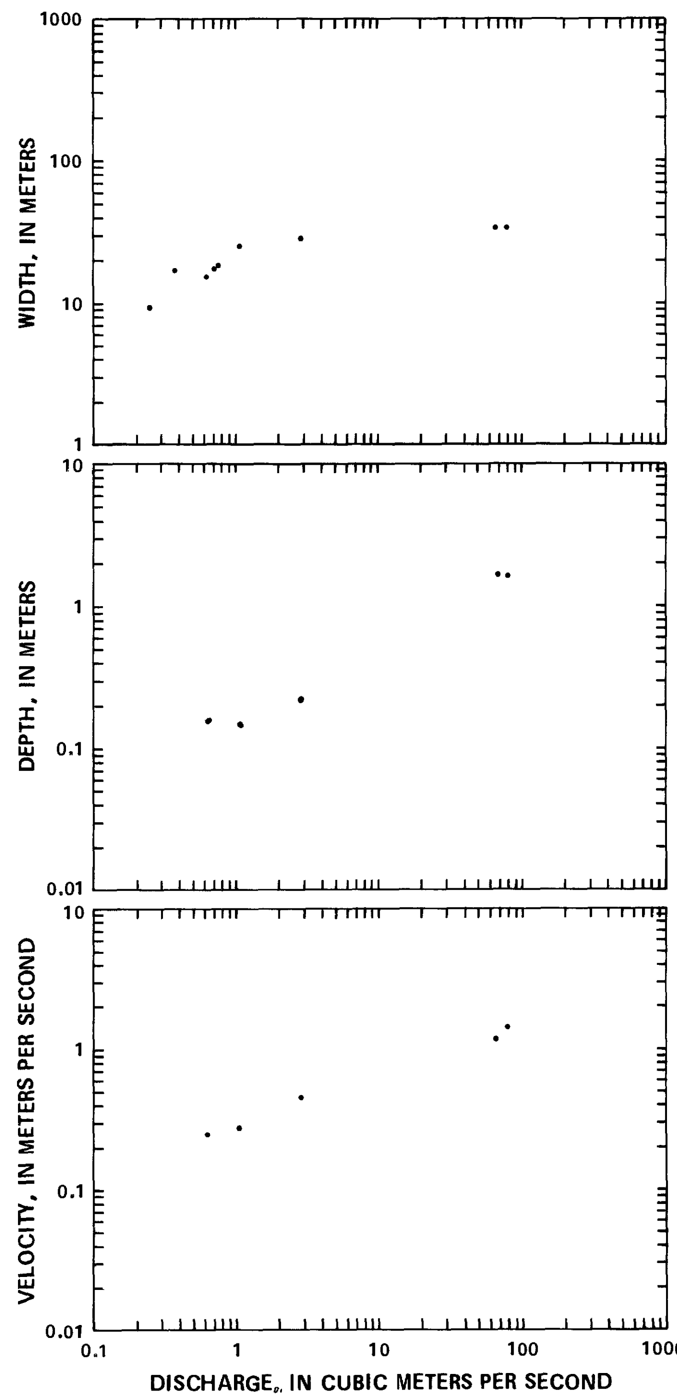


FIGURE 13.—Relation of width, depth, and velocity to discharge, Platte River near Cozad, Nebraska.

The number of field data points is too small to be significant, but the figures suggest that, in some instances, power functions are not appropriate. Plots of the field data indicate that the power-function model adequately describes the velocity-discharge relation at Cozad, the width-, depth-, and velocity-discharge relations at the Johnson-2 section, and the width-discharge relation at the Odessa section. Power functions apparently describe all three hydraulic-geometry relations for the section near Lexington. There is a suggestion of a complex

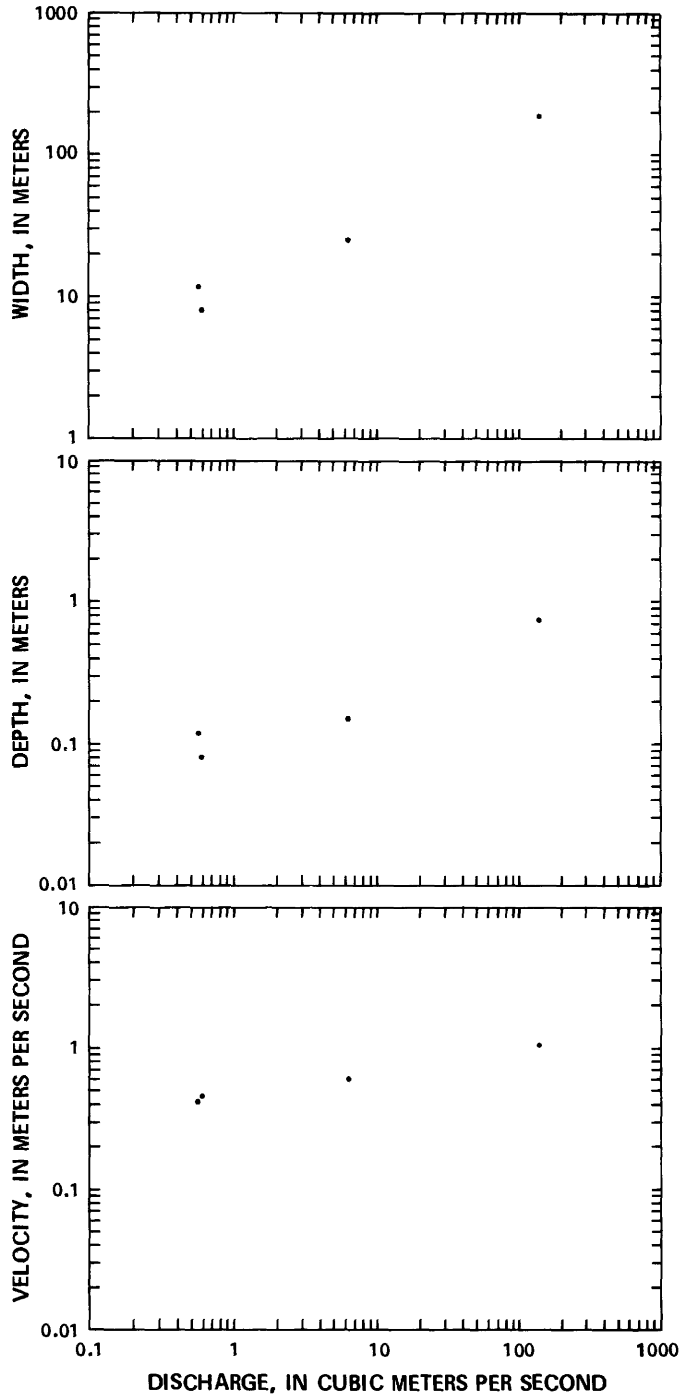


FIGURE 14.—Relation of width, depth, and velocity to discharge, Platte River near Lexington, Nebraska.

relation between width and discharge, and between depth and discharge, but the few data points do not define the relation well enough to make meaningful inferences about its nature. The width- and depth-discharge relations at Cozad do not appear to follow a single power-function model.

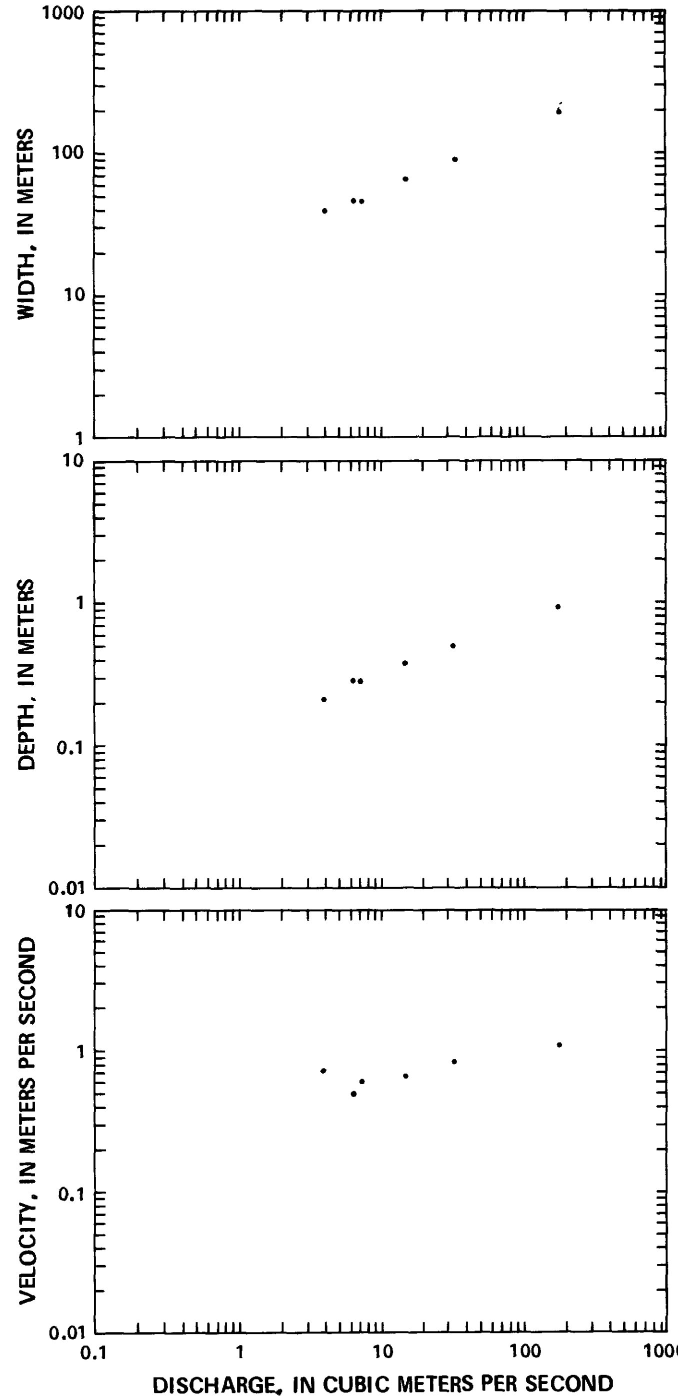


FIGURE 15.—Relation of width, depth, and velocity to discharge, Platte River downstream from Johnson-2 Return near Lexington, Nebraska.

COMPLEX AT-A-STATION HYDRAULIC GEOMETRY

Hydraulic-geometry relations for the Platte River are not described adequately by power functions in all instances. This complex hydraulic geometry is not peculiar to the Platte River. Wolman (1955) stated of Brandywine Creek, in Pennsylvania, "There is a suggestion in some of the data * * * that the depth-discharge and velocity-discharge curves may actually plot as curved rather than straight lines on a log-log paper. Such a relationship of the at-a-station curves is not uncommon." Richards (1973) noted that non-linear changes of depth and velocity with discharge may result from non-linear changes of roughness with discharge. Richards (1976) also proposed that channel cross-section shape can produce breaks or discontinuities in the width-discharge relationship. Williams (1978a) showed that all three hydraulic-geometry exponents vary with discharge for the Humbolt River in Nevada.

At least three causes may explain the complex hydraulic geometry in the study area. The first explanation may lie in the range of discharges observed. At some sections only a small range of discharges was observed (fig. 7). The scatter of the predicted variables (width, depth, and velocity) may be sufficient to make the relation appear to be complex. This explanation does not apply to all sections, because at some sections at which the range of observed discharges is low, there is little scatter of the data (figs. 5 and 7); and because at some sections at which the range of observed discharges is high, the relations are nevertheless complex (fig. 10 and 12). Conversely, it may be that changes in the rates of adjustment of width, depth, and velocity with increasing discharge were not observed because of the small range of observed discharges. Secondly, the velocity-discharge and depth-discharge relationships may be complex because of changes in roughness (Richards, 1973). In addition to changes in roughness associated with dunes and other small-scale bed forms, changes in roughness may occur as vegetated or unvegetated larger bed forms, such as macroforms (Crowley, 1981), are inundated. Finally, and for this study, most importantly, channel shape may preclude a constant rate of water-depth and water-width increase. Near Cozad, for example (fig. 16), the banks are cohesive and near vertical at many locations. At low flows, the channel bottom generally is not wetted entirely. As discharge increases, width increases very rapidly as the channel floor is covered, but depth increases slowly.

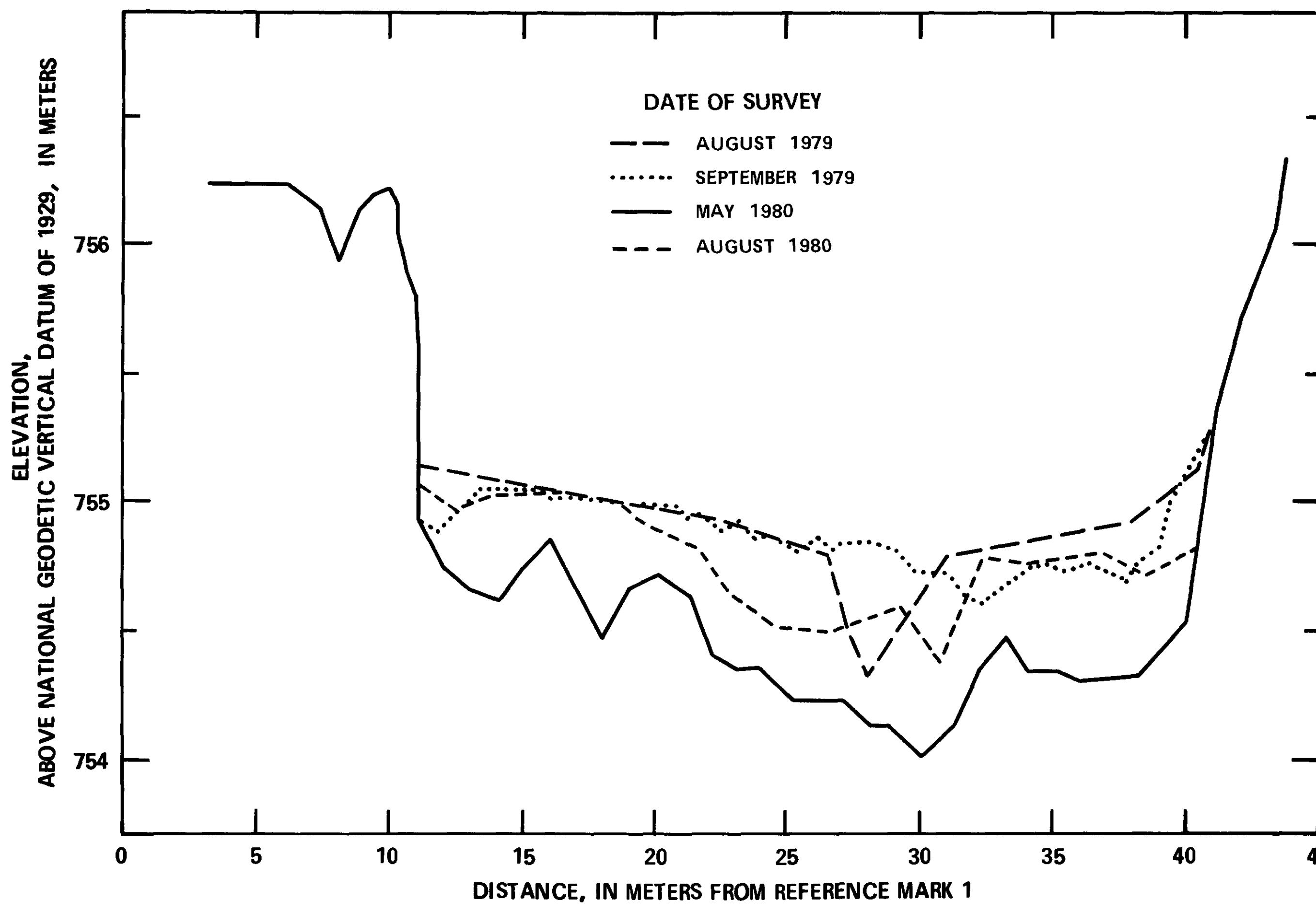


FIGURE 16.—Cross-section surveys of the Platte River at the Cozad field section.

Once the entire channel bed is covered and the banks are reached, width cannot increase appreciably, although depth may increase rapidly. Such sudden decreases in the rate of width increase and sudden increases in the rate of depth increase will cause discontinuities in the slopes of hydraulic-geometry plots.

The shapes of the hydraulic-geometry relations have their bases in the physical characteristics of the channel and flow. Based on the channel shape (fig. 16), the width-discharge relation should be concave downward for sections at which the power function does not hold. In figures 4 through 15 the width-discharge relation either is a power function or is concave downward. Where the power function holds for the width-discharge relation, the depth-discharge and velocity-discharge relations both may be power functions or both may be complex with opposite curvature. Where the width-discharge relation is not a power function, the depth-discharge and velocity-discharge relations each may be a power function or complex, with curvature in either direction. The channel shape, which controls the curvature of the width-discharge relation, also controls the shape of the depth-discharge relation. The depth-discharge relation must be concave upward if it is not a power function. In figures 4 through 15 the depth-discharge relation either is a straight line or it is concave up. The velocity-discharge relation varies in shape from concave up (figs. 5 and 7) to a power function (figs. 4 and 8) to concave down (figs. 9 and 10). The physical significance of the velocity-discharge curve shapes is difficult to ascertain. Richards (1973, 1977) suggested that the curves should be concave downward because the increase in roughness as dunes form offsets any increased efficiency due to increased depth. Knighton (1979) cited data showing that the resistance-discharge relation for sand-bed streams is concave upward, corroborating Richards' suggestion that the velocity-discharge curve is concave downward. The velocity-discharge curves may be concave upward at sections where the effect of form roughness decreases as depth increases.

Two alternatives to power functions hve been proposed as models for hydraulic geometry. Thornes (1970) partitioned each set of bivariate data into two subsets and obtained a discrete power-function regression for each subset. The break between the subsets was determined by minimizing the combined error sums of squares of the regressions. Williams (1978a) used two sets of exponents to describe hydraulic-geometry relations; one set was for discharges less than a specified value, the other set was for discharges greater than the specified value. Richards (1976) argued that fitting of power-law relationships to discrete subsets of a data set was unnecessarily complicated, although possible. He proposed instead that polynomials be fit to the logarithms of the data, because fewer parameters need to be estimated than for partitioned data sets and because of the analogy with the power-function situation.

For this study, where a single power function did not adequately describe the relation, data sets were partitioned based on breaks in slope of the hydraulic geometry plots. Separate power functions were then fit to the different discharge ranges. Although cumbersome to apply, discrete power functions accurately describe the changes in hydraulic variables with increasing discharge. Polynomials compromise the relations that would be obtained from the partitioned data sets and do not allow the points to be identified at which the width-, depth-, and velocity-discharge relations change.

MEANING OF THE EXPONENTS

Exponents of the first-order equations represent the rates of change of the dependent variables with changing discharge. Rewritten as power functions, for example:

$$(\log W) = \log a + b(\log Q);$$

first derivatives of the equations are exponents of the first-order equations. Thus, exponents of the power functions are slopes of the first-order equations. Because of continuity, the first derivatives or exponents of the width-, depth-, and velocity-discharge relationships will sum to one.

The question then is: What do the slopes of the hydraulic-geometry relations mean? The slopes represent the rates of change of width, depth, and velocity with changing discharge. Comparison of numerical values of the exponent indicates which variables show greater rates of change at which sections. However, numerical comparison of the exponents does not provide information about the meaning of the exponents themselves or their implications about channel conditions.

The *b-f-m* diagram allows the similarity or difference in responses of width, depth, and velocity to changing discharge to be interpreted based on physical considerations (Rhodes, 1977). The use of the *b-f-m* diagram is possible only when the exponents sum to one. For power functions, this constraint presents no problems because the exponents sum to one; however, in some instances individual exponent values are either negative numbers or greater than one, making plotting on the *b-f-m* diagram impossible. Expansion of the diagram to include negative values and values greater than one would be possible, but would make interpretation of the exponents more difficult. Exponents for the first-order

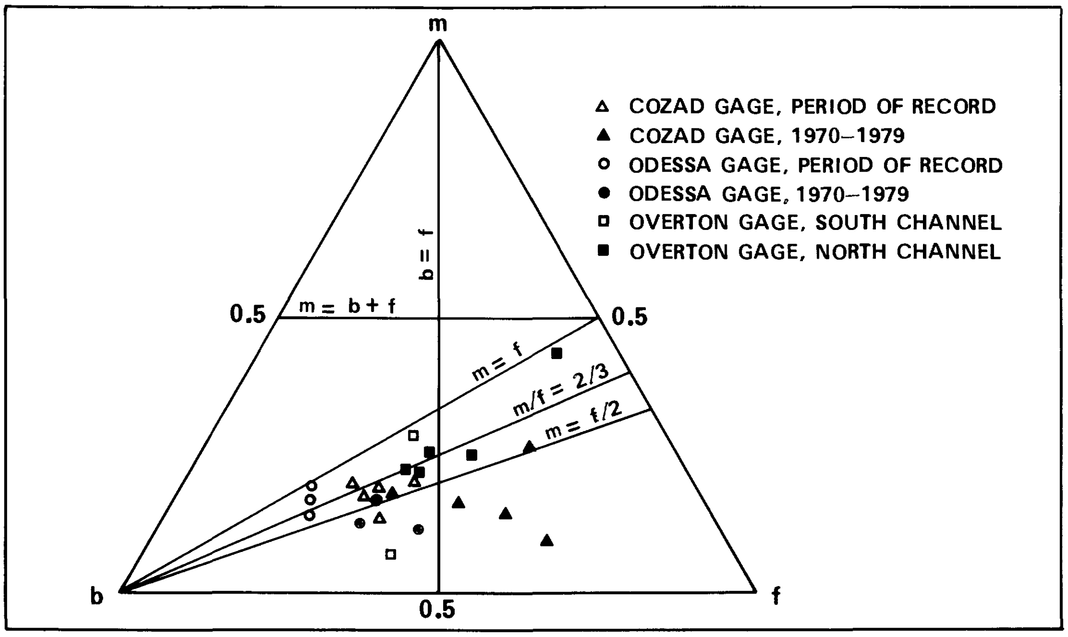


FIGURE 17.—*B-f-m* diagram showing plotting positions of current at-a-station hydraulic-geometry exponents and exponents from the period of record.

equations for entire data sets from table 1 for the periods of record and since 1969 are presented graphically on a *b-f-m* diagram (fig. 17). Although these exponents may not in all instances represent the correct model, they will serve as a starting point from which to examine the *b-f-m* diagram.

HYDRAULIC AND MORPHOLOGIC INFORMATION FROM THE *B-F-M* DIAGRAM

The *b-f-m* diagram not only allows hydraulic-geometry exponents to be presented graphically, but also allows inferences to be made about hydraulic and morphologic parameters. Hydraulic-geometry exponents for the summarized data (for the period of record and since 1969) plot in six of the ten fields of the *b-f-m* diagram.

Only six of the 23 data points plot to the right of the line, $b=f$; at most sections the width-depth ratio increases with increasing discharge. Four of the six points to the right of the $b=f$ line represent sections in the vicinity of the Cozad gage on the north channel of the Platte River. This reach of the river is deeper relative to width than any other river reach within the study area. The remaining points to the right of the line $b=f$ are from the north channel near Overton. All of the points from the period of record, including those from the north channel near Cozad, plot to the left of the line, $b=f$.

None of the data points plot above the line, $m=0.50$. Rapid velocity increases are not likely considering the shallow depth of the river and the increased wetted perimeter as discharge increases. In addition, vegetation present on many of the bars will increase roughness as it is inundated, further decreasing the possibility of rapid velocity increase.

Six data points plot above the line, $m/f=2/3$, which represents the ratio $S^{1/2}/n$. Points above this line should represent sections at which roughness decreases with increasing discharge. Of these six points, one near Cozad and two near Odessa represent the entire period of record, and the other three represent sections near Overton. Thus, roughness apparently increased with increasing discharge at almost half of the sections for the period of record. However, for the period since 1969, plotting positions for exponents from unpartitioned data sets indicate that roughness increased with increasing discharge at 14 of 17 sections.

None of the data points from the Platte River plot above the line, $m=f$. Therefore, in all instances, the rate of change of velocity with increasing discharge is less than the rate of change of depth with increasing discharge. This implies that competence will not increase with increasing discharge at any of the sections studied (Wilcock, 1971).

The line, $m=f/2$, represents sections at which Froude number is constant with increasing discharge. Six of the 15 data points from the summarized data since 1969 plot below the line, $m=f/2$, in fields in which Froude number decreases with increasing discharge. The remaining nine points representing summarized data since 1969 plot above the line, $m=f/2$, representing sections at which Froude number increases with increasing discharge. Of these nine points, six are from the vicinity of the Overton gage. The remaining three points, two near the Cozad gage and one near the Odessa gage, almost plot on the line. For the eight data values from the period of record, only one point plots below the line, $m=f/2$, although four other values lie close to the line. Thus, based on unpartitioned data sets for the period of record, Froude number should have increased with increasing discharge at seven of eight sections.

The *b-f-m* diagram can be used to interpret, in a general sense, the way morphologic and hydraulic parameters adjust to increasing discharge. Exponent values from hydraulic-geometry relations from summarized data for unpartitioned data sets for the period of record plot only in fields five, seven, and nine of the *b-f-m* diagram. Thus, for these sections, the width-depth ratio increases with increasing discharge; the velocity-area ratio decreases with increasing discharge; Froude number generally increases with increasing discharge; and the slope-roughness ratio generally decreases, presumably indicating an increase in roughness with increasing discharge. Exponent values for the hydraulic geometry computed from summarized data for unpartitioned data sets since 1969 plot in fields five through ten of the *b-f-m* diagram. For these sections, the width-depth ratio may increase or decrease; in general, it increases. The velocity-area ratio decreased in all instances. In general, both Froude number and roughness increased with increasing discharge.

The meaning or significance of the fields of the *b-f-m* diagram is relatively clear; the meaning of the variation displayed by the hydraulic-geometry exponents and hydraulic variables is unclear. Note, for example, the inferred differences in roughness among the Cozad sections or the Overton sections, and the differences between the Cozad and Overton sections. Changes in bedforms with increasing discharge, such as from dunes to plane bed with transport, may cause roughness to decrease. The question of why this should occur at only a few sections remains. The different changes of the width-depth ratio can be understood, based on the morphology of the cross sections. Variations of $m=f/2$, indicative of the Froude number, also are less readily understandable. An inferred decrease in roughness may account for some of the sections showing an increase in Froude number with increasing discharge. However, other sections show an increase in Froude number with increasing discharge, and yet also show an increase in roughness (fields seven and eight of the *b-f-m* diagram).

At least four explantions can be offered for the variation of hydraulic-geometry exponents computed for unpartitioned data sets, and different reactions of hydraulic and morphologic variables as inferred from the b-f-m diagrams.

1. Morphologic or vegetative differences between sections may be so great that all of the hydraulic-geometry exponents are influenced. This could cause variation in plotting position on the *b-f-m* diagram also.
2. Inferences drawn from the *b-f-m* diagram may be incorrect. The fields of the diagram may not actually group like channels or channels that respond in a similar manner to increasing discharge.
3. Part of the variation may be due to the different time periods used. For example, great differences exist between the unpartitioned data from the Cozad sections for the period of record and for the period since 1969. Data from the period of record represent a time average of the hydraulic-geometry exponents; whereas, the data since 1969 presumably represent a more homogeneous period, due to the shorter time period. Changes in the plotting positions of the exponents then may show changes in the response of the river, both morphologically and hydraulically, with time.
4. Part or all of the variation of exponents and plotting positions may be due to the assumption in this section that single power functions are the appropriate model for hydraulic geometry.

Two of these four explanations for the variation in exponents, systematic variation (3) and analytic error (4), will be examined in more detail in the next section of this chapter.

SYSTEMATIC VARIATION AND ANALYTICAL ERROR

Changes in channel morphology should influence the rates of change of width, depth, and velocity with increasing discharge. As a result, the hydraulic geometry computed for short time intervals of a period during which a channel section was undergoing substantial change should show systematic variation with time. Unfortunately, long-term records either are not available or are unsuitable for use in hydraulic-geometry computations. In most instances, early discharge measurements were made near bridges. Bridge sections may have been unaltered near the turn of the century, but they were increasingly filled to facilitate bridge construction. Riprap generally has been placed on the banks immediately upstream and downstream of the bridge section. These factors tend to establish bridge sections as highly modified, almost rigid boundary sections, incapable of significant morphologic adjustment to changes in flow.

For this analysis, each location grouping of discharge measurements was further divided into time-period groups, the ends of which were coincident with the years of aerial photography. The equations of hydraulic geometry were computed for the individual time groupings at each location. Comparison of exponents and coefficients can be made between locations or between time periods, or both, if the limitation imposed by the limited ranges of data is recognized.

The hydraulic-geometry exponents for the different time groupings are listed in table 1. The success of time and location groupings varied from gage to gage. Five locations were separable from the Cozad measurements. At three of these locations sufficient records are available to make three time groupings. A series of gage location changes at Overton made the records difficult to compare directly with those from Cozad and Odessa. For most locations, records are available for the entire channel for two time periods, but starting in 1969 each channel was gaged independently. The records from Odessa allow three locations, each with three time periods, to be established.

In general, for the unpartitioned data the width exponent at each location for the Cozad and Odessa sites decreased with time. However, there are instances when the width exponent increased with time. The depth and velocity exponents for Cozad (fig. 18) and Overton generally do not show trends, either among stations or at a given station with time. This implies that depth and velocity adjust in different ways at different times. At Odessa depth appears to be increasing, while velocity is decreasing or remaining constant with time (fig. 19).

Interpretation of the changes in width exponents for the Overton section are not made easily. Width exponents decreased at three of the four locations for which records are available for the period prior to 1963 or for the period 1964 to 1969. At the fourth station, the width exponent increases. Records for the post-1969 period are available only for individual channels. In all cases, however, the individual channels have width exponents smaller than those computed for earlier periods.

Plots of the hydraulic-geometry exponents for unpartitioned data on *b-f-m* diagrams provide visual interpretations of the changes in hydraulic geometry with time (figs. 18 and 19). These plots show, as discussed above, a general decrease in the rate of width increase with discharge and, for Odessa, an increase in the rate of depth increase with discharge. The implication of the width change is that channel width is not as great for large discharges as it once was, a point borne out by the examination of aerial photographs. The hydraulic-geometry changes at Odessa indicate that the channel should be incising, as depth is increasing simultaneously with the width decrease. This conforms to Williams' (1978b) observed decrease in bed elevation at Odessa.

The apparent change in hydraulic geometry exponents with time (figs. 18 and 19) may result from changes in the range of discharges represented in each of the different time intervals, rather than from significant changes in the width-, depth-, and velocity-discharge relations themselves. If a hydraulic geometry relation at a site is assumed to be represented by a single power function, as in figure 18, when in fact it would be better represented using two different power functions (fig. 5), then the single power function exponent for that hydraulic geometry relation will be a compromise between the two exponents that would better describe the relation. The slope of the single relation will depend on the range of discharge values present. A preponderance of data values from what would be one subset of data if the data were partitioned, would result in a single exponent that approximates the exponent for the subset. If the range of discharges represented at a site changes with time, the slope of a single hydraulic geometry relation at that site may also change with time. Thus, the observed changes in hydraulic geometry exponents with time may result because the discharge ranges, upon which those exponents are dependent, change with time.

Examples of hydraulic geometry exponents from partitioned data sets from Cozad and Odessa are plotted in figures 20 and 21. Although there is a suggestion in figure 18 that the width exponent generally has decreased with time near Cozad, partitioning of the data sets (fig. 20) indicates that some of the apparent reduction of the width exponent results from changes in the range of discharges represented in different time intervals. Nevertheless, the width exponent decreases with time near Cozad even within the hydraulic geometry relations for partitioned data sets. The gradual, systematic change of exponents through time near Odessa (fig. 19) does not occur when the data sets are partitioned (fig. 21). Although fewer points are plotted on figure 21 than on figure 19 because of small data sets, it is apparent that there is not a change in exponent values through time. Rather, the change in plotting positions on figure 21 results from partitioning of the data.

SIGNIFICANCE OF COMPLEX HYDRAULIC-GEOMETRY RELATIONS

Analysis of at-a-station hydraulic geometry showed that some of the sections within the study reach were not described adequately by conventional hydraulic

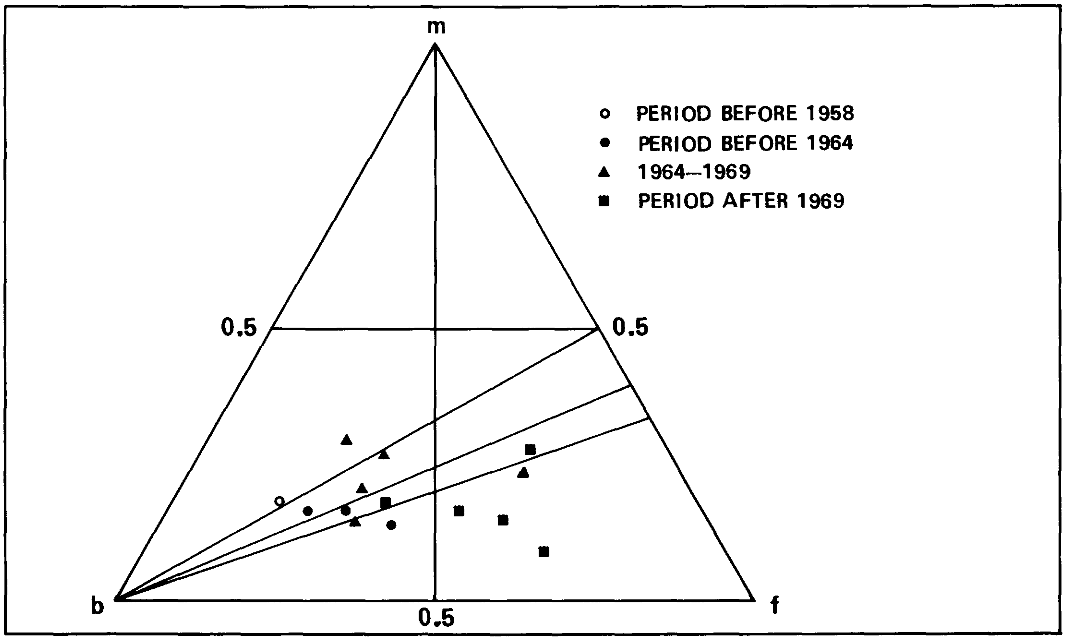


FIGURE 18.—*B-f-m* diagram showing changes in hydraulic-geometry exponents with time. Data from the north channel of the Platte River in the vicinity of the gage near Cozad, Nebraska. 0=period before 1958. 1=period before 1964. 2=1964-1969. 3=period after 1969.

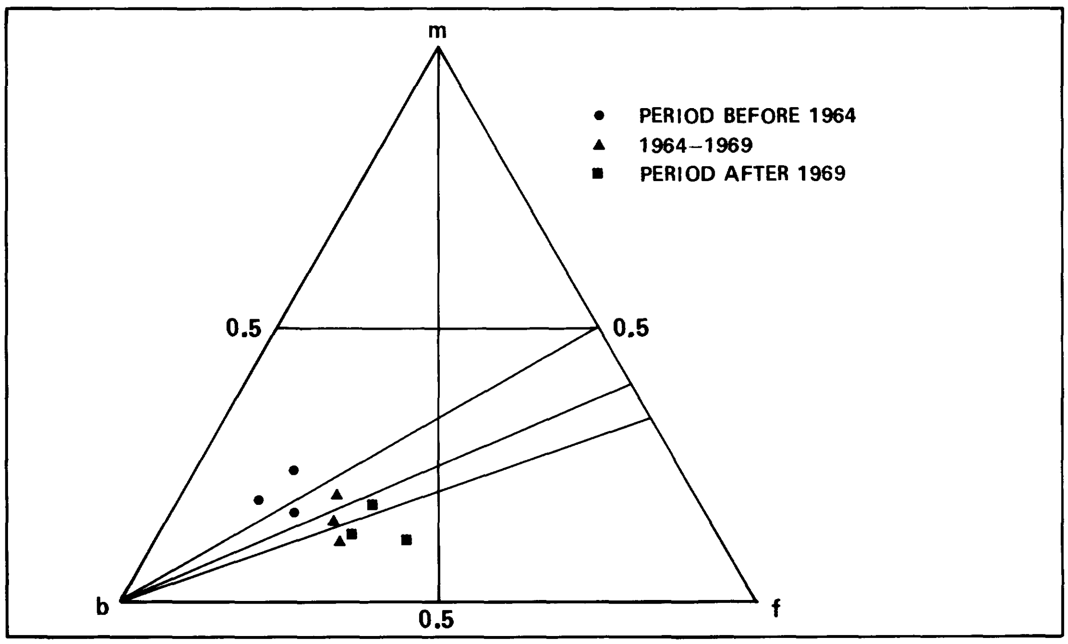


FIGURE 19.—*B-f-m* diagram showing changes in hydraulic-geometry exponents with time. Data from the Platte River in the vicinity of the gage near Odessa, Nebraska. 1=period before 1964. 2=1964-1969. 3=period after 1969.

geometry. In general, sections of this type show a rapid width increase as the channel bed is covered; then, a much slower increase in width as the channel fills with water; a slow depth increase until the banks are reached; followed by a rapid increase in depth as discharge increases. Rate of increase of velocity with increasing discharge either may be slow initially and then increase, or may be rapid initially and then decrease.

The significance of complex hydraulic geometry is twofold. Log-linear regression of partitioned data sets

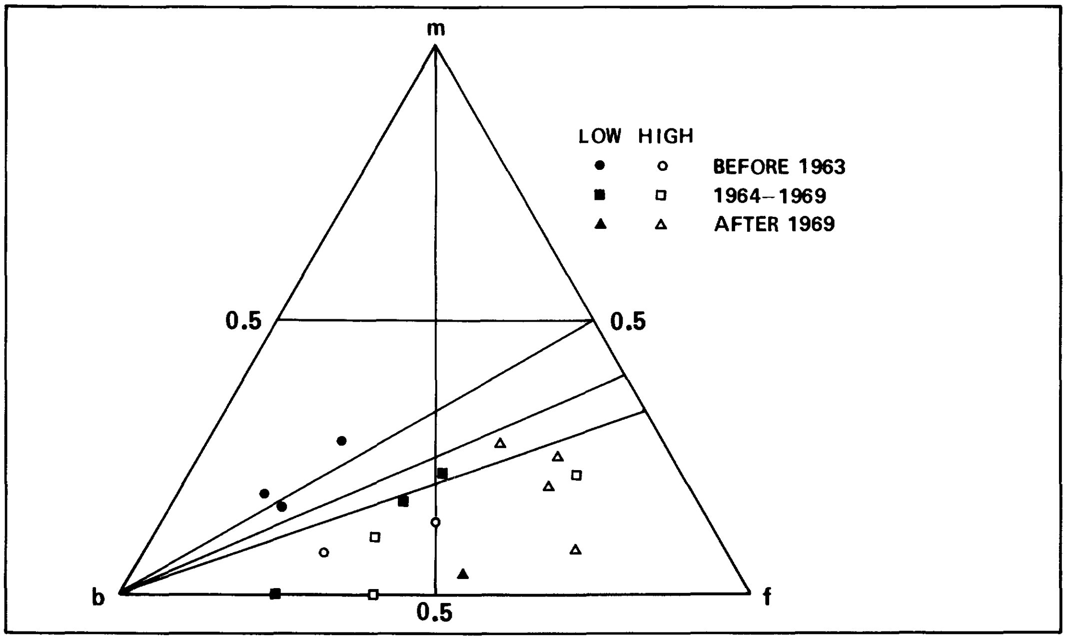


FIGURE 20.—*B-f-m* diagram showing changes in hydraulic-geometry exponents with time. Data from the north channel of the Platte River in the vicinity of the gage near Cozad, Nebraska; partitioned data sets.

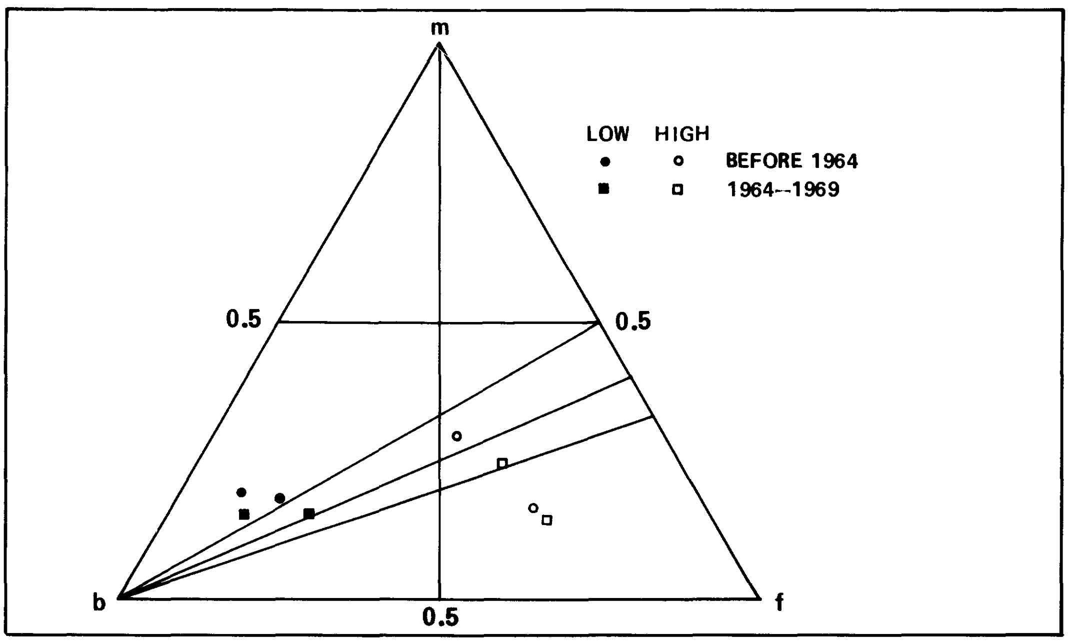


FIGURE 21.—*B-f-m* diagram showing changes in hydraulic-geometry exponents with time. Data from the Platte River in the vicinity of the gage near Odessa, Nebraska; partitioned data sets.

describe how width, depth, and velocity change at certain cross sections with increasing discharge more accurately than do single-power functions of the entire data set. Thus, at least the shape of the relations is conveyed correctly, enabling changes in the width-, depth-, or velocity-discharge relations to be predicted at those sections more accurately than they might be predicted using power functions. Use of partitioned data sets in hydraulic-geometry equations, where appropriate, should reduce or eliminate autocorrelation of the residuals from the single linear relation, resulting in a more accurate estimation of standard errors.

The existence of a break in the slope of the width-discharge relation is of primary importance for this study (for example, fig. 5). Above the break, the entire channel width may be occupied, at a shallow depth, by a discharge of relatively high duration. Because vegetative encroachment and stabilization of the channel banks and bars is part of the process of width reduction on the Platte River (Eschner, Hadley, and Crowley, 1981), the further establishment of vegetation must be prevented if the existing channel width is to be maintained.

Seeds may be prevented from germinating if there is no exposed substrate on which they can grow. Young vegetation may be removed if it is inundated with water of a velocity sufficient to scour it out, or it may be killed if inundated for a sufficient period of time. The sections of channel where a single power function does not describe the hydraulic geometry may be kept free of vegetation by relatively low flows, because the bed will be covered completely by those flows. For example, near Cozad, the mean annual discharge for the period 1953 to 1979 was 14.0 m^3/s. Discharges at which the slope of the hydraulic-geometry relations from the north channel near Cozad changes (figs. 9 and 10) are much lower than mean annual discharge. For the section 60 m below the Cozad gage, the width-discharge and depth-discharge relations appear to change slope at about 2 m^3/s. For the section 120 m below the Cozad gage, the width-discharge relation flattens out at about 3 m^3/s and the depth-discharge relation exhibits a break in slope at about 3 m^3/s. Thus, the discharge of the north channel at which the hydraulic-geometry relations change is less than half of the mean annual discharge for the entire channel near Cozad.

IMPLICATIONS AND LIMITATIONS OF AT-A-STATION HYDRAULIC-GEOMETRY RELATIONS

The form of some of the at-a-station hydraulic-geometry relations for the Platte River suggests that present channel dimensions may be related to relatively high-duration discharges. This analysis indicates that the discharges at which the rates of change of hydraulic and morphologic variables change are well below bankfull discharge, and may approximate the lower mean annual discharge. These discharges may not maintain the present channel characteristics, but it surely can be assumed that discharges below these values will probably not be able to maintain the channel. When these minimum values are compared with the values necessary for channel maintenance obtained by other methods, the applicability and limitations of the minimum values become evident.

Kircher (1981) determined the effective discharge, defined as the mean of the small range of discharges, that moves the most sediment during a year, for several sections along the Platte River. For the area near Overton, Kircher obtained a value of 40.9 m^3/s as the effective discharge for the period 1950–1980. Mean annual discharge for the same period was 39.4 m^3/s. The effective discharge, then, was close to the mean annual discharge. The effective discharge for the months May to August for 1950 to 1980 was determined to be 157.7 m^3/s, much greater than the mean annual discharge. The months May to August were selected, because germination occurs during this period. The effective discharge for this period should both prevent germination and uproot small seedlings.

Karlinger and others (1981) applied theoretical equations developed by Parker (1978) to estimate the discharge necessary for maintaining cross-sectional characteristics of the Platte River channel. For a reach near Overton where the width is about 180 m, the necessary discharge was determined to be 107.6 m^3/s. The depth corresponding to this discharge was estimated to be 0.6 m. The discharge necessary to cover the channel bed at this section, hence the discharge at which the width- and depth-discharge relations change, is estimated to be about 22 m^3/s. The value obtained by Karlinger and others (1981) lies between that obtained from the width-discharge relation and that determined by Kircher (1981) as the effective discharge for the critical germination period.

Crowley (1981) discussed the movement of macroforms, bedforms which average 1 to 1½ m in height, and their effect on maintenance of channel width. By moving downstream, these large bedforms can uproot vegetation. In order to move, the macroform must be covered by at least 20 cm of water. For the river near Overton, approximately 80 m^3/s would be required to move the macroforms. This value is twice the mean annual discharge, and is about three-fourths of the value obtained from the theoretical equations.

SUMMARY AND CONCLUSIONS

Hydrology and morphology of the Platte River in south-central Nebraska have changed since settlement of the river basin (Eschner, Hadley, and Crowley, 1981). Peak discharges have decreased, and the formerly wide, open channel has narrowed, as sandbars have become vegetated and formed permanent islands. These changes in the Platte River have prompted concern for the habitat of migratory birds, particularly whooping cranes and sandhill cranes. This study was undertaken to compute at-a-station hydraulic geometry at selected sites, to examine how the relations have changed with time, and to determine the significance of the relations for channel maintenance.

At-a-station hydraulic geometry of the Platte River in south-central Nebraska is complex. The range of exponents of simple log-linear relations is large, both between different reaches of the river, and among different sectons within a given reach of the river (table 1). The at-a-station exponents plot in several fields of the *b-f-m* diagram (fig. 17) suggesting that morphologic and hydrologic changes with increasing discharge vary considerably. Systematic changes in the plotting positions of the hydraulic-geometry exponents from simple power functions with time indicate that the rates of change of the width, depth, and velocity with increasing discharge have varied with time. In general, the width exponent has decreased, although trends are not readily apparent in the other exponents.

Breaks in the slopes of the width-, depth-, and velocity-discharge relations at a certain discharge on plots of the hydraulic-geometry for both data summarized from discharge notes (figs. 4 through 12) and data from field measurements made for this study (figs. 13, 14, and 15) indicate that simple power functions are not the proper model in all instances. These breaks in slope can serve to partition the data sets. Power functions fit separately to the partitioned data fit the data significantly better than simple power functions for several locations. The exponents of hydraulic geometry relations based on partitioned data sets indicate the effect of the range of discharge values. Part of the observed change in plotting positions on the *b-f-m* diagram of the exponents from simple power functions results because the range of discharges for different time intervals is not the same. Much of the change of plotting positions is eliminated if the data sets are partitioned.

The shape of the channel cross section and, perhaps, changes in roughness with increasing discharge account for the shape of complex hydraulic-geometry relations. As the channel bed is inundated, width increases rapidly and depth increases slowly. Once the entire channel bed is covered and the banks are reached, width cannot increase appreciably but depth can increase rapidly.

Complex at-a-station hydraulic-geometry relations have significance for channel maintenance and suggest that existing channel dimensions may be related to relatively low-magnitude flows. Vegetation must not become established in the channel if the existing width is to be maintained. This can be accomplished by preventing germination of seeds or by uprooting young established seedlings. The discharge at which the entire channel bed is covered and at which the width- and depth-discharge relations change represents a minimum value for channel maintenance. Although this minimum discharge may not maintain the channel, discharges below this value will afford channel area for seed germination and thus cannot prevent vegetation establishment. For a given cross section, the discharge at which the hydraulic geometry relations change is generally less than annual mean discharge.

REFERENCES CITED

Carlston, C. W., 1969, Downstream variations in the hydraulic geometry of streams: Special emphasis on mean velocity: American Journal of Science, v. 267, p. 499–509.

Crowley, K. D., 1981, Large-scale bedforms in the Platte River: Structure process, and relation to channel narrowing: U.S. Geological Survey Open-File Report 81-1059, 33 p.

Eschner, T. R., Hadley, R. F., and Crowley, K. D., 1981, Hydrologic and morphologic changes in channels of the Platte River Basin: A historical perspective: U.S. Geological Survey Open-File Report 81-1125, 57 p.

Fenneman, N. M., 1931, Physiography of western United States: New York, McGraw-Hill, 534 p.

Frith, Charles, 1974, The ecology of the Platte River as related to sandhill cranes and other waterfowl in southcentral Nebraska: MS thesis, Kearney, Nebraska, Kearney State College, 115 p.

Karlinger, M. R., Mengis, R. C., Kircher, J. E., and Eschner, T. R., 1981, Application of theoretical equations to estimate the discharge needed to maintain channel width in a reach of the Platte River near Lexington, Nebraska: U.S. Geological Survey Open-File Report 81-697, 16 p.

Kircher, J. E., 1981, Sediment transport and effective discharge for the North Platte, South Platte, and Platte Rivers in Nebraska: U.S. Geological Survey Open-File Report 81-53, 26 p.

Kircher, J. E., and Karlinger, M. R., 1981, Changes in surface-water hydrology for the Platte River basin: U.S. Geological Survey Open-File Report 81-818, 77 p.

Knighton, A. D., 1975, Variations in at-a-station hydraulic geometry: American Journal of Science, v. 275, p. 186–218.

_____1977, Short-term changes in hydraulic geometry, *in* Gregory, K. J., ed., River channel changes: Chichester, England, John Wiley, p. 101–119.

_____1979, Comments on log-quadratic relations in hydraulic geometry: Earth Surface Processes, v. 4, p. 205–209.

Langbein, W. B., 1964, Geometry of river channels: American Society of Civil Engineers Journal of Hydraulics Division, v. 90, p. 301–312.

Leopold, L. B., and Langbein, W. B., 1962, The concept of entropy in landscape evolution: U.S. Geological Survey Professional Paper 500-A, 20 p.

Leopold, L. B., and Maddock, Thomas, Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geological Survey Professional Paper 252, 57 p.

Nadler, C. T., Jr., 1978, River metamorphosis of the South Platte and Arkansas Rivers, Colorado: MS thesis, Fort Collins, Colorado, Colorado State University, 151 p.

Park, C. C., 1977, World-wide variations in hydraulic geometry exponents of stream channels: An analysis and some observations: Journal of Hydrology, v. 38, p. 133–146.

_____1978, World-wide variations in hydraulic geometry exponents of stream channels: An analysis and some observations—reply: Journal of Hydrology, v. 39, p. 199–202.

Parker, Gary, 1978, Self-formed straight rivers with equilibrium banks and mobile bed. Part I. The sand-silt river: Journal of Fluid Mechanics, v. 89, pt. 1, p. 109–125.

Pickup, G., and Rieger, W. A., 1979, A conceptual model of the relationship between channel characteristics and discharge: Earth Surface Processes, v. 4, p. 37-42.

Rhodes, D. D., 1977, The b-f-m diagram: Graphical representation and interpretation of at-a-station hydraulic geometry: American Journal of Science, v. 277, p. 73-96.

_____1978, World-wide variations in hydraulic geometry exponents of stream channels: An analysis and some observations—comments: Journal of Hydrology, v. 39, p. 193-197.

Richards, K. S., 1973, Hydraulic geometry and channel roughness: A non-linear system: American Journal of Science, v. 273, p. 877-896.

_____1976, complex width-discharge relations in natural river sections: Geological Society of America Bulletin, v. 87, p. 199-206.

_____1977, Channel and flow geometry: a geomorphological perspective: Progress in Physical Geometry, v. 1, p. 65-102.

Schumm, S. A., 1960, The shape of alluvial channels in relation to sediment type: U.S. Geological Survey Professional Paper 352-B, p. 17-30.

_____1968, River adjustment to altered hydrologic regimen, Murrumbidgee River and paleochannels, Australia: U.S. Geological Survey Professional Paper 598, 65 p.

Smith, T. R., 1974, A derivation of the hydraulic geometry of steady state channels from conservation principles and sediment transport laws: Journal of Geology, v. 82, p. 98-104.

Thornes, J. B., 1970, The hydraulic geometry of stream channels in the Xingu-Araguaia headwaters: Geographical Journal, v. 136, p. 376-382.

_____1977, Hydraulic geometry and channel change, *in* Gregory, K. J., ed., River channel changes: Chichester, England, John Wiley, p. 91-100.

U.S. Fish and Wildlife Service, 1978, Determination of critical habitat for the whooping crane: Federal Register, v. 43, no. 94, p. 20938-20942.

_____1981, The Platte River ecology study: U.S. Department of the Interior, Fish and Wildlife Service Special Research Report, 187 p.

Wilcock, D. N., 1971, Investigation into the relations between bedload transport and channel shape: Geological Society of America Bulletin, v. 82, p. 2159-2176.

Williams, G. P., 1978a, Hydraulic geometry of river cross sections—theory of minimum variance: U.S. Geological Survey Professional Paper 1029, 47 p.

_____1978b, The case of the shrinking channels—the North Platte and Platte Rivers in Nebraska: U.S. Geological Survey Circular 781, 48 p.

Wolman, M. G., 1955, The natural channel of Brandywine Creek Pennsylvania: U.S. Geological Survey Professional Paper 271, 56 p.

Wolman, M. G., and Brush, L. M., Jr., 1961, Factors controlling the size and shape of stream channels in coarse noncohesive sands: U.S. Geological Survey Professional Paper 282-G, 28 p.

SUMMARY OF STATISTICAL DATA

TABLE 2.—*Significance levels for at-a-station hydraulic-geometry equations from summarized data*

Variable	Platte River near:	Distance below gage (meters)	Testing regression	Period of record	n	Regression sum of squares	Error sum of squares	F-statistic	Significance level 0.10	0.05	0.01	0.001
W	Cozad	30	Y on X	1961–1979	30	2.469174	0.006662	370.75	x	x	x	x
V	Cozad	30	Y on X	1961–1979	30	0.279886	0.001833	152.95	x	x	x	x
D	Cozad	30	Y on X	1961–1979	30	3.673960	0.007333	193.21	x	x	x	x
W	Cozad	30	Y on X	1961–1963	3	0.57133	0.00290	196.84	x	x		
V	Cozad	30	Y on X	1961–1963	3	0.04949	0.000031	1,594.40	x	x		
D	Cozad	30	Y on X	1961–1963	3	0.14535	0.00353	41.09	x			
W	Cozad	30	Y on X	1964–1969	6	0.15573	0.00960	16.24	x	x		
V	Cozad	30	Y on X	1964–1969	6	0.05462	0.00337	16.24	x	x		
D	Cozad	30	Y on X	1964–1969	6	0.03028	0.00228	13.32	x	x		
W	Cozad	30	Y on X	1970–1979	21	1.09755	0.005369	204.39	x	x	x	x
V	Cozad	30	Y on X	1970–1979	21	0.132768	0.001145	115.45	x	x	x	x
D	Cozad	30	Y on X	1970–1979	21	0.531339	0.003656	145.33	x	x	x	x
W	Cozad	45	Y on X	1954–1979	30	2.10585	0.01251	168.33	x	x	x	x
			Low		8	.59899	.01741	34.40	x	x	x	x
			High		22	.38114	.005845	65.21	x	x	x	x
V	Cozad	45	Y on X	1954–1979	30	0.155475	0.008515	18.26	x	x	x	x
			Low		8	.00560	.01163	.48				
			High		22	.04997	.00821	6.09	x	x		
D	Cozad	45	Y on X	1954–1979	30	1.01994	0.01442	70.73	x	x	x	x
			Low		8	.01542	.00710	2.17				
			High		22	.65535	.01281	51.16	x	x	x	x
W	Cozad	45	Y on X	1954–1969	9	1.7758	0.0199	84.49	x	x	x	x
			Low		5	.27336	.03425	7.98	x	x		
			High		4	.31156	.00460	67.75	x	x	x	
V	Cozad	45	Y on X	1954–1969	9	0.1384	0.0101	13.76	x	x	x	
			Low		5	.00011	.01826	.01				
			High		4	.02003	.00028	72.59	x	x	x	
D	Cozad	45	Y on X	1954–1969	9	0.52064	0.00394	132.25	x	x	x	x
			Low		5	.02872	.03425	.84				
			High		4	.13875	.00460	30.17	x	x		
W	Cozad	45	Y on X	1970–1979	21	0.138480	0.002437	56.82	x	x	x	x
			High		18	.06605	.00245	26.96	x	x	x	x
V	Cozad	45	Y on X	1970–1979	21	0.015929	0.008576	1.86				
			High		18	.00767	.00973	.79				
D	Cozad	45	Y on X	1970–1979	21	0.704423	0.008997	78.30	x	x	x	x
			High		18	.56005	.00963	58.13	x	x	x	x
D	Cozad	60	Y on X	1953–1979	73	11.49118	0.01671	687.68	x	x	x	x
			Low		25	4.45530	.01960	227.31	x	x	x	x
			High		48	.56799	.00827	68.69	x	x	x	x
V	Cozad	60	Y on X	1953–1979	73	1.51974	0.01029	147.69	x	x	x	x
			Low		25	.36342	.02412	15.07	x	x	x	x
			High		48	.16379	.00382	42.86	x	x	x	x
D	Cozad	60	Y on X	1953–1979	73	2.98305	0.01182	252.37	x	x	x	x
			Low		25	.15681	.00617	25.40	x	x	x	x
			High		48	.90036	.00739	121.88	x	x	x	x
W	Cozad	60	Y on X	1953–1957	11	2.7491	0.0389	70.56	x	x	x	x
V	Cozad	60	Y on X	1953–1957	11	0.1933	0.0497	3.88	x			
D	Cozad	60	Y on X	1953–1957	11	0.16872	0.00335	50.41	x	x	x	x
W	Cozad	60	Y on X	1958–1963	15	2.0328	0.0158	128.60	x	x	x	x
V	Cozad	60	Y on X	1958–1963	15	0.20856	0.00334	62.41	x	x	x	x
D	Cozad	60	Y on X	1958–1963	15	1.0032	0.0123	81.72	x	x	x	x
W	Cozad	60	Y on X	1953–1963	26							
			Low		15	3.03395	0.02966	102.29	x	x	x	x
			High		11	.26945	.01690	15.94	x	x	x	
V	Cozad	60	Y on X	1953–1963	26							
			Low		15	0.21365	0.03581	5.97	x	x		
			High		11	.02390	.00350	6.65	x	x		
D	Cozad	60	Y on X	1953–1963	26							
			Low		15	0.12763	0.00736	17.33	x	x	x	x
			High		11	.27101	.01106	24.50	x	x	x	x
W	Cozad	60	Y on X	1964–1969	13	0.93046	0.00483	179.02	x	x	x	x
			Low		3	.15643	.00649	24.11	x	x		
			High		10	.22226	.00126	176.09	x	x	x	x
V	Cozad	60	Y on X	1964–1969	13	0.34010	0.00230	147.62	x	x	x	x
			Low		3	.02848	.00909	3.13				
			High		10	.07628	.00120	63.36	x	x	x	x
D	Cozad	60	Y on X	1964–1969	13	0.37346	0.00721	51.70	x	x	x	x
			Low		3	.00268	.00022	12.39	x			
			High		10	.26363	.00157	167.44	x	x	x	x
W	Cozad	60	Y on X	1970–1979	34	0.675620	0.007885	85.68	x	x	x	x
			Low		7	.15766	.00403	39.06	x	x	x	x
			High		27	.03985	.00445	8.94	x	x	x	
V	Cozad	60	Y on X	1970–1979	34	0.125167	0.004224	29.63	x	x	x	x
			Low		7	.00006	.00060	.10				
			High		27	.08001	.00462	17.14	x	x	x	x

TABLE 2.—*Significance levels for at-a-station hydraulic-geometry equations from summarized data*—Continued

Variable	Platte River near:	Distance below gage (meters)	Testing regression	Period of record	n	Regression sum of squares	Error sum of squares	F-statistic	Significance level 0.10	0.05	0.01	0.001
D	Cozad	60	Y on X	1970–1979	34	0.964612	0.007636	126.32	x	x	x	x
			Low		7	.00004	.00275	.01				
			High		27	.41468	.00706	58.68	x	x	x	x
W	Cozad	75	Y on X	1961–1979	46	1.585857	0.006428	246.71	x	x	x	x
			Low		15	.21177	.00505	41.99	x	x	x	x
			High		31	.67218	.00580	115.99	x	x	x	x
V	Cozad	75	Y on X	1961–1979	46	0.346376	0.002718	127.44	x	x	x	x
			Low		15	.08656	.00164	52.85	x	x	x	x
			High		31	.03916	.00219	17.81	x	x	x	x
D	Cozad	75	Y on X	1961–1979	46	1.103953	0.005522	199.92	x	x	x	x
			Low		15	.00106	.00321	.32				
			High		31	.31658	.00443	71.40	x	x	x	x
W	Cozad	75	Y on X	1961–1963	15	0.043926	0.00375	117.07	x	x	x	x
			Low		6	.04431	.00244	18.15	x	x	x	
			High		9	.28454	.00198	143.76	x	x	x	x
V	Cozad	75	Y on X	1961–1963	15	0.3549	0.00195	18.23	x	x	x	x
			Low		6	.01336	.00091	14.75	x	x		
			High		9	.05634	.00453	12.46	x	x	x	
D	Cozad	75	Y on X	1961–1963	15	0.22520	0.00371	60.68	x	x	x	x
			Low		6	.00757	.00075	10.05	x	x		
			High		9	.00354	.00205	1.72				
W	Cozad	75	Y on X	1964–1969	12	1.12738	0.00484	232.87	x	x	x	x
			Low		5	.10291	.00618	16.65	x	x		
			High		7	.16234	.00347	46.79	x	x	x	x
V	Cozad	75	Y on X	1964–1969	12	0.18892	0.00135	140.42	x	x	x	x
			Low		5	.02361	.00046	51.55	x	x	x	
			High		7	.00575	.00029	19.54	x	x	x	
D	Cozad	75	Y on X	1964–1969	12	0.34943	0.00526	66.42	x	x	x	x
			Low		5	.00225	.00352	.64				
			High		7	.06900	.00211	32.60	x	x	x	
W	Cozad	75	Y on X	1970–1979	19	0.085085	0.002278	37.35	x	x	x	x
			High		15	.004352	.00249	17.47	x	x	x	
V	Cozad	75	Y on X	1970–1979	19	0.132970	0.001599	83.16	x	x	x	x
			High		15	.05019	.00186	27.04	x	x	x	x
D	Cozad	75	Y on X	1970–1979	19	0.486102	0.003464	140.33	x	x	x	x
			High		15	.14776	.00400	36.97	x	x	x	x
W	Cozad	120	Y on X	1951–1979	153	19.87165	0.01202	1,65322	x	x	x	x
			Low		63	12.66166	.00906	1,397.26	x	x	x	x
			High		90	.25444	.00272	93.70	x	x	x	x
V	Cozad	120	Y on X	1951–1979	153	2.785591	0.004004	695.70	x	x	x	x
			Low		63	.95552	.00746	127.92	x	x	x	x
			High		90	.18221	.00153	119.03	x	x	x	x
D	Cozad	120	Y on X	1951–1979	153	7.799154	0.009340	835.03	x	x	x	x
			Low		63	1.39596	.00603	231.65	x	x	x	x
			High		90	1.63983	.00243	676.00	x	x	x	x
W	Cozad	120	Y on X	1951–1963	32	8.4442	0.0129	656.38	x	x	x	x
			Low		28	5.388868	.01296	415.75	x	x	x	x
V	Cozad	120	Y on X	1951–1963	32	0.5925	0.0129	46.10	x	x	x	x
			Low		28	.29907	.01474	20.25	x	x	x	x
D	Cozad	120	Y on X	1951–1963	32	1.07189	0.00682	257.25	x	x	x	x
			Low		28	.43142	.00661	65.29	x	x	x	x
W	Cozad	120	Y on X	1964–1969	82	0.34519	0.00272	127.01	x	x	x	x
			Low		42	.18675	.00406	45.97	x	x	x	x
			High		40	.02623	.00153	17.14	x	x	x	x
V	Cozad	120	Y on X	1964–1969	82	0.39503	0.00078	504.45	x	x	x	x
			Low		42	.02481	.00082	30.36	x	x	x	x
			High		40	.04738	.00055	86.68	x	x	x	x
D	Cozad	120	Y on X	1964–1969	82	1.66396	0.00208	800.89	x	x	x	x
			Low		42	.11284	.00370	30.47	x	x	x	x
			High		40	.37284	.00092	404.41	x	x	x	x
W	Cozad	120	Y on X	1970–1979	39	0.701922	0.004423	158.70	x	x	x	x
			Low		14	.11042	.00515	21.44	x	x	x	x
			High		25	.16778	.00218	76.91	x	x	x	x
V	Cozad	120	Y on X	1970–1979	39	0.151930	0.002814	53.99	x	x	x	x
			Low		14	.00083	.00256	.32				
			High		25	.14213	.00221	64.32	x	x	x	x
D	Cozad	120	Y on X	1970–1979	39	1.969314	0.004547	433.10	x	x	x	x
			Low		14	.15802	.00327	48.30	x	x	x	x
			High		25	1.21734	.00323	376.75	x	x	x	x
W	Overton, north channel	30	Y on X	1968–1976	14	0.196206	0.006256	31.36	x	x	x	x
V	Overton, north channel	30	Y on X	1968–1976	14	0.051963	0.001103	47.11	x	x	x	x

TABLE 2.—*Significance levels for at-a-station hydraulic-geometry equations from summarized data*—Continued

Variable	Platte River near:	Distance below gage (meters)	Testing regression	Period of record	n	Regression sum of squares	Error sum of squares	F-statistic	Significance level 0.10	0.05	0.01	0.001
D	Overton, north channel	30	Y on X	1968–1976	14	0.130150	0.004312	30.18	x	x	x	x
W	Overton, south channel	30	Y on X	1968–1976	20	0.952106	0.002543	374.40	x	x	x	x
V	Overton, south channel	30	Y on X	1968–1976	20	0.0161493	0.0009511	16.98	x	x	x	x
D	Overton, south channel	30	Y on X	1968–1976	20	0.528872	0.002149	246.10	x	x	x	x
W	Overton	30	Y on X	1961–1968	11	0.67557	0.00997	67.73	x	x	x	x
V	Overton	30	Y on X	1961–1968	11	0.00714	0.00163	4.37	x			
D	Overton	30	Y on X	1961–1968	11	0.14293	0.00900	1.59				
W	Overton, north channel	45	Y on X	1968–1976	25	0.326028	0.002975	109.59	x	x	x	x
			Low		10	.03135	.00533	5.86	x	x		
			High		15	.01072	.00108	9.92	x	x	x	
V	Overton, north channel	45	Y on X	1968–1976	25	0.142227	0.001261	112.79	x	x	x	x
			Low		10	.05074	.00159	31.92	x	x	x	x
			High		15	.01344	.00070	19.18	x	x	x	
D	Overton, north channel	45	Y on X	1968–1976	25	0.28635	0.003402	84.17	x	x	x	x
			Low		10	.03162	.00696	4.54	x			
			High		15	.06995	.00101	69.22	x	x	x	x
W	Overton	45	Y on X	1961–1963	7	0.47005	0.00759	61.94	x	x	x	x
V	Overton	45	Y on X	1961–1963	7	0.00128	0.00592	.21				
D	Overton	45	Y on X	1961–1963	7	0.01013	0.00142	7.13	x	x		
W	Overton, north channel	60	Y on X	1968–1976	53	0.680470	0.004211	161.59	x	x	x	x
			Low		20	.21689	.00700	31.02	x	x	x	x
			High		33	.00064	.00134	.48				
V	Overton, north channel	60	Y on X	1968–1976	53	0.203593	0.001548	131.52	x	x	x	x
			Low		20	.00762	.00043	9.73	x	x	x	
			High		33			17.72	x	x	x	x
D	Overton, north channel	60	Y on X	1968–1976	53	0.541680	0.004389	123.42	x	x	x	x
			Low		20	.05723	.00703	8.12	x	x		
			High		33	.17544	.00125	139.95	x	x	x	x
W	Overton	60	Y on X	1954–1968	46	2.12162	0.00878	241.80	x	x	x	x
			Low		16	.02629	.01214	2.16				
			High		30	.3977	.00357	111.30	x	x	x	x
V	Overton	60	Y on X	1954–1968	46	0.11113	0.00301	36.97	x	x	x	x
			Low		16	.00014	.00424	.03				
			High		30	.09061	.00204	44.49	x	x	x	x
D	Overton	60	Y on X	1954–1968	46	0.19631	0.00610	32.15	x	x	x	x
			Low		16	.03116	.00921	3.39	x			
			High		30	.18349	.00292	62.88	x	x	x	x
W	Overton	60	Y on X	1954–1963	18	1.57824	0.00813	194.04	x	x	x	x
			Low		7	.02303	.01267	1.82				
			High		11	.20046	.00215	93.32	x	x	x	x
V	Overton	60	Y on X	1954–1963	18	0.05105	0.00130	39.44	x	x	x	x
			Low		7	.00071	.00098	.72				
			High		11	.03467	.00097	35.64	x	x	x	x
D	Overton	60	Y on X	1954–1963	18	0.05669	0.00479	11.83	x	x	x	
			Low		7	.00033	.00846	.04				
			High		11	.05523	.00173	32.04	x	x	x	x
W	Overton	60	Y on X	1964–1968	28	0.67519	0.00465	145.20	x	x	x	x
			Low		9	.00608	.00080	7.56	x	x		
			High		19	.12427	.00449	27.67	x	x	x	x
V	Overton	60	Y on X	1964–1968	28	0.04065	0.00362	11.22	x	x	x	
			Low		9	.00007	.00617	.01				
			High		19	.02435	.00278	8.76	x	x	x	
D	Overton	60	Y on X	1964–1968	28	0.11258	0.00515	21.90	x	x	x	x
			Low		9	.05027	.00479	10.50	x	x		
			High		19	.07082	.00375	18.92	x	x	x	x
W	Overton	75	Y on X	1962–1968	51	0.85980	0.00436	197.20	x	x	x	x
			Low		17	.17490	.00492	35.52	x	x	x	x
			High		34	.21246	.003344	61.78	x	x	x	x
V	Overton	75	Y on X	1962–1968	51	0.27048	0.00234	115.59	x	x	x	x
			Low		17	.00246	.001129	2.19				
			High		34	.14042	.00258	54.46	x	x	x	x
D	Overton	75	Y on X	1962–1968	51	0.20581	0.00290	70.97	x	x	x	x
			Low		17	.00573	.00357	1.61				
			High		34	.07405	.00267	27.77	x	x	x	x

TABLE 2.—*Significance levels for at-a-station hydraulic-geometry equations from summarized data*—Continued

Variable	Platte River near:	Distance below gage (meters)	Testing regression	Period of record	n	Regression sum of squares	Error sum of squares	F-statistic	Significance level 0.10	0.05	0.01	0.001
W	Overton, north channel	75	Y on X	1968–1976	8	0.0012756	0.0005457	2.34				
V	Overton, north channel	75	Y on X	1968–1976	8	0.0368640	0.0006871	53.65	x	x	x	x
D	Overton, north channel	75	Y on X	1968–1976	8	0.0447134	0.0003512	127.32	x	x	x	x
W	Overton	75	Y on X	1962–1963	8	0.05917	0.00877	6.76	x	x		
V	Overton	75	Y on X	1962–1963	8	0.02833	0.00061	46.79	x	x	x	x
D	Overton	75	Y on X	1962–1963	8	0.04782	0.00540	8.88	x	x		
W	Overton	75	Y on X	1964–1968	43	0.79032	0.00370	213.74	x	x	x	x
			Low		13	.11570	.00296	39.19	x	x	x	x
			High		30	.20058	.00355	56.55	x	x	x	x
V	Overton	75	Y on X	1964–1968	43	0.24402	0.00266	91.78	x	x	x	x
			Low		13	.00050	.00120	.50				
			High		30	.13332	.00285	46.79	x	x	x	x
D	Overton	75	Y on X	1964–1968	43	0.16379	0.00253	64.64	x	x	x	x
			Low		13	.00615	.00265	2.31				
			High		30	.05425	.00264	20.52	x	x	x	x
W	Overton, north channel	90	Y on X	1968–1978	33	0.281233	0.003713	75.74	x	x	x	x
			Low		10	.06885	.00167	41.09	x	x	x	x
			High		23	.02127	.00307	6.92	x	x		
V	Overton, north channel	90	Y on X	1968–1978	33	0.178685	0.001486	120.25	x	x	x	x
			Low		10	.00381	.00114	3.31				
			High		23	.09554	.00121	78.85	x	x	x	x
D	Overton, north channel	90	Y on X	1968–1978	33	0.530304	0.001724	307.60	x	x	x	x
			Low		10	.00595	.00157	3.80	x			
			High		23	.17726	.00142	124.99	x	x	x	x
W	Overton, south channel	90	Y on X	1968–1978	23	0.25592	0.01347	19.00	x	x	x	x
V	Overton, south channel	90	Y on X	1968–1978	23	0.143793	0.003713	38.73	x	x	x	x
D	Overton, south channel	90	Y on X	1968–1978	23	0.178088	0.009934	17.93	x	x	x	x
W	Overton	90	Y on X	1962–1968	160	2.71652	0.00421	645.25	x	x	x	x
			Low		75	1.15854	.00546	212.28	x	x	x	x
			High		85	.03305	.00076	43.56	x	x	x	x
V	Overton	90	Y on X	1962–1968	160	0.51750	0.00152	340.46	x	x	x	x
			Low		75	.03573	.00201	17.72	x	x	x	x
			High		85	.04231	.00088	47.89	x	x	x	x
D	Overton	90	Y on X	1962–1968	160	1.24976	0.00426	293.37	x	x	x	x
			Low		75	.06586	.00606	10.89	x	x	x	
			High		85	.29093	.00140	207.65	x	x	x	x
W	Overton	90	Y on X	1962–1963	41	0.80779	0.00549	147.14	x	x	x	x
			Low		22	.54046	.00400	135.26	x	x	x	x
			High		19	.00309	.00031	9.92	x	x		
V	Overton	90	Y on X	1962–1963	41	0.11225	0.00107	105.06	x	x	x	x
			Low		22	.00893	.00134	6.71	x	x		
			High		19	.01487	.00045	33.41	x	x	x	x
D	Overton	90	Y on X	1962–1963	41	0.28229	0.00363	77.79	x	x	x	x
			Low		22	.00141	.00274	.52				
			High		19	.06553	.00072	91.58	x	x	x	x
W	Overton	90	Y on X	1964–1968	119	1.90815	0.00380	501.76	x	x	x	x
			Low		53	.63762	.00581	109.83	x	x	x	x
			High		66	.03121	.00088	35.52	x	x	x	x
V	Overton	90	Y on X	1964–1968	119	0.40611	0.00168	241.49	x	x	x	x
			Low		53	.02596	.00232	11.16	x	x	x	
			High		66	.02836	.00101	27.98	x	x	x	x
D	Overton	90	Y on X	1964–1968	119	0.96578	0.00453	213.45	x	x	x	x
			Low		53	.08278	.00724	11.42	x	x	x	
			High		66	.22458	.00161	139.24	x	x	x	x
W	Odessa	60	Y on X	1962–1979	55	8.280655	0.006983	1,185.83	x	x	x	x
			Low		38	3.79507	.00929	408.85	x	x	x	x
			High		17	.01874	.00133	14.06	x	x	x	
V	Odessa	60	Y on X	1962–1979	55	0.469099	0.004171	112.47	x	x	x	x
			Low		38	.25506	.00447	57.00	x	x	x	x
			High		17	.00091	.00360	.25				

TABLE 2.—*Significance levels for at-a-station hydraulic-geometry equations from summarized data*—Continued

Variable	Platte River near:	Distance below gage (meters)	Testing regression	Period of record	n	Regression sum of squares	Error sum of squares	F-statistic	Significance level			
									0.10	0.05	0.01	0.001
D	Odessa	60	Y on X	1962–1979	55	1.03098	0.01269	81.24	x	x	x	x
			Low		38	.29176	.01567	18.58	x	x	x	x
			High		17	.041148	.00464	8.88	x	x	x	
W	Odessa	60	Y on X	1962–1963	26	5.39766	0.00600	900.00	x	x	x	x
			Low		15	2.55189	.00901	283.25	x	x	x	x
			High		11	.00632	.00133	4.75	x			
V	Odessa	60	Y on X	1962–1963	26	0.39093	0.00339	115.56	x	x	x	x
			Low		15	.18391	.00606	30.36	x	x	x	x
			High		11	.00546	.00012	45.70	x	x	x	x
D	Odessa	60	Y on X	1962–1963	26	0.21598	0.00846	25.50	x	x	x	x
			Low		15	.05000	.01351	3.69	x			
			High		11	.00907	.00137	6.66	x	x		
W	Odessa	60	Y on X	1964–1969	19	1.66754	0.00521	320.05	x	x	x	x
V	Odessa	60	Y on X	1964–1969	19	0.06890	0.00368	18.66	x	x	x	x
D	Odessa	60	Y on X	1964–1969	19	0.4186	0.0101	41.47	x	x	x	x
W	Odessa	60	Y on X	1970–1979	10	0.325985	0.006496	50.18	x	x	x	x
V	Odessa	60	Y on X	1970–1979	10	0.018275	0.005656	3.23				
D	Odessa	60	Y on X	1970–1979	10	0.22677	0.01112	20.39	x	x	x	
W	Odessa	75	Y on X	1961–1979	60	8.185083	0.006655	229.91	x	x	x	x
			Low		40	6.11130	.00952	641.61	x	x	x	x
			High		20	.00355	.00058	6.10	x	x		
V	Odessa	75	Y on X	1961–1979	60	0.858114	0.004192	204.70	x	x	x	x
			Low		40	.74553	.00544	137.12	x	x	x	x
			High		20	.00201	.00080	2.53				
D	Odessa	75	Y on X	1961–1979	60	0.934258	0.005211	179.29	x	x	x	x
			Low		40	.47876	.00594	80.64	x	x	x	x
			High		20	.01641	.00087	18.84	x	x	x	x
W	Odessa	75	Y on X	1961–1963	9	3.4736	0.0148	235.32	x	x	x	x
V	Odessa	75	Y on X	1961–1963	9	0.5731	0.0146	39.19	x	x	x	x
D	Odessa	75	Y on X	1961–1963	9	0.25476	0.00424	60.06	x	x	x	x
W	Odessa	75	Y on X	1964–1969	45	2.74704	0.00482	569.78	x	x	x	x
			Low		27	1.91408	.00706	271.26	x	x	x	x
			High		18	.00329	.00065	5.02	x	x		
V	Odessa	75	Y on X	1964–1969	45	0.16580	0.00120	138.53	x	x	x	x
			Low		27	.00395	.00154	73.79	x	x	x	x
			High		18	.00109	.00075	1.44				
D	Odessa	75	Y on X	1964–1969	45	0.57759	0.00417	138.53	x	x	x	x
			Low		27	.25188	.00553	45.56	x	x	x	x
			High		18	.01842	.00083	22.28	x	x	x	x
W	Odessa	75	Y on X	1970–1979	6	0.300151	0.005752	52.18	x	x	x	
V	Odessa	75	Y on X	1970–1979	6	0.013869	0.001560	8.89	x	x		
D	Odessa	75	Y on X	1970–1979	6	0.088113	0.004935	17.85	x	x		
W	Odessa	90	Y on X	1953–1979	187	26.01329	0.00751	3,463.82	x	x	x	x
			Low		66	16.14536	.01115	1,448.56	x	x	x	x
			High		121	.14149	.00258	54.91	x	x	x	x
V	Odessa	90	Y on X	1953–1979	187	2.067655	0.001675	1,234.42	x	x	x	x
			Low		66	.95615	.00221	432.64	x	x	x	x
			High		121	.06631	.00136	48.86	x	x	x	x
D	Odessa	90	Y on X	1953–1979	187	2.925669	0.006222	470.21	x	x	x	x
			Low		66	.82710	.00838	98.80	x	x	x	x
			High		121	.34679	.00283	122.54	x	x	x	x
W	Odessa	90	Y on X	1953–1963	45	17.0072	0.0053	3,188.86	x	x	x	x
			Low		18	7.46218	.00899	829.44	x	x	x	x
			High		27	.01986	.00144	13.79	x	x	x	
V	Odessa	90	Y on X	1953–1963	45	1.19649	0.00353	338.93	x	x	x	x
			Low		18	.57036	.00333	171.09	x	x	x	x
			High		27	.00796	.00373	2.13				
D	Odessa	90	Y on X	1953–1963	45	1.64721	0.00739	222.90	x	x	x	x
			Low		18	.45667	.00881	51.84	x	x	x	x
			High		27	.08951	.00428	20.88	x	x	x	x
W	Odessa	90	Y on X	1964–1969	134	4.53298	0.00701	646.68	x	x	x	x
			Low		43	2.52567	.01216	207.65	x	x	x	x
			High		91	.08429	.00185	45.70	x	x	x	x
V	Odessa	90	Y on X	1964–1969	134	0.576022	0.00093	619.01	x	x	x	x
			Low		43	.11170	.00155	72.25	x	x	x	x
			High		91	.07122	.00050	143.28	x	x	x	x
D	Odessa	90	Y on X	1964–1969	134	0.94740	0.00487	194.32	x	x	x	x
			Low		43	.07312	.00827	8.82	x	x	x	
			High		91	.26072	.00170	153.02	x	x	x	x
W	Odessa	90	Y on X	1970–1979	8	0.926422	0.003596	257.63	x	x	x	x
V	Odessa	90	Y on X	1970–1979	8	0.1065735	0.0007208	147.85	x	x	x	x
D	Odessa	90	Y on X	1970–1979	8	0.401328	0.004560	88.01	x	x	x	x

Interpretation of Sediment Data for the South Platte River in Colorado and Nebraska, and the North Platte and Platte Rivers in Nebraska

By JAMES E. KIRCHER

HYDROLOGIC AND GEOMORPHIC STUDIES OF THE PLATTE RIVER BASIN

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1277-D

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1983

CONTENTS

ILLUSTRATIONS

TABLES

INTERPRETATION OF SEDIMENT DATA FOR THE SOUTH PLATTE RIVER IN COLORADO AND NEBRASKA, AND THE NORTH PLATTE AND PLATTE RIVERS IN NEBRASKA

By JAMES E. KIRCHER

ABSTRACT

Sediment data were collected on the South Platte, North Platte, and Platte Rivers during the 1979 and 1980 runoff seasons for a determination of quantity and distribution of sediment in the basin. These data show a decrease in median bed-material size in a downstream direction, except near Overton, Nebraska, where an increase in size corresponds to an increase in local slope. The median grain size varies little with increasing discharge at two stations along the Platte River.

Measured suspended sediment and bedload discharges were combined for a determination of total sediment discharge at four locations in the Platte River basin. The measured total sediment discharge was then compared to the total sediment discharges computed by the modified Einstein procedure and Colby method. This comparison was made by size class and total load for all size classes; it showed very close agreement indicating that field conditions in the Platte River approximate the principles of the two computational methods.

The measured total sediment discharge was then used for the computation of mean daily sediment discharge at four stations in the basin. The mean daily sediment discharges at the four locations were: (1) 597 metric tons per day for the North Platte River at North Platte, Nebraska; (2) 307 metric tons per day for the South Platte River at North Platte, Nebraska; (3) 1,100 metric tons per day for the Platte River near Overton, Nebraska; and (4) 1,130 metric tons per day for the Platte River near Grand Island, Nebraska.

INTRODUCTION

The Platte River is one of the most important rivers of the Great Plains—a source of irrigation water for agriculture and the unique habitat for several species of migrating waterfowl. Ongoing channel and hydraulic changes along the Platte River and its tributaries (Kircher and Karlinger, 1981) caused concern among wildlife and agricultural managers. Therefore, prediction of channel response to anticipated changes in hydraulic factors and the determination of discharges required to maintain a channel of specified or existing cross-sectional properties are critical to management schemes. The prediction of channel response can aid managers in the planning of future projects.

Effective evaluation of management plans requires information on sediment transport in the Platte River. This investigation was undertaken to determine the quantity and distribution of sediment in transport in the Platte River basin. Data presented in this report were collected in 1979 and 1980. Data collected were used to determine suspended-sediment discharges, bedload discharges, bed-material sizes, and total sediment discharges at several locations in the basin. Changes in bed-material size in a downstream direction were also determined along the North Platte and Platte Rivers. Sediment-water-discharge relations and information on bed-material size can be used by resource managers, hydrologists, and other earth scientists to better understand and accommodate the process of sediment discharge in the basin. This information on the sediment characteristics of the river can be used with existing techniques to obtain an estimate of the discharge necessary to maintain a specified channel size.

ACKNOWLEDGMENTS

The author would like to thank the following for helping collect and reduce the data during the 1979 and 1980 field seasons: L. E. Dobson, T. R. Eschner, E. M. Fryer, E. M. Held, M. R. Karlinger, L. R. Newmeyer, and D. Reynolds.

PHYSICAL SETTING

The South Platte and North Platte Rivers originate as snowmelt streams in the Rocky Mountains of Colorado, flowing across the Great Plains to form the Platte River at their confluence at North Platte, Nebraska (fig. 1 and table 1). Total drainage area of the South Platte River is about 62,900 km^2 (square kilometers) and

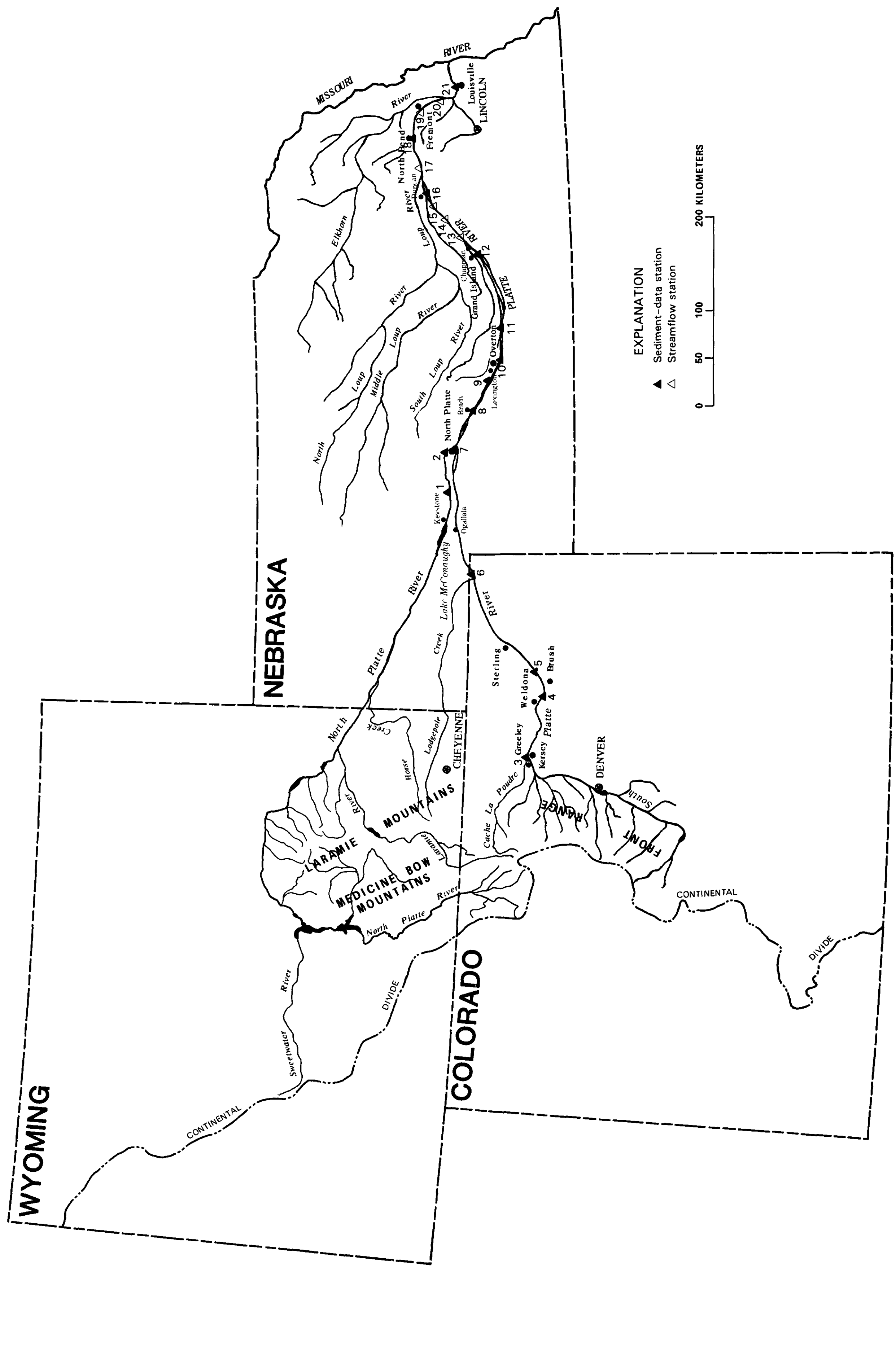


FIGURE 1.—Location of sediment-data stations along the North Platte, South Platte, and Platte Rivers.

TABLE 1.—*Number and name of sediment-data stations*

Station No. in figure 1	U.S. Geological Survey station No.	Station name
1	06691000	North Platte River near Sutherland, Nebraska
2	06693000	North Platte River at North Platte, Nebraska
3	06754000	South Platte River near Kersey, Colorado
4	06758500	South Platte River near Weldona, Colorado
5	06760000	South Platte River at Balzac, Colorado
6	06764000	South Platte River at Julesburg, Colorado
7	06765500	South Platte River at North Platte, Nebraska
8	06766000	Platte River at Brady, Nebraska
9	06766500	Platte River near Cozad, Nebraska
10	06768000	Platte River near Overton, Nebraska
11	06770000	Platte River near Odessa, Nebraska
12	06770500	Platte River near Grand Island, Nebraska
13	06772600	Platte River near Central City, Nebraska
14	06772800	Platte River near Clarks, Nebraska
15	06772850	Platte River near Silver Creek, Nebraska
16	06774000	Platte River near Duncan, Nebraska
17	06794700	Platte River near Schuyler, Nebraska
18	06796000	Platte River near North Bend, Nebraska
19	06796500	Platte River near Fremont, Nebraska
20	06796550	Platte River near Venice, Nebraska
21	06805500	Platte River near Louisville, Nebraska

the river is about 720 river km (kilometers) long (Bentall, 1975, p. 6). The North Platte River drains approximately 80,000 km^2 and is about 1,050 km long.

The area studied includes a 380 river-km reach of the South Platte River from Kersey, Colorado to North Platte, Nebraska; a 86 river-km reach of the North Platte River from Lake McConaughy near Ogallala, Nebraska to the confluence with the South Platte River; and a 460 river-km reach of the Platte River from North Platte to Louisville, Nebraska. The major emphasis of the study was the 120 river-km reach between Lexington and Chapman, Nebraska; this reach was designated by the U.S. Fish and Wildlife Service as the habitat of several species of endangered migratory waterfowl.

DATA COLLECTION

Sediment data were collected at twenty-one locations along the North Platte, South Platte, and Platte Rivers (fig. 1 and table 1). Primary station identification is the eight digit U.S. Geological Survey station number; however, station numbers used in this report (fig. 1 and tables 10 to 16 (see Summary of Data section at end of report)) were assigned to each station with higher numbers in downstream direction (Kircher, 1981a).

Sampling stations were located at bridge crossings for convenience of sampling at high flows. Sampling was done from May through September to insure that observations were made for a variety of bed and hydraulic conditions. Frequency and type of sampling were variable among stations. Bed-material samples were collected at all locations, but water-discharge, suspended-sediment, and bedload measurements were made at only a few of the locations (tables 10 to 16) within and near the reach of river designated as critical habitat by the U.S. Fish and Wildlife Service.

SUSPENDED SEDIMENT

Suspended sediment is that sediment carried in suspension by the turbulent components of streamflow. Samples were collected by depth-integrating with either a DH-48 or D-74 suspended-sediment sampler according to the equal-width increments method (Office of Water-Data Coordination, 1977). Fifteen to twenty verticals were sampled to determine the average discharge-weighted concentrations (table 11) and particle-size distribution (table 12) of the sediment in the streamflow. Suspended-sediment discharge (in metric tons per day) was computed as the product of the discharge-weighted concentration (in milligrams per liter), the water discharge (in cubic meters per second), and a units conversion constant, 0.0864 (table 11).

BEDLOAD

Bedload is the material moving on or near the streambed by rolling and sliding, and sometimes making brief excursions into the flow a few particle diameters above the bed. Bedload particles move in a series of steps interrupted by periods of no motion. A particle moves whenever the lift and drag forces produced by the flow or the impact of another moving particle overcome the resisting forces and dislodge the particle. Movement of bedload particles deforms the bed and produces bed forms, which, in turn, affect flow and bedload transport. Because bed forms and other factors influence bedload transport even in steady flow, bedload discharge fluctuates with time at a point and varies substantially from one point to another over the bed.

Bedload was measured at several different stations in the study reached during the summers of 1979 and 1980 using a Helley-Smith bedload sampler (Helley and Smith, 1971). The measurements supplement suspended-sediment measurements, and enabled a calculation of total sediment discharge. Procedures for the collection of bedload samples are described by Emmett (1980). Channel width was divided into at least 20 increments of equal width. Bedload was measured twice at the midpoint of each increment to define the average bedload discharge for the cross section (tables 13 and 14).

BED MATERIAL

Bed-material samples were collected at all twenty-one stations using a BMH-60 (Guy and Norman, 1970). Size distributions of the samples were determined to define the change in bed-material size in a downstream direction, and to compute total sediment discharge. By giving each sample a weight proportional to the increment of channel width it represents, a weighted mean grain-size distribution for each station was calculated (table 15). A statistical summary of grain-size distributions, expressed as grain diameters at given percent-finer values, is presented in table 16.

Median grain diameter (D_{50}), defined as the size for which half the material, by weight, is finer and half is coarser, changes in a systematic way downstream. On the basis of synoptic sampling in August 1979, the median diameter apparently decreases in the North Platte River downstream to the confluence of the North Platte and South Platte and increases in the Platte River from that point downstream to Overton, where it reaches its maximum; from Overton, the median diameter decreases in the downstream direction (fig. 2). The increase in median diameter in the reach of the Platte River upstream from Overton coincides with an increase in the slope of the river channel in the same reach (fig. 3). The increased slope may be due to the influx of coarser sediment from the South Platte River, or to widening of the channel caused by the addition of flow from the large powerplant return canal between Brady and Overton, or a combination of both (T. R. Eschner, U.S. Geological Survey, written commun., 1981). Error bars in figure 2 were calculated by computing the median bed-material size for the cross section from different numbers of samples. The number of samples per cross section was varied from 2 to 15 samples and then each weighted again to arrive at median bed-material sizes. These error bars are shown to give the reader an indication of the variation in gradation curves that can be observed, if fewer cross-section samples are collected than were used in this report. The line drawn between stations passes through median particle size computed from the maximum number of samples, based on Hubbell's (1956) statement that numerous samples in a cross section should be collected to obtain a representative sample. The error bars indicate that any future sampling for particle sizes should be based on numerous samples in a cross section. Plots of median grain size versus water discharge for the Platte River show that the median diameter decreases somewhat with increasing discharge at Overton (fig. 4), but that no trend is exhibited at Grand Island (fig. 5).

TOTAL SEDIMENT DISCHARGE

Total sediment discharge was computed using three different methods for four sites on the North Platte, South Platte, and Platte Rivers between North Platte and Grand Island, Nebraska. The methods are: (1) Addition of the measured suspended-sediment and bedload discharges; (2) the modified Einstein procedure (Colby and Hembree, 1955); (3) and addition of the measured suspended-sediment discharge and unmeasured sediment computed by a graphical method presented by Colby (1957); this third method is hereinafter called the Colby method. Sediment discharge computed by the three methods were compared to see if all three provided similar rates at Platte River cross sections. The four sites chosen for the comparisons were: (1) North Platte River at North Platte, Nebraska; (2) South Platte River at North Platte, Nebraska; (3) Platte River near Overton, Nebraska; and (4) Platte River near Grand Island, Nebraska.

Adding the measured suspended-sediment discharge and the bedload discharge measured with a Helley-Smith bedload sampler may produce an erroneous estimate of total sediment discharge, because part of the suspended-sediment discharge in the "unsampled depth" (bottom 0.091 m (meter)) is accounted for in both the measured suspended-sediment discharge and the measured bedload discharge. In the calculation of measured suspended-sediment discharge, the measured suspended-sediment concentration is multiplied by the entire water discharge. Hence, part of the suspended sediment in the bottom 0.091 m of flow is included in the measured suspended-sediment discharge. Suspended material, in the "unsampled depth" coarser than 0.25 mm also is trapped in the Helley-Smith sampler. Measured suspended-sediment discharges for the North Platte, South Platte, and Platte Rivers were adjusted to represent only the suspended-sediment discharge in the sampled depth, by multiplying measured rates by the fraction of flow in the sampled depth (Colby and Hembree, 1955). The corrected suspended-sediment discharge then was added to the measured bedload discharge to estimate total sediment discharge.

The modified Einstein procedure (Colby and Hembree, 1955) is a method for computing total sediment discharge from suspended-sediment samples and other relevant data. Data required for the modified Einstein procedure are obtained from a single cross section and include the mean velocity, stream width, mean depth at sampled verticals, concentration, and size distribution of the measured suspended-sediment, size distribution

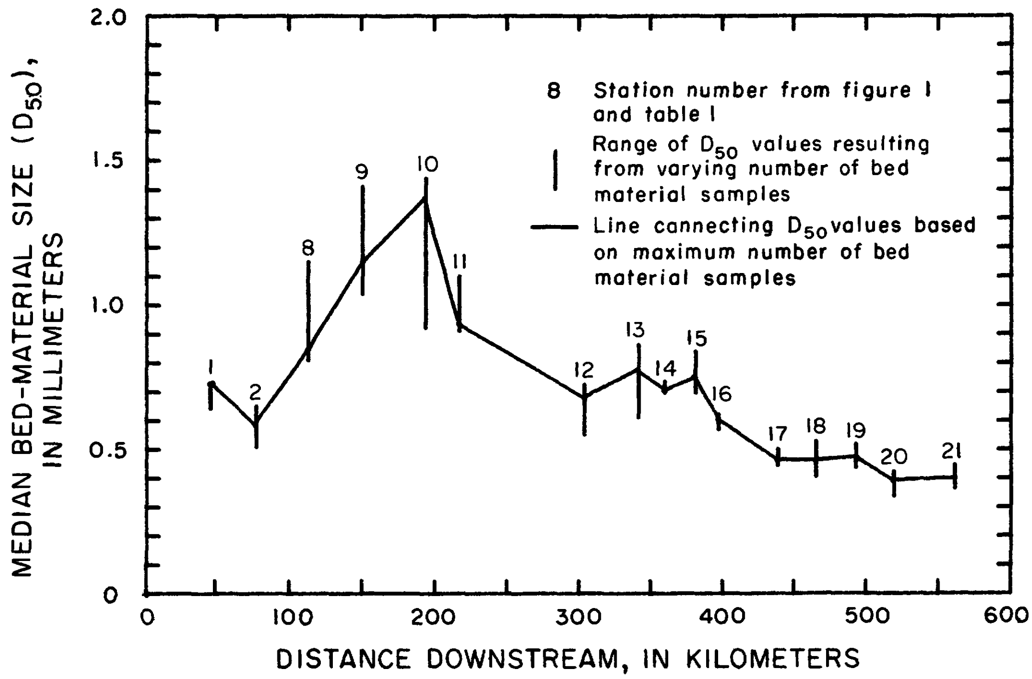


FIGURE 2.—Variation in sediment size with distance downstream for the North Platte and Platte Rivers, August 1979.

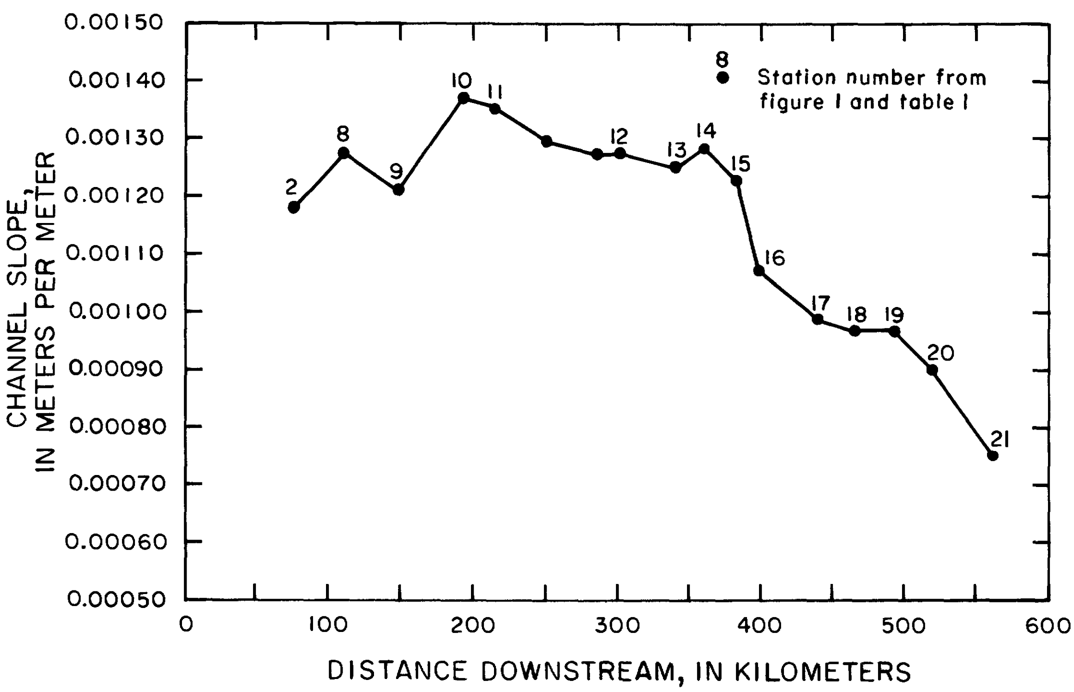


FIGURE 3.—Variation in local channel slope with distance downstream for the North Platte and Platte Rivers.

of the bed material, and water temperature. From these data, sediment discharge for each sediment size class can be determined and summed to obtain a total sediment discharge for the entire range of sediment sizes.

Colby's (1957) graphical method for estimating the unmeasured sediment discharge consists of several empirical relationships based on some of the same stream measurement data employed in developing the modified

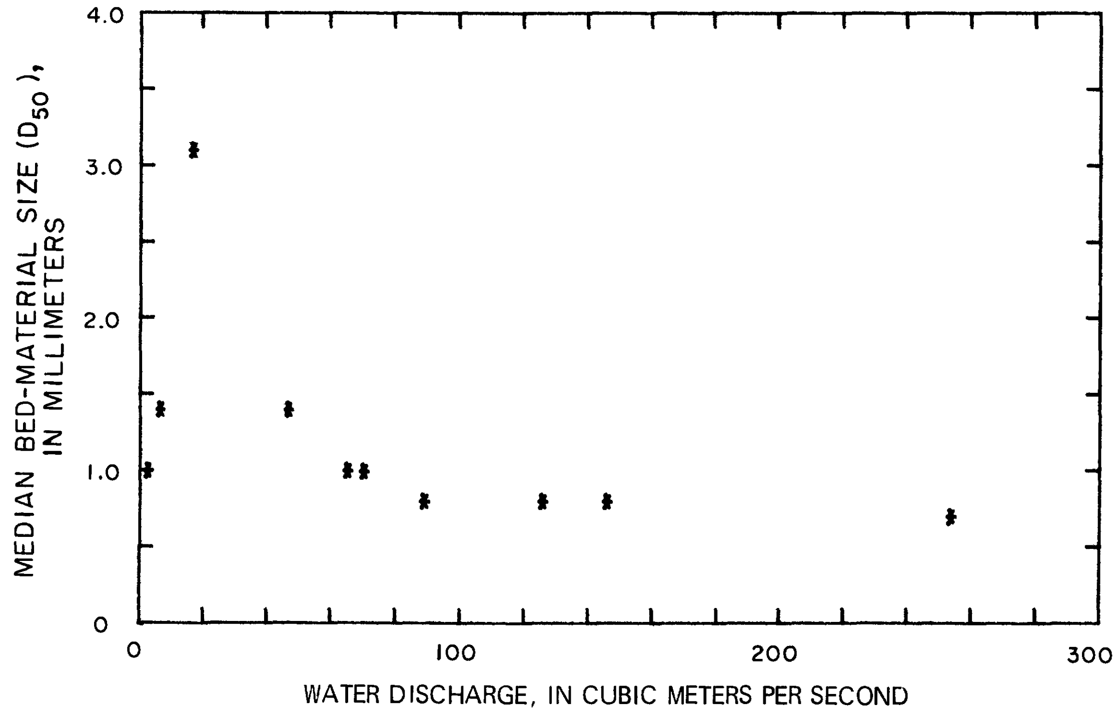


FIGURE 4.—Variation in median bed-material size with discharge for the Platte River near Overton, Nebraska.

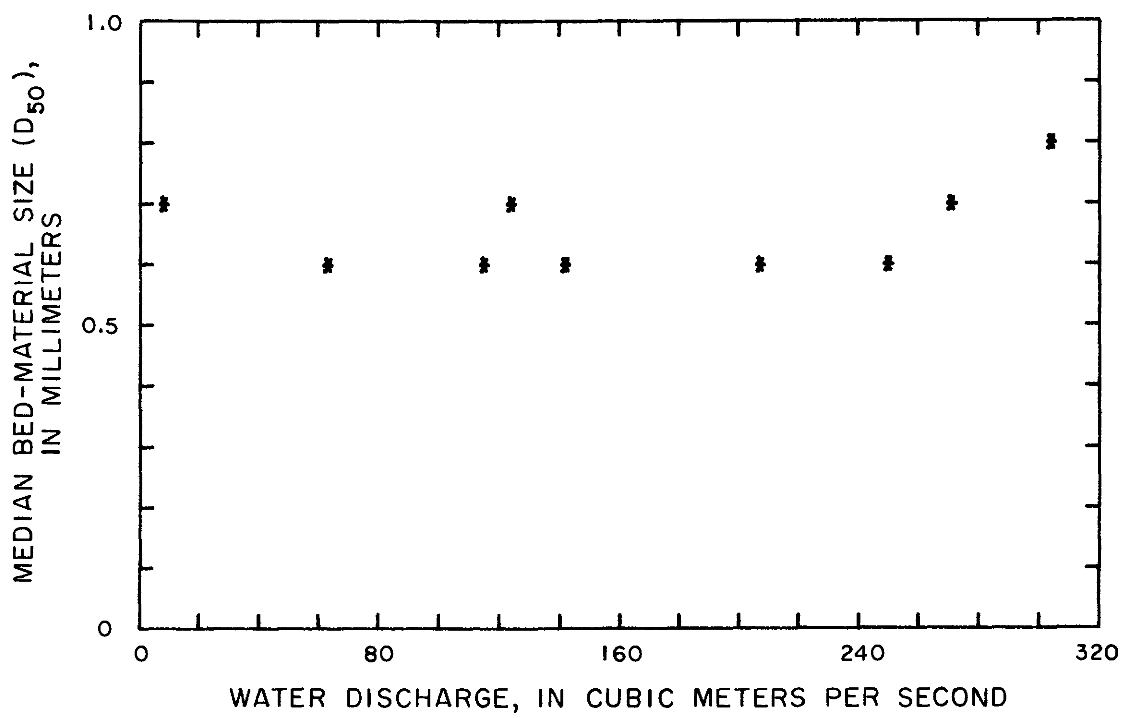


FIGURE 5.—Variation in median bed-material size with discharge for the Platte River near Grand Island, Nebraska.

Einstein method. The graphical method is simple to apply; however, it does not give a breakdown of the unmeasured sediment discharge into size fractions, and requires a precise determination of mean velocity, because unmeasured sediment discharge is very sensitive to changes in velocity.

Application of the graphical method requires mean stream velocity, stream width, mean depth, and measured suspended-sediment concentrations of sand particles. Size distribution of bed material is not needed. From these measured values, an estimate of the unmeasured-sediment discharge is made. The unmeasured sediment discharge then is added to the measured suspended-sediment discharge to obtain the total sediment discharge according to the Colby method.

Total sediment discharges calculated by all three methods were used to define water-sediment discharge relations for the four stations—except for the South

TABLE 2.—*Water-sediment discharge relations, derived by log-linear regression, for selected Platte River stations*

[Q_s, sediment discharge in metric tons per day; Q, water discharge in cubic meters per second; ln, natural logarithm of function]

U.S. Geological Survey station number	Station name	Regression equation*	Type of equation (see footnotes)	Number of data points
06693000	North Platte River at North Platte, Nebraska	$\ln(Q_s) = 2.45 + 1.29 \ln(Q)$	(1)	5
		$\ln(Q_s) = 2.44 + 1.39 \ln(Q)$	(2)	5
		$\ln(Q_s) = 1.77 + 1.58 \ln(Q)$	(3)	3
06765500	South Platte River at North Platte, Nebraska	$\ln(Q_s) = 2.55 + 1.32 \ln(Q)$	(1)	7
		$\ln(Q_s) = 2.72 + 1.32 \ln(Q)$	(2)	7
06768000	Platte River near Overton, Nebraska	$\ln(Q_s) = 2.12 + 1.29 \ln(Q)$	(1)	7
		$\ln(Q_s) = 2.23 + 1.27 \ln(Q)$	(2)	7
		$\ln(Q_s) = 1.74 + 1.36 \ln(Q)$	(3)	4
06770500	Platte River near Grand Island, Nebraska	$\ln(Q_s) = 2.34 + 1.26 \ln(Q)$	(1)	8
		$\ln(Q_s) = 2.74 + 1.19 \ln(Q)$	(2)	8
		$\ln(Q_s) = 1.44 + 1.45 \ln(Q)$	(3)	6

*The dependent variable in the regression equation is:
(1) Total measured sediment discharge.
(2) Total sediment discharge computed using the Colby (1957) method.
(3) Total sediment discharge computed using the modified Einstein method (Colby and Hembree, 1955).

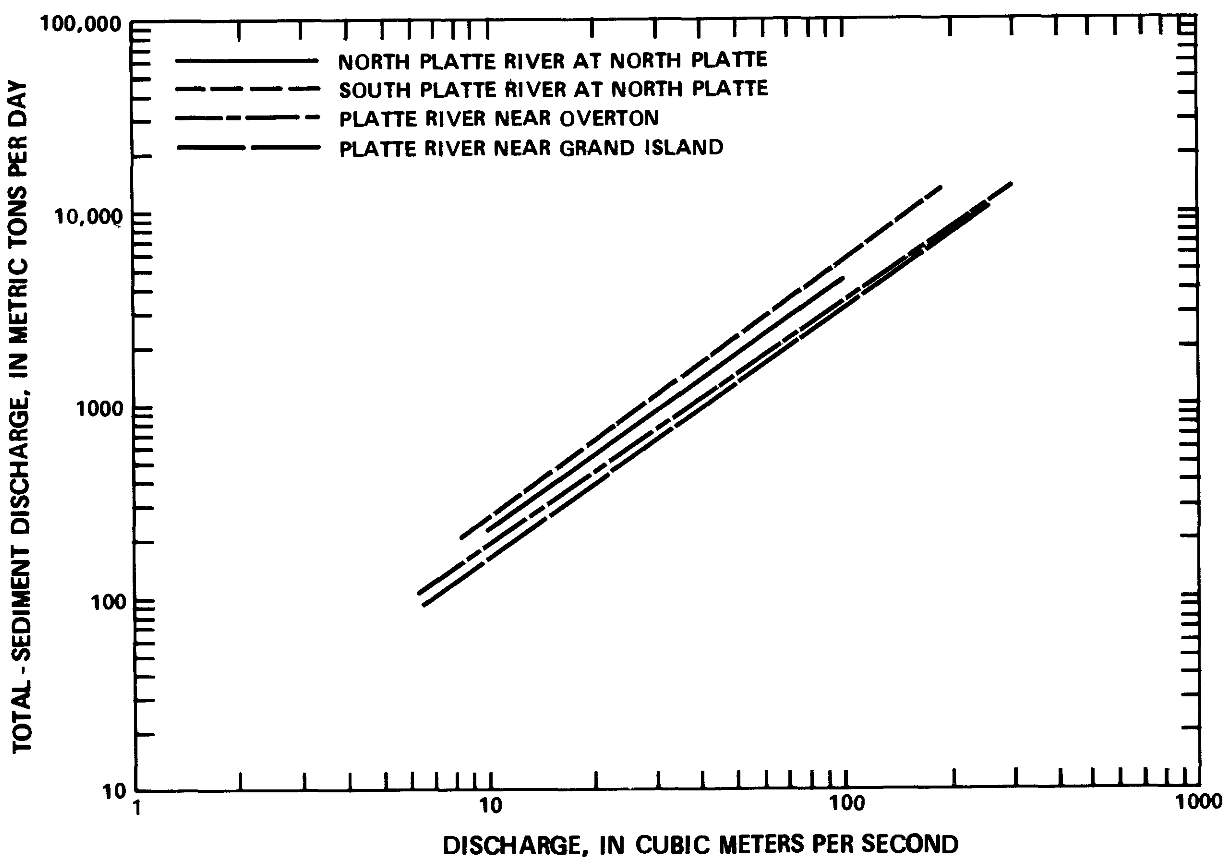


FIGURE 6.—Relations between water and measured total sediment discharges for the North Platte, South Platte, and Platte Rivers (Kircher, 1981b).

Platte River at North Platte, where sufficient data were not available for the modified Einstein procedure; curves were defined by least-squares regression on the log-transformed data. Equations of these curves are presented in table 2. The measured total sediment discharge relations are presented in figure 6 (Kircher, 1981b) for all four stations for a comparison of station variability.

COMPARISON OF TOTAL SEDIMENT DISCHARGE METHODS

The three total sediment discharge methods were compared to determine if they all could be applied to the Platte River system, because some methods are more simple to use than others. Total sediment discharges computed by the modified Einstein procedure were first compared to measured total sediment discharges by individual size classes. Relations expressing the total sediment discharge in each particle-size class as functions of total sediment discharge were determined for both the measured total sediment discharge and the modified Einstein total sediment discharge. A least-squares linear regression of the log-tranformed data was used to obtain an equation for each size class from 0.062 to 16.00 mm. The equation obtained is of the form:

$$\ln(q_s) = A + B\,(\ln(Q_s)) \qquad (1)$$

where ln = natural logarithm,

q_s = total sediment discharge by size class in metric tons per day, and

Q_s = total sediment discharge, in metric tons per day.

Regression equations and statistics are presented in table 3 for measured total sediment discharge and in table 4 for the modified Einstein total sediment discharge. The ratio $\overline{Y}/\overline{X}$ is included in these tables. It is the ratio of the mean of the dependent variable to the mean of the independent variable, computed prior to transforming the data. This ratio gives an indication of what percentage of the total sediment transport is in each size class. Mean percentages will not add to 100, because the sediment transport finer than 0.062 mm is not included, and also because the mean value of total bedload is variable. Graphs showing individual data points for various particle-size classes together with the least-square line, are presented in figures 7 to 14. The least-square lines are also shown except where the coefficient of determination (r^2) was less than 0.50. The modified Einstein total sediment discharge data were omitted for the size classes 4.000 to 8.000 mm because most of the data points were equal to zero and zero values cannot be used in log-transformed regressions.

TABLE 3.—*Coefficients and statistics for linear regression equations of log-transformed values of measured total sediment discharge by size class versus measured total sediment discharge.*

[q_s, total sediment discharge in each size class; Q_s, total sediment discharge; ln, natural logarithm]

Particle-size class (millimeters)	Number of data points	$\ln(q_s)=A+B(\ln(Q_s))$ A	B	r^2	SE (log units)	$\overline{Y}/\overline{X}$ (percent)
0.062- 0.125	17	-	-	-	-	5.47
.125- .250	17	−3.38	1.16	78.4	0.64	16.69
.250- .500	17	−1.42	.977	89.5	.35	22.85
.500- 1.000	17	−1.35	.945	91.4	.31	17.21
1.000- 2.000	17	−2.22	.998	87.4	.40	11.07
2.000- 4.000	17	−3.52	1.10	82.6	.53	7.13
4.000- 8.000	17	−5.19	1.22	79.3	.66	3.84
8.000-16.000	17	−17.9	2.58	56.1	2.36	1.10

TABLE 4.—*Coefficients and statistics for linear regression equations of log-transformed values of total sediment discharge by the modified Einstein procedure (Colby and Hembree, 1955) by size class versus total sediment discharge by the modified Einstein procedure.*

[q_s, total sediment discharge in each size class; Q_s, total sediment discharge; ln, natural logarithm]

Particle-size class (millimeters)	Number of data points	$\ln(q_s)=A+B(\ln(Q_s))$ A	B	r^2	SE (log units)	$\overline{Y}/\overline{X}$ (percent)
0.062- 0.125	17	-	-	-	-	5.99
.125- .250	17	−2.44	1.08	88.0	0.47	20.01
.250- .500	17	−3.02	1.16	92.2	.40	23.52
.500- 1.000	17	−2.69	1.11	96.4	.25	19.46
1.000- 2.000	17	−4.47	1.29	86.4	.60	13.41
2.000- 4.000	17	−14.3	2.23	71.8	1.62	2.47
4.000- 8.000	17	-	-	-	-	.19
8.000-16.000	17	-	-	-	-	.0004

Statistical data from linear regressions of log-transformed data are summarized for the measured-bedload discharge in table 5 and for the computed unmeasured sediment discharge from the modified Einstein procedure in table 6. The curves presented in figures 7–14 and the equations in table 3 to 6 reflect the way the percentage of material in each size class varies with the corresponding computed sediment discharge (modified Einstein procedure or measured sediment discharge). The coefficients depend only on the percentage of material in a size class associated with each computed (measured) sediment discharge, and in no way relate to the absolute accuracy of the total sediment discharge or the sediment discharge in each size class. As such, the equations for a given procedure are unrelated in absolute terms to the equations developed for a different procedure. Therefore, these figures and tables should only be used to determine the respective load in each size class for the particular method used.

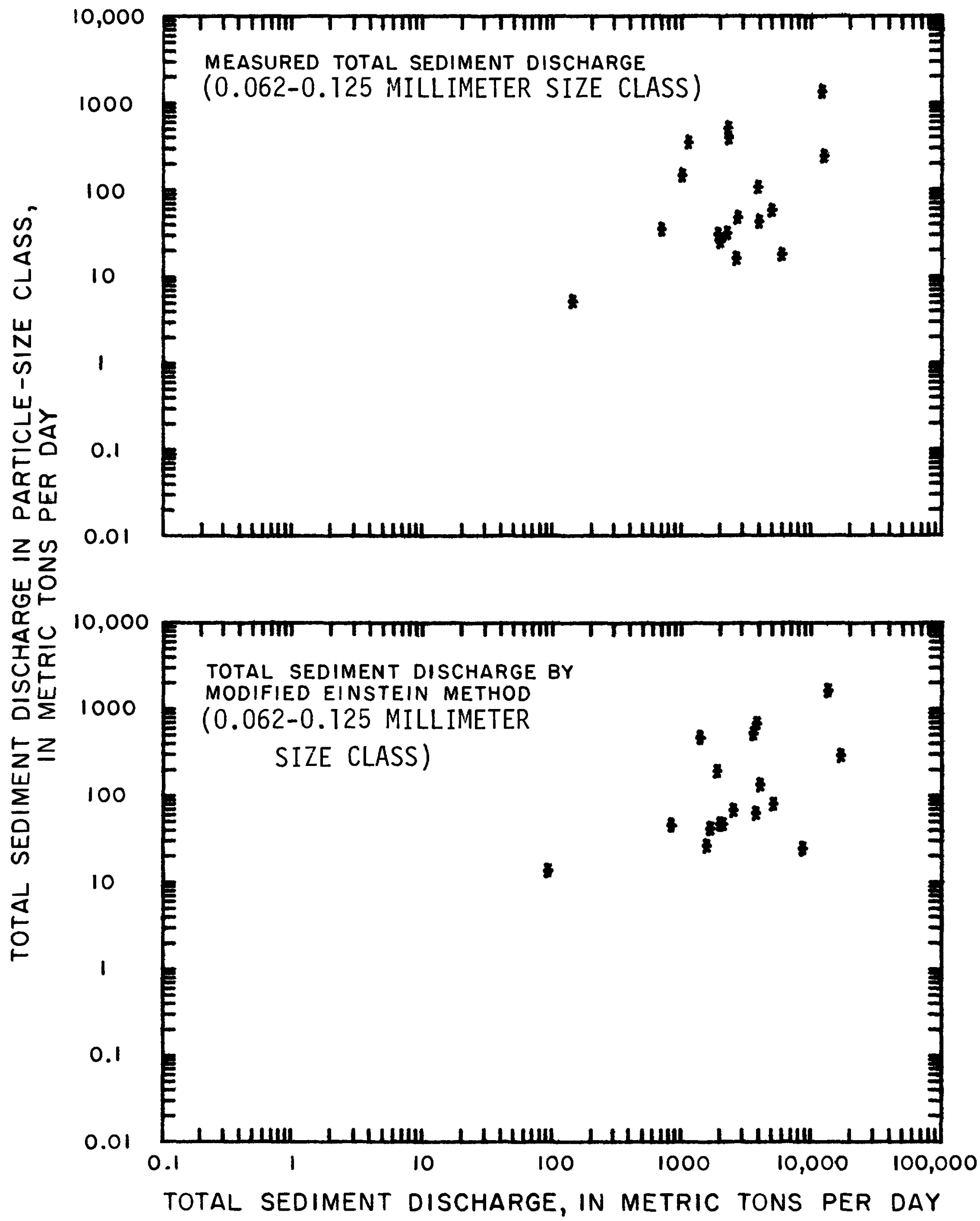


FIGURE 7.—Relation of total sediment discharge in individual size class as a function of total sediment discharge: 0.062- to 0.125-millimeter size class.

Sediment discharges in individual particle-size classes, as computed by the modified Einstein procedure and determined from measured discharges, have been compared by least-squares linear regression, using log-transformed discharge values (table 7). Graphs (figs. 15-22) show the data and the least-squares line for regressions in which the coefficient of determination (r^2) was greater than 0.50; the line of perfect agreement also is shown.

The agreement between the methods is good for particle sizes finer than 2.000 mm. However, for those greater than 2.000 mm, the modified Einstein procedure yields smaller sediment discharges than the measured sediment discharge method does.

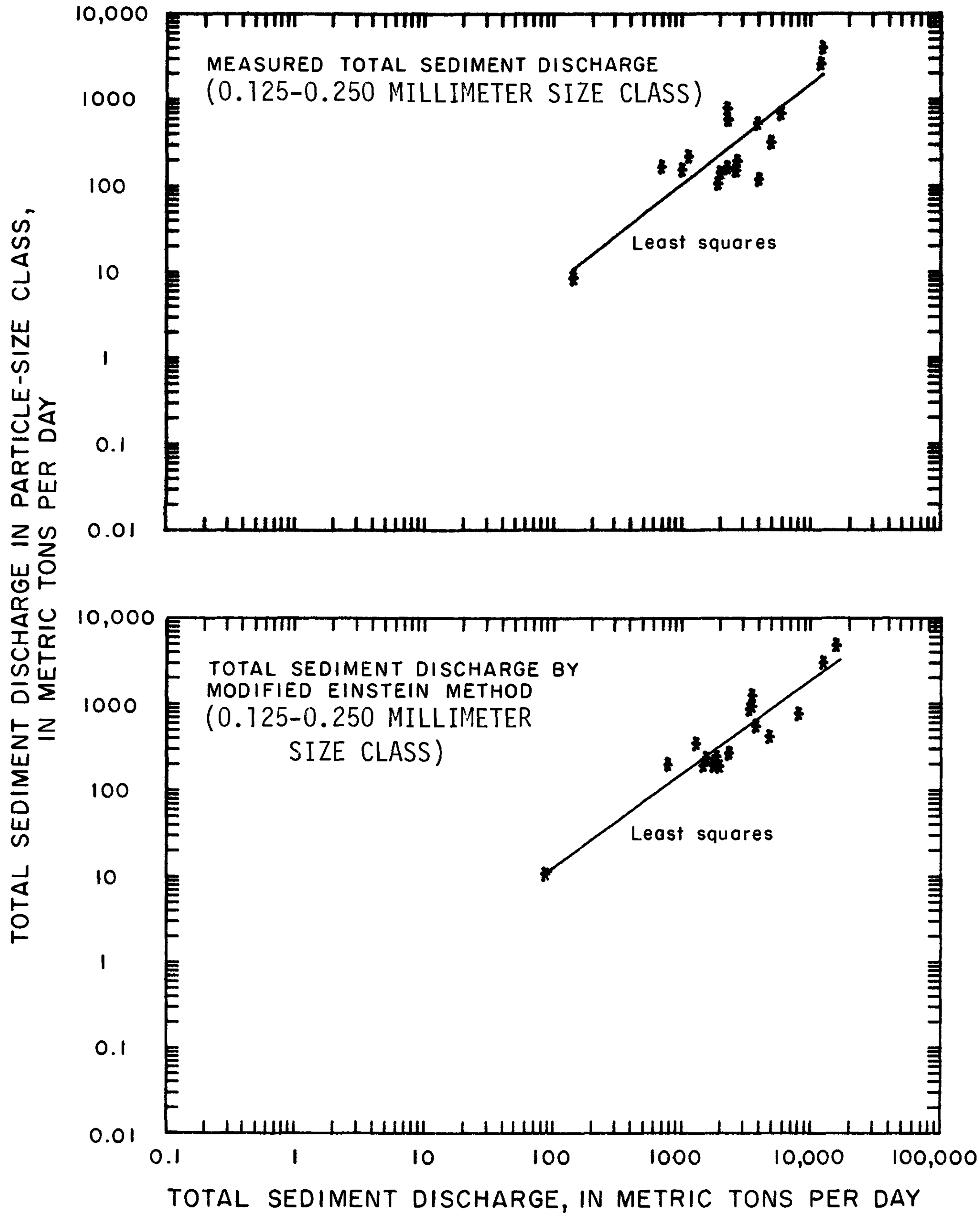


FIGURE 8.—Relation of total sediment discharge in individual size class as a function of total sediment discharge: 0.125- to 0.250-millimeter size class.

Total sediment discharges determined by the three methods are compared in figures 23–25. These figures show the data plotted around the line of perfect agreement. Although they do not agree perfectly, this exemplifies how close the results are. Agreement among the discharges is better than that among individual size class discharges. The agreement among these relations implies that the Colby and modified Einstein methods might be used for bed-material sizes beyond those for which they were developed. It appears that the field conditions seem to approximate the principles of the modified Einstein procedure and the Colby method well, indicating that the suspended sediment can be used as an index to the bedload movement in the Platte River

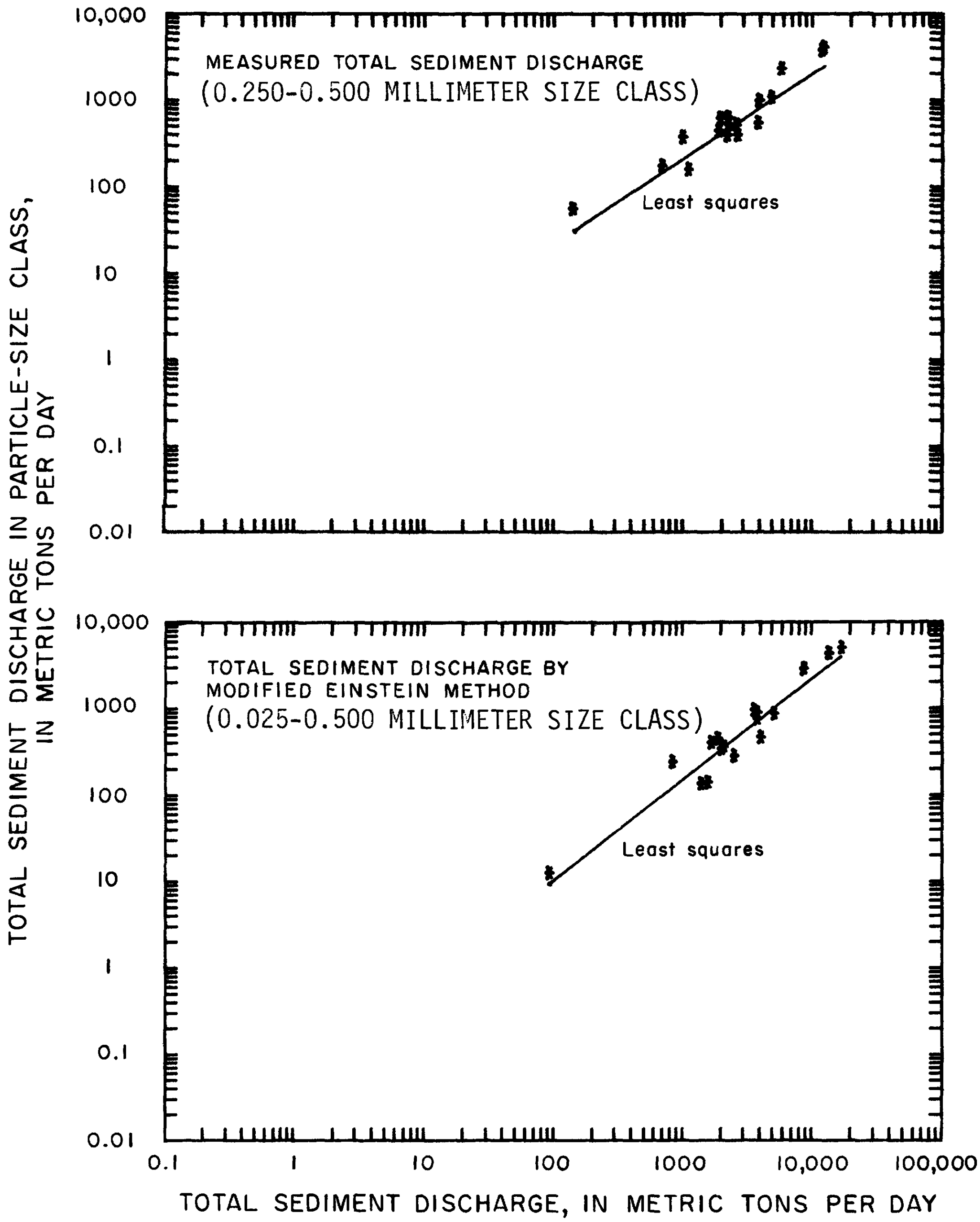


FIGURE 9.—Relation of total sediment discharge in individual size class as a function of total sediment discharge: 0.250- to 0.500-millimeter size class.

system. Of the two computational methods, the Colby method is the easier to use, and it could be used for estimates of total sediment discharge within the study reach investigated in this report. However, as the hydraulic conditions and sediment characteristics deviate from those for which the total- discharge methods were formulated, the advantages of measuring bedload increase.

MEAN-DAILY SEDIMENT DISCHARGE

Mean-daily sediment discharge can be determined by calculating the expected value of sediment discharge $[E(Q_S)]$. The expected value is defined as:

$$E(Q_s) = \int_0^\infty Q_s\, h(Q_s) dQ_s \qquad (2)$$

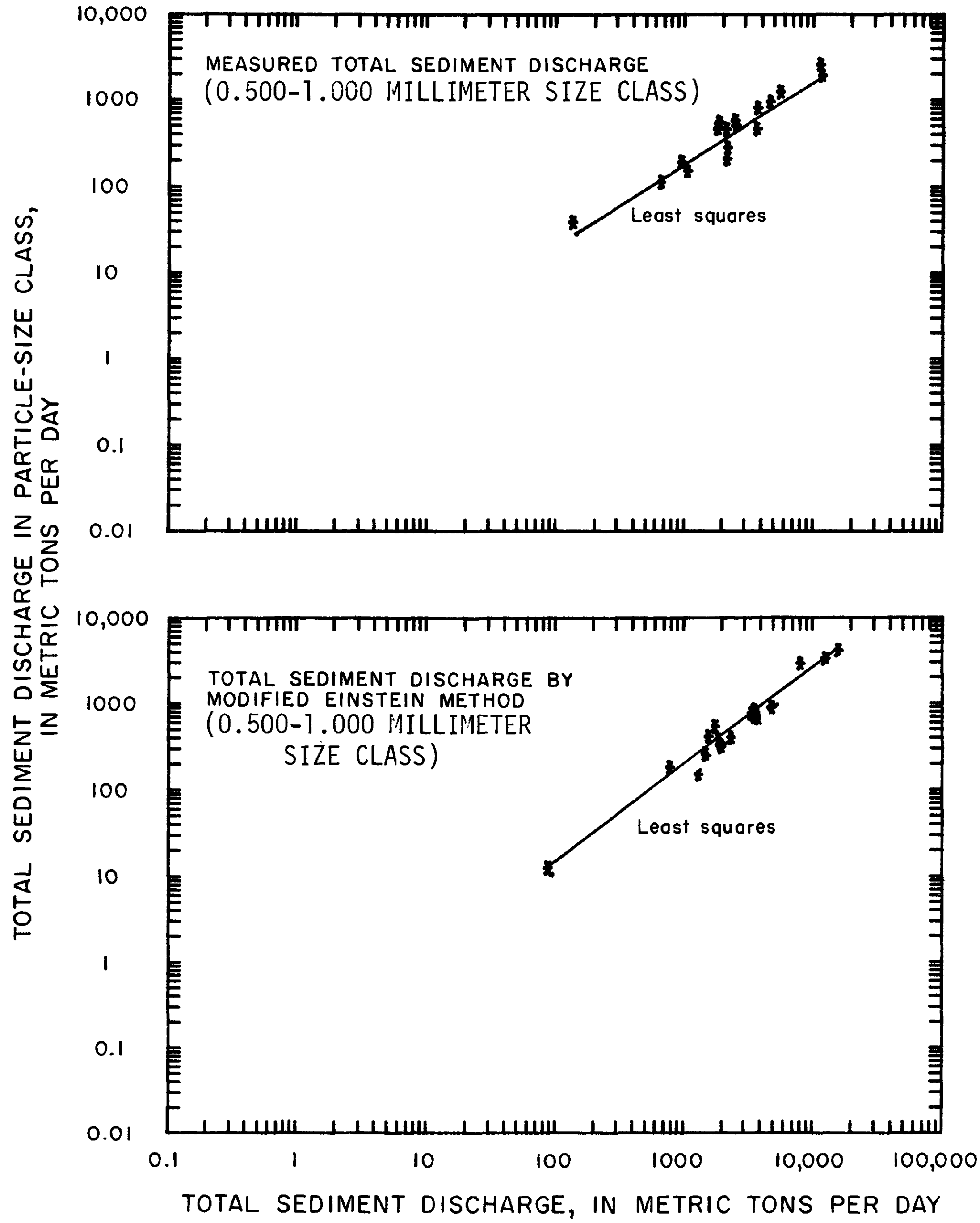


FIGURE 10.—Relation of total sediment discharge in individual size class as a function of total sediment discharge: 0.500- to 1.000-millimeter size class.

where Q_s = sediment discharge in metric tons per day,

$h(Q_s)$ = sediment density function, and

$E(Q_s)$ = expected value of the sediment discharge or mean daily sediment discharge in tons per day.

For the Platte River stations, the sediment density function is unknown, because of the lack of comprehensive sediment discharge data, but Q_s is a known function of water discharge from the water-sediment discharge relations. Therefore, by probability theory, the following substitution can be made for equation 2:

$$E(Q_s) = \int_0^\infty g(Q)f(Q)dQ \qquad (3)$$

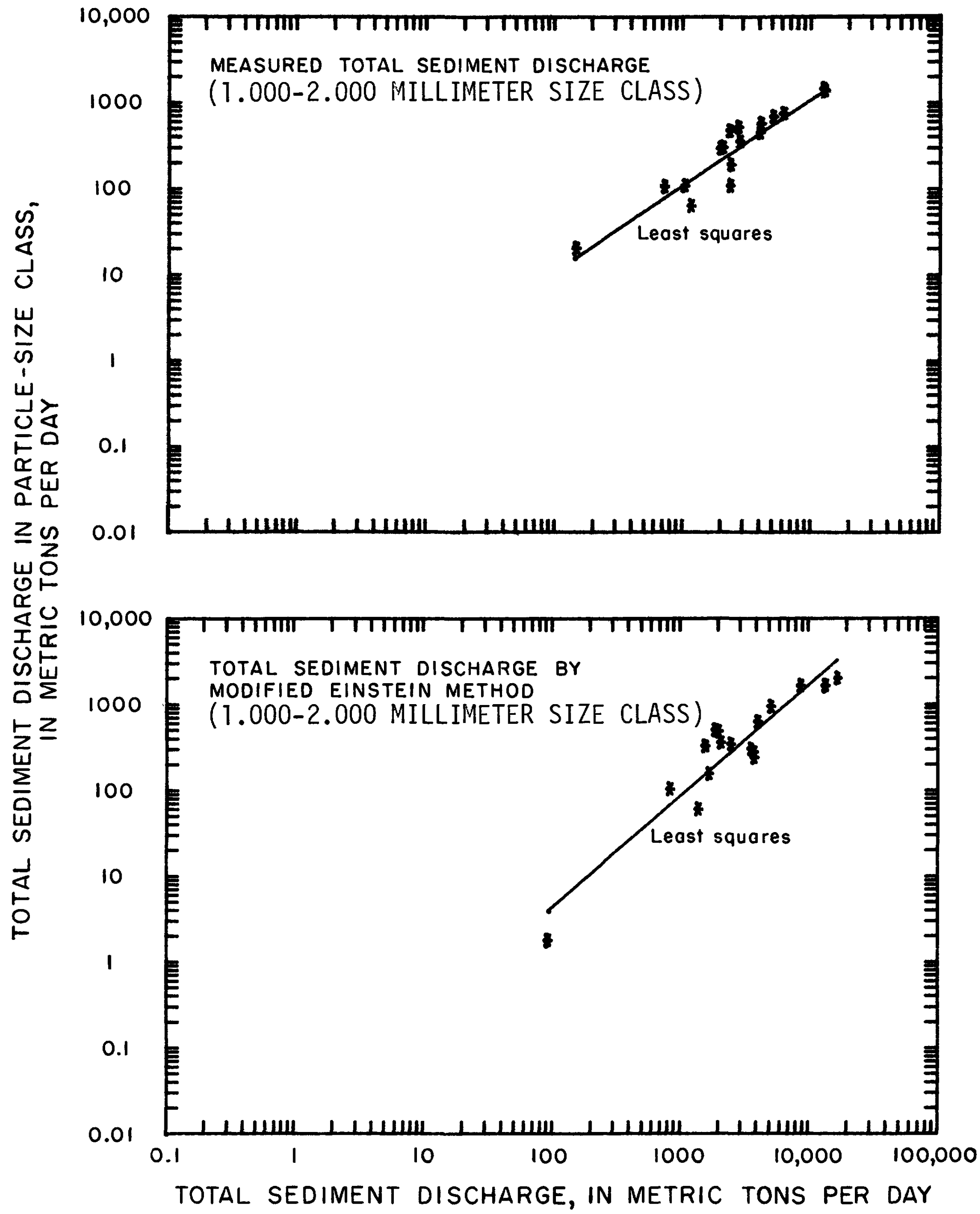


Figure 11.—Relation of total sediment discharge in individual size class as a function of total sediment discharge: 1.000- to 2.000-millimeter size class.

where $g(Q) = Q_s$, in metric tons per day, and
$f(Q)$ = the water-discharge density function.

The water-discharge density function can be obtained from the flow-duration curve. The cumulative frequency of daily mean water discharges at a gaging station defines a flow-duration curve. Flow-duration curves show the percentage of time a specific water discharge was equaled or exceeded during the period of record. Flow-duration curves based on several years of record described the approximate probability of various daily mean water discharges being equaled or exceeded. Flow-duration curves used in this report were defined during a period in which large changes in flow and channel morphology no longer occur (Kircher and Karlinger, 1981)

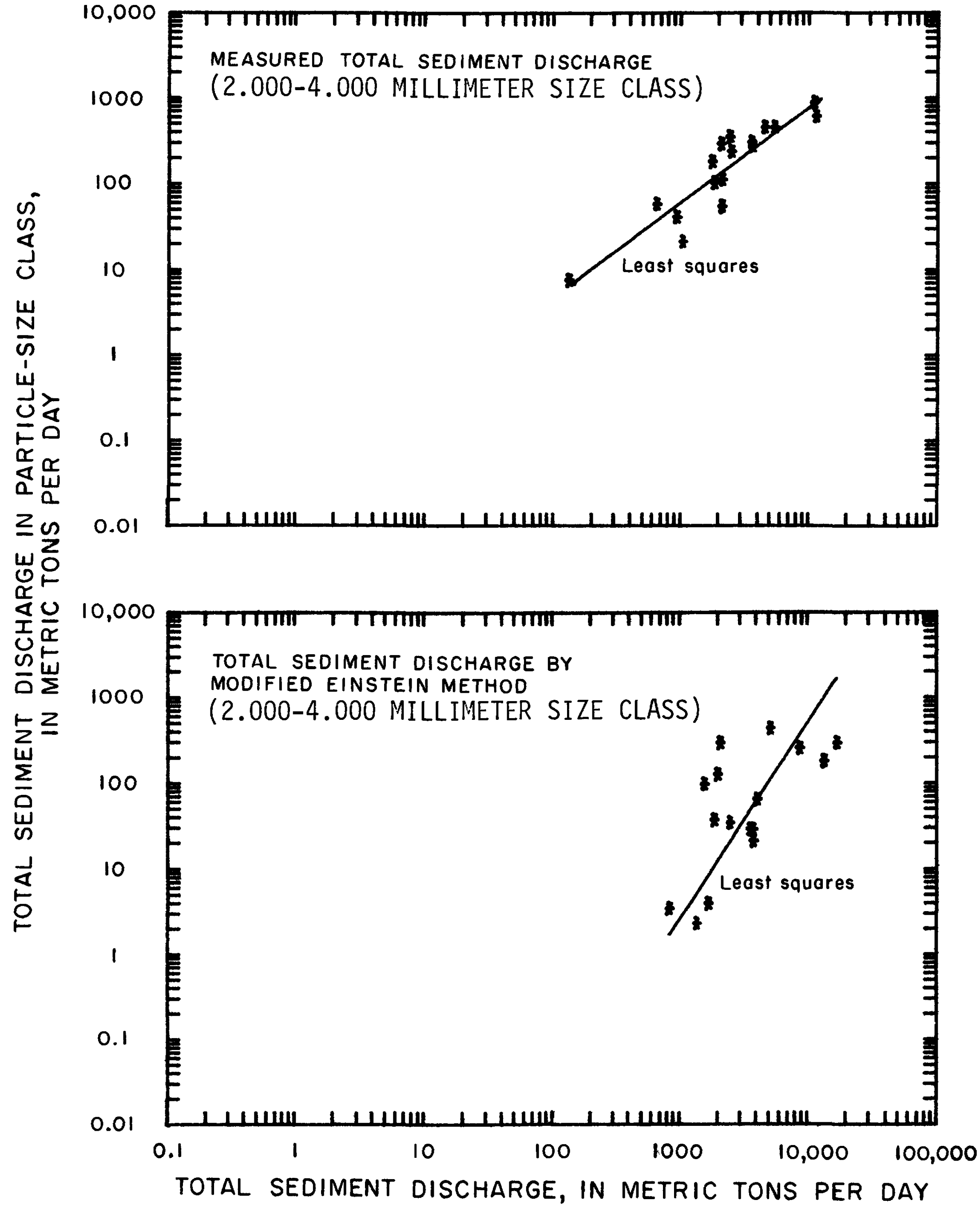


FIGURE 12.—Relation of total sediment discharge in individual size class as a function of total sediment discharge: 2.000- to 4.000-millimeter size class.

(figs. 26–29). Although the analytical form of the flow-duration curve is unknown, the integral in equation 3 can be approximated by a summation of the discretized integrand, which has the following form:

$$E(Q_s) \approx \sum_{j=1}^{N} g(Q_j) f(Q_j) \Delta Q_j \qquad (4)$$

With this form, the expected value of the Q_s is determined by first dividing the discharge scale of the flow-duration curve into N equal intervals. Then, the midpoint of each interval is used to obtain the corresponding sediment discharges from the water sediment discharge relations for each station. The sediment discharge is then multiplied by the probability of occur-

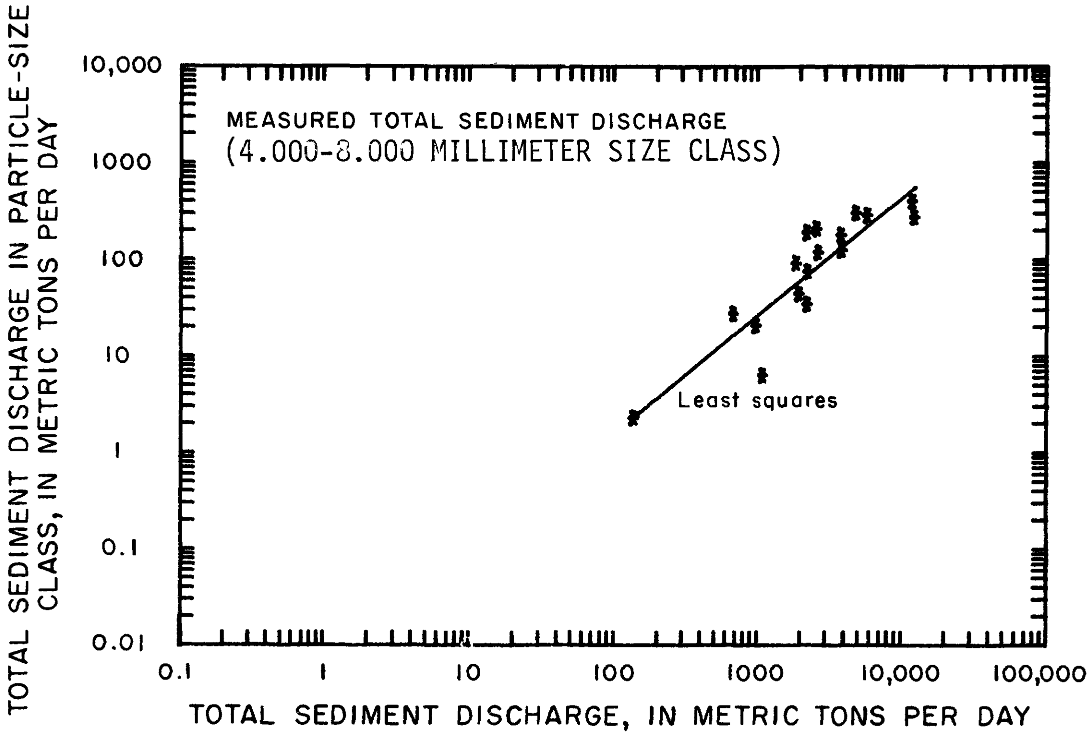


FIGURE 13.—Relation of total sediment discharge in individual size class as a function of total sediment discharge: 4.000- to 8.000-millimeter size class.

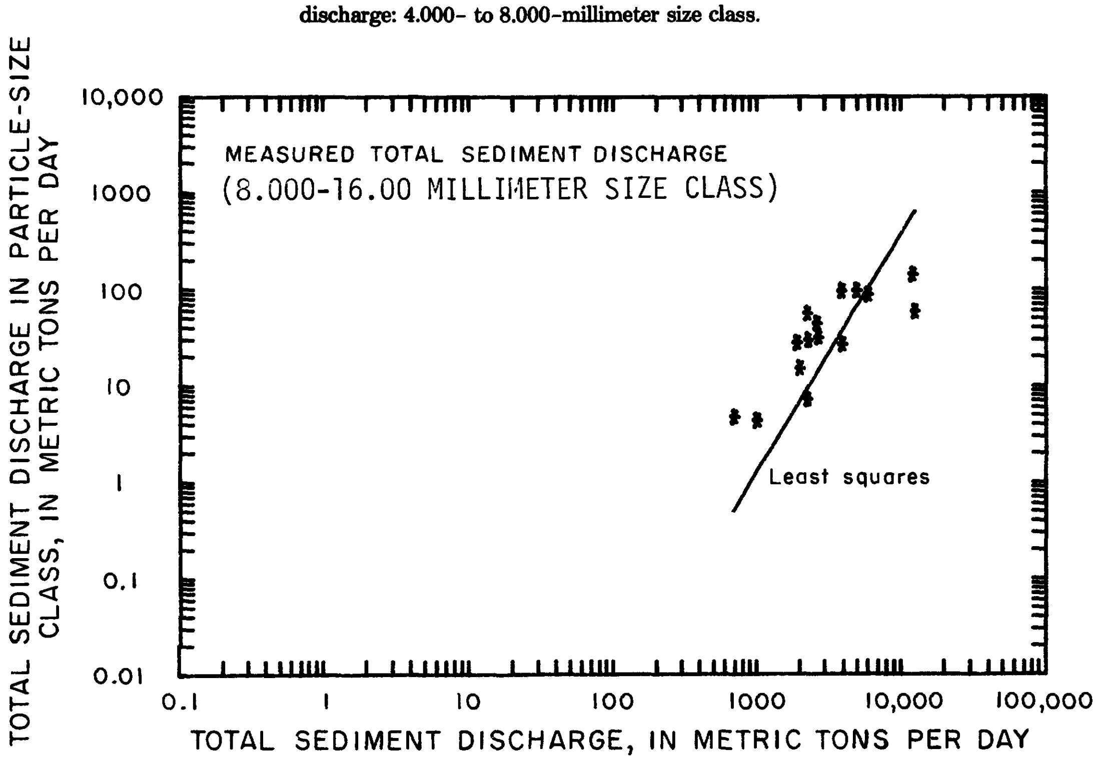


FIGURE 14.—Relation of total sediment discharge in individual size class as a function of total sediment discharge: 8.000- to 16.00-millimeter size class.

rence of the associated water discharge $f(Q_j)\ \Delta Q_j$ to yield a weighted quantity of sediment. The summation of all $g(Q_j)f(Q_j)\Delta Q_j$ values gives the expected value of the sediment discharge which is an approximation of the mean-daily sediment discharge. The mean-daily sediment discharge based on the measured total sediment

TABLE 5.—*Coefficients and statistics for linear regression equations of log-transformed values of measured bedload discharge by size class versus total measured bedload discharge.*

[q_B, measured bedload discharge in each size class; Q_B, total measured bedload discharge; ln, natural logarithm]

Particle-size class (millimeters)	Number of data points	$\ln(q_B)=A+B(\ln(Q_B))$ A	B	r^2	SE (log units)	$\overline{Y}/\overline{X}$ (percent)
0.062- 0.125	17	-	-	-	-	0.005
.125- .250	17	−3.08	0.961	79.4	0.53	.016
.250- .500	17	− .44	.873	93.3	.25	3.95
.500- 1.000	17	−1.13	.985	98.2	.14	24.82
1.000- 2.000	17	−1.85	1.03	98.4	.14	29.69
2.000- 4.000	17	−3.21	1.15	95.3	.28	19.87
4.000- 8.000	17	−4.82	1.27	91.0	.44	12.79
8.000-16.000	17	−17.4	2.73	67.1	2.05	6.90

TABLE 6.—*Coefficients and statistics for linear regression equations of log-transformed values of unmeasured-sediment discharges computed by the modified Einstein procedure by size class versus total unmeasured-sediment discharge*

[q_u, unmeasured sediment discharge in each size class; Q_u, total unmeasured-sediment discharge; ln, natural logarithm]

Particle-size class (millimeters)	Number of data points	$\ln(q_u)=A+B(\ln(Q_u))$ A	B	r^2	SE (log units)	$\overline{Y}/\overline{X}$ (percent)
0.062- 0.125	17	-	-	-	-	2.11
.125- .250	17	−1.57	0.922	81.3	0.52	12.25
.250- .500	17	−2.41	1.12	93.9	.33	25.44
.500- 1.000	17	−2.48	1.15	98.1	.19	30.42
1.000- 2.000	17	−4.01	1.31	89.1	.54	21.60
2.000- 4.000	17	−13.5	2.27	74.3	1.55	3.98
4.000- 8.000	17	-	-	-	-	.31
8.000-16.000	17	-	-	-	-	.0006

TABLE 7.—*Coefficients and statistics for linear regression equations of log-transformed values of sediment discharges in different size classes computed by the modified Einstein procedure (Colby and Hembree, 1955) and from measured sediment discharges*

[Q_{MEP}, total sediment discharge computed by the modified Einstein procedure; Q_M, total measured sediment discharge; ln, natural logarithm]

Particle-size class (millimeters)	Number of data points	$\ln(Q_{MEP})=A+B(\ln(Q_M))$ A	B	r^2	SE (log units)	$\overline{Y}/\overline{X}$ (percent)
0.062- 0.125	17	0.741	0.911	99.1	0.13	127.75
.125- .250	17	.562	.972	98.7	.15	140.04
.250- .500	17	−1.42	1.22	87.4	.51	120.21
.500- 1.000	17	− .609	1.11	74.6	.67	132.06
1.000- 2.000	17	−1.31	1.26	74.9	.82	141.48
2.000- 4.000	17	−6.99	2.03	69.7	1.69	40.50
4.000- 8.000	17	-	-	-	-	5.85
8.000-16.000	17	-	-	-	-	.04
Total	17	−0.47	1.07	92.9	0.31	116.78

discharge relations, for the South Platte River at North Platte, the North Platte River at North Platte, the Platte River near Overton, and the Platte River near Grand Island were computed based on $N = 69$ (table 8).

From equation 4 it can be seen that as N increases, the closer the approximation of the mean-daily sediment should be to the value obtained from equation 3. The variation of mean-daily sediment discharge with increasing N can be seen in table 9. The flow-duration curve was divided into 35, 69, 103, and 137 equal discharge intervals and an expected value of sediment discharge computed. The flow-duration curve was also

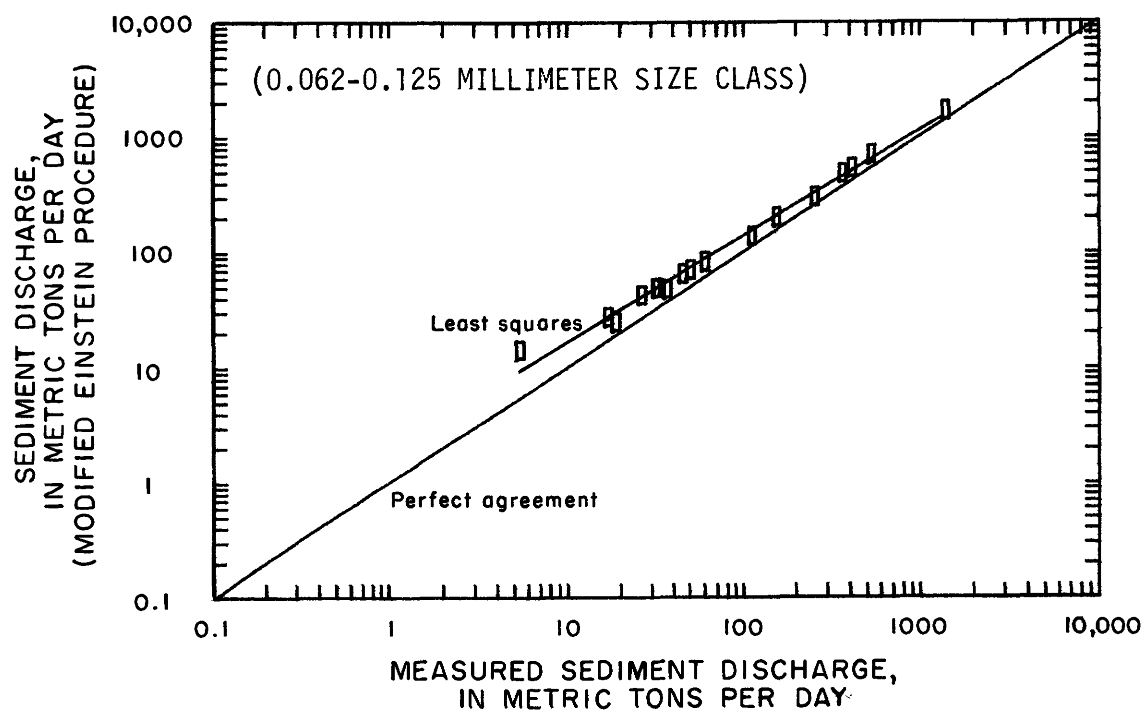


FIGURE 15.—Comparison of sediment discharges computed by the modified Einstein procedure for an individual particle-size class with corresponding measured sediment discharges for the class; 0.062- to 0.125-millimeter size class.

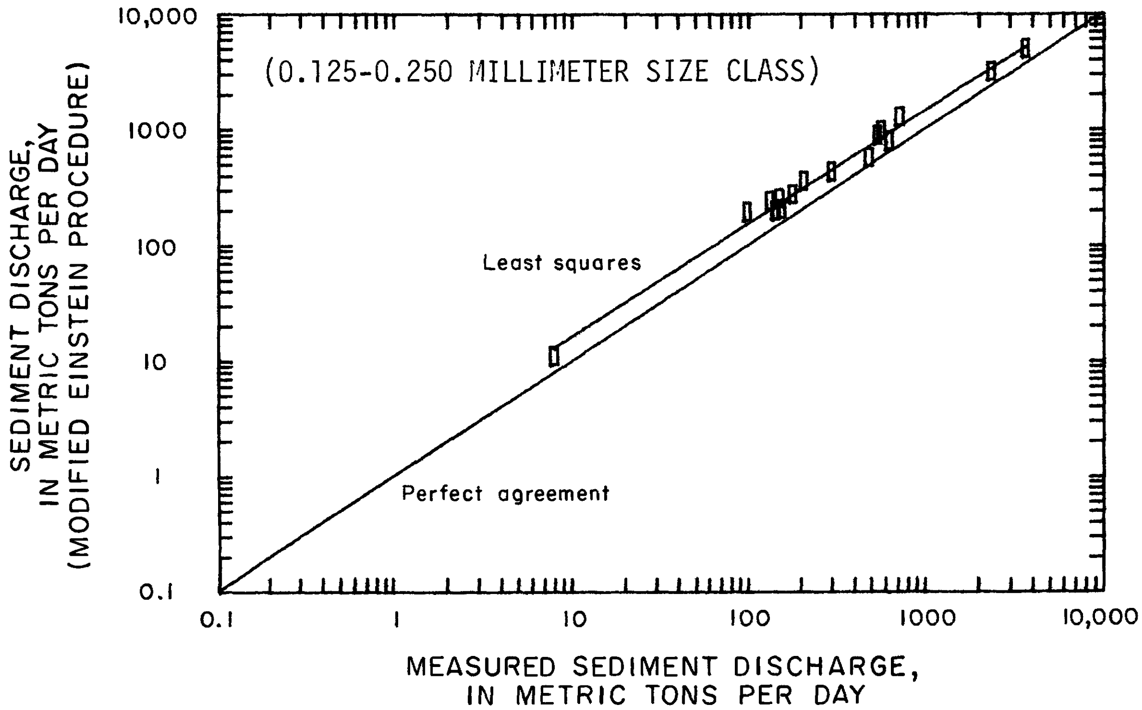


FIGURE 16.—Comparison of sediment discharges computed by the modified Einstein procedure for an individual particle-size class with corresponding measured sediment discharges for the class; 0.125- to 0.250-millimeter size class.

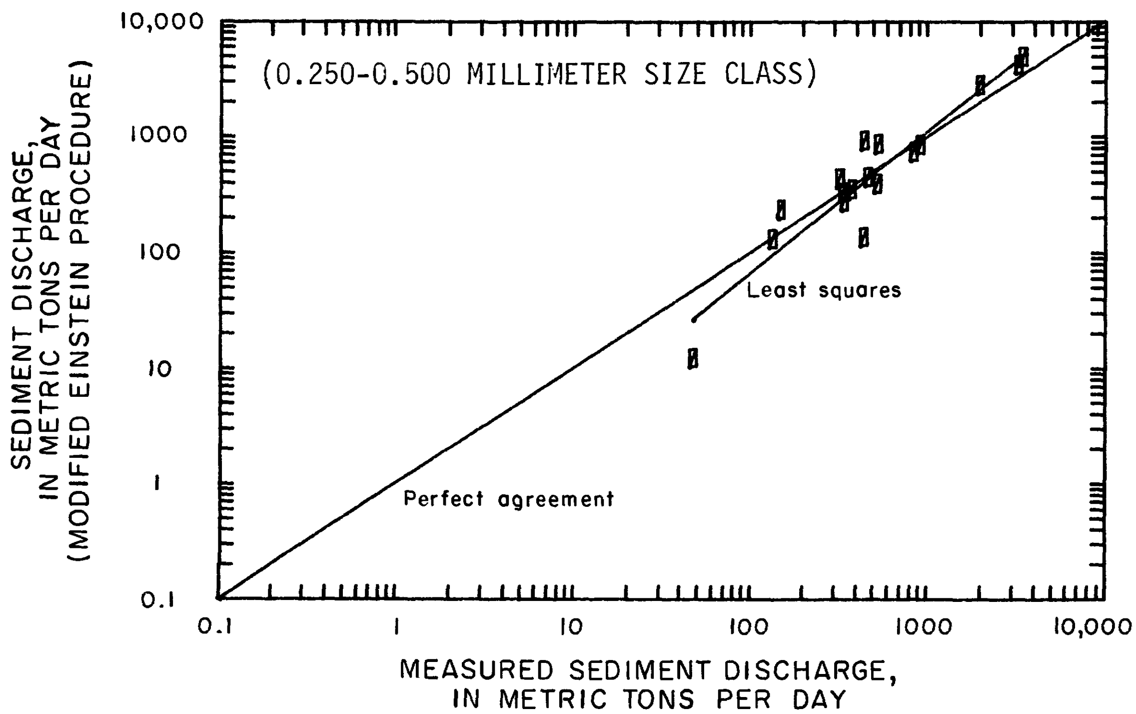


FIGURE 17.—Comparison of sediment discharges computed by the modified Einstein procedure for an individual particle-size class with corresponding measured sediment discharges for the class; 0.250- to 0.500-millimeter size class.

divided into 35, 69, 103, and 137 equal logarithmic intervals in an attempt to reduce the error caused by the skewness of the flow distribution.

It can be seen in table 9 that the variation in the number of intervals does cause a variation in the mean-daily sediment discharge; however, the difference is less

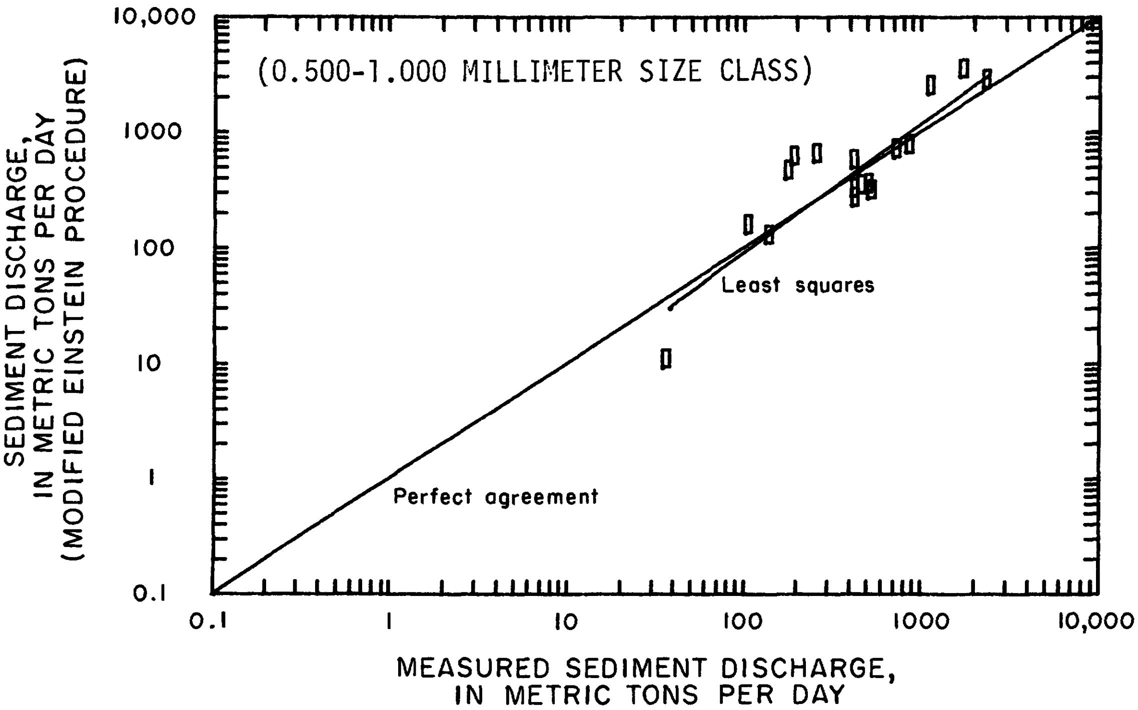


FIGURE 18.—Comparison of sediment discharges computed by the modified Einstein procedure for an individual particle-size class with corresponding measured sediment discharges for the class; 0.500- to 1.000-millimeter size class.

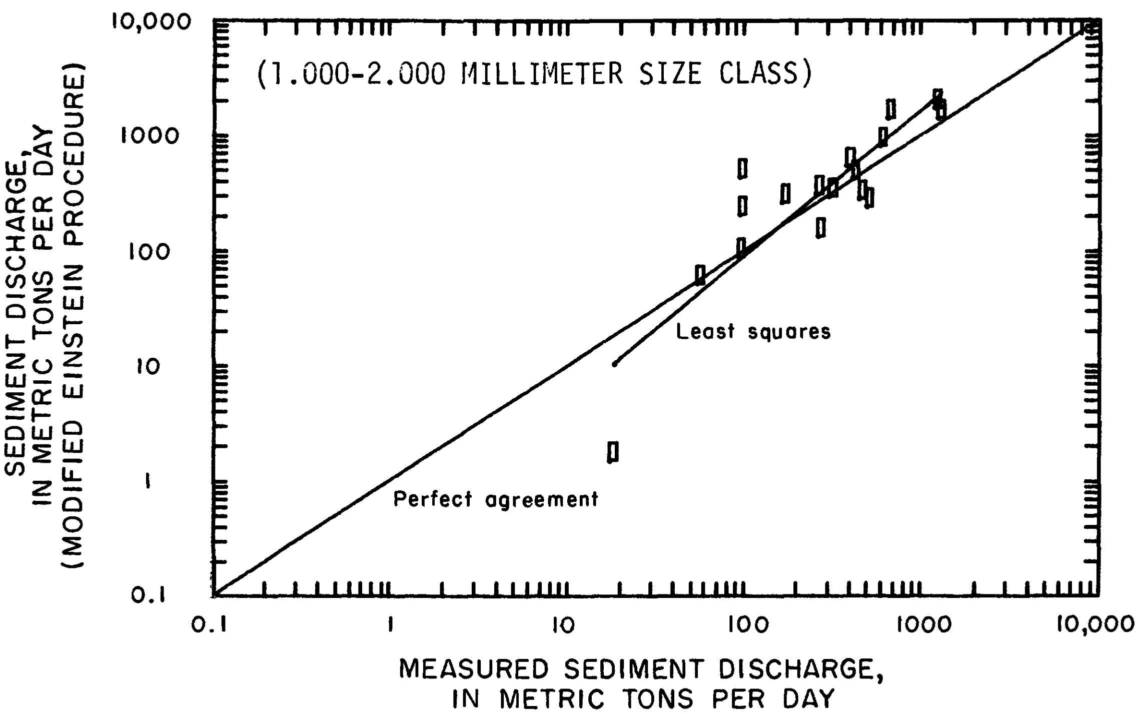


FIGURE 19.—Comparison of sediment discharges computed by the modified Einstein procedure for an individual particle-size class with corresponding measured sediment discharges for the class; 1.000- to 2.000-millimeter size class.

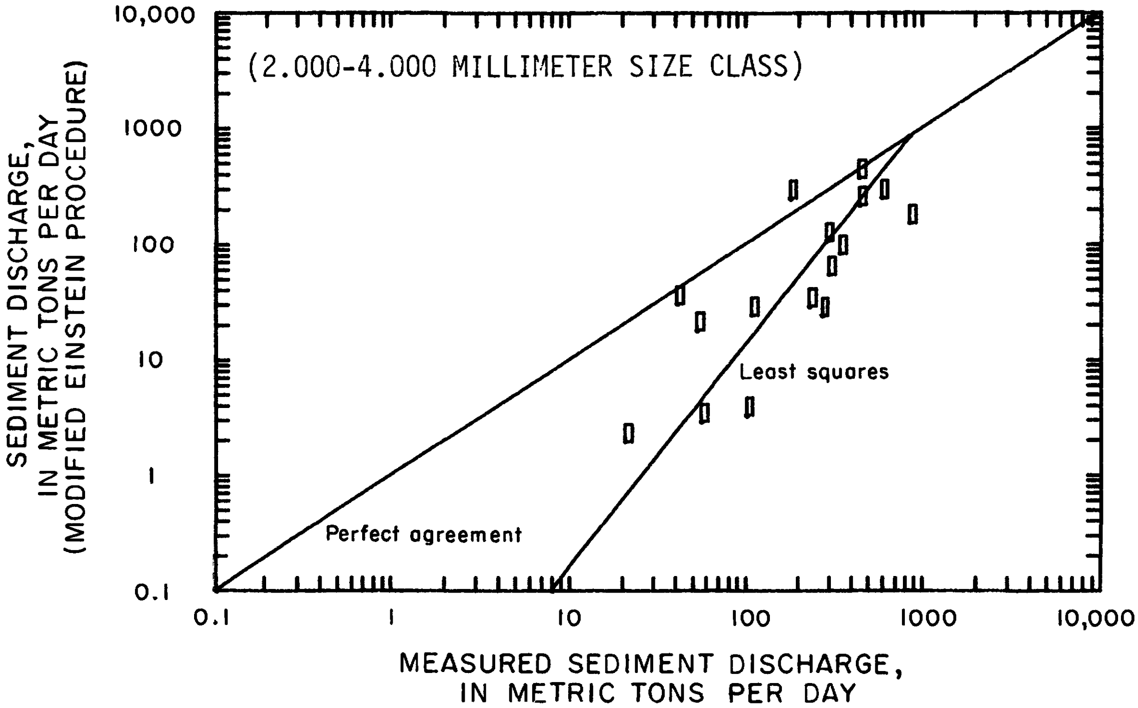


FIGURE 20.—Comparison of sediment discharges computed by the modified Einstein procedure for an individual particle-size class with corresponding measured sediment discharges for the class; 2.000- to 4.000-millimeter size class.

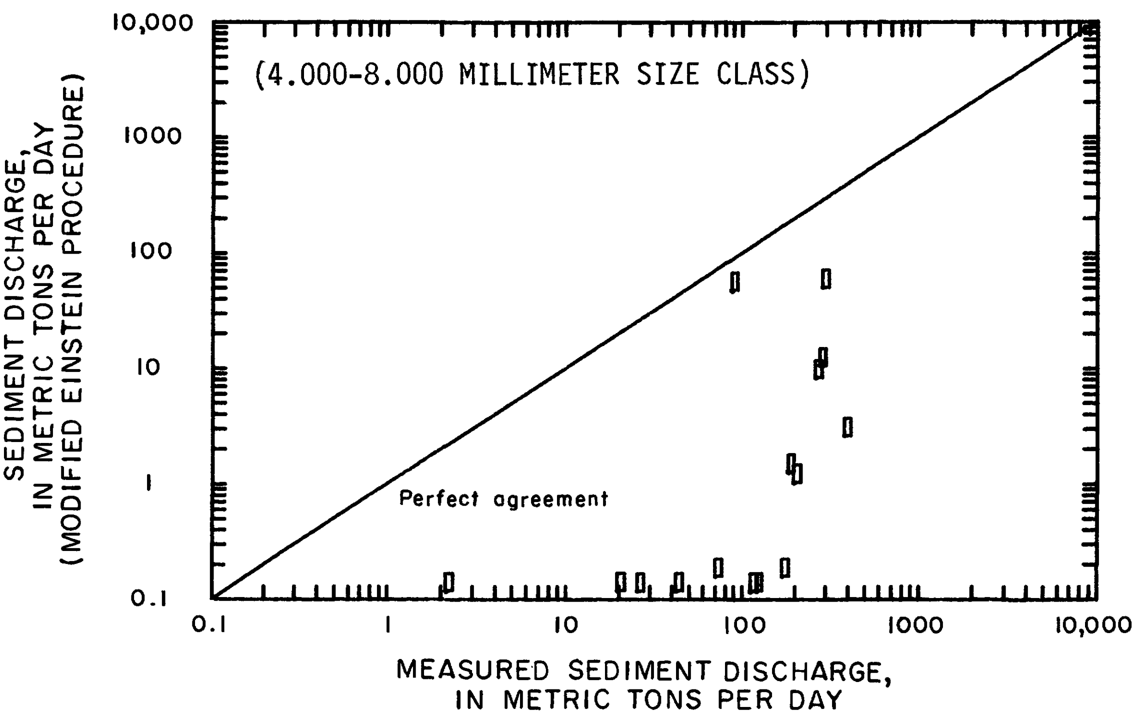


FIGURE 21.—Comparison of sediment discharges computed by the modified Einstein procedure for an individual particle-size class with corresponding measured sediment discharges for the class; 4.000- to 8.000-millimeter size class.

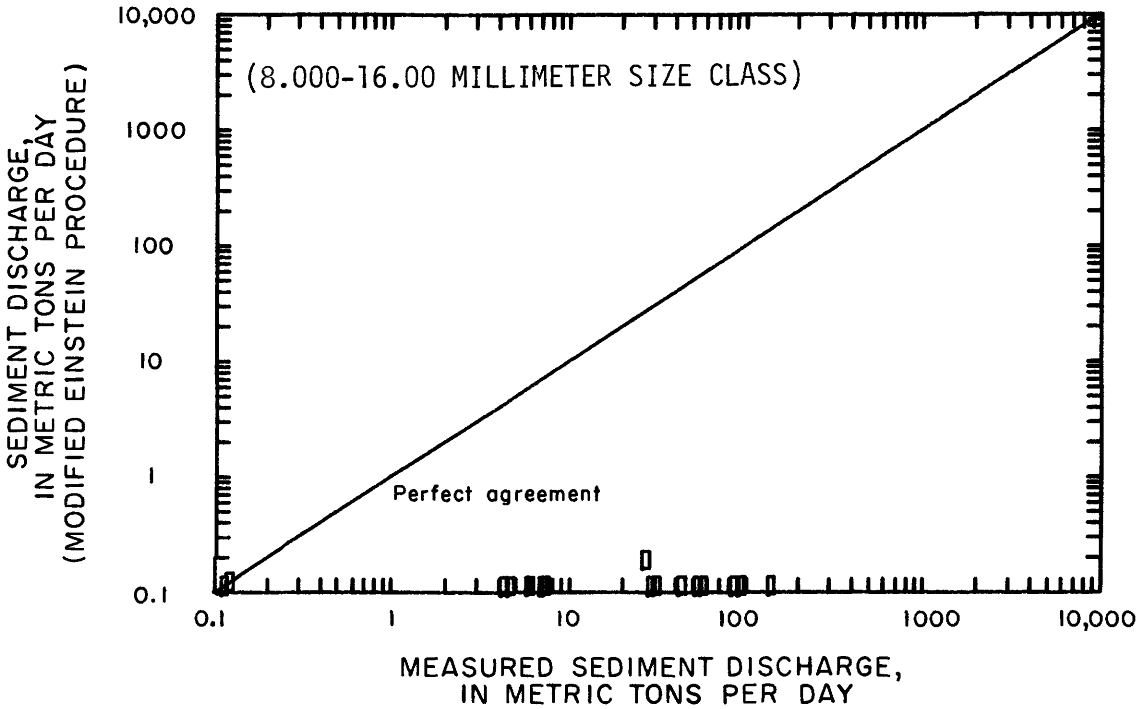


FIGURE 22.—Comparison of sediment discharges computed by the modified Einstein procedure for an individual particle-size class with corresponding measured sediment discharges for the class; 8.000- to 16.00-millimeter size class.

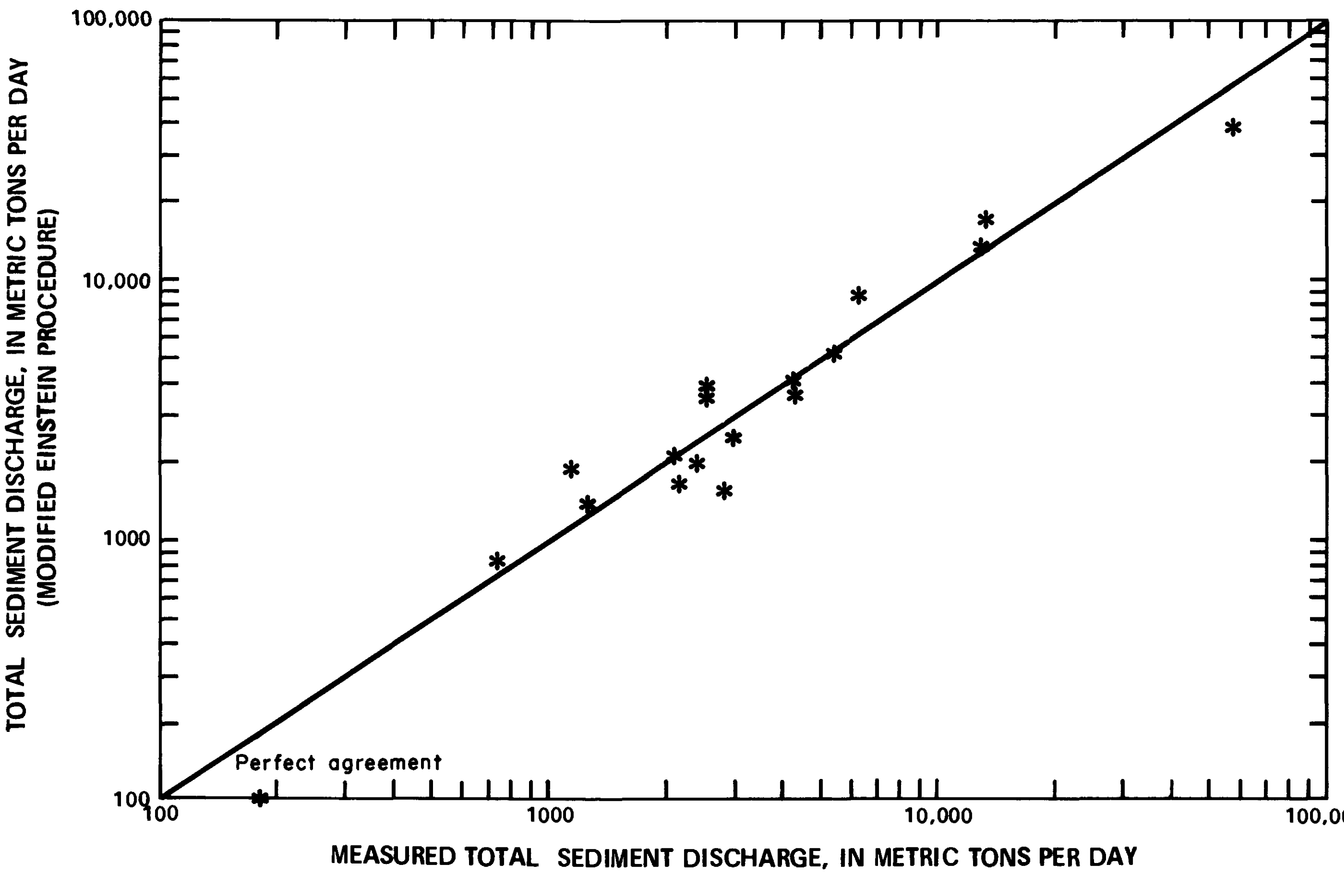


FIGURE 23.—Comparison between total sediment discharges computed by the modified Einstein procedure (Colby and Hembree, 1955) and measured total sediment discharges.

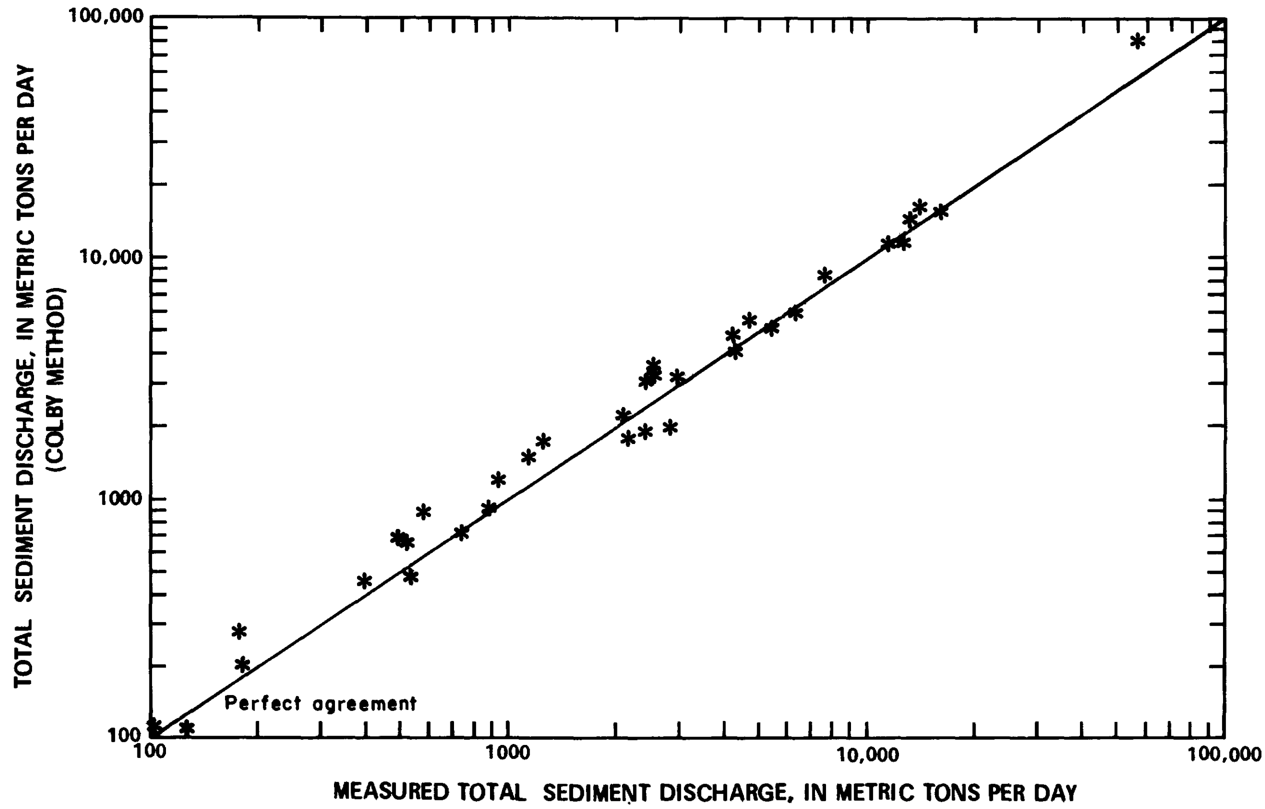


FIGURE 24.—Comparison between total sediment discharges computed by the Colby method and measured total sediment discharges.

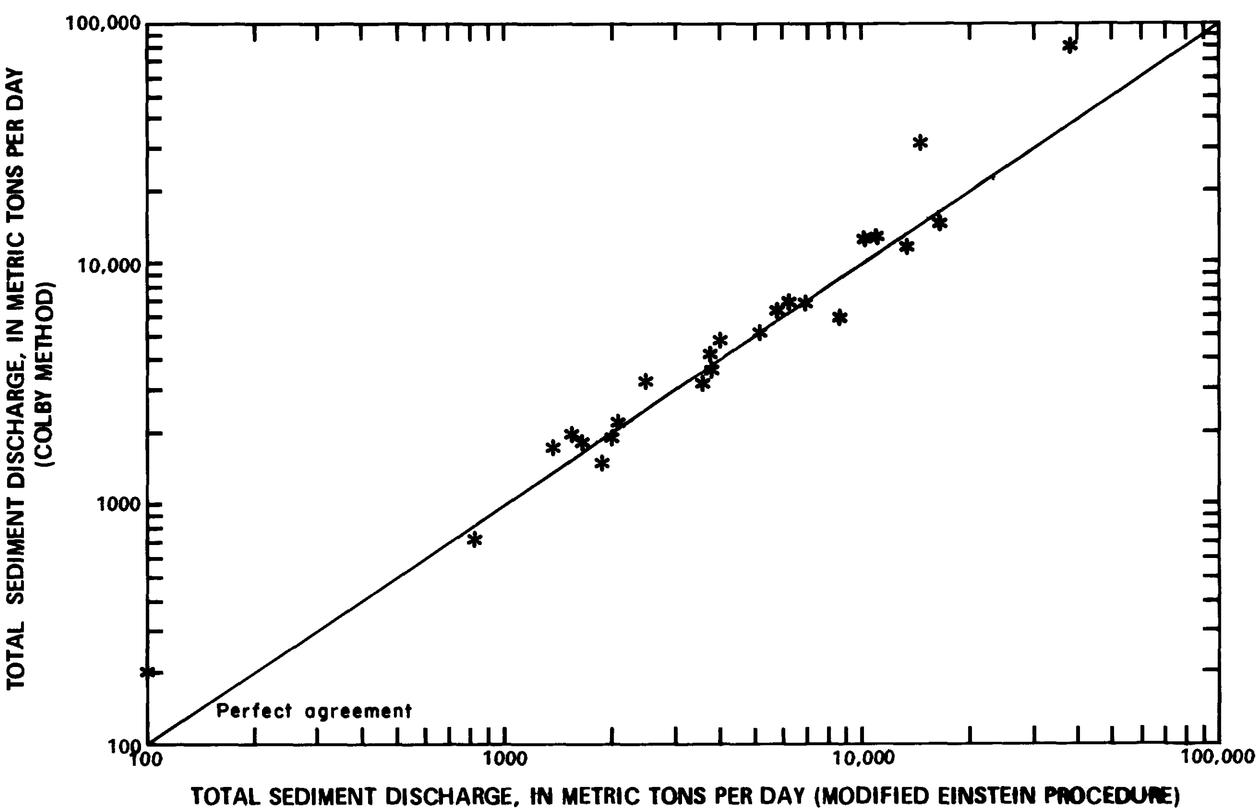


FIGURE 25.—Comparison between total sediment discharges computed by the Colby's method and total sediment discharges computed by the modified Einstein procedure (Colby and Hembree, 1955).

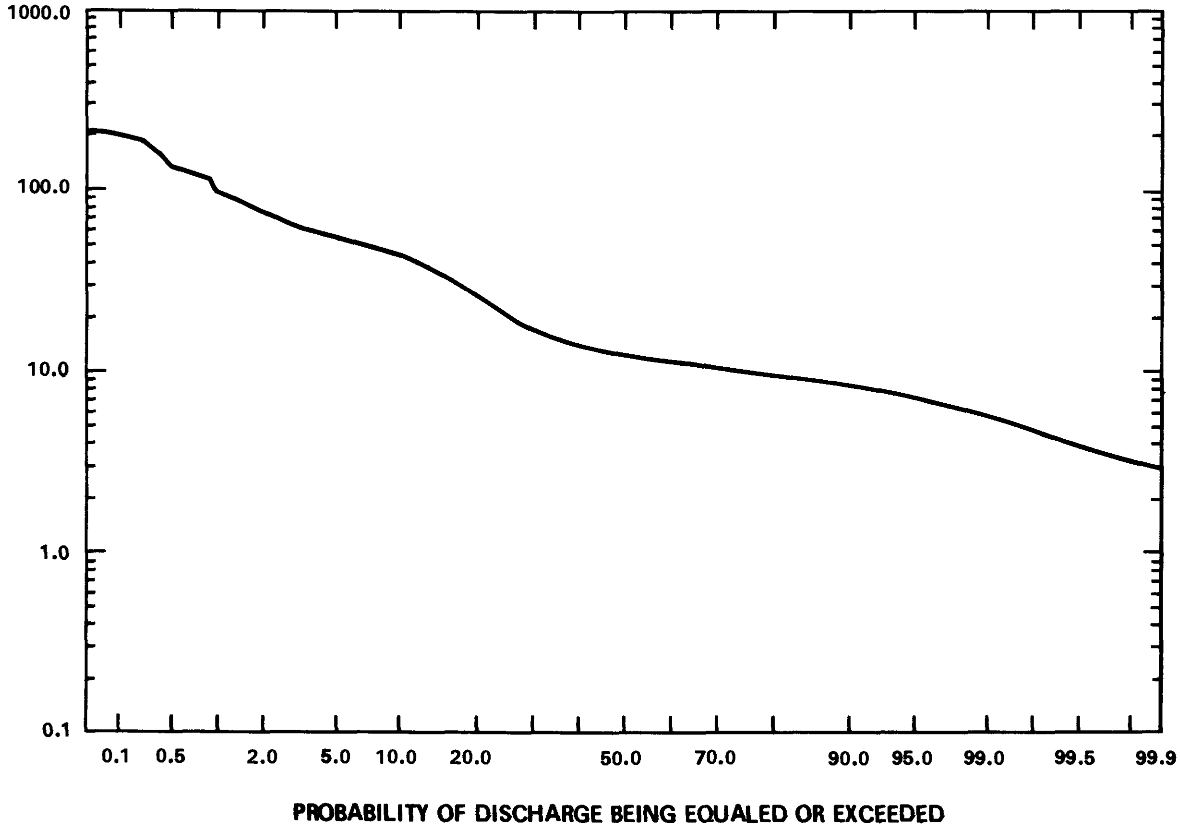


FIGURE 26.—Flow-duration curve for the North Platte River at North Platte, Nebraska (1941–79).

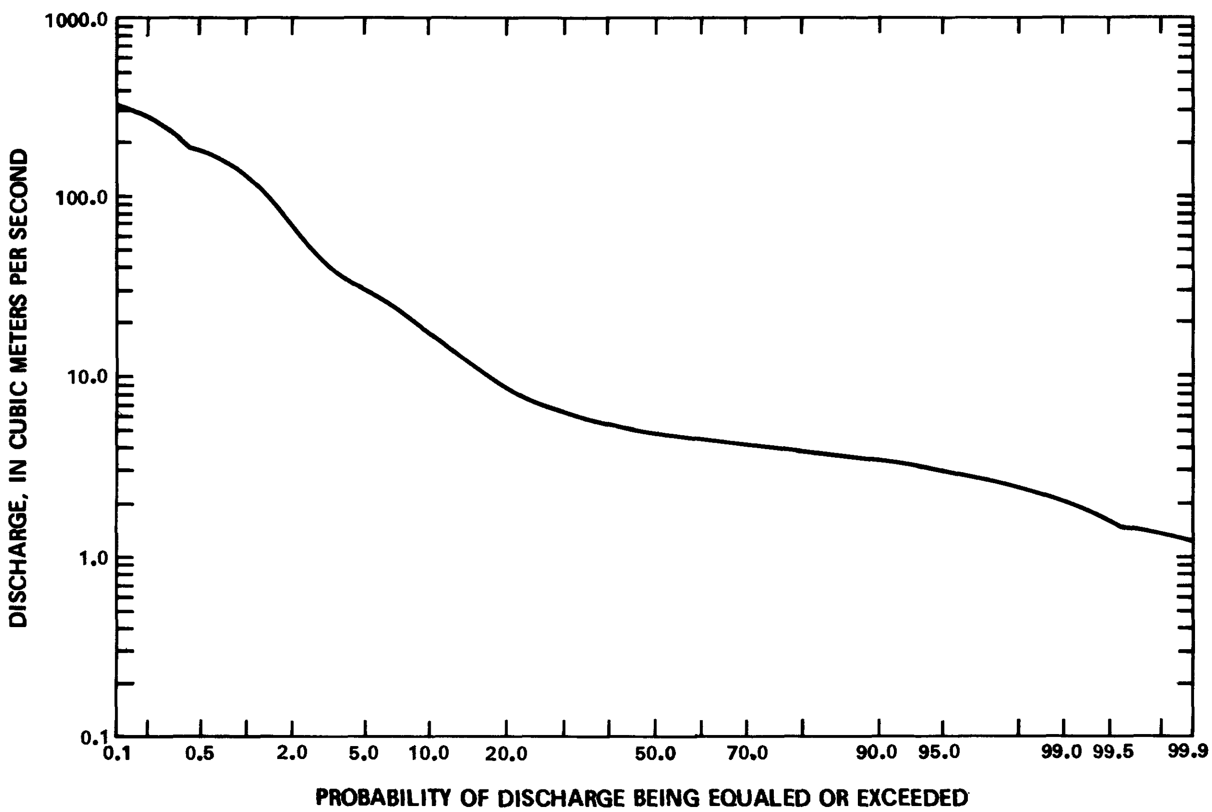


FIGURE 27.—Flow-duration curve for the South Platte River at North Platte, Nebraska (1941–79).

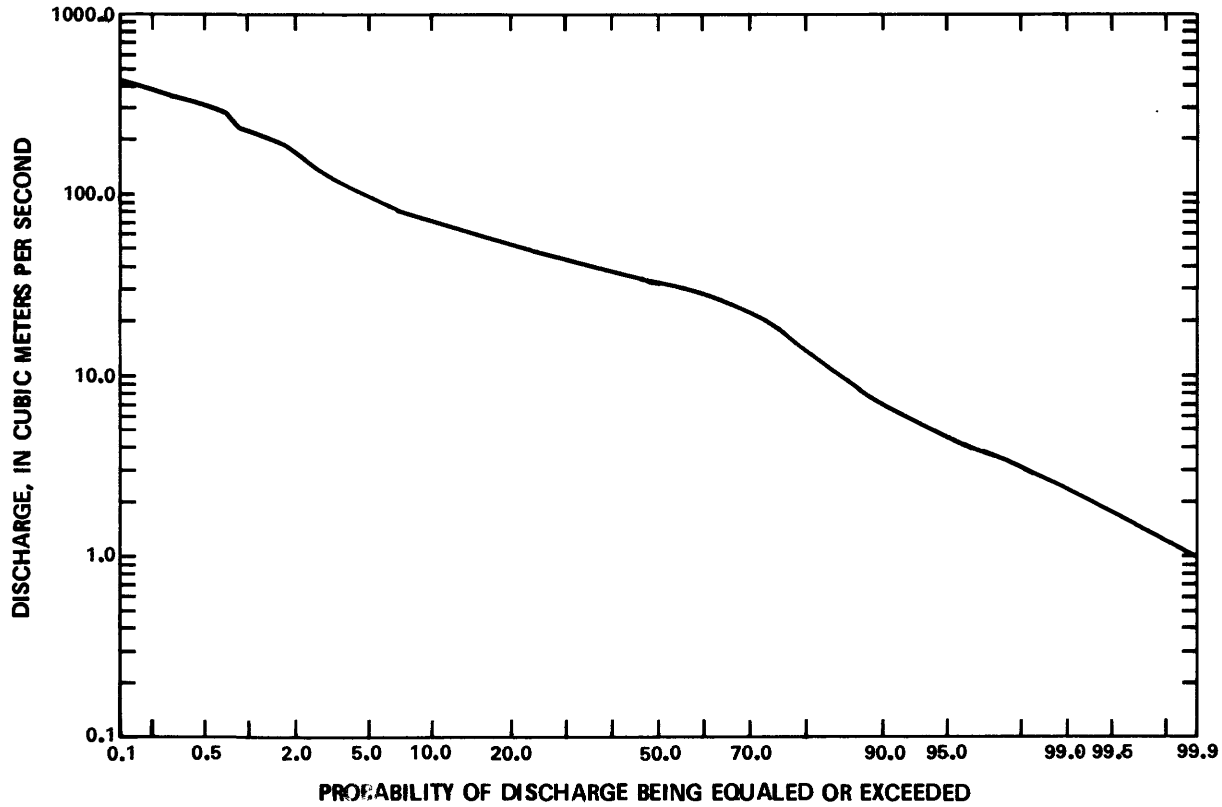


FIGURE 28.—Flow-duration curve for the Platte River near Overton, Nebraska (1950–79).

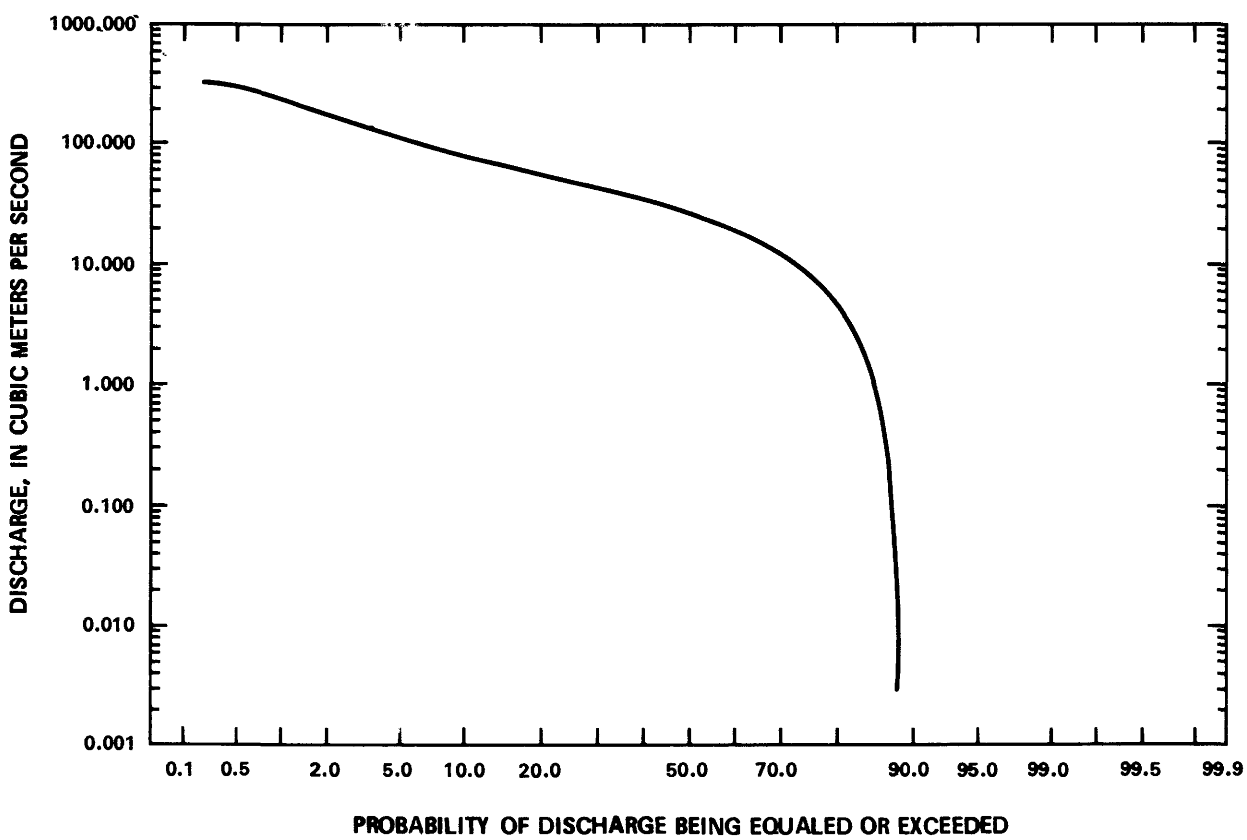


FIGURE 29.—Flow-duration curve for the Platte River near Grand Island, Nebraska (1935–79).

TABLE 8.—*Summary of mean-daily water discharge and measured total sediment discharge at four gaging stations.*

[km², square kilometers; m³/s, cubic meters per second; t/d, metric tons per day]

U.S. Geological Survey station number	Station name	Drainage area (km²)	Mean daily discharge (m³/s)	Mean daily total measured sediment discharge (t/d)
06693000	North Platte River at North Platte, Nebraska	80,000	23.5	597
06765500	South Platte River at North Platte, Nebraska	62,900	9.5	307
06768000	Platte River near Overton, Nebraska	149,400	39	1,100
06770500	Platte River near Grand Island, Nebraska	152,300	35.6	1,130

TABLE 9.—*Comparison of mean-daily water sediment discharges obtained by varying the number of subdivisions of the flow-duration curve for the Platte River near Overton, Nebraska*

[t/d, metric tons per day; ln, natural logarithm]

Type of intervals	Number of intervals	Mean-daily measured total sediment discharge (t/d)
Equal water discharge	35	1115
Equal water discharge	69	1110
Equal water discharge	103	1107
Equal water discharge	137	1107
Equal ln(water discharge)	35	747
Equal ln(water discharge)	69	1095
Equal ln(water discharge)	103	1100
Equal ln(water discharge)	137	1108

than 2 percent if the 35-interval equal-logarithmic intervals value is omitted.

SUMMARY

Streamflow and sediment data were collected at several locations along the Platte River and its major tributaries, the North Platte River and the South Platte River. The data were analyzed to determine the change in bed-material size in a downstream direction, and also to determine relations between water and total sediment discharges at four locations in the study reach.

The median bed material decreases in a downstream direction except near Overton, Nebraska, where it increases as a result of an increase in local slope at the same location. The median bed material at two locations in the Platte River was found to vary little with increasing water discharge.

Total sediment discharge was calculated by three methods for four stations in the critical reach. The four stations were the North Platte River at North Platte, Nebraska; the South Platte River at North Platte, Nebraska; the Platte River near Overton, Nebraska; and the Platte River near Grand Island, Nebraska. The three methods were: (1) summing measured bedload and suspended-sediment discharges; (2) summing measured suspended sediment discharge with unmeasured sediment discharge computed by Colby (1957) method; and (3) using the modified Einstein procedure (Colby and Hembree, 1955). Total sediment discharges computed by the three methods were compared and found to agree closely. From this comparison it was found that the sediment and hydraulic characteristics of the Platte River closely approximate the principles of the Colby method and modified Einstein procedure, indicating that the suspended sediment can be used as an indicator of bedload. When the modified Einstein and measured total sediment discharge were compared by particle-size class the agreement between the two methods was good for particle sizes finer than 2 mm; however, for sizes greater than 2 mm the modified Einstein procedure yielded smaller sediment discharges than were measured.

The mean daily sediment discharge for the four locations was computed by combining the relations between water discharge and measured total sediment discharge with the stations respective flow-duration curve. The mean daily sediment discharge for each site was found to be: (1) 579 t/d (metric tons per day) for the North Platte River at North Platte, Nebraska; (2) 307 t/d for the South Platte River at North Platte, Nebraska; (3) 1,100 t/d for the Platte River near Overton, Nebraska; and (4) 1,130 t/d for the Platte River near Grand Island, Nebraska.

REFERENCES CITED

Andrews, E. D., 1980, Effective and bankful discharges of streams in the Yampa River basin, Colorado and Wyoming: Journal of Hydrology, v. 46, 20 p.

Bentall, Ray, 1975, Hydrology, Nebraska mid-state division and associated areas: Nebraska University Conservation and Survey Division, Institute of Agriculture and Natural Resources Report, 256 p.

Colby, B. R., 1957, Relationship of unmeasured sediment discharge to mean velocity: Transactions of the American Geophysical Union, v. 38, no. 5, 9 p.

Colby, B. R., and Hembree, C. H., 1955, Computations of total sediment discharge, Niobrara River near Cody, Nebraska: U.S. Geological Survey Water-Supply Paper 1357, 187 p.

Emmett, W. W., 1980, A field calibration of the sediment-trapping characteristics of the Helley-Smith bedload sampler: U.S. Geological Survey Professional Paper 1139, 43 p.

Guy, H. P., and Norman, V. W., 1970, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter C2, 59 p.

Helley, E. J., and Smith, Winchell, 1971, Development and calibration of pressure-difference bedload sampler: U.S. Geological Survey open-file report, 18 p.

Hubbell, D. W., and others, 1956, Progress Report Number 1- Investigations of some sedimentation characteristics of a sand-bed stream: U.S. Geological Survey open-file report, 78 p.

Kircher, J. E., 1981a, Sediment analysis for selected sites on the South Platte River in Colorado and Nebraska, and the North Platte and Platte Rivers in Nebraska—Suspended sediment, bedload, and bed material: U.S. Geological Survey Open-File Report 81-207, 48 p.

_____1981b, Sediment transport and effective discharge of the North Platte, South Platte, and Platte Rivers, Nebraska: U.S. Geological Survey Open-File Report 81-53, 26 p.

Kircher, J. E., and Karlinger, M. R., 1981, Changes in surface water hydrology, Platte River basin in Colorado, Wyoming, and Nebraska upstream from Duncan, Nebraska: U.S. Geological Survey Open-File Report 81-818, 77 p.

U.S. Geological Survey, 1977, National handbook of recommended methods for water-data acquisition: Office of Water-Data Coordination, 100 p.

SUMMARY OF DATA

TABLE 10.—*Summary of water-discharge measurements*

[m, meters; m³/s, cubic meters per second; m/s, meters per second; C, degrees Celsius]

Station number in figure 1	Date	Time	Stage (m)	Discharge (m^3/s)	Width (m)	Mean Depth (m)	Mean Velocity (m/s)	Area (m^2)	Water Temperature (°C)
1	8/ 9/79	800	0.59	22.6	83.5	0.39	0.70	32.3	21.0
1	8/11/79	1555	.69	27.9	89.3	.49	.64	43.7	21.0
2	8/ 8/79	940	1.02	16.2	76.2	.32	.67	24.3	23.0
2	8/12/79	930	1.19	31.4	75.3	.59	.70	44.6	18.5
2	5/13/80	1630	1.07	17.5	76.5	.40	.58	30.4	17.0
2	6/ 5/80	1630	1.22	26.3	76.5	.55	.63	42.0	27.5
2	8/ 4/80	930	1.50	58.4	89.3	.73	.90	64.8	20.0
2	8/ 5/80	930	1.50	58.4	89.3	.73	.90	64.8	20.0
3	6/27/79	1200	1.64	71.2	96.0	.85	.87	81.4	
3	7/15/79	1055	.91	11.9	49.4	.32	.76	15.6	21.5
3	8/21/79	930	1.79	98.8	111	1.04	.86	115	23.0
3	9/25/79	955	1.05	20.5	51.2	.51	.79	26.1	17.0
3	5/ 6/80	1230	2.78	351	197	1.91	.93	376	13.5
4	6/20/79	1200	2.53	234	105	1.64	1.36	172	
4	6/26/79	1200	1.83	92.7	88.4	.95	1.10	84.2	
4	7/18/79	1200	.99	9.80	38.4	.38	.67	14.6	
4	8/16/79	1200	1.58	53.2	83.8	.70	.90	59.0	23.0
4	9/26/79	1200	1.19	17.7	39.6	.56	.79	22.3	17.5
5	6/20/79	1700	2.76	253	302	1.06	.79	321	20.5
5	6/25/79	1250	2.41	107	85.6	1.21	1.03	104	
5	7/17/79	1430	1.19	7.50	40.5				
5	8/17/79	1230	1.73	39.5	72.5	.66	.82	47.9	23.0
5	9/27/79	820	1.11	4.30	27.7	.28	.56	7.7	16.0
6	7/ 2/79	1400	1.52	36.6	92.4	.49	.80	45.5	
6	7/17/79	900	.87	2.18	16.5	.24	.55	4.0	24.0
6	8/15/79	1230	1.01	5.21	23.8	.33	.67	7.8	15.0
6	9/27/79	1255	1.00	5.64	21.3	.40	.65	8.6	22.0
7	7/28/79	930	1.63	8.18	30.8	.36	.74	11.1	22.5
7	8/ 8/79	745	1.51	4.50	31.7	.22	.66	6.9	22.0
7	5/22/80	1300	3.44	351	146	1.53	1.57	224	19.0
7	6/ 5/80	1300	2.98	189	148	1.11	1.15	164	23.5
7	6/12/80	1100	2.72	113	139	.71	1.14	99.0	22.5
7	6/22/80	1230	2.52	78.3	142	.59	.94	83.4	23.0
7	6/26/80	1025	2.33	47.2	122	.44	.87	54.1	27.0
7	6/29/80	1115	2.18	32.4	121	.41	.65	50.0	23.0
8	8/10/79	1145	.80	19.1	65.5	.50	.59	32.5	
9	7/15/79	1200	.48	1.50	22.9	.15	.45	3.3	
9	8/ 8/79	1530	.49	1.08	20.4	.32	.17	6.5	
10	7/18/79	1030	.50	16.7	116	.29	.50	33.1	21.0
10	8/15/79	1130	.40	6.54	81.1	.20	.40	16.2	17.0
10	5/ 1/80	1330	1.08	146	198	.86	.85	171	17.5
10	6/ 4/80	1150	1.37	254	204	1.13	1.10	231	24.0
10	6/11/80	1000	.99	126	200	.79	.80	158	22.0
10	6/21/80	815	.86	89.3	192	.61	.76	117	20.5
10	6/23/80	750	.79	65.4	188	.46	.75	87.2	23.0
10	6/24/80	830	.97	70.5	189	.49	.76	92.9	24.5
10	6/25/80	900	.59	46.8	154	.44	.69	67.9	24.0
10	6/28/80	1800	.43	22.7	116	.32	.62	36.8	30.0
11	7/17/79	1630	.48	8.69	83.5	.21	.50	17.4	
11	8/15/79	1500	.39	1.93	29.9	.16	.39	4.9	
12	8/16/79	1045	.43	8.10	138	.15	.40	20.4	18.0
12	4/30/80	1200	1.01	142	266	.65	.83	172	18.0
12	5/15/80	1145	1.32	271	268	1.02	.99	273	15.0
12	5/21/80	930	1.32	250	268	.97	.96	261	18.2
12	6/ 3/80	1210	1.35	304	268	1.06	1.07	285	22.0
12	6/10/80	1600	1.13	207	260	.79	1.00	206	26.0
12	6/20/80	1000	.98	124	242	.60	.86	145	21.0
12	6/24/80	940	.97	115	243	.59	.80	144	24.5
12	6/27/80	1100	.84	63.0	230	.41	.66	95.4	27.5
16	7/24/79	1100	.53	22.7	194	.24	.48	47.3	
16	8/17/79	1030	.26	4.81	98.8	.15	.32	15.0	24.0
18	8/20/79	1230	.46	42.3	248	.35	.49	85.7	25.5

TABLE 11.—*Summary of measured sediment-transport data*

[m^3/s, cubic meters per second; mg/L, milligrams per liter; tons/d, metric tons per day; kg/s/m, kilograms per second per meter]

Station number in figure 1	Date	Water discharge (m^3/s)	Suspended-sediment concentration (mg/L)	Suspended-sediment discharge (tons/d)	Unit bedload transport rate (kg/s/m)	Bedload-transport rate (tons/d)
1	8/ 9/79	22.6	370	720	0.058	420
1	8/11/79	27.9	120	290	.059	450
2	8/ 8/79	16.2	170	240	.043	280
2	8/12/79	31.4	350	950	.048	310
2	5/13/80	17.5	1430	2160	.043	281
2	6/ 5/80	26.3	140	320	.028	184
2	8/ 4/80	58.4	310	1560	.123	944
2	8/ 5/80	58.4	370	1870	.089	688
3	6/27/79	71.2	710	4370		
3	7/15/79	11.9	140	140		
3	8/21/79	98.8	1000	8540		
3	9/25/79	20.5	84	150	.087	383
3	5/ 6/80	351	950	28800	.267	28300
4	6/20/79	234	190	3840		
4	6/26/79	92.7	410	3280		
4	7/18/79	9.80	580	490	.026	87.5
4	8/16/79	53.2	400	1840		
4	9/26/79	17.7	100	150	.070	239
5	6/20/79	253	520	11400		
5	6/25/79	107	900	8320		
5	7/17/79	7.50	900	580		
5	8/17/79	39.5	1350	4610		
5	9/27/79	4.30	100			
6	7/17/79	2.18			.013	18.6
6	8/15/79	5.21			.008	17.3
6	9/27/79	5.64			.036	66.7
7	7/28/79	8.18	130	100	.033	88.0
7	8/ 8/79	4.50	62		.038	104
7	5/22/80	351	1160	35200	.670	8410
7	6/ 5/80	189	570	9310	.371	4720
7	6/12/80	113	390	3810	.313	3740
7	6/22/80	78.3	350	2370	.250	3060
7	6/26/80	47.2	190	770	.125	1310
7	6/29/80	32.4	170	480	.045	470
10	7/18/79	16.7			.051	511
10	8/15/79	6.54	69		.009	63.6
10	6/ 4/80	254	240	5270	.353	6210
10	6/11/80	126	220	2400	.105	1810
10	6/21/80	89.3	190	1470	.091	1500
10	6/23/80	65.4	130	730	.130	2100
10	6/24/80	70.5	110	670	.107	1740
10	6/25/80	46.8	70	280	.045	602
10	6/28/80	22.7			.017	169
12	8/16/79	8.10	100	100	.010	113
12	5/15/80	271	330	7730	.241	5570
12	5/21/80	250	270	5830	.293	6780
12	6/ 3/80	304	270	7090	.386	8920
12	6/10/80	207	120	2150	.185	4150
12	6/20/80	124	230	2460	.107	2230
12	6/24/80	115	180	1790	.121	2530
12	6/27/80	63.0	120	650	.075	1490

TABLE 12.—*Grain-size distribution of suspended sediment*

Station number in figure 1	Date	Percentage finer than indicated sieve size; sieve size (millimeters)								
		1.0	0.7	0.5	0.35	0.25	0.175	0.125	0.088	0.062
1	8/ 9/79	100	100	94	64	57	49	35	21	10
1	8/11/79	100	100	100	97	94	75	44	38	30
2	8/12/79	100	100	95	95	92	83	69	49	26
2	8/ 4/80	100	100	99	96	87	73	50	25	21
2	8/ 5/80	100	100	98	97	84	65	41	14	9
3	6/19/79	69	62	53	43	34	28	26	26	26
3	6/27/79	100	95	78	58	49	41	38	36	36
3	8/21/79	100	100	99	99	95	91	86	82	78
3	5/ 6/80	100	100	100	87	85	66	60	57	53
4	6/26/79	100	100	99	96	89	82	74	71	70
4	8/16/79	100	100	97	92	81	64	52	48	47
4	8/16/79	100	97	96	89	82	75	73	71	68
4	9/26/79	100	100	100	100	98	83	77	62	56
4	9/26/79	100	100	100	99	95	83	73	67	64
5	6/20/79	100	100	98	90	74	47	35	31	31
5	6/25/79	100	98	92	84	75	62	55	51	49
5	7/17/79	100	100	97	95	82	39	31	30	30
5	8/17/79	100	100	97	90	82	69	61	47	42
6	6/14/79	97	85	66	46	38	31	28	27	26
6	7/ 2/79	100	100	100	97	89	72	54	52	51
6	8/15/79	92	63	45	34	24	23	23	23	23
7	5/22/80	68	65	63	60	57	54	53	53	52
7	6/ 5/80	100	100	98	91	80	69	64	63	61
7	6/22/80	100	100	98	95	86	78	74	73	71
7	6/26/80	100	100	99	97	88	77	74	72	69
10	6/11/80	100	100	99	96	91	80	74	70	69
10	6/11/80	100	100	99	96	91	80	74	70	69
10	6/21/80	100	100	100	98	96	90	85	83	81
10	6/23/80	100	100	100	100	97	87	83	82	80
10	6/24/80	100	100	100	100	97	81	75	72	69
10	6/25/80	100	100	100	100	100	99	98	95	89
12	8/16/79	100	100	97	94	89	85	78	70	61
12	5/15/80	100	100	99	98	70	40	22	19	18
12	5/21/80	100	99	97	89	67	43	28	25	2
12	6/10/80	100	100	100	91	64	49	41	40	40
12	6/24/80	100	100	100	98	92	71	62	59	59
12	6/27/80	100	100	100	100	98	84	78	74	73

TABLE 13.—*Grain-size distribution of bedload*

Station number in figure 1	Date	Percentage finer than indicated sieve size; sieve size (millimeters)								
		16.0	8.0	4.0	2.0	1.0	0.5	0.25	0.125	0.062
1	8/ 9/79	100.0	99.0	94.0	84.0	61.0	26.0	3.0	0.0	0.0
1	8/11/79	100.0	99.0	93.0	80.0	59.0	35.0	6.0	0.0	0.0
2	8/ 8/79	100.0	100.0	97.0	89.0	74.0	47.0	7.0	0.1	0.0
2	8/12/79	100.0	100.0	98.0	91.0	73.0	40.0	5.0	0.2	0.0
2	5/13/80	100.0	100.0	96.0	90.0	76.0	47.0	5.0	0.2	0.0
2	6/ 5/80	100.0	100.0	98.0	90.0	77.0	53.0	8.0	0.2	0.0
2	8/ 4/80	100.0	97.0	89.0	77.0	59.0	33.0	4.0	0.2	0.0
2	8/ 5/80	100.0	99.0	94.0	86.0	72.0	47.0	5.0	0.2	0.0
3	9/25/79	97.0	94.0	83.0	66.0	46.0	25.0	4.0	0.0	0.0
3	5/ 6/80	88.0	79.0	63.0	43.0	25.0	13.0	3.0	0.1	0.1
4	7/18/79	100.0	98.0	90.0	75.0	54.0	30.0	4.0	0.1	0.0
4	9/26/79	100.0	99.0	93.0	78.0	56.0	28.0	5.0	0.2	0.0
6	7/17/79	100.0	100.0	97.0	89.0	72.0	37.0	3.0	0.0	0.0
6	8/15/79	100.0	99.0	96.0	89.0	74.0	38.0	10.0	1.0	0.7
6	9/27/79	100.0	100.0	96.0	83.0	60.0	27.0	4.0	0.1	0.0
7	7/28/79	100.0	99.0	88.0	68.0	41.0	11.0	0.6	0.1	0.0
7	8/ 8/79	100.0	100.0	94.0	75.0	43.0	13.0	0.3	0.0	0.0
7	5/22/80	93.0	90.0	80.0	61.0	37.0	13.0	2.0	0.0	0.0
7	6/ 5/80	100.0	94.0	82.0	67.0	48.0	24.0	2.0	0.0	0.0
7	6/12/80	100.0	95.0	85.0	70.0	52.0	26.0	3.0	0.0	0.0
7	6/22/80	100.0	97.0	87.0	72.0	52.0	24.0	2.0	0.0	0.0
7	6/26/80	100.0	98.0	91.0	77.0	57.0	24.0	0.9	0.0	0.0
7	6/29/80	100.0	99.0	96.0	87.0	68.0	33.0	2.0	0.0	0.0
10	7/18/79	100.0	99.0	95.0	85.0	68.0	32.0	2.0	0.0	0.0
10	8/15/79	100.0	100.0	97.0	85.0	65.0	28.0	2.0	0.3	0.1
10	5/ 1/80	94.0	93.0	84.0	68.0	48.0	22.0	3.0	0.0	0.0
10	6/ 4/80	100.0	96.0	86.0	69.0	45.0	17.0	2.0	0.0	0.0
10	6/11/80	100.0	95.0	85.0	68.0	46.0	23.0	7.0	0.2	0.1
10	6/21/80	100.0	98.0	90.0	74.0	53.0	21.0	3.0	0.0	0.0
10	6/23/80	100.0	98.0	88.0	71.0	49.0	23.0	3.0	0.0	0.0
10	6/24/80	100.0	97.0	86.0	69.0	45.0	20.0	2.0	0.0	0.0
10	6/25/80	100.0	99.0	89.0	71.0	42.0	15.0	0.3	0.0	0.0
10	6/28/80	100.0	99.0	93.0	80.0	62.0	27.0	2.0	0.1	0.0
12	8/16/79	100.0	100.0	98.0	91.0	75.0	43.0	4.0	0.0	0.0
12	4/30/80	100.0	98.0	94.0	81.0	59.0	24.0	3.0	0.0	0.0
12	5/15/80	100.0	99.0	94.0	83.0	61.0	30.0	5.0	0.0	0.0
12	5/21/80	100.0	98.0	92.0	79.0	60.0	27.0	4.0	0.0	0.0
12	6/ 3/80	98.0	94.0	86.0	72.0	51.0	23.0	3.0	0.0	0.0
12	6/10/80	100.0	98.0	91.0	80.0	64.0	36.0	5.0	0.0	0.0
12	6/20/80	100.0	99.0	96.0	88.0	73.0	44.0	7.0	0.0	0.0
12	6/24/80	100.0	99.0	94.0	83.0	63.0	33.0	5.0	0.0	0.0
12	6/27/80	100.0	99.0	96.0	89.0	71.0	36.0	2.0	0.0	0.0

TABLE 14.—*Statistical data, grain-size distribution of bedload*

Station number in figure 1	Date	Particle-size (millimeters) at given percentage finer; percentage finer paramenter									
		5	16	25	35	50	65	75	84	90	95
1	8/ 9/79	0.3	0.4	0.5	0.6	0.8	1.1	1.5	2.0	2.9	4.5
1	8/11/79	0.2	0.3	0.4	0.5	0.8	1.2	1.7	2.4	3.2	4.6
2	8/ 8/79	0.2	0.3	0.4	0.4	0.5	0.8	1.0	1.5	2.1	3.1
2	8/12/79	0.3	0.3	0.4	0.5	0.6	0.8	1.1	1.5	1.9	2.8
2	6/ 5/80	0.2	0.3	0.4	0.4	0.5	0.7	0.9	1.4	2.0	2.9
2	8/ 4/80	0.3	0.4	0.4	0.5	0.8	1.2	1.8	2.9	4.2	6.1
2	8/ 5/80	0.3	0.3	0.4	0.4	0.5	0.8	1.1	1.8	2.8	4.4
2	5/13/80	0.2	0.3	0.4	0.4	0.5	0.8	1.0	1.4	2.0	3.3
3	9/25/79	0.3	0.4	0.5	0.7	1.1	2.0	2.8	4.1	5.8	9.7
3	5/ 6/80	0.3	0.6	1.0	1.5	2.6	4.4	6.7	11.6	19.2	32.8
4	7/18/79	0.3	0.4	0.5	0.6	0.9	1.4	2.0	2.9	4.0	5.4
4	9/26/79	0.2	0.4	0.5	0.6	0.9	1.3	1.8	2.5	3.3	4.6
6	7/17/79	0.3	0.4	0.4	0.5	0.6	0.9	1.1	1.6	2.2	3.1
6	8/15/79	0.2	0.3	0.4	0.5	0.6	0.8	1.1	1.6	2.2	3.6
6	9/27/79	0.3	0.4	0.5	0.6	0.8	1.1	1.5	2.1	2.7	3.7
7	8/ 8/79	0.4	0.6	0.7	0.9	1.2	1.6	2.0	2.6	3.3	4.3
7	7/28/79	0.4	0.6	0.7	0.9	1.3	1.8	2.4	3.4	4.3	5.5
7	6/ 5/80	0.3	0.4	0.5	0.7	1.1	1.9	2.8	4.4	6.0	8.5
7	5/22/80	0.4	0.6	0.7	1.0	1.5	2.3	3.3	5.3	8.7	25.1
7	6/12/80	0.3	0.4	0.5	0.6	1.0	1.6	2.5	3.9	5.3	7.8
7	6/22/80	0.3	0.4	0.5	0.7	1.0	1.5	2.2	3.4	4.5	6.2
7	6/26/80	0.3	0.4	0.5	0.6	0.9	1.3	1.8	2.7	3.9	5.6
7	6/29/80	0.3	0.4	0.5	0.5	0.7	0.9	1.3	1.8	2.4	3.6
10	7/18/79	0.3	0.4	0.5	0.5	0.7	0.9	1.3	1.9	2.6	3.9
10	8/15/79	0.3	0.4	0.5	0.6	0.8	1.0	1.4	1.9	2.5	3.4
10	5/ 1/80	0.3	0.4	0.5	0.7	1.1	1.8	2.6	4.1	6.3	25.2
10	6/ 4/80	0.3	0.5	0.6	0.8	1.1	1.8	2.5	3.7	4.9	6.9
10	6/11/80	0.2	0.4	0.5	0.7	1.1	1.8	2.6	3.9	5.3	8.0
10	6/21/80	0.3	0.4	0.6	0.7	0.9	1.4	2.0	2.9	4.0	5.6
10	6/23/80	0.3	0.4	0.5	0.7	1.0	1.6	2.3	3.2	4.3	6.0
10	6/24/80	0.3	0.5	0.6	0.8	1.1	1.8	2.5	3.7	4.9	6.7
10	6/25/80	0.4	0.5	0.7	0.9	1.2	1.7	2.3	3.2	4.1	5.1
10	6/28/80	0.3	0.4	0.5	0.6	0.8	1.1	1.6	2.4	3.3	4.8
12	8/16/79	0.3	0.3	0.4	0.5	0.6	0.8	1.0	1.4	1.9	2.6
12	6/ 3/80	0.3	0.4	0.5	0.7	1.0	1.5	2.2	3.6	5.4	9.1
12	4/30/80	0.3	0.4	0.5	0.6	0.8	1.2	1.6	2.3	3.1	4.6
12	5/15/80	0.3	0.4	0.5	0.6	0.8	1.1	1.5	2.1	2.9	4.4
12	5/21/80	0.3	0.4	0.5	0.6	0.8	1.2	1.7	2.5	3.5	5.1
12	6/10/80	0.3	0.4	0.4	0.5	0.7	1.0	1.6	2.4	3.6	5.4
12	6/20/80	0.2	0.3	0.4	0.4	0.6	0.8	1.1	1.6	2.3	3.5
12	6/24/80	0.3	0.4	0.4	0.5	0.8	1.1	1.5	2.1	2.9	4.4
12	6/27/80	0.3	0.4	0.4	0.5	0.7	0.9	1.1	1.6	2.2	3.4

TABLE 15.—*Grain-size distribution of bed material*

Station number in figure 1	Date	Percentage finer than indicated sieve size; sieve size (millimeters)								
		16.0	8.0	4.0	2.0	1.0	0.5	0.25	0.125	0.062
1	6/28/79	100.0	100.0	99.0	92.0	76.0	46.0	10.0	1.0	0.2
1	8/ 9/79	99.0	96.0	89.0	75.0	54.0	32.0	15.0	5.0	0.7
1	8/11/79	98.0	95.0	89.0	77.0	60.0	38.0	12.0	2.0	0.2
2	8/ 8/79	100.0	98.0	89.0	77.0	62.0	41.0	11.0	2.0	0.2
2	8/12/79	100.0	99.0	97.0	89.0	73.0	43.0	9.0	0.9	0.0
2	8/21/79	100.0	99.0	95.0	87.0	69.0	41.0	9.0	0.5	0.0
2	5/13/80	100.0	99.0	94.0	85.0	71.0	51.0	26.0	11.0	1.0
2	6/ 5/80	100.0	99.0	97.0	92.0	79.0	53.0	20.0	8.0	1.0
2	8/ 4/80	100.0	98.0	94.0	87.0	72.0	45.0	12.0	0.8	0.1
2	8/ 5/80	100.0	98.0	94.0	88.0	74.0	50.0	18.0	2.0	0.0
3	6/27/79	98.0	94.0	82.0	62.0	45.0	26.0	9.0	2.0	0.8
3	7/16/79	95.0	84.0	68.0	43.0	28.0	13.0	3.0	0.5	0.1
3	8/21/79	98.0	93.0	84.0	70.0	54.0	31.0	10.0	1.0	0.2
3	9/25/79	95.0	84.0	74.0	63.0	48.0	28.0	15.0	9.0	3.0
3	5/ 6/80	95.0	86.0	72.0	57.0	44.0	29.0	18.0	16.0	15.0
4	6/20/79	99.0	94.0	85.0	65.0	42.0	18.0	5.0	2.0	0.6
4	6/26/79	99.0	93.0	83.0	61.0	40.0	17.0	4.0	0.4	0.1
4	7/18/79	100.0	95.0	82.0	59.0	46.0	29.0	6.0	0.4	0.1
4	9/26/79	100.0	97.0	86.0	64.0	43.0	19.0	4.0	2.0	2.0
5	6/20/79	99.0	97.0	92.0	83.0	76.0	65.0	45.0	18.0	5.0
5	6/25/79	100.0	98.0	94.0	84.0	69.0	45.0	20.0	6.0	1.0
5	7/17/79	100.0	97.0	87.0	69.0	52.0	28.0	6.0	0.6	0.1
5	8/17/79	100.0	99.0	90.0	78.0	61.0	30.0	9.0	2.0	0.5
5	9/27/79	100.0	98.0	91.0	79.0	61.0	34.0	4.0	0.2	0.0
6	6/14/79	100.0	97.0	91.0	79.0	66.0	44.0	18.0	2.0	0.9
6	6/27/79	100.0	99.0	93.0	72.0	49.0	20.0	3.0	0.1	0.0
6	7/ 2/79	100.0	98.0	91.0	74.0	54.0	26.0	8.0	3.0	0.9
6	7/17/79	100.0	95.0	87.0	64.0	45.0	22.0	3.0	0.1	0.0
6	8/15/79	98.0	90.0	76.0	60.0	44.0	22.0	4.0	0.3	0.1
6	9/27/79	100.0	97.0	90.0	75.0	51.0	23.0	5.0	0.3	0.0
7	7/28/79	98.0	93.0	78.0	54.0	35.0	16.0	3.0	0.1	0.0
7	8/ 8/79	96.0	91.0	78.0	59.0	37.0	14.0	0.9	0.0	0.0
7	8/21/79	96.0	87.0	76.0	64.0	46.0	25.0	8.0	1.0	0.3
7	5/22/80	100.0	98.0	94.0	85.0	65.0	32.0	6.0	0.7	0.1
7	6/12/80	87.0	92.0	84.0	72.0	59.0	29.0	4.0	0.2	0.1
7	6/22/80	98.0	90.0	78.0	64.0	48.0	26.0	4.0	0.3	0.0
7	6/26/80	89.0	80.0	65.0	52.0	42.0	27.0	6.0	0.4	0.0
7	6/29/80	100.0	96.0	86.0	72.0	54.0	25.0	2.0	0.0	0.0
7	7/26/80	100.0	97.0	87.0	74.0	57.0	27.0	2.0	0.0	0.0
8	6/28/79	100.0	100.0	98.0	91.0	70.0	30.0	5.0	0.2	0.0
8	8/10/79	100.0	98.0	89.0	76.0	57.0	29.0	5.0	0.1	0.0
9	7/15/79	100.0	100.0	97.0	88.0	72.0	28.0	2.0	0.0	0.0
9	7/20/79	98.0	90.0	79.0	60.0	44.0	23.0	3.0	0.7	0.0
9	8/ 8/79	99.0	96.0	82.0	66.0	46.0	22.0	5.0	0.8	0.2
10	7/18/79	100.0	80.0	57.0	39.0	23.0	9.0	1.0	0.0	0.0
10	8/15/79	96.0	92.0	80.0	62.0	40.0	18.0	3.0	0.2	0.0
10	5/ 1/80	100.0	96.0	89.0	76.0	59.0	33.0	10.0	0.8	0.0
10	6/ 4/80	100.0	97.0	87.0	71.0	58.0	42.0	21.0	8.0	4.0
10	6/11/80	100.0	98.0	92.0	80.0	58.0	27.0	8.0	0.9	0.1
10	6/21/80	100.0	98.0	93.0	82.0	63.0	32.0	7.0	0.2	0.0
10	6/23/80	99.0	94.0	82.0	68.0	50.0	25.0	7.0	0.3	0.0
10	6/24/80	100.0	94.0	82.0	67.0	49.0	28.0	7.0	0.1	0.0
10	6/25/80	98.0	89.0	74.0	58.0	42.0	23.0	5.0	0.3	0.0
10	6/28/80	99.0	93.0	82.0	68.0	51.0	24.0	6.0	0.1	0.0
11	7/17/79	100.0	97.0	92.0	86.0	74.0	39.0	5.0	0.3	0.2
11	8/15/79	100.0	98.0	88.0	74.0	52.0	24.0	5.0	0.0	0.0
12	8/16/79	100.0	99.0	94.0	82.0	66.0	37.0	7.0	0.2	0.1
12	8/27/79	100.0	98.0	94.0	82.0	71.0	47.0	8.0	0.3	0.0
12	4/29/80	100.0	99.0	94.0	82.0	64.0	39.0	8.0	0.7	0.3
12	4/30/80	100.0	99.0	96.0	88.0	74.0	45.0	11.0	0.1	0.0

TABLE 15.—*Grain-size distribution of bed material*—Continued

Station number in figure 1	Date	Percentage finer than indicated sieve size; sieve size (millimeters)								
		16.0	8.0	4.0	2.0	1.0	0.5	0.25	0.125	0.062
12	5/15/80	100.0	98.0	92.0	83.0	66.0	36.0	6.0	0.0	0.0
12	5/21/80	100.0	100.0	95.0	86.0	69.0	40.0	7.0	0.0	0.0
12	6/ 3/80	100.0	97.0	90.0	77.0	57.0	29.0	6.0	1.0	0.0
12	6/10/80	100.0	98.0	92.0	84.0	68.0	40.0	8.0	0.1	0.0
12	6/20/80	100.0	99.0	94.0	81.0	61.0	35.0	7.0	0.1	0.0
12	6/24/80	100.0	100.0	96.0	87.0	73.0	43.0	9.0	0.2	0.0
12	6/27/80	100.0	98.0	95.0	86.0	70.0	41.0	10.0	0.5	0.0
13	8/18/79	100.0	99.0	93.0	81.0	62.0	30.0	4.0	0.1	0.0
14	8/18/79	100.0	100.0	95.0	83.0	65.0	34.0	5.0	0.0	0.0
15	8/18/79	100.0	99.0	92.0	82.0	63.0	32.0	5.0	0.1	0.0
16	8/17/79	100.0	99.0	95.0	85.0	66.0	34.0	5.0	0.0	0.0
16	8/18/79	100.0	99.0	97.0	91.0	75.0	40.0	6.0	0.2	0.0
17	8/18/79	100.0	97.0	93.0	87.0	78.0	56.0	11.0	0.7	0.1
18	8/20/79	100.0	100.0	97.0	91.0	81.0	56.0	12.0	0.7	0.1
19	8/19/79	100.0	99.0	96.0	86.0	73.0	53.0	18.0	4.0	2.0
20	8/19/79	100.0	100.0	99.0	96.0	89.0	68.0	19.0	2.0	0.4
21	8/19/79	100.0	100.0	98.0	91.0	82.0	62.0	25.0	10.0	9.0

TABLE 16.—*Statistical data, grain-size distribution of bed material*

Station number in figure 1	Date	Particle size (millimeters) at given percentage finer; percentage finer parameter									
		5	16	25	35	50	65	75	84	90	95
1	6/28/79	0.2	0.3	0.4	0.4	0.5	0.8	1.0	1.3	1.8	2.4
1	8/ 9/79	0.1	0.3	0.4	0.6	0.9	1.4	2.0	3.0	4.4	7.2
1	8/11/79	0.2	0.3	0.4	0.5	0.7	1.2	1.8	2.8	4.3	8.0
2	8/ 8/79	0.2	0.3	0.4	0.4	0.7	1.1	1.8	2.9	4.2	5.8
2	8/12/79	0.2	0.3	0.4	0.4	0.6	0.8	1.1	1.5	2.1	3.2
2	8/21/79	0.2	0.3	0.4	0.5	0.6	0.9	1.2	1.7	2.4	3.9
2	5/13/80	0.1	0.2	0.2	0.3	0.5	0.8	1.2	1.9	2.8	4.4
2	6/ 5/80	0.1	0.2	0.3	0.4	0.5	0.7	0.9	1.3	1.8	2.9
2	8/ 4/80	0.2	0.3	0.3	0.4	0.6	0.8	1.1	1.7	2.6	4.4
2	8/ 5/80	0.2	0.2	0.3	0.4	0.5	0.8	1.1	1.6	2.5	4.6
3	6/27/79	0.2	0.3	0.5	0.7	1.2	2.2	3.0	4.4	6.1	9.3
3	7/16/79	0.3	0.6	0.9	1.4	2.4	3.6	5.3	8.1	10.7	15.4
3	8/21/79	0.2	0.3	0.4	0.6	0.9	1.6	2.5	4.0	5.9	9.5
3	9/25/79	0.1	0.3	0.4	0.6	1.1	2.2	4.2	8.0	10.9	16.0
3	5/ 6/80	0.0	0.1	0.4	0.7	1.4	2.8	4.5	7.1	10.0	15.3
4	6/20/79	0.3	0.5	0.6	0.8	1.3	2.0	2.7	3.8	5.5	8.6
4	6/26/79	0.3	0.5	0.7	0.9	1.4	2.2	3.0	4.3	6.1	9.1
4	7/18/79	0.2	0.4	0.5	0.7	1.3	2.3	3.1	4.3	5.6	7.8
4	9/26/79	0.3	0.5	0.6	0.8	1.3	2.1	2.7	3.8	4.8	6.5
5	6/20/79	0.1	0.1	0.2	0.2	0.3	0.5	0.9	2.2	3.3	5.5
5	6/25/79	0.1	0.2	0.3	0.4	0.6	0.9	1.3	2.1	2.9	4.4
5	7/17/79	0.2	0.4	0.5	0.6	0.9	1.7	2.4	3.5	4.6	6.4
5	8/17/79	0.2	0.3	0.4	0.6	0.8	1.1	1.8	2.8	4.0	5.2
5	9/27/79	0.3	0.4	0.4	0.5	0.8	1.1	1.7	2.6	3.8	5.4
6	6/14/79	0.2	0.2	0.3	0.4	0.6	1.0	1.6	2.6	3.8	6.2
6	6/27/79	0.3	0.5	0.6	0.7	1.0	1.6	2.1	2.8	3.5	4.7
6	7/ 2/79	0.2	0.4	0.5	0.6	0.9	1.4	2.1	2.9	3.8	5.6
6	7/17/79	0.3	0.4	0.6	0.8	1.2	2.0	2.7	3.6	4.9	7.6
6	8/15/79	0.3	0.4	0.6	0.8	1.3	2.4	3.8	5.7	8.0	11.2
6	9/27/79	0.3	0.4	0.5	0.7	1.0	1.5	2.0	2.9	4.0	6.3
7	7/28/79	0.3	0.5	0.7	1.0	1.7	2.7	3.7	5.1	6.7	10.1
7	8/ 8/79	0.4	0.5	0.7	0.9	1.5	2.4	3.6	5.4	7.6	13.1
7	8/21/79	0.2	0.4	0.5	0.7	1.2	2.1	3.7	6.6	9.6	14.4
7	5/22/80	0.2	0.4	0.4	0.5	0.7	1.0	1.4	1.9	2.8	4.5
7	6/12/80	0.3	0.4	0.5	0.6	0.8	1.4	2.3	4.0	6.5	4.8
7	6/22/80	0.3	0.4	0.5	0.7	1.1	2.1	3.5	5.5	8.1	11.4
7	6/26/80	0.2	0.4	0.5	0.7	1.7	4.0	6.2	10.7	17.5	32.8
7	6/29/80	0.3	0.4	0.5	0.7	0.9	1.5	2.3	3.6	4.9	7.1
7	7/26/80	0.3	0.4	0.5	0.6	0.9	1.4	2.1	3.4	4.7	6.7
8	6/28/79	0.2	0.4	0.5	0.6	0.7	0.9	1.1	1.5	1.9	2.7
8	8/10/79	0.2	0.4	0.5	0.6	0.9	1.3	1.9	2.9	4.1	5.8
9	7/15/79	0.3	0.4	0.5	0.6	0.7	0.9	1.1	1.6	2.2	3.2
9	7/20/79	0.3	0.4	0.5	0.8	1.3	2.4	3.4	5.3	8.0	11.4
9	8/ 8/79	0.3	0.4	0.6	0.7	1.1	1.9	2.8	4.3	5.4	7.4
10	7/18/79	0.4	0.7	1.1	1.7	3.1	5.0	6.8	8.4	9.2	10.3
10	8/15/79	0.3	0.5	0.6	0.9	1.4	2.2	3.2	4.8	6.8	13.3
10	5/ 1/80	0.2	0.3	0.4	0.5	0.8	1.2	1.9	3.0	4.4	7.3
10	6/ 4/80	0.1	0.2	0.3	0.4	0.7	1.4	2.3	3.4	4.7	6.8
10	6/11/80	0.2	0.4	0.5	0.6	0.8	1.2	1.7	2.4	3.5	5.0
10	6/21/80	0.2	0.3	0.4	0.5	0.8	1.1	1.5	2.2	3.2	5.1
10	6/23/80	0.2	0.4	0.5	0.7	1.0	1.8	2.7	4.3	5.8	8.3
10	6/24/80	0.2	0.4	0.5	0.6	1.0	1.9	2.8	4.3	5.8	8.3
10	6/25/80	0.3	0.4	0.5	0.8	1.4	2.7	4.2	6.0	8.3	11.6
10	6/28/80	0.2	0.4	0.5	0.7	1.0	1.8	2.8	4.5	6.3	9.2
11	7/17/79	0.2	0.3	0.4	0.5	0.6	0.8	1.1	1.8	3.1	5.9
11	8/15/79	0.3	0.4	0.5	0.7	0.9	1.5	2.1	3.1	4.3	5.9
12	8/16/79	0.2	0.3	0.4	0.5	0.7	1.0	1.4	2.2	3.0	4.5
12	8/27/79	0.2	0.3	0.4	0.4	0.5	0.8	1.3	2.2	3.0	4.6
12	4/29/80	0.2	0.3	0.4	0.5	0.7	1.0	1.5	2.2	3.1	4.4
12	4/30/80	0.2	0.3	0.4	0.4	0.6	0.8	1.0	1.6	2.2	3.6

TABLE 16.—*Statistical data, grain-size distribution of bed material*—Continued

Station number in figure 1	Date	Particle size (millimeters) at given percentage finer; percentage finer parameter									
		5	16	25	35	50	65	75	84	90	95
12	5/15/80	0.2	0.4	0.4	0.5	0.7	1.0	1.4	2.2	3.3	5.3
12	5/21/80	0.2	0.3	0.4	0.5	0.6	0.9	1.2	1.8	2.5	3.9
12	6/ 3/80	0.2	0.4	0.5	0.6	0.8	1.3	1.8	2.8	4.0	6.2
12	6/10/80	0.2	0.3	0.4	0.5	0.6	0.9	1.3	2.0	3.2	5.2
12	6/20/80	0.2	0.3	0.4	0.5	0.7	1.1	1.6	2.3	3.1	4.5
12	6/24/80	0.2	0.3	0.4	0.4	0.6	0.8	1.1	1.7	2.4	3.7
12	6/27/80	0.2	0.3	0.4	0.5	0.6	0.9	1.2	1.8	2.5	3.9
13	8/18/79	0.3	0.4	0.5	0.6	0.8	1.1	1.6	2.4	3.3	4.7
14	8/18/79	0.3	0.4	0.4	0.5	0.7	1.0	1.4	2.1	2.8	4.1
15	8/18/79	0.2	0.4	0.4	0.5	0.7	1.1	1.5	2.3	3.4	4.8
16	8/17/79	0.3	0.4	0.4	0.5	0.7	1.0	1.3	2.0	2.7	4.1
16	8/18/79	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.4	1.9	3.0
17	8/18/79	0.2	0.3	0.3	0.4	0.5	0.7	0.9	1.5	2.6	5.0
18	8/20/79	0.2	0.3	0.3	0.4	0.5	0.6	0.8	1.2	1.8	3.0
19	8/19/79	0.1	0.2	0.3	0.4	0.5	0.7	1.1	1.8	2.5	3.7
20	8/19/79	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.8	1.1	1.8
21	8/19/79	0.0	0.2	0.3	0.3	0.4	0.5	0.8	1.1	1.8	2.6

Relation of Channel-Width Maintenance to Sediment Transport and River Morphology: Platte River, South-Central Nebraska

By MICHAEL R. KARLINGER, THOMAS R. ESCHNER, RICHARD F. HADLEY,
and JAMES E. KIRCHER

HYDROLOGIC AND GEOMORPHIC STUDIES OF THE PLATTE RIVER BASIN

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1277-E

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1983

CONTENTS

ILLUSTRATIONS

TABLES

LIST OF SYMBOLS

a = regression coefficient

a' = regression coefficient

α = acute angle formed by intersection of channel bank with macroform crestline (degrees)

d_c = center (average) depth of channel (m) meters

D_s = bed-material particle size for which s percent is finer (mm) millimeters

Δ = difference operator

$E(\cdot)$ = expected value of sediment discharge (t/d) metric tons per day

$f(\cdot)$ = water discharge density function

$g(\cdot)$ = sediment discharge-water discharge relation

g = acceleration of gravity (m/s^2) meter per second per second

G = channel slope (m/m) meter per meter

h_s = depth of scour (m) meter

$h(\cdot)$ = sediment density function

H = height of macroform (m) meter

j = summation index

L_f = length of macroform (m) meter

λ_L = distance of macroform movement oblique to channel (m) meter

λ_L = distance macroform must move in downstream direction to achieve scour depth h_s (m) meter

n' = regression coefficient

n = regression coefficient

N = number of increments in numerical integration

Q = water discharge (m^3/s) cubic meter per second

Q_s = total sediment discharge (t/d) metric tons per day

Q_E = effective discharge (m^3/s) cubic meter per second

R_c = relative smoothness (roughness) of channel

R_f = $V_s/\sqrt{RD_s g}$ dimensionless fall velocity expression

R = difference in specific gravity between sediment and water (1.65)

Θ = acute angle of downstream sloping face of macroform with horizontal (degrees)

t_{L_f} = time required to move macroform one wavelength (days)

t_{λ_L} = time required to move macroform distance λ_L (days)

V_s = particle fall velocity (m/s) meter per second

RELATION OF CHANNEL-WIDTH MAINTENANCE TO SEDIMENT TRANSPORT AND RIVER MORPHOLOGY: PLATTE RIVER, SOUTH-CENTRAL NEBRASKA

By MICHAEL R. KARLINGER, THOMAS R. ESCHNER, RICHARD F. HADLEY, and JAMES E. KIRCHER

ABSTRACT

Study of the physical characteristics of the Platte River channel provides a basis for understanding channel-forming processes in the river. These physical characteristics and an understanding of channel-forming processes are used to estimate discharges necessary to maintain channel width. Maintenance of channel width is important for preservation of migratory-bird habitat in south-central Nebraska.

Channel width, depth, and slope are spatially variable; but, in addition, width has decreased significantly at many sites during the last 80 years. Bed sediment generally decreases in size in a downstream direction, with some anomalies because of local inflows.

Bedload movement in the Platte River results in two scales of bed forms: (1) Ripples and dunes, and (2) macroforms (large bars and islands). The bed forms cause the channel pattern to change as water discharge changes: at low flows, the river has a distinct braided appearance, while, at higher flows, the river has a straight, single channel. Insufficient water discharge has resulted in macroform stabilization, island formation, and subsequent channel narrowing along the river.

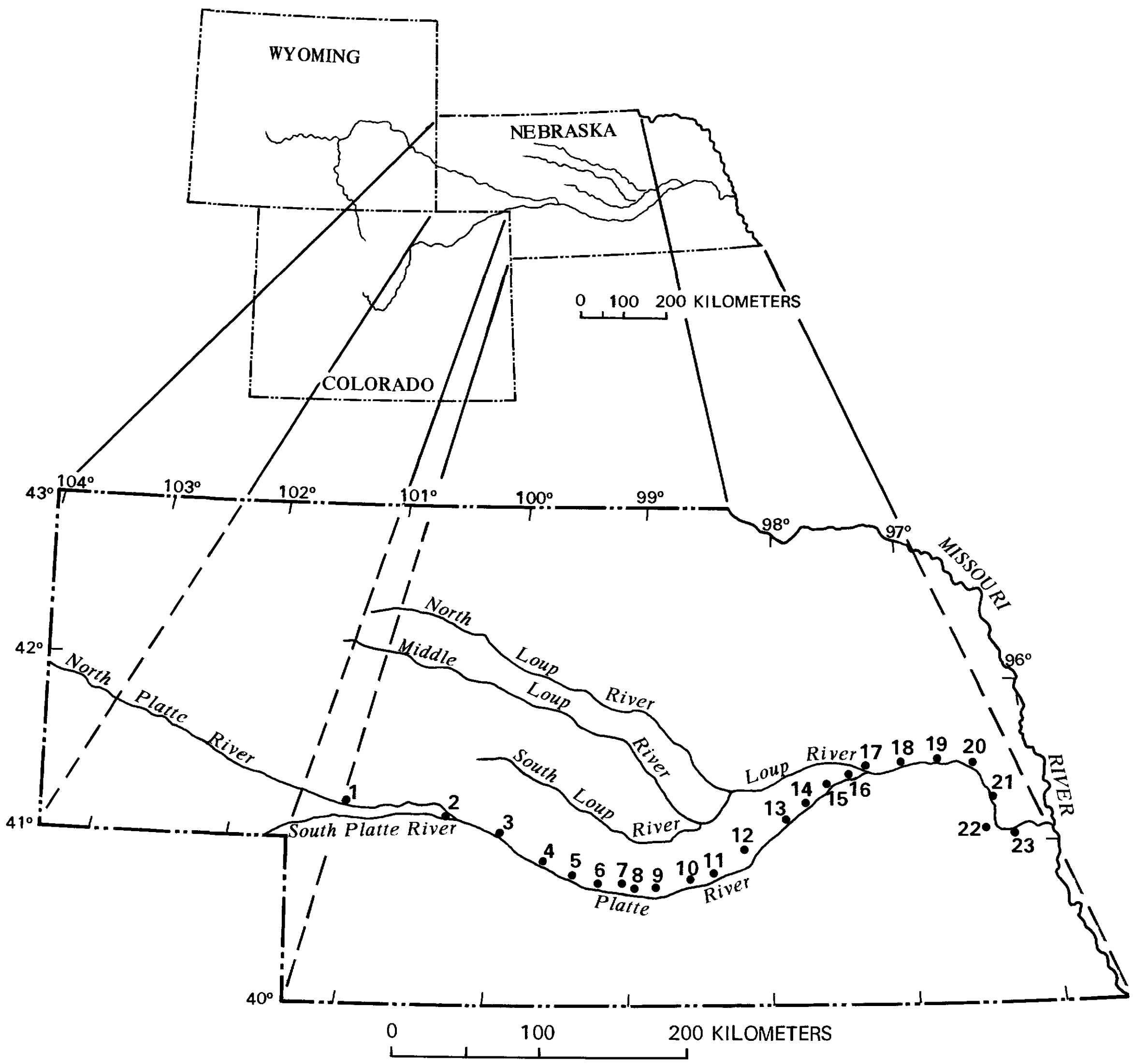
To estimate water discharge needed to maintain the present channel width, three methods were developed, based on the relationship between sediment transport and channel width. In the first method, an empirical estimation of effective discharge is computed from a sediment-water-discharge relation and flow statistics. This sediment-water-discharge relation is combined with a flow-duration curve to produce a frequency-dependent sediment volume. The second method is developed from the geometry of macroforms and their migration in the Platte River downstream from Grand Island, Nebraska. The depth of scour necessary to uproot vegetation on the stoss (upstream) side of macroforms is related to downstream movement of the forms. Macroforms must be inundated with at least 20 centimeters of water for movement to occur: discharges of this magnitude are relatively infrequent. A third method, based on works by Parker (1977), analyzes channel formation from the theoretical perspective of bed-bank sediment interchange. Our data are used to calibrate Parker's equations for applications to the Platte River in south-central Nebraska.

INTRODUCTION

The Platte River in south-central Nebraska (fig. 1) is a prominent feature in the economy and environment of the region. In the middle of the 19th century, the Platte River valley marked the route of early westward migrations. Beginning in the latter part of the 19th century and continuing until 1982, an increasing proportion of the river flow has been appropriated for irrigation, municipal, industrial, and hydropower uses. In addition, migratory birds long have used the valley as a stop-over in their annual migration.

The regulation of the river flow in the past century has had a marked influence on the channel morphology (Eschner, Hadley, and Crowley, 1982; Williams, 1978) by reducing flood peaks, extending low-flow periods, changing sediment-transport characteristics, and allowing increased vegetation growth in the channels. Channel changes that have occurred in the Platte River and its tributaries since about 1860 have significantly changed the migratory bird habitat. Optimum roosting conditions occur when at least 75 m (meters) or more of unobstructed view exist (U.S. Fish and Wildlife Service, 1981). Thus, a minimum unobstructed channel width of 150 m is required for optimum roosting conditions. The changes in flow regime, sediment-transport characteristics, and vegetation-growth patterns have reduced channel width to less than 150 m at many locations in the study area.

This paper will examine the channel-forming processes in the Platte River, describe how these processes have changed the channels, and consider solutions of



KEY TO NUMBERED TOWNS

1 KEYSTONE	9 KEARNEY	17 COLUMBUS
2 NORTH PLATTE	10 GIBBON	18 SCHUYLER
3 BRADY	11 WOOD RIVER	19 NORTH BEND
4 COZAD	12 GRAND ISLAND	20 FREMONT
5 LEXINGTON 1 and 2	13 CENTRAL CITY	21 VENICE
6 OVERTON	14 CLARKS	22 ASHLAND
7 ELM CREEK	15 SILVER CREEK	23 LOUISVILLE
8 ODESSA	16 DUNCAN	

FIGURE 1.—The study area in Nebraska.

the problem of preserving channel characteristics through knowledge of the fluvial processes. The primary objective of preserving these characteristics is to prevent deterioration of the riverine habitat used by migratory birds.

DESCRIPTION OF THE STUDY AREA

The North Platte and South Platte Rivers originate as snowmelt-runoff streams in the Rocky Mountains of Colorado. They flow across the Great Plains and form the Platte River at their confluence at North Platte, Nebraska (fig. 1). Downstream from North Platte, the Platte River flows generally eastward through Nebraska to the Missouri River at the eastern edge of the State. The Platte River downstream from North Platte has a drainage area of about 79,000 km^2 (square kilometers) and is about 460 river km (kilometers) long. The study area for this report extends from North Platte to Ashland, Nebraska, along the Platte River (fig. 1).

PHYSICAL CHARACTERISTICS OF THE CHANNEL

The Platte River is diverse in channel form; in general, it is wide and shallow. The sand and gravel bed has bed forms of various scales. Generally, channel banks do not exceed 2 m in height and are silt, sand, and gravel. Channel pattern varies from meandering to island-braided to straight. Numerous sandbars cause the degree of braiding to vary with discharge.

CHANNEL GEOMETRY

CHANNEL PATTERN

The pattern of the Platte River varies with time, space, and discharge. Since development of irrigation, channel patterns have changed by formation of islands and their subsequent attachment to the flood plain. The formerly broad open channel has been transformed at many locations upstream from Grand Island into a series of small channels intertwining among islands of various sizes (Eschner, Hadley, and Crowley, 1982; Williams, 1978). The well-defined channels in the upper Platte River (near Cozad) disappear downstream into numerous channels and islands (near Overton) (fig. 2). Downstream from Grand Island, the Platte River flows primarily in a single broad channel with relatively few islands. Large bed forms within the channel cause the pattern to change as discharge changes. At low flows, emergent bed forms give the river a braided appearance. At high flows, water fills the channel from bank to bank, submerging all bed forms. Although the pattern at high flow appears straight, major flow lines meander within the bankfull channel.

FIGURE 2.—The Platte River near Overton, Nebraska. View is to the northwest. Note the heavily vegetated banks and braided channels (taken in 1979).

WIDTH

Channel width is defined here as the width of unvegetated bed within the channel banks at a given section,

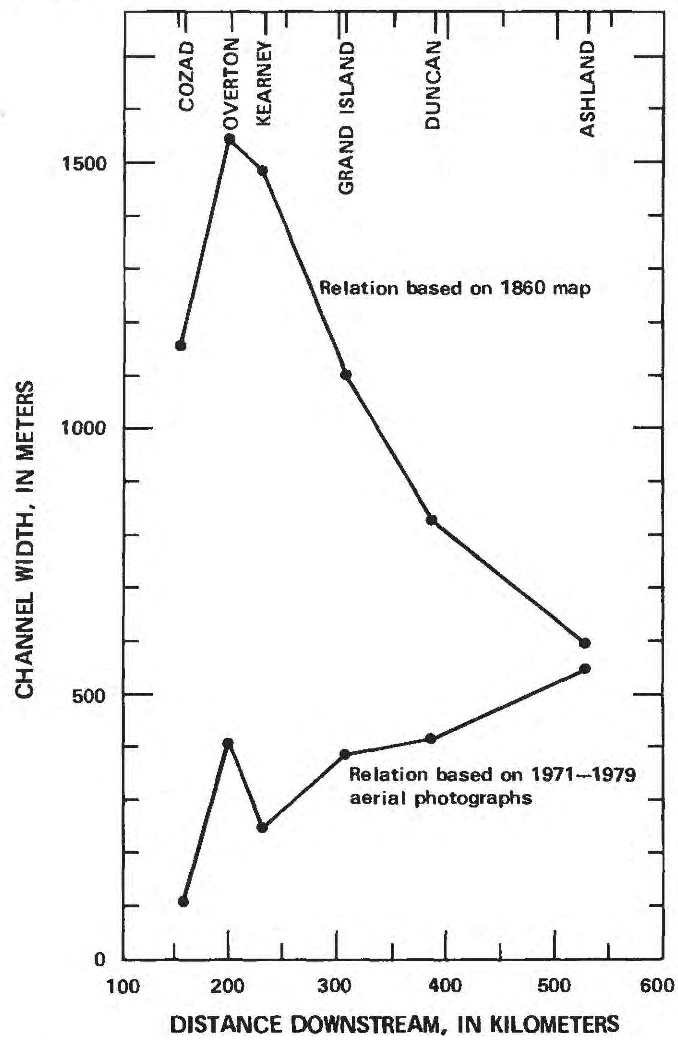


FIGURE 3.—Variation in channel width with distance downstream for the Platte River, Nebraska.

excluding islands. Thus, the width is a maximum channel bed width. Many of the width measurements reported here were made from aerial photographs rather than from measurements in the field.

Width of the Platte River ranged from about 100 m to over 500 m in 1979 (table 1). In general, channel width varies considerably, but increases in a downstream direction (fig. 3). Some of this variation can be related to diversions from the river or to returns of surface water. For example, the relatively large width at Overton may be due to the Johnson-2 Power Return, (Lexington-2 on figure 1) 12 km upstream. This return accounts for about 60 percent of the flow at Overton. Part of the local variation in channel width in other reaches probably can be attributed to variations in sediment characteristics and channel slope.

The downstream increase in channel width evident in the 1970's is in contrast to the downstream decrease in channel width evident in the 1860's (fig. 3). The large decrease in channel width of the upstream part of the Platte River channel has resulted from hydrologic changes that have occurred since the development of irrigation in the basin (Eschner, Hadley, and Crowley, 1982; Kircher and Karlinger, 1982; Williams, 1978). The relative lack of change further downstream perhaps can be attributed to the small initial size of the channel, and the diminished effect on surface water of irrigation development downstream from the junction with the Loup River near Columbus, Nebraska.

DEPTH

Depth was measured by topographic surveys at low water, and by sounding at higher stages. Mean channel depth was obtained from the sounded water depth by relating the surface to a known elevation. Channel depth is variable in space and with discharge, because

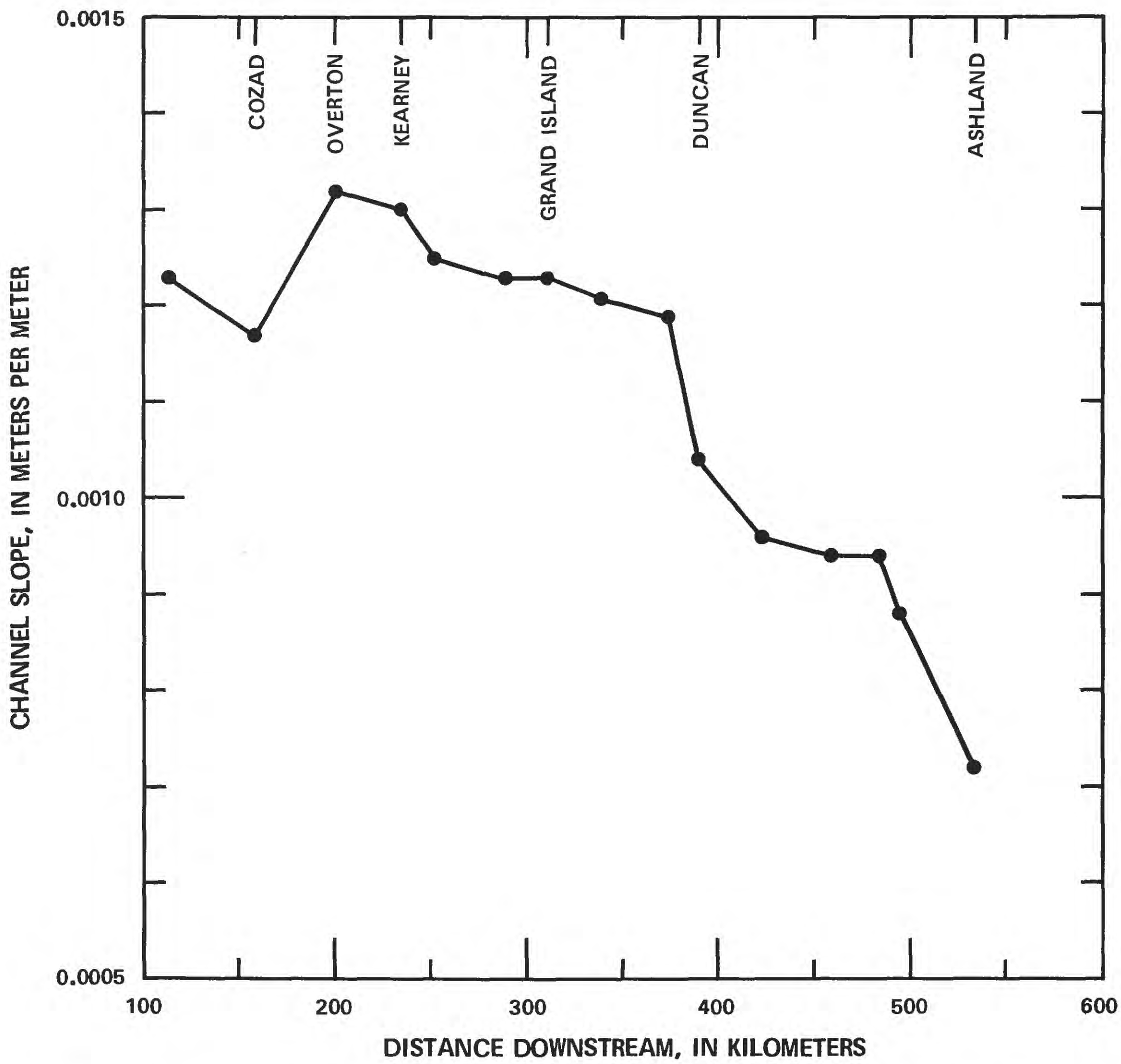


FIGURE 4.—Variation in local channel slope with distance downstream for the Platte River, Nebraska

TABLE 1.—*Channel widths of the Platte River, Nebraska, in downstream order, measured from General Land Office maps (1860) and aerial photographs (1938–1979) from Eschner, Hadley, and Crowley (1982)*

Year	Cozad	Overton	Kearney	Grand Island	Duncan	Ashland
	Channel width, in meters					
1860	1,161	1,545	1,484	1,100[1]	826	594
1938	1,015	890	1,298	704	---	---
1941	---	---	---	---	600	515
1949	---	---	---	---	---	539
1950	---	---	---	643	543	---
1951	204	451	698	---	---	---
1955	---	---	---	---	---	521
1957	113	460	695	664	521	---
1959	---	---	---	---	---	533
1963	110	408	308	530	---	---
1964	---	---	---	---	448	---
1965	---	---	---	---	---	530
1969	113	387	293	472	---	---
1970	---	---	---	---	424	---
1971	---	---	---	---	---	549
1978	---	---	---	---	411	---
1979	110	405	247	387	---	---

[1]From 1898 edition 30′ U.S. Geological Survey topographic map (General Land Office map incomplete).

at least some of the bed sediment is moved readily by all flows. The cross section and longitudinal profile at a station along the channel also change with time. For example, high flows during the spring of 1980 moved a large bedform into a cross section near Lexington, shifting the thalweg about 50 m toward the right bank. Lower flows gradually shifted the thalweg back to the left. Water depths at low flow may range from a few mm (millimeters) to more than 1 m. Maximum channel depths generally do not exceed 2 m.

SLOPE

Channel slope was measured from U.S. Geological Survey 7.5-minute topographic quadrangles for several reaches along the river (table 2). The measured segments were a minimum of 20 times the channel width. Slope was calculated as the average rate of elevation change per unit distance. The slope of the Platte River ranges from about 0.00070 to about 0.00135; slope generally decreases downstream from Cozad (fig. 4). This downstream variation of slope may relate to changes in channel sediment size. The slope near Overton is an exception to the downstream trend: channel slope increases from Cozad to Overton. This increase in slope may be a response to the return flow from the Johnson-2 (Lexington-2 on figure 1) power plant upstream from Overton.

BED FORMS

At least two scales of bed forms exist in the Platte River: (1) Ripples and dunes—small bed forms of the lower flow regime; and (2) macroforms—large bed forms proportional to the channel dimensions (Crowley, 1981a), which are submerged only during the highest flows.

In plan view, macroforms are situated obliquely, at about 30°, to the direction of flow (fig. 5). Width of macroforms is about 0.6 times the channel width, and length is about 1.9 times the channel width. The height of macroforms generally does not exceed 2 meters. A steep slipface forms the downstream end of a macroform. Small channels, oriented about perpendicular to the slipface, occur near the downstream end of

FIGURE 5.—Vertical photograph showing external geometry of the Platte River macroforms, Platte River near Grand Island, Nebraska (from Crowley, 1981a).

TABLE 2.—*Channel slope for selected reaches of the Platte River, Nebraska*

Reach	Distance downstream from Keystone, Nebraska (kilometers)	Slope (meters per meter)
Brady	112	0.00123
Cozad	159	.00117
Overton	200	.00132
Kearney	234	.00130
Gibbon	252	.00125
Wood River	289	.00123
Grand Island	311	.00123
Central City	339	.00121
Silver Creek	374	.00119
Duncan	390	.00104
Schuyler	424	.00096
North Bend	459	.00094
Fremont	479	.00094
Venice	496	.00088
Ashland	532	.00072

macroforms. These channels carry only a small percentage of the flow in the channel. The thalweg of the channel lies immediately downstream from the macroform slipface.

The formation of macroforms is not well understood. Crowley (1981b) has concluded that macroforms are not large-scale equivalents of ripples and dunes. Flow separation and reattachment, generally thought to form dunes, are only weakly developed over macroforms at high flows. Ratios of macroform dimensions and flow variables are generally at least an order of magnitude larger than corresponding ratios for ripples and dunes. In addition, macroforms are not sensitive to small changes of flow regime. Macroforms move only during the highest flows when they are submerged; they move by downstream migration of smaller bed forms, such as ripples and dunes, superimposed on the macroforms. The smaller forms transport sediment across the stoss side of the macroform to the crest, where the sediment slides down the slipface. Downstream migration rates of 1.0 to 1.5 m/hr (meters per hour) were measured in the Platte River during 1980 high flows. Long-term rates of migration, computed from measurements on aerial photographs, varied between about 10 and 24 m/yr (meters per year). The rate of migration apparently increases downstream, perhaps as a result of downstream increase in discharge (Crowley, 1981a).

SEDIMENT CHARACTERISTICS

Unconsolidated deposits in the Platte River valley overlie rocks of Pennsylvanian to Tertiary age. These unconsolidated sediments consist of loess, alluvium, and proglacial deposits up to 125 m thick. Recent alluvium, ranging in size from clay to gravel, is exposed on the channel bed.

In a study of the relative percentages of quartz, potassium feldspar, and plagioclase in Platte River

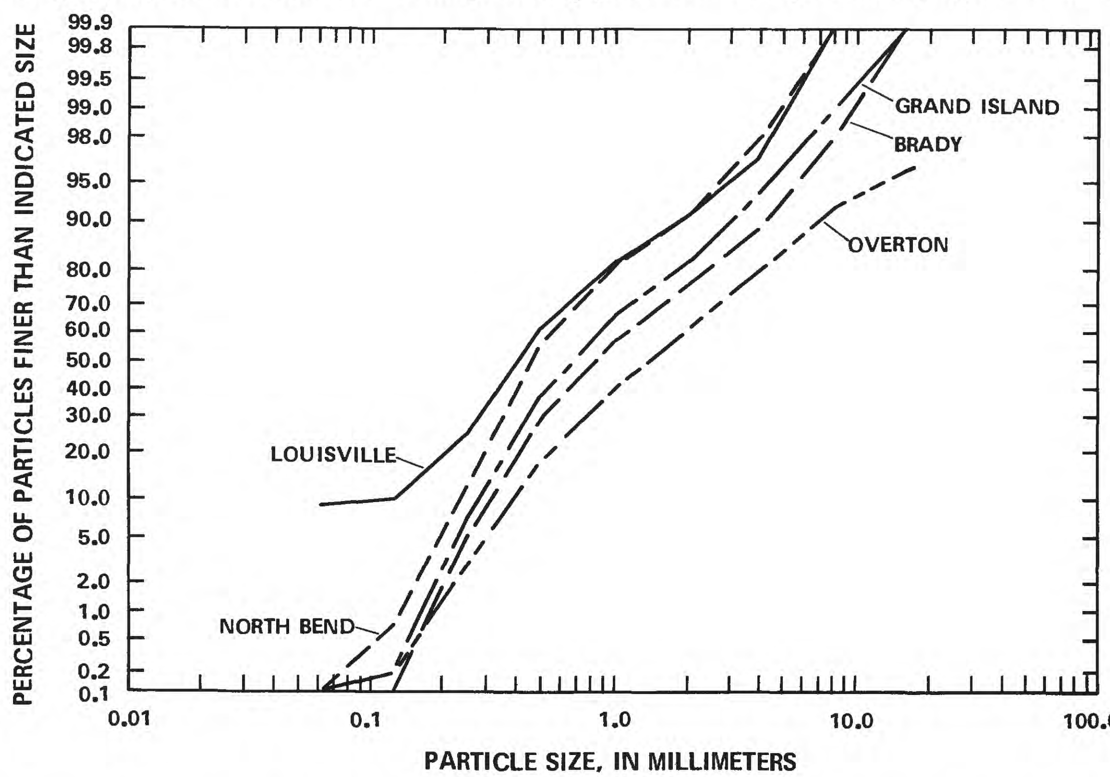


FIGURE 6.—Selected grain-size distributions of bed material from the Platte River, Nebraska (data from Kircher, 1981a).

sand, Hayes (1962) concluded that quartz increases uniformly downstream, and both potassium feldspar and plagioclase decrease downstream. Hayes' (1962) data suggest that the quartz and feldspar contents of Platte River sediment are relatively stable upstream from the Loup River confluence. Mineralogy of the bed sediment changes with distance downstream from the Loup confluence: the percentage of quartz increases; whereas, the percentages of feldspars decrease.

There are many possible sources for Platte River sediment. Erosion in the Rocky Mountains yields sediment to both the North and South Platte Rivers. Direct erosion of bedrock beneath the Platte River rarely occurs because of the thickness of unconsolidated deposits. However, reworking of valley fill beneath and adjacent to the Platte River provides sediment to the river. Sediment contributions from tributaries may be significant. For example, sediment from the Loup River system probably accounts for the change in mineral composition of Platte River sediment downstream from the Loup confluence.

BED SEDIMENT

Bed-material samples were collected with a BMH 60 sampler at 14 cross sections along the Platte River (Kircher, 1981a). Sampling was done from May to September to insure a variety of bed conditions. Samples were sieved (table 3), and the percentages in size classes were plotted to determine the size distributions. Selected representative distributions are plotted in figure 6.

The size of bed material in the Platte River ranges from less than 0.062 mm (millimeters) to greater than 16 mm; grain-size distributions are listed in table 3. Median size (D_{50}), defined as the diameter of which half the particles of the sample are finer, somewhat changes systematically downstream. Median diameter increases downstream to Overton, but then decreases downstream from Overton (Kircher, 1982) (fig. 7). A secondary peak of large median diameter occurs from Central City to Silver Creek. Examination of figure 9 indicates that not only median diameter but also overall sizes change downstream. Bed material at Overton is coarser for almost all percentiles than bed material at Brady. Grain sizes at all percentiles become finer with increasing distance downstream from Overton for the reaches sampled.

The median bed-material particle size varies little with changes in discharge, at two stations for which data are available. Plots of median grain size (D_{50}) of bed material and discharge for the Platte River show no positive trend, or decrease in grain size with increasing discharge near Overton (fig. 8), and no significant trend near Grand Island (fig. 8). The increase in bed material

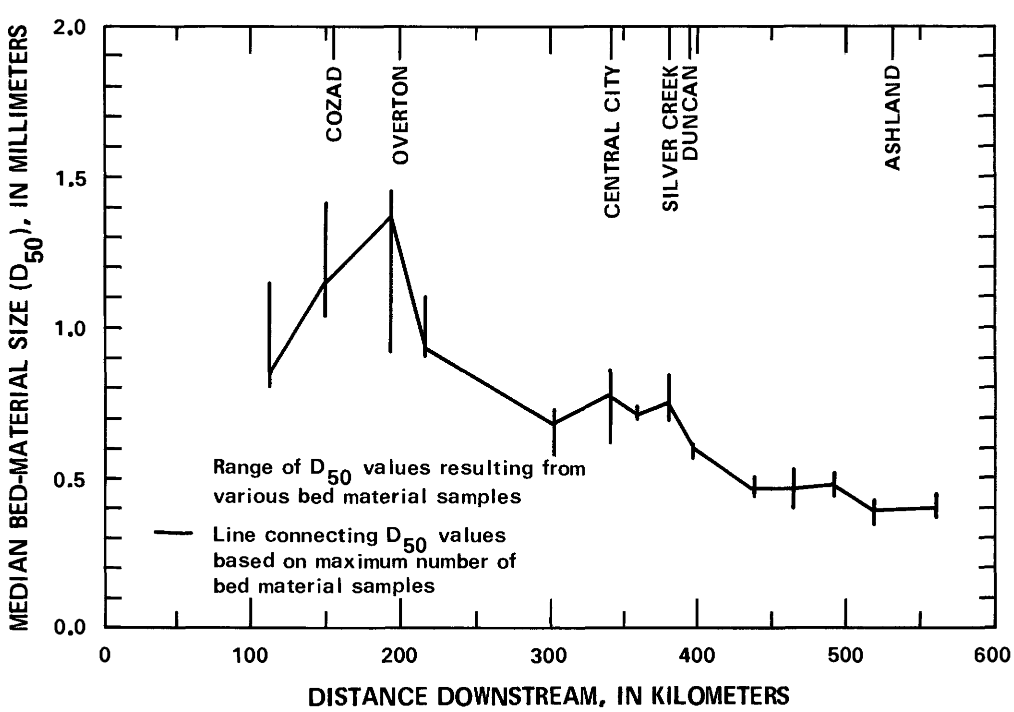


FIGURE 7.—Variation in sediment size with distance downstream for the Platte River, August 1979. Zero on the distance scale (abscissa) corresponds to the North Platte River near Keystone, Nebraska (from Kircher, 1982).

TABLE 3.—*Grain-size distribution of bed and bank sediment from the Platte River, Nebraska*

[Data from Kircher (1981a) and Eschner (1981)]

Section	Distance downstream from Keystone, Nebraska, on the North Platte River in kilometers	Date	Percent finer than indicated size, in millimeters										Median grain size, in millimeters
			32	16	8	4	2	1	0.5	0.25	0.125	0.0625	
Bed Sediment													
Brady	112	6/28/79		100	100	98	91	70	30	5	0.2	0.0	0.7
Cozad	159	8/10/79		100	98	89	76	57	29	5	.1	.0	.9
		7/15/79		100	100	97	88	72	28	2	.0	.0	.7
		7/20/79		98	90	79	60	44	23	3	.7	.0	1.3
		8/ 8/79		99	96	82	66	46	22	5	.8	.2	1.1
Overton	200	7/18/79		100	80	57	39	23	9	1	.0	.0	3.1
		8/15/79		96	92	80	62	40	18	3	.2	.0	1.4
		5/ 1/80		100	96	89	76	59	33	10	.8	.0	.8
		6/ 4/80		100	97	87	71	58	42	21	8	4	.7
		6/11/80		100	98	92	80	58	27	8	.9	.1	.8
		6/21/80		100	98	93	82	63	32	7	.2	.0	.8
		6/23/80		99	94	82	68	50	25	7	.3	.0	1.0
		6/24/80		100	94	82	67	49	28	7	.1	.0	1.0
		6/25/80		98	89	74	58	42	23	5	.3	.0	1.4
		6/28/80		99	93	82	68	51	24	6	.1	.0	1.0
Odessa	223	7/17/79		100	97	92	86	74	39	5	.3	.2	.6
		8/15/79		100	98	88	74	52	24	5	.0	.0	.9
Grand Island	311	8/16/79		100	99	94	82	66	37	7	.2	.1	.7
		8/27/79		100	98	94	82	71	47	8	.3	.0	.5
		4/29/80		100	99	94	82	64	39	8	.7	.3	.7
		4/30/80		100	99	96	88	74	45	11	.1	.0	.6
		5/15/80		100	98	92	83	66	36	6	.0	.0	.7
		5/21/80		100	100	95	86	69	40	7	.0	.0	.6
Grand Island	311	6/ 3/80		100	97	90	77	57	29	6	1	.0	.8
		6/10/80		100	96	92	84	68	40	8	.1	.0	.6
		6/20/80		100	99	94	81	61	35	7	.1	.0	.7
		6/24/80		100	100	96	87	73	43	9	.2	.0	.6
		6/27/80		100	98	95	86	70	41	10	.5	.0	.6
Central City	339	8/19/79		100	99	94	83	64	32	5	.1	.0	.7
Clarks	357	8/18/79		100	100	95	83	65	34	5	.0	.0	.7
Silver Creek	374	8/18/79		100	99	92	82	63	32	5	.1	.0	.8
Duncan	390	8/17/79		100	99	95	65	66	34	5	.0	.0	.7
		8/18/79		100	98	95	89	77	48	9	.4	.0	.5
Schuyler	424	8/18/79		100	97	93	87	78	56	11	.7	.1	.5
North Bend	459	8/20/79		100	100	97	91	81	56	12	.7	.1	.5
Fremont	479	8/19/79		100	99	96	86	73	53	18	4	2	.5
Venice	496	8/19/79		100	100	99	96	89	68	19	2	.4	.4
Louisville	533	8/19/79		100	100	98	91	82	62	25	10	9	.4
Bank Sediment													
Cozad	159	1980			99.4	98.6	96.1	93.7	87.3	70.7	40.3	21.0	.16
Lexington-1	189	1980		99.6	92.8	85.7	75.5	61.1	41.5	17.5	4.7	2.2	.68
Lexington-2	190	1980			99.3	95.2	90.4	83.3	68.0	38.1	11.8	4.3	.33
Overton	200	1980		92.2	82.6	73.3	68.1	60.0	45.7	28.5	11.7	5.1	.63
Elm Creek	215	1980			98.1	95.8	91.6	84.9	76.9	55.4	22.4	14.7	.23
Odessa	223	1980			99.8	99.4	93.8	69.4	31.0	10.2	5.2	3.2	.71

size does not occur that might be expected as increasing discharge removes finer particles from the bed. The apparent decrease in grain size with increasing discharge near Overton may be due to the accumulation of lag gravel, as sand is removed from the bed at low discharges.

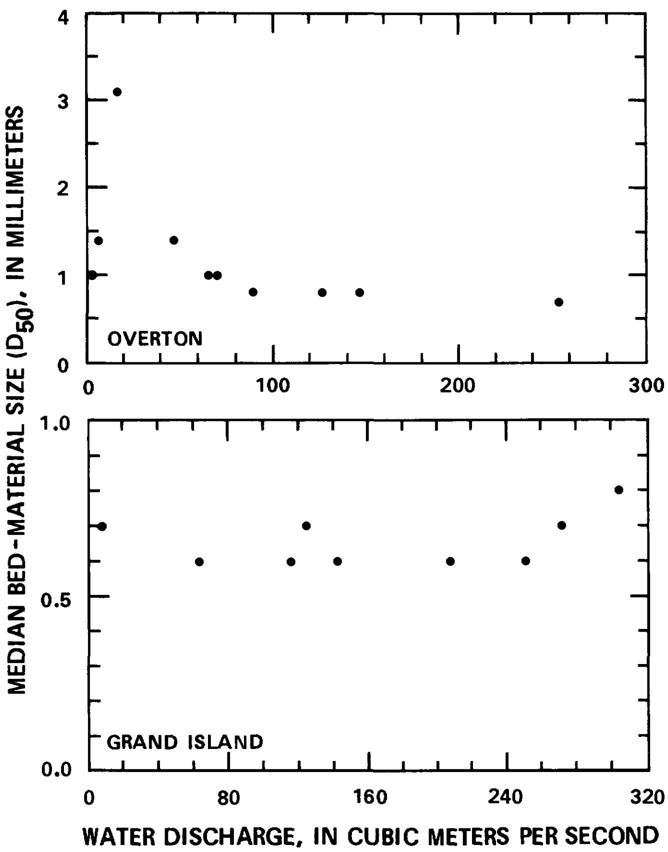


FIGURE 8.—Change in median bed-material particle size with increasing discharge for the Platte River near Overton and Grand Island, Nebraska (from Kircher, 1982).

BANK SEDIMENT

Composite bank material samples were collected at six sections from Cozad to Odessa. The variability of bank sediment is high, ranging from less than 0.062 mm to greater than 16 mm (fig. 9 and table 3). Median grain sizes (D_{50}) are generally lower than median grain sizes of the bed at corresponding locations. Grain size distributions do not show a progression in a downstream direction and the curves do not all have the same shape. Variability in grain size of bank sediment may result from the limited number of samples.

VEGETATION EFFECTS

Many species of vegetation are present along the Platte River. Annual and biennial grasses occur along banks and on islands along the entire river. Shrubs and trees are particularly common in the upper parts of the study reach. The most common trees are cottonwood, willow, elm, and ash. Extensive vegetation in the Platte River valley is a relatively recent phenomenon (Eschner, Hadley, and Crowley, 1982). Accounts of explorers and early settlers indicate that timber was scarce in many places as recently as 1860. Hydrologic changes in the Platte River since 1860, such as reduction of flood peaks, have made conditions more favorable for germination and preservation of vegetation. Vegetation has, in turn, had a significant effect on channel morphology and processes. For example, establishment of vegetation on sandbars is the chief method by which channel width is reduced (Eschner, Hadley, and Crowley, 1982). The total amount of sediment in transport is also changed, because of reduction of channel width and the presence of vegetation on low bars within the channel.

DISCHARGE-RELATED THEORETICAL METHODS FOR MAINTAINING CHANNEL WIDTH

Geomorphic processes in a river involve the interrelationships between channel cross-section characteristics, sediment transport, and hydrology. Although channel cross-sectional configuration is partly a function of sediment movement, sediment discharge is difficult to study directly. However, the relationship between water discharge and sediment discharge allows channel maintenance to be related to water discharge.

This chapter describes three methods that use this dependence between water and sediment discharge to estimate the functional relationships between channel width and water discharge. The three methods have been calibrated in the Platte River. Sediment transport plays an important role in all three methods.

In the first method, a sediment-water discharge relation is combined with a steady-state flow-duration curve to empirically estimate an effective discharge, defined here as the water discharge that maintains the present channel cross section. The second method is based on results of field studies of macroform formation and migration in the Platte River downstream from Grand Island, Nebraska. If these bed forms are not moved downstream, they can become stabilized with vegetation to form islands, thereby narrowing the channel. The third method analyzes channel formation from the theoretical perspective of bed-bank sediment interchange. Data used to calibrate regime equations from this latter method were collected in a reach of the river from Cozad downstream to Odessa, Nebraska.

EFFECTIVE DISCHARGE

The rate of sediment movement in a channel depends in part on the magnitude of water discharge. The relationship between water discharge and sediment discharge can be expressed by a sediment-discharge rating curve of the form:

$$Q_s = aQ^n \quad (1)$$

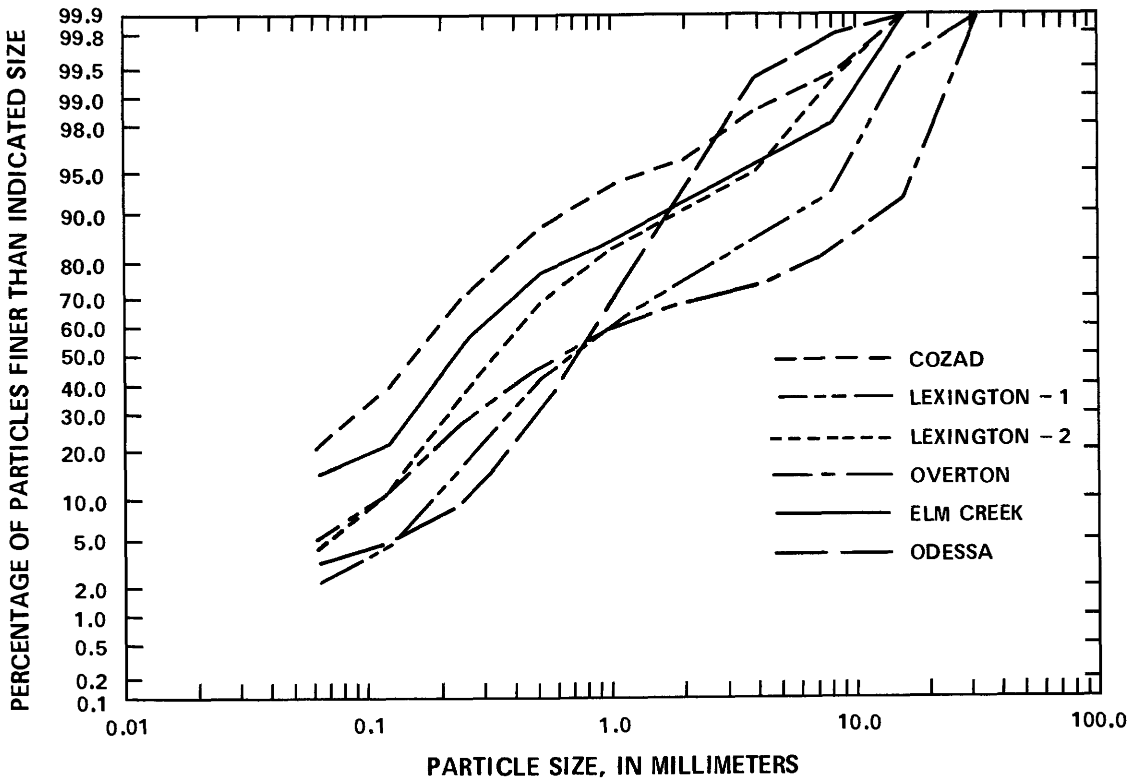


FIGURE 9.—Grain-size distributions of bank sediment for the Platte River, Nebraska (from Eschner, 1981).

where

Q_s = sediment discharge;

Q = water discharge; and

a and n = regression coefficients, here determined by regression analysis.

The sediment-water discharge relation should accurately describe the period under consideration; a sediment-water discharge relation does not necessarily remain constant over many years. For example, figure 10, representing data from the Platte River near Overton, shows that the sediment-water discharge relation for this station has changed since the 1950's. The sediment discharge near Overton in 1980 at water discharges less than 74 m^3/s (cubic meters per second) was greater than the sediment discharge for corresponding water discharges in the 1950's; but, the rate of increase of sediment discharge with increasing water discharge was less in 1980 than it was in the 1950's.

The significance of a given discharge in moving a quantity of sediment during a specified period depends on frequency of the discharge. Frequency with which a given discharge occurs is represented by the flow-duration curve (fig. 11). The most frequent discharges are small and transport relatively small amounts of sediment; large discharges are less frequent, but they transport greater amounts of sediment.

Relative effectiveness of a given water discharge to influence channel morphology can be described by the maximum product of sediment discharge and the frequency of occurrence associated with the corresponding flow (fig. 12). A range of intermediate flows transports most of the annual sediment load. This range of discharges may be represented by the maximum sediment load; the midpoint of this range will be called the effective discharge (Andrews, 1980). Therefore, the effective discharge can be described as the discharge that maintains the channel by virtue of its frequency of occurrence and transporting capacity, by transporting, on the average, more sediment during the period of record than any other discharge.

Effective discharge can be obtained from the computations necessary for determination of mean annual sediment discharge. Mean annual sediment discharge is determined by calculating the expected value of sediment discharge $E(Q_s)$. The expected value is defined as:

$$E(Q_s)=\int_0^\infty Q_s h(Q_s) dQ_s \qquad (2)$$

where

$E(Q_s)$ = expected value of the sediment discharge or mean annual sediment discharge in tons per day;

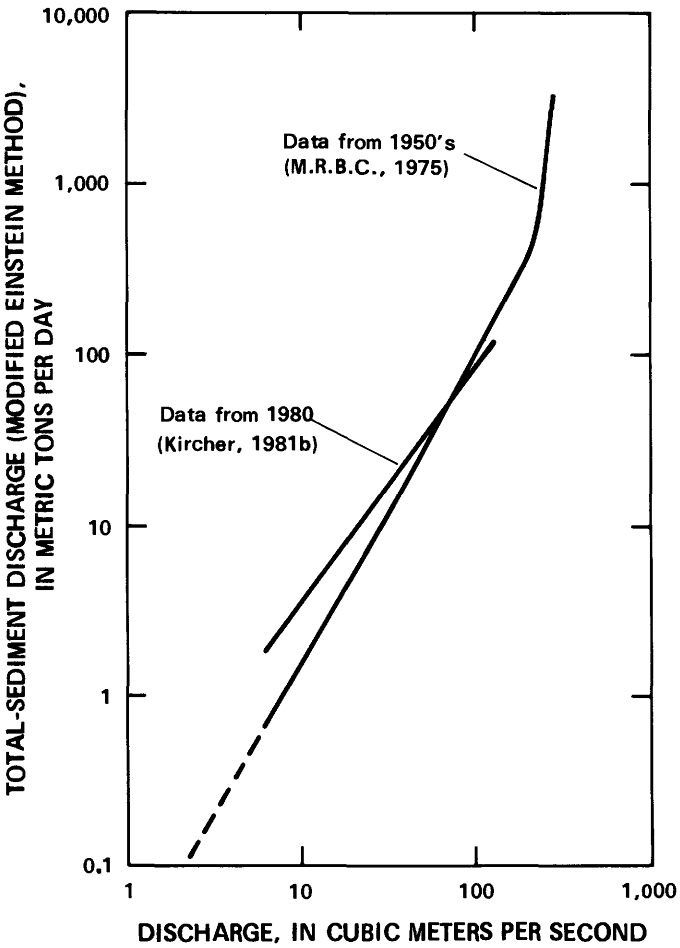


FIGURE 10.—Sediment-water-discharge relations for the Platte River near Overton, Nebraska (from Missouri River Basin Commission, 1975; and Kircher, 1981b).

Q_s = sediment discharge in metric tons per day; and

$h(Q_s)$ = sediment discharge density function.

The sediment-density function, $h(Q_s)$, is unknown, but Q_s is a known function of water discharge from the sediment-water-discharge relation (fig. 12A). Therefore, by probability theory, the following substitution can be made for equation 2:

$$E(Q_s)=\int_0^\infty g(Q)f(Q)dQ \qquad (3)$$

where

$g(Q)$ = Q_s, in metric tons per day; and

$f(Q)$ = the water-discharge density function.

The water-discharge density function (fig. 12B) can be obtained from a flow-duration curve, such as the type shown in figure 11. Although the analytical form of the flow-duration curve is unknown, the integral in equation 3 can be approximated by a summation of the discretized integrand (fig. 12C) which has the following form:

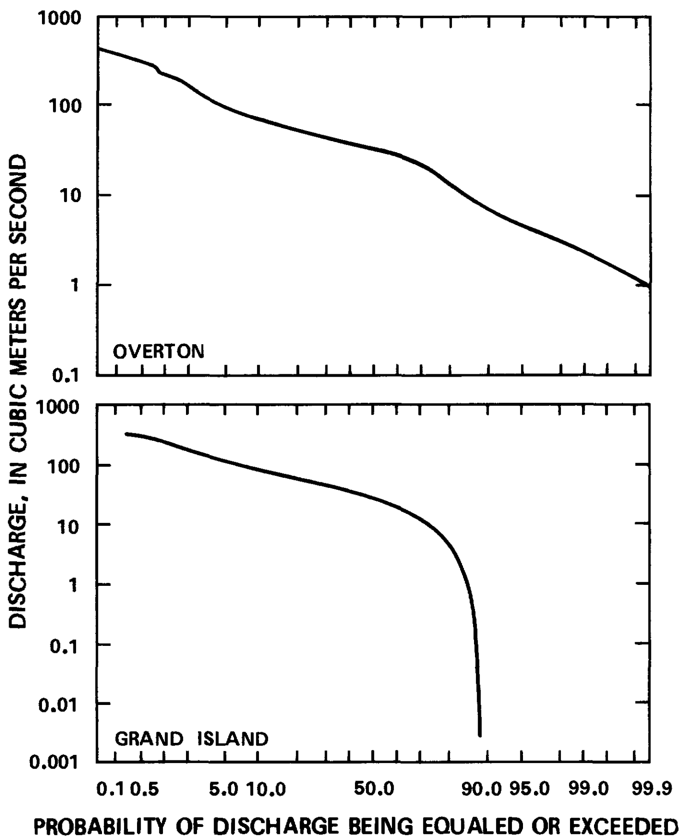


FIGURE 11.—Flow-duration curves for the Platte River near Overton from 1950 to 1979, and Grand Island from 1935 to 1979 (from (Kircher, 1981b).

$$E(Q_s)\approx \sum_{j=1}^{N} g(Q_j)f(Q_j)\Delta Q_j \qquad (4)$$

where

Q_j = midpoint of discretized interval.

With this form, the flow-duration curve can be divided into N equal intervals. The midpoint of each interval is then determined and inserted into the sediment-water-discharge relation for each station, thus providing a sediment-discharge value. This sediment-discharge value is then multiplied by the probability of occurrence of that associated water discharge, $f(Q_j)\Delta Q_j$, to yield a weighted quantity of sediment. The discharge that carried the most sediment during a period of record is the peak of the integrand in equation 3 or the peak summand in equation 4. An example of a plot of the summand in equation 4 is shown in figure 12C for the Platte River near Overton.

Equation 4 with N equal to about 20 is the form most commonly used (Andrews, 1980; Benson and Thomas, 1966). However, the location of the peak summand is dependent on N. The greater the number of intervals,

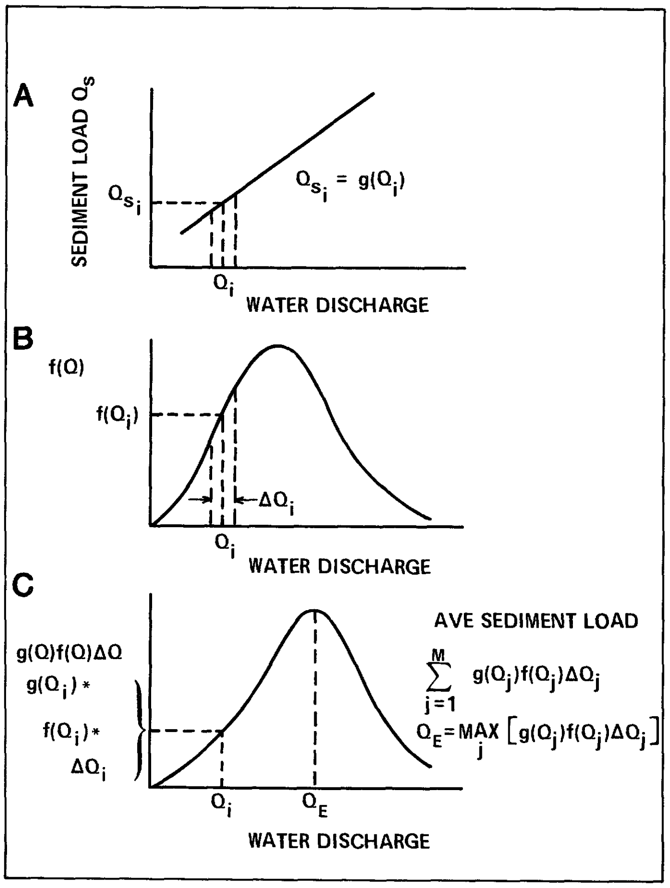


FIGURE 12.—Procedure for computation of effective discharge.

the closer the result will be to the true value. Variation of the resulting effective-discharge by varying N can be seen in table 4 for the Platte River near Overton and the Platte River near Grand Island. Flow-duration curves were also divided into equal natural logarithm (log) (water-discharge) intervals to reduce the error caused by skewness of the flow distribution. The computation of effective discharge for these two stations is based on the total sediment-water-discharge relations of each.

TABLE 4.—*Variation in computed effective discharge resulting from variation of the number and type of water-discharge intervals*

[N, number of intervals; $E(X)$, expected value of mean annual total-sediment discharge; Q_E, effective discharge; t/d, metric tons per day; m³/s, cubic meters per second]

	Platte River near Overton, Nebraska			Platte River near Grand Island, Nebraska		
Type of interval	N	$E(X)$ (t/d)	Q_E (m³/s)	N	$E(X)$ (t/d)	Q_E (m³/s)
Arithmetic	35	1115	46	35	1099	46
	69	1110	35	69	1086	45
	103	1107	34	103	1098	40.5
	137	1107	31	137	1075	36
	171	1101	32.5	171	1076	32.5
Logarithmic	35	747	33	35	1064	59.5
	69	1095	41	69	1066	55
	103	1100	44	103	----	----
	137	1108	46	137	1073	43

Effective discharge varies considerably with N and the type of intervals used. Table 4 shows that the maximum number of divisions give results differing by as much as 29 percent, when compared to the minimum number of divisions. Because a constant sediment-water-discharge relation and flow-duration curve were used in all cases for each station, study of the differences in effective discharge can be limited to the discretized approximation of the flow-duration curve. Further research is necessary to determine if the differences are due to the errors in the integration approximation, or if the method yields a statistically inconsistent estimator of effective discharge.

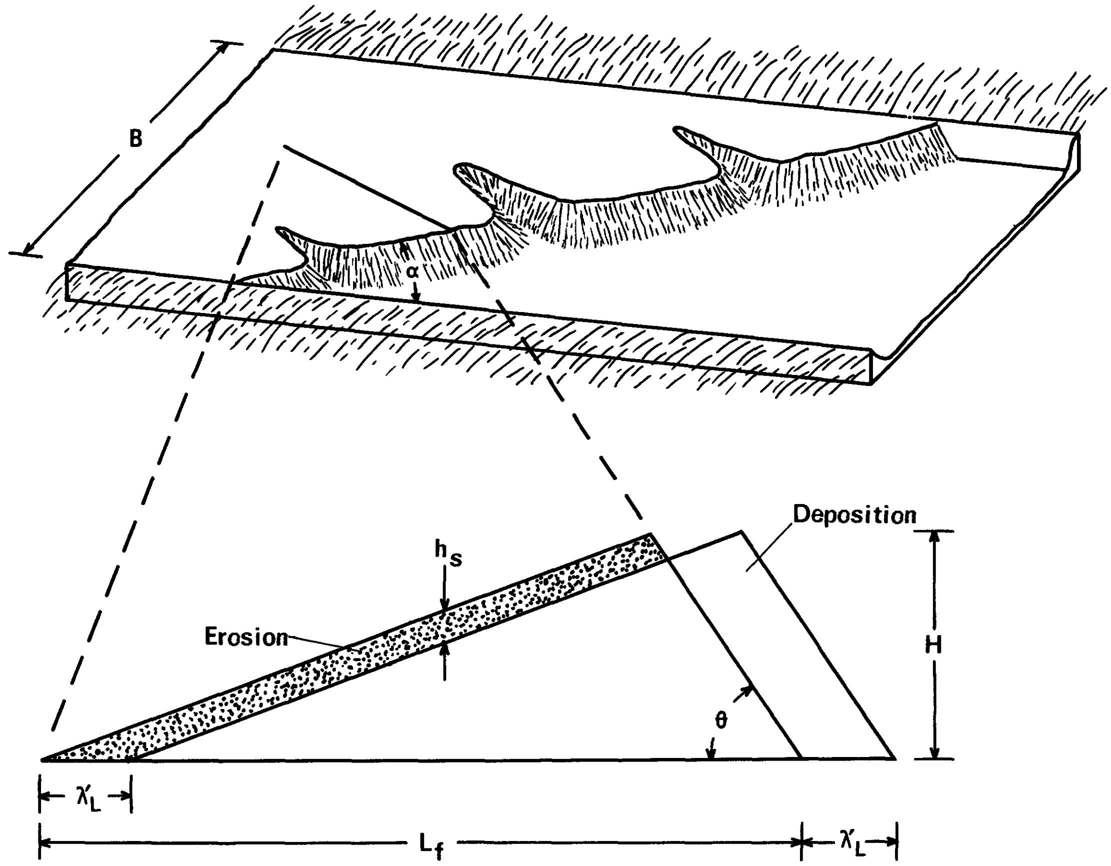
Nonstationarity of the hydrologic record may introduce a second source of error. Use of a flow-duration curve developed for a period of changing flow would result in an effective discharge that is time-averaged. As a result, errors associated with the averaging of the flow-duration curve will carry over to the computation of the effective discharge.

MACROFORMS AND CHANNEL WIDTH

Formation of islands and their subsequent attachment to the flood plain is a major cause of channel narrowing in the Platte River (Eschner, Hadley, and Crowley, 1982). Islands form as vegetation becomes established on macroforms and stabilizes them. Vegetation also increases hydraulic roughness over the macroform and promotes deposition of sediment. Vegetation continues to proliferate on the newly deposited sediment, increasing both the stability of the macroform and the likelihood of further deposition. In this manner, a macroform can grow vertically until the surface is at the same elevation as the flood plain.

Prevention of seedling germination and removal of vegetation from macroforms inhibit stabilization of macroforms. Seeds can be removed from the macroform surface and seedlings uprooted by scour on the stoss side of the macroform. The depth of scour is a direct function of downstream translation of the macroform as explained in the following paragraph. The maximum scour depth (the macroform height) is obtained if the bed form is translated a distance equal to its length.

In cross section, macroforms are triangular, with a stoss side dipping gently upstream and a steep slipface downstream of the macroform crest (fig. 13). The relationship between the depth of scour and the distance through which a macroform moves is developed by using plane geometry; it is based on the work of Crowley (1981a). This development requires specification of the depth of scour, h_s, the amplitude or height of the macroform, H, the macroform length, L_f, and the acute



EXPLANATION

$$\lambda'_L = \frac{h_s}{H}\left(L_f - \frac{H}{\tan\theta}\right)$$

λ'_L MACROFORM TRANSLATION PERPENDICULAR TO SLIPFACE

h_s EROSION DEPTH ON STOSS SIDE

H AMPLITUDE

L_f MACROFORM LENGTH

θ SLIPFACE ANGLE

B CHANNEL WIDTH

α ANGLE FORMED BY MACROFORM AND CHANNEL BANK

FIGURE 13.—Macroform geometry (from Crowley, 1981a).

angle of the downstream sloping face with the horizontal, Θ. Because the crestlines of macroforms are not perpendicular to the flow, a correction must be made which is a function of the acute angle, α, formed by the intersection of the channel bank with the crestline. From proportionality of right triangles, the expression for the distance of macroform movement, λ'_L, oblique to channel banks is:

$$\lambda'_L = \frac{h_s}{H}(L_f - H/\tan\Theta) \qquad (5)$$

To establish the macroform movement in the downstream direction, λ_L, that is, parallel to the flow, λ'_L must be divided by sinα:

$$\lambda_L = \lambda_L'/\sin\alpha = \frac{h_s}{H}\left(L_f/\sin\alpha - H/(\tan\Theta\sin\alpha)\right) \qquad (6)$$

Crowley (1981a) reports that macroform heights average about 2 m, and lengths average about 300 m, for the Platte River below Grand Island. The angle Θ is approximately 30°, and the angle α averages about 28°. Therefore, the factor $H/(\tan\Theta\sin\alpha)$ is negligible compared to $L_f/\sin\alpha$. Equation 6 can thus be simplified:

$$\lambda_L = \frac{h_s}{H}(L_f/\sin\alpha) \qquad (7)$$

An estimate of flow and its duration required to transport a macroform a distance, λ_L, and insure a scour depth, h_s, can now be made for a given L_f and sediment-transport rate per unit width of channel, Q_s. The time required to move a unit width of macroform a distance of one (macroform) length, t_{L_f}, is obtained from the conservation of sediment transport for a triangular bed form:

$$\frac{1}{2}HL_f = Q_s t_{L_f} \qquad (8a)$$

or

$$t_{L_f} = HL_f/(2Q_s) \qquad (8b)$$

The following identity holds for a constant speed of the macroform:

$$\frac{L_f}{t_{L_f}} = \frac{\lambda_L}{t_{\lambda_L}} \qquad (9)$$

Equations 8b and 9 can be combined to yield:

$$t_{\lambda_L} = \frac{\lambda_L H}{2Q_s} \qquad (10)$$

where

t_{λ_L} is the time required to move a unit width of macroform a distance λ_L.

Inserting the expression for λ_L (eq. 7) into equation 10 gives the time necessary to scour the stoss side of the macroform to a depth, h_s:

$$t_{\lambda_L} = \frac{h_s}{2Q_s}(L_f/\sin\alpha) \qquad (11)$$

Kircher (1981b) presents unit width regression relationships for sediment discharges as functions of water discharge, Q, for several stations along the Platte River. These relationships are of the form:

$$Q_s = aQ^n \qquad (12)$$

where a and n are regression coefficients. If equation 12 applies to the reach of interest, an expression for the water discharge as a function of scour depth and translation time can be obtained by combining equations 11 and 12:

$$Q = \left|\frac{h_s}{2at_{\lambda_L}}(L_f/\sin\alpha)\right|^{1/n} \qquad (13)$$

This direct substitution of equation 12 into equation 13 presents some statistical inconsistencies. Because Q is the independent variable in equation 12, technically it should not be expressed as a function of the regression parameters a and n. However, if the explained variation of the equations given in equation 12 is reasonably high, then the effects of this direct substitution are minimal. If the explained variation of the equations (12) is not large enough, then a new regression of Q on Q_s should be performed; in which case:

$$Q = a'Q_s^{n'} \qquad (14)$$

where a' and n' are regression coefficients; and

$$Q = a'\left|\frac{h_s}{2t_{\lambda_L}}\frac{L_f}{\sin\alpha}\right|^{n'} \qquad (15)$$

As noted previously, incipient motion of sediment particles on the macroforms in the Platte River occurs when there are approximately 20 cm (centimeters) of water over the bed form. Therefore, the admissible discharges obtained from equation 13 or 15 are limited to those discharges associated with the river stage necessary to barely cover the macroforms.

BED-BANK SEDIMENT INTERCHANGE

GENERAL THEORY AND CONCEPTS

If riparian vegetation is absent, the channel width of an alluvial river depends on the relative balance between scour and deposition of sediment along the banks. Excess scour along the base of the banks erodes the banks by undercutting, resulting in channel widening. This process is hastened where bank sediment is noncohesive and streamflow is perennial. When bed scour is counterbalanced by deposition of suspended sediment in slack water along channel banks, for relatively constant discharge, erosion decreases and an equilibrium width is established. However, a decrease in discharge followed by reduced movement of bed material along the banks may induce vegetation growth. If this vegetation is not uprooted by subsequent floods, the banks become stabilized and the channel resists further widening by erosion.

Various empirical regime relations have been developed that estimate changes in channel width as a function of channel depth (Lane, 1937), or changes in channel width and depth as power functions of discharge (Leopold and Maddock, 1953). Parker (1977) developed regime equations that go beyond similar studies by theoretically examining the multivariate structure of the empirical relations. These equations comprise an algorithm that is unique, in that channel cross-sectional characteristics (top width and maximum depth in a uniform bed) are mathematically integrated with bed-material size, sediment load, channel slope, and discharge.

This report compares theoretically determined channel characteristics, using Parker's method, to onsite Platte River data. This analysis was made for five sites in or near the reach from Lexington to Grand Island, Nebraska.

REGIME EQUATIONS

Parker (1977) uses concepts of water and sediment movement that specify conditions for balance of bed-load transport and lateral diffusion of suspended sediment necessary to attain channel equilibrium. These conditions are integrated into a set of three regime equations that relate channel slope, G, center depth of channel, d_c, width of channel, B, water discharge, Q, total bed material load, Q_s, and the particle size, of which s percent of the bed material is finer, D_s. In Parker's development, the channel bed was assumed uniform, with center depth equaling maximum depth. Because the bed in the Platte River is irregular, due to bed forms, center depth does not retain its connotation of the theory; therefore, average depth will be used in lieu of center depth.

Using Parker's terminology, the first regime equation relates relative roughness of channel to slope, depth, and particle size. Parker's expression of relative roughness (d_c/D_s) is the reciprocal of the conventional definition of relative roughness and may be more appropriately termed relative smoothness.

$$R_c = d_c/D_s = 46.5\, R_f^{0.4} G^{-0.6} \qquad (16)$$

where

R_c = relative smoothness (roughness) of channel;
d_c = center (average) depth of channel (meter);
D_s = bed-material particle size, in meters, for which s percent is finer;
R_f = $V_s/\sqrt{R\ D_s g}$ dimensionless fall velocity expression;
V_s = particle-fall velocity (meter per second);
R = difference in specific gravity between sediment and water (1.65);
g = acceleration of gravity (9.8 meter per second per second);
G = channel slope (m/m) meter per meter.

The remaining two regime equations establish water discharge, Q, and sediment discharge, Q_s, as functions of particle size and channel features.

$$Q=0.958\, R_c^{3}\, G \ln(1.06\, R_c^{2}\, G)* \left[B/d_c - 0.921\, R_c^{1/2}\, G^{1/2}\, R_f^{-1}\right] \qquad (17)$$

$$Q_s=0.601\, R_c^{11/2}\, G^{9/2}* \left[B/d_c - 1.41\, R_c^{1/2}\, G^{1/2}\, R_f^{-1}\right] + 2.97*10^{-4} *R_c^{13/2}\, G^{9/2}\, R_f^{-1} \ln(1.06\, R_c^{3}\, G)* \left[\mathrm{B}/d_c - 1.33\, R^{1/2}\, G^{1/2}\, R_f^{-1}\right] \qquad (18)$$

In equations 17 and 18:
B = channel top width, in meters.

A graph of selected solutions to equations 16 and 17 for various combinations of variables is given in figure 14. Equation 16 is solved first, using particle attributes V_s, R, and D_s, and channel slope G. The resulting value of R_c is then inserted into equation 17 with the other required variables, to solve for Q. Depth is shown, because it is determined by equation 16 through a choice of sediment size and slope. The selection of dependent and independent variables shown in figure 14 reflects the intent to estimate water discharge necessary to maintain a desired width of channel.

The particle-fall velocity for a given sediment size is required to calculate R_f in the regime equations. Fall velocities were obtained from the U.S. Inter-Agency Committee on Water Resources (1957), using the 20°C (degrees Celsius) temperature curve for naturally worn quartz particles having a shape factor of 0.7. Channel slopes were obtained from topographic maps.

CALIBRATION OF SEDIMENT SIZE INPUT

Parker (1977) bases his conclusions on three primary assumptions: (1) Regime equations apply only to

TABLE 5.—*Cross-sectional characteristics and sediment sizes for given discharges (modified from Karlinger and others, 1981)*

[*B*, maximum width, in meters; *Q*, water discharge, in cubic meters per second; *d*, depth, in meters; *G*, channel slope, (dimensionless) in meters per meter; *D*, sediment size, in millimeters; D_s, design size of sediment, in millimeters]

Site	Obtained from onsite measurements							Calculated from regime equations		
	$B_{maximum}$ (m)	Q (m^3/s)	B (m)	d (m)	G (m/m)	$D_{15(bed)}$ (mm)	$D_{50(bank)}$ (mm)	D_s (mm)	B (m)	d (m)
Cozad	31	11	31	0.62	.00125	0.36	0.15	0.20	30	0.37
		8	30	.53	.00125	--	--	.18	28	.32
Lexington	201	85	.137	.61	.00114	.37	.68	.25	133	.52
		102	152	.66	.00114	--	--	.26	144	.55
		122	168	.70	.00114	--	--	.27	162	.57
		142	183	.76	.00114	--	--	.28	172	.60
Lexington 2	201	159	183	.79	.00114	.31	.33	.29	178	.63
		184	198	.91	.00114	--	--	.30	191	.66
Overton	178	127	178	.70	.00119	.37	.44	.27	171	.56
Odessa	229	198	229	.64	.00112	.38	.71	.29	222	.64

straight reaches of channel; (2) bed and bank material are noncohesive; and (3) particle size is uniform throughout the channel. Of the three, only the assumption of uniform particle size is not met in an approximate way for the Platte River. Therefore, there is some question as to the best value to use for D_s in equations 16 and 17; this question was not satisfactorily resolved in Parker's (1977) study.

To determine an input sediment size for application of regime equations to the Platte River, a trial solution procedure based on measurements from five locations was used. These measurements were made near Cozad, Overton, and Odessa, Nebraska; measurements were made at two sites near Lexington, Nebraska. At each site, cross-sections were surveyed at several water discharges. Bed-material samples were also obtained at each cross section. Water-surface widths and their corresponding discharges obtained from the field measurements were used with local channel slope and depth as input variables in equations 16 and 17, to determine that sediment size, D_s, necessary for calculated width to equal measured width for the given discharge. These

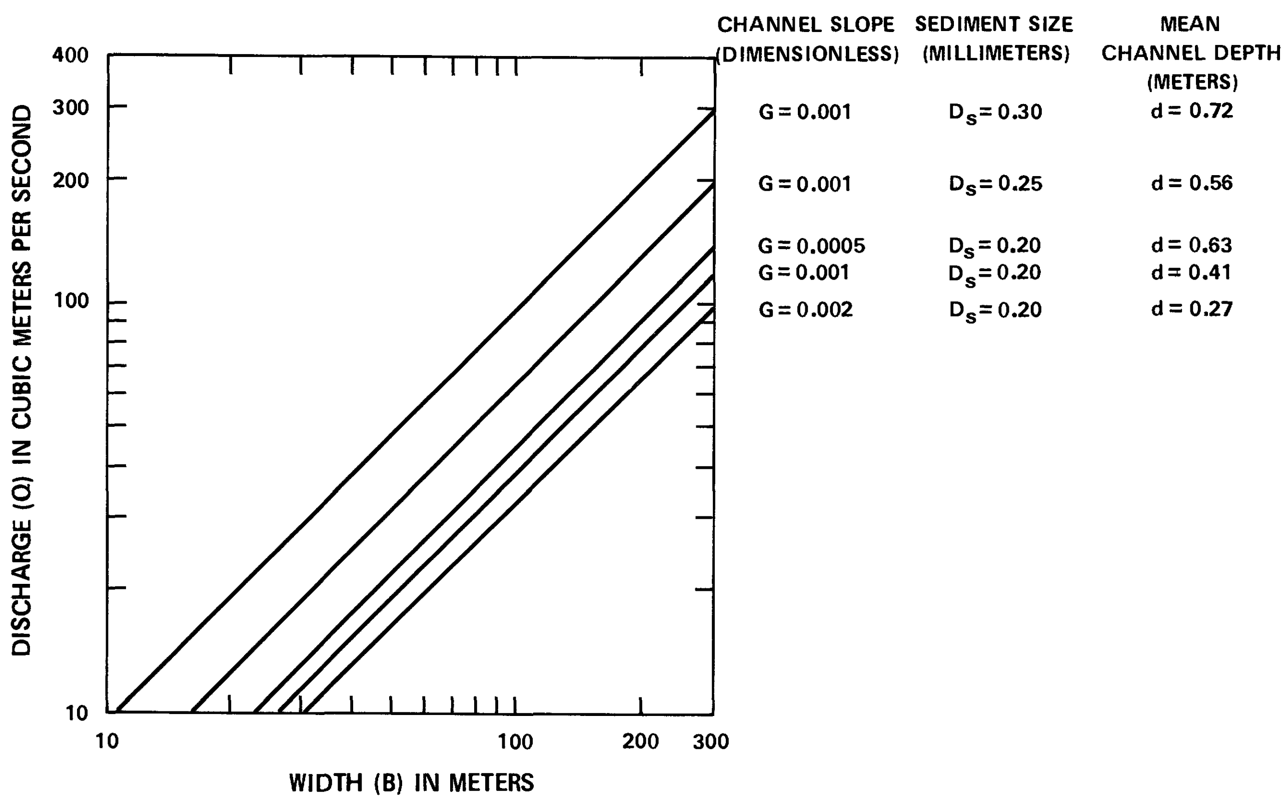


FIGURE 14.—Selected solutions of Parker's regime equations (16) and (17a) (from Karlinger and others, 1981).

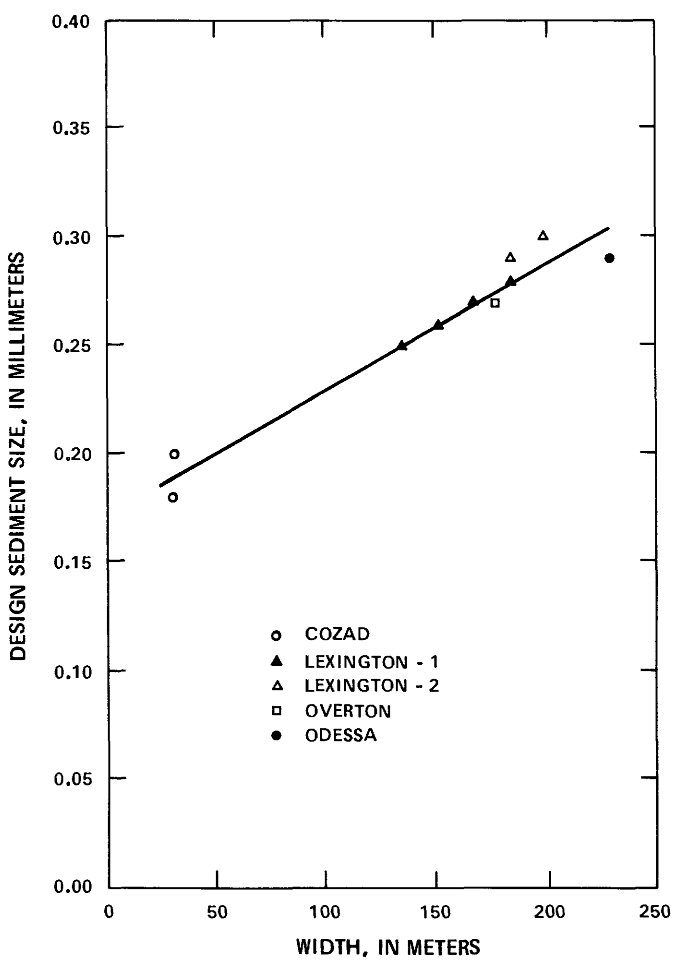


FIGURE 15.—Width-sediment size design curve for Cozad, Lexington 1 and 2, Overton, and Odessa sites (from Karlinger and others, 1981).

sediment sizes were plotted against width to establish a design relation (fig. 15) to apply equations 16 and 17 for any site within the reach. Data used to develop figure 15 are summarized in table 5.

SPECIAL CONSIDERATIONS CONCERNING THE CALIBRATION CURVE

The calibration curve (fig. 15) derived from data obtained at the five sites is acceptable only:

1. If the sediment sizes estimated from figure 15 are within the sediment-size distribution of each site. Parker (1977) also proposed that an appropriate effective particle size might be among the smaller sizes. These smaller sizes would be dominant in the bed-bank interchange.

2. For the calibration curve to be useful at any other site within the Cozad-Odessa reach, sediment-size distribution at such sites must also contain the calibrated size. The particle-size distribution curves of figure 16 indicate that both of these requirements are met for this reach of the Platte River. As can be seen from figure 16, all of the calibrated sediment sizes are acceptably within the sediment-size distribution curves and are in the lower range of the size distribution. Parker (1977) found that an estimate of D_{15} for the bed material gave the best results in a study of the Niobrara River in Nebraska. Overlap of the distribution curves strongly indicates a homogeneity in sediment-size distribution for all intermediate sites within this reach.

Sediment size as a function of width only is shown in figure 15. However, channel slope is an implicit additional independent variable in the graph. For a given width, sensitivity of discharge to slope is much smaller than sensitivity of discharge (fig. 14) to sediment size. Therefore, dependence of the design sediment size on channel slope is assumed to be negligible for the calibration curve.

Another consideration in the use of figure 15 is that maximum widths were constraints in development of the figure. For all sites, especially Cozad and Overton, stabilizing vegetation on the banks prevents any widening of the channel in response to increasing discharge; any increase in conveyance is reflected in an increase in depth. Therefore, to apply the proposed procedure to any intermediate site, a maximum width needs to be estimated if there is constraining vegetation; larger values than this width would render the method inappropriate for determining a maintenance discharge.

SUMMARY

Physical characteristics of the Platte River channels and the sediment that forms channel boundaries may serve as bases for assessing the effects of water-management decisions on channel changes. Channel geometry and hydrologic data, used with analysis data of bed and bank sediment, can estimate channel response to changes in river flow regime.

Channel characteristics of the Platte River have been documented sufficiently for the period 1900–80 to permit correlation of channel response to historical changes in hydrology, including water use. The channel has narrowed by 50 percent near Duncan, Nebraska, since about 1900; the width has decreased as much as 90 percent since 1900 near Cozad, Nebraska. The channel, which was once broad and relatively free of vegetation and islands, has been transformed at many locations into a series of narrow channels separated by islands of various sizes. Sediment transport also has been altered extensively because of reduced flow in narrow channels,

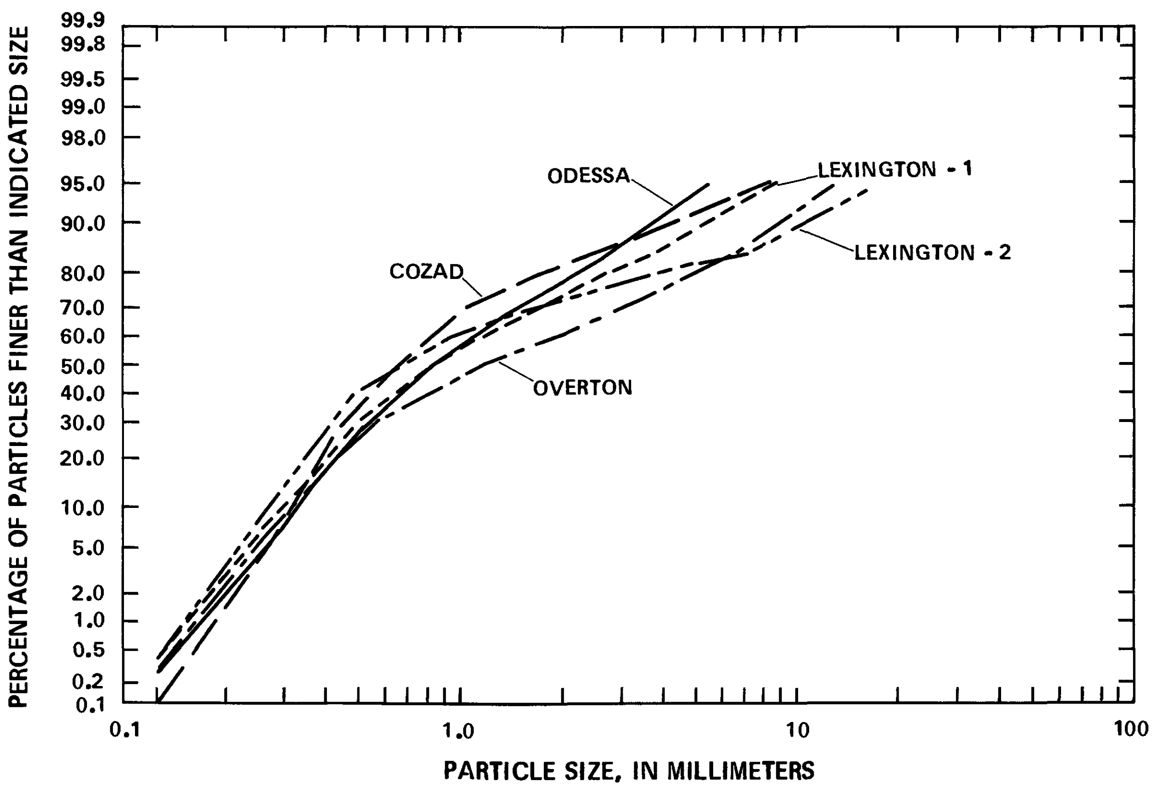


FIGURE 16.—Particle-size distribution curves for bed material at Cozad, Lexington 1 and 2, Overton, and Odessa sites (from Karlinger and others, 1981).

some of which are clogged with vegetation, islands, and aggrading bed forms. How much more will these channels change as a result of future water-management practices?

Three methods relating water discharge to channel cross-section characteristics have been presented to allow assessment of the consequences of future river-management practices. A statistically based effective discharge computation is presented, but it lacks a physical basis for understanding fluvial processes. The methods involving movement of macroforms and bed and bank sediment interchange are both more physically based than the effective discharge method, but both may be subject to errors because theoretical assumptions are only approximated for the Platte River channels. Each of the three methods has limitations for determining channel-maintenance discharges. However, with some understanding of the fluvial processes operating in the channels and the relationship of water discharge to sediment discharge, channel-maintenance discharges may be estimated.

REFERENCES CITED

Andrews, E. D., 1980, Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming: Journal of Hydrology, v. 46, 20 p.

Benson, M. A., and Thomas, D. M., 1966, A definition of dominant discharge: Bulletin of the International Association of Scientific Hydrology, v. 11, no. 2, p. 76-80.

Crowley, K. D., 1981a, Large-scale bedforms in the Platte River downstream from Grand Island, Nebraska: Structure, process, and relationship to channel narrowing: U.S. Geological Survey Open-File Report 81-1059, 31 p.

_____1981b, Hierarchies of bedforms: Princeton University, Princeton, New Jersey, pt. 1, unpublished Ph. D. dissertation, 98 p.

Eschner, T. R., 1981, Morphologic and hydrologic changes of the Platte River, south-central Nebraska: Colorado State University, Fort Collins, M. S. thesis, 269 p.

Eschner, T. R., Hadley, R. F., and Crowley, K. D., 1983, Hydrologic and morphologic changes in channels of the Platte River basin: A historical perspective: U.S. Geological Survey Professional Paper 1277-A, 39 p.

Hayes, John R., 1962, Quartz and fieldspar content in South Platte, Platte, and Missouri River sands: Journal of Sedimentary Petrology, v. 32, no. 4, p. 793-800.

Karlinger, M. R., Mengis, R. C., Kircher, J. E., and Eschner, T. R., 1981, Application of theoretical equations to estimate the discharge needed to maintain channel width in a reach of the Platte River near Lexington, Nebraska: U.S. Geological Survey Open-File Report 81-697, 16 p.

Kircher, J. E., 1981a, Sediment analysis for selected sites on the South Platte River in Colorado and Nebraska, and the North Platte and Platte Rivers in Nebraska—Suspended sediment, bedload, and bed material: U.S. Geological Survey Open-File Report 81-207, 48 p.

_____1981b, Sediment transport and effective discharge of the North Platte, South Platte, and Platte Rivers in Nebraska: U.S. Geological Survey Open-File Report 81-53, 26 p.

Kircher, J. E., 1983, Interpretation of sediment data for the South Platte River in Colorado and Nebraska, and the North Platte and Platte Rivers in Nebraska: U.S. Geological Survey Professional Paper 1277-D, 37 p.

Kircher, J. E., and Karlinger, M. R., 1983, Changes in surface water hydrology, Platte River basin in Colorado, Wyoming, and Nebraska upstream from Duncan, Nebraska: U.S. Geological Survey Professional Paper 1277-B, 49 p.

Lane, E. W., 1937, Stable channels in erodible material: American Society of Civil Engineers Transactions 63, p. 123-142.

Leopold, L. B., and Maddock, Thomas, Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geological Survey Professional Paper 252, 57 p.

Missouri River Basin Commission, 1975, Land conservation and sedimentation, Platte River basin, Nebraska—Level B Study, Technical Paper: Omaha, Nebraska, 214 p.

Parker, Gary, 1977, Self-formed straight rivers with stable banks and mobile bed in non-cohesive alluvium. Part I. The sand-silt river: Dept. of Civil Engineering, University of Alberta, Alberta, Canada, 56 p.

U.S. Fish and Wildlife Service, 1981, Platte River ecology study—Summary report: U.S. Department of the Interior, Northern Prairie Wildlife Research Service, Jamestown, N. Dak., 187 p.

U.S. Inter-Agency Committee on Water Resources, 1957, Some fundamentals of particle size analysis, Report No. 12, *in* A Study of methods used in measurement and analysis of sediment loads in streams: Minneapolis, Minnesota, St. Anthony Falls Hydraulic Laboratory, 55 p.

Williams, G. P., 1978, The case of the shrinking channels—the North Platte and Platte Rivers in Nebraska: U.S. Geological Survey Circular 781, 48 p.

A Stochastic Streamflow Model and Precipitation Model for the Platte River from Gothenburg to Grand Island, Nebraska

By ALDO V. VECCHIA, JR.

HYDROLOGIC AND GEOMORPHIC STUDIES OF THE PLATTE RIVER BASIN

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1277-F

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1983

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION TABLE

Multiply	*By*	*To Obtain*
inches	0.0254	meters
cubic feet per second	0.028	cubic meters per second

LIST OF SYMBOLS

E = expected value
C = nonnegative transformation constant
F = mass function value
I = counter based on drought limits
J = total number of stations
j = station index
k = season index
L = size of random sample in drought calculation
ℓ = rainfall level in drought analysis (inches)
N = length of precipitation record
n = year index
s = number of seasons per year
t = time index (years)
U = March-April precipitation totals (inches)
V = May-August precipitation totals (inches)
X = variable representation for seasonal time series
Z = variable representation for transformed series
α = vectors of parameters in precipitation model
δ = residual component for Grand Island streamflow
ϵ = residual component in precipitation model (inches)
η = independent normal random variate
Γ = streamflow covariance matrix
γ = residual component for Overton streamflow model (cubic feet per second)
λ = parameter in Box-Cox transformation
ξ = residual component for Overton streamflow model (cubic feet per second)
σ = standard deviation of residual component in precipitation models (inches)

A STOCHASTIC STREAMFLOW MODEL AND PRECIPITATION MODEL FOR THE PLATTE RIVER FROM GOTHENBURG TO GRAND ISLAND, NEBRASKA

By ALDO V. VECCHIA, JR.

ABSTRACT

A stochastic model of monthly precipitation at Gothenburg, Kearney, and Grand Island, Nebraska, is developed. The model allows for simulation of single-station or joint-station precipitation and estimation of probabilities of future precipitation events. Some probabilities of droughts of differing severities and durations over the next 50 years are estimated by using the resulting model.

A stochastic model of seasonal streamflow at the Overton, Odessa, and Grand Island, Nebraska, gaging stations of the Platte River is also presented. Three seasons were chosen to correspond to differing periods of flow and vegetation development along the river: (1) Season 1 consists of aggregated flows for September through February (base flow period); (2) season 2, aggregated flows for March and April (snowmelt flows); and (3) season 3, aggregated flows for May through August (time of seed drop by riparian vegetation). The model can be used for single-station or joint-station simulation of streamflow and estimation of probabilities.

Finally, it is recognized that the precipitation series may have an effect on the streamflow series. Although this effect is not modeled because of limited data collection, some cross correlations between the two hydrologic series are presented to allow preliminary estimation of the changes in streamflow resulting from changes in precipitation.

INTRODUCTION

A reach of the Platte River in south-central Nebraska has been designated a critical habitat reach for migratory waterfowl, especially sandhill and whooping cranes. These birds are attracted to the area partly because of the local geomorphic characteristics of the river channel; to maintain these geomorphic processes and preserve these habitat characteristics, the hydrology of the region must be effectively managed. Perhaps the two most critical elements for properly managing both the habitat and the economic development along the river valley are understanding and predicting the hydrology.

This report presents stochastic models of precipitation and streamflow for the critical reach of the Platte River, which is defined as the reach extending from Lexington to Grand Island, Nebraska (fig. 1). Precipitation stations at Gothenburg, Kearney, and Grand Island, Nebraska, are assumed to represent adequately the precipitation patterns within the critical reach. Data from these stations are used to model joint-monthly precipitation values. A three-season flow series is jointly modeled for the gaging stations at Overton, Odessa, and Grand Island, Nebraska, because of complexity of the monthly streamflow time series. The three flow seasons are defined as September through February (season 1), March and April (season 2), and May through August (season 3). season 1 represents the base flow period; season 2 represents the period of high flows from snowmelt in the Rocky Mountains; and season 3 represents the approximate time of seed drop by riparian vegetation and seedling germination and establishment in the channel.

The precipitation and streamflow models are used for simulation and evaluaton of probabilities pertaining to events of interest, including periods of low precipitation and high or low streamflow occurrences. These events become important when causes of channel narrowing, such as vegetation encroachment and maintenance of wetland environment, are studied.

The precipitation and streamflow models were developed individually rather than jointly because of time and resource limitations. A joint model would involve a detailed study of the effects of drought on nearby irrigation pumping, and, in turn, on the operating rules of the many diversions and timed reservoir releases of this highly regulated river. Some statistical correlations between the precipitation and streamflow series are presented in a later section of this report.

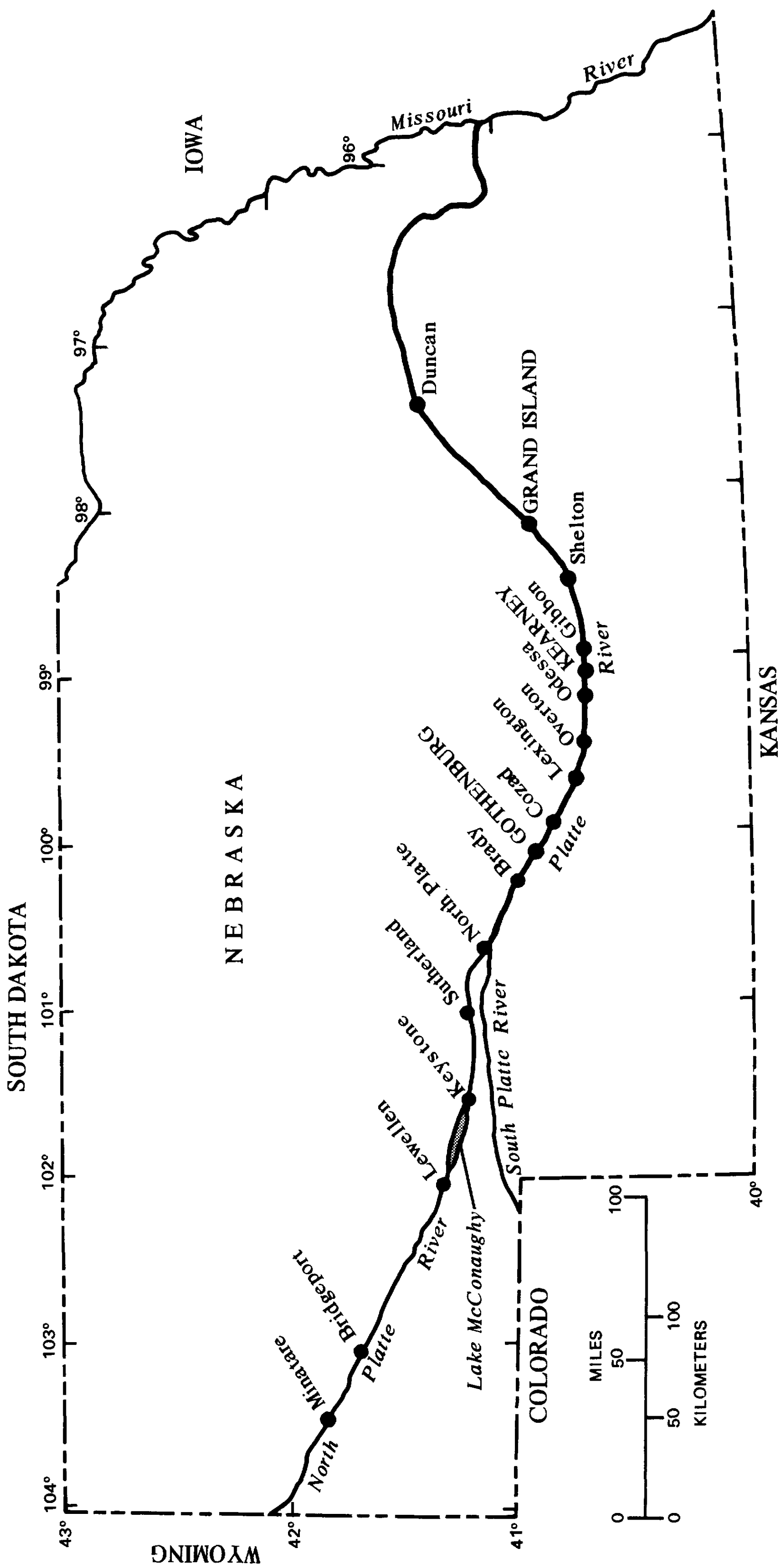


FIGURE 1.—Location of the Platte River Study area from Gothenburg to Grand Island.

Both the precipitation and streamflow models are designed to maintain cross correlation between stations, to allow simultaneous simulation of the three station series; however, individual models for each station remain autonomous, to allow concentration on a single station for special purpose studies. The interstation correlation structure is maintained by allowing residuals from the single-station models to be correlated.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to the following for their valuable assistance: M. R. Karlinger, R. F. Hadley, and C. F. Nordin, Jr. In addition, part of this research was conducted by the author under a grant from the National Science Foundation that was supervised by Prof. D. C. Boes, Department of Statistics, Colorado State University, Fort Collins, Colorado.

GENERAL MODELING SCHEME

Both the precipitation and streamflow models are applications of a general technique for modeling multistation seasonal time series. This technique is briefly outlined in this section. A discussion of alternative modeling methods will not be given; the method used here is justified by showing its applicability to the precipitation and streamflow series.

Suppose one has observed a seasonal time series consisting of s seasons per year for each of N consecutive years, at each of J interrelated stations. Denote this time series as:

$$\left\{X^{(j)}_{t(n,k)},\ j=1,2,\ldots,\ J,\ n=0,1,\ldots,\ N\text{-}1,\ k=1,2,\ldots,\ s\right\},$$

where

j is the station index;
n is the year index;
k is the season index; and
$t(n,k)=ns+k$ is the cumulative time index.

The likelihood of certain extreme events involving the process over the years N, $N+1,\ldots, N+M$, where M is large in comparison to N, can be determined by using a stochastic model based on the observed series.

Let $X^{(j)}_{t(n,k)} = \hat{X}^{(j)}_{t(n,k)} + \epsilon^{(j)}_{t(n,k)}$ denote the model for the j^{th} station, where $\hat{X}^{(j)}_{t(n,k)}$ is the deterministic or predicted component of $X^{(j)}_{t(n,k)}$, and $\epsilon^{(j)}_{t(n,k)}$ is the random or residual component. To allow both autonomy of the individual station models and recursive simulation of the time series, $\hat{X}^{(j)}_{t(n,k)}$ is assumed to be the linear function of previous values of the series at the j^{th} station, and of certain parameters that may be dependent on seasons but not on years:

$$\left(\hat{X}^{(j)}_{t(n,k)} = f_k\,(\alpha_k(j), X_1^{(j)}, X_2^{(j)}, \ldots X^{(j)}_{t(n,k)-1}\right)$$

where α_k (j), $k = 1,2\ldots, s$, are vectors of parameters to be estimated. The single-station model residuals, which could be correlated, are assumed to follow a normal distribution with mean 0. Correlation of the within-station residuals occurs in the streamflow model but not in the precipitation model. Interrelations between stations can be maintained in the model by allowing residuals from single-station models to be correlated between stations. For example, if a high (low) value for station 1 is usually accompanied by a high (low) value for station 2, then $\epsilon^{(1)}_{t(n,k)}$ and $\epsilon^{(2)}_{t(n,k)}$ would be positively correlated.

Many types of time-series models useful for analysis of hydrologic data fit the general form given in the previous paragraph. Some examples are auto-regressive integrated moving average (ARIMA) models (Box and Jenkins, 1975), periodic autoregression models (Pagano, 1978), and trigonometric linear models (Graybill, 1976). Trigonometric linear models were chosen for the precipitation model and periodic autoregressions with moving average components in the residuals were chosen for the streamflow model. Parameters were estimated by the method of least squares.

The assumption that residuals are normally distributed is often not true when untransformed time series are modeled, especially hydrologic data. To achieve normality for residuals, a Box-Cox transformation often can be utilized (Box and Cox, 1964). This transformation follows the form (the station index is dropped for convenience):

$$\left(Z_{t(n,k)}\right)_\lambda = \left\{\begin{array}{ll} \left[\left(X_{t(n,k)}+C\right)^\lambda - 1\right]/\lambda, & \text{if } \lambda \neq 0 \\ \log_e\left(X_{t(n,k)}+C\right) & \text{, if } \lambda = 0 \end{array}\right\}$$

where

$X_{t(n,k)}$ is the untransformed series, and
C is the nonnegative constant, for which $X_{t(n,k)}+C>0$ for all $t(n,k)$, $n=0,1,\ldots, N-1$, $k=1,2,\ldots, s$.

The value of λ for which residuals from the model of the resulting series, $\left\{\left(Z_{t(n,k)}\right)\lambda\right\}$, most closely followed a normal distribution was determined for both the precipitation and streamflow series, using a maximum likelihood technique. For details of this technique and for an analytic interpretation of the resulting transformation, see Vecchia (1981a).

PRECIPITATION MODEL

The time series used for development of the precipitation model consists of monthly precipitation totals, in inches, at the Gothenburg, Kearney, and Grand Islands, Nebraska stations, from January 1934 through December 1978. Monthly means and standard deviations of these series are listed in table 1. The large differences in means and standard deviations among months must be accounted for in the model either by inclusion of seasonally varying mean and variance components or by transforming the raw data; the Box-Cox transformation is adequate for removing seasonality in the variances; a periodically varying deterministic component is added to account for the monthly means. Graphs of the series (figs. 2, 3, and 4) show that the data truncated at zero and positively skewed, indicating that a model fit to the untransformed data would have a nonnormally distributed random component. For example, if the deterministic part of the model yields a value of 0.5 inch for January 1951, then the random component for that month cannot be less than −0.5 inch, because negative precipitation values are impossible. The Box-Cox transformation of the data alleviated this problem.

SINGLE-STATION MODELS

Estimated autocorrelations and spectral density for Kearney (fig. 5) indicate a strong periodicity of 12 months. Two classes of models that can be fit to series exhibiting periodic autocorrelation structure are autoregressive integrated moving average (ARIMA) models (Box and Jenkins, 1975) and trigonometric linear models (Graybill, 1976). For a complete description of the fitting of these two types of models to the single-station series, as well as a comparison between models, see Vecchia (1981a). Only the trigonometric models are presented here, because they fit the observed series better than the ARIMA models, and because they are easier for simulation and evaluation of drought probabilities.

Let $\{X_t^{(j)},\ t=1,2,3...\}$ denote the precipitation series for the j^{th} station with $j=1$ corresponding to Gothenburg; $j=2$ corresponding to Kearney; and $j=3$ corresponding to Grand Island, with $t=1$ corresponding to January 1934. The values $\lambda=1/3$ and $C=0.01$ yielded the optimal Box-Cox transformation for all three stations, so the original series were transformed to:

$$Z_t^{(j)}=\left[(X_t^{(j)}+.01)^{1/3}-1\right]*3,\ j=1,2,3.$$

The cube-root transformation has been analyzed by quantifying an explanation of skewness in precipitation distributions (Stidd, 1970). The transformed series were modeled as follows:

Gothenburg:

$$Z_t^{(1)}=0.2009-1.1956*\cos\frac{2\pi t}{12}-0.1595*\sin\frac{2\pi t}{12}+0.1293*\cos\frac{2\pi t}{3}+0.1089*\sin\frac{2\pi t}{4}-0.1054*\sin\frac{2\pi t}{6}+\epsilon_t^{(1)}; \quad (1)$$

where $\{\epsilon_t^{(1)}\}$ are iid (independent, identically distributed) normal $(0,0.861^2)$; $R^2=50.2$ percent.

Kearney:

$$Z_t^{(2)}=0.3492-1.1637*\cos\frac{2\pi t}{12}-0.1708*\sin\frac{2\pi t}{12}+0.1699*\sin\frac{2\pi t}{4}-0.1367*\sin\frac{2\pi t}{6}+\epsilon_t^{(2)}; \quad (2)$$

where $\{\epsilon_t^{(2)}\}$ are iid normal $(0,0.898^2)$; $R^2=47.0$ percent.

TABLE 1.—*Precipitation statistics for Gothenburg, Kearney, and Grand Island, 1934 to 1978*

Month	Gothenburg		Kearney		Grand Island	
	Mean (inches)	Standard deviation (inches)	Mean (inches)	Standard deviation (inches)	Mean (inches)	Standard deviation (inches)
Jan.	0.459	0.381	0.511	0.401	0.525	0.390
Feb.	.500	.440	.688	.539	.786	.641
Mar.	1.220	.881	1.357	1.138	1.238	1.067
Apr.	2.156	1.516	2.420	1.670	2.421	1.493
May.	3.431	2.120	3.915	2.227	3.864	2.080
June.	4.118	2.279	4.141	2.781	3.871	2.331
July.	2.587	1.610	2.962	1.911	2.710	2.040
Aug.	2.493	1.285	2.410	1.479	2.447	1.621
Sept.	1.892	1.453	2.451	1.986	2.443	2.153
Oct.	1.045	1.163	1.348	1.252	1.031	.951
Nov.	.597	.588	.730	.849	.787	.837
Dec.	.473	.344	.576	.473	.603	.550

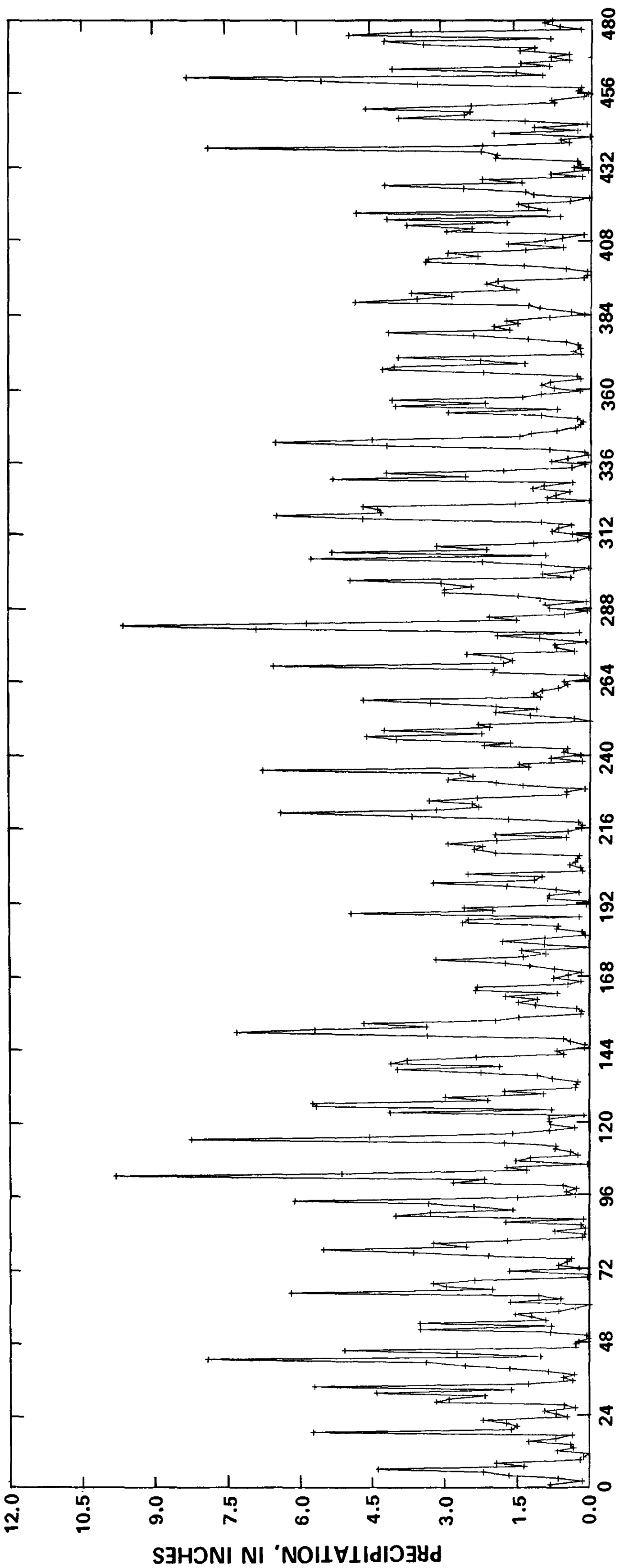


FIGURE 2.—Monthly precipitation at Gothenburg, January 1, 1939 through December 31, 1978.

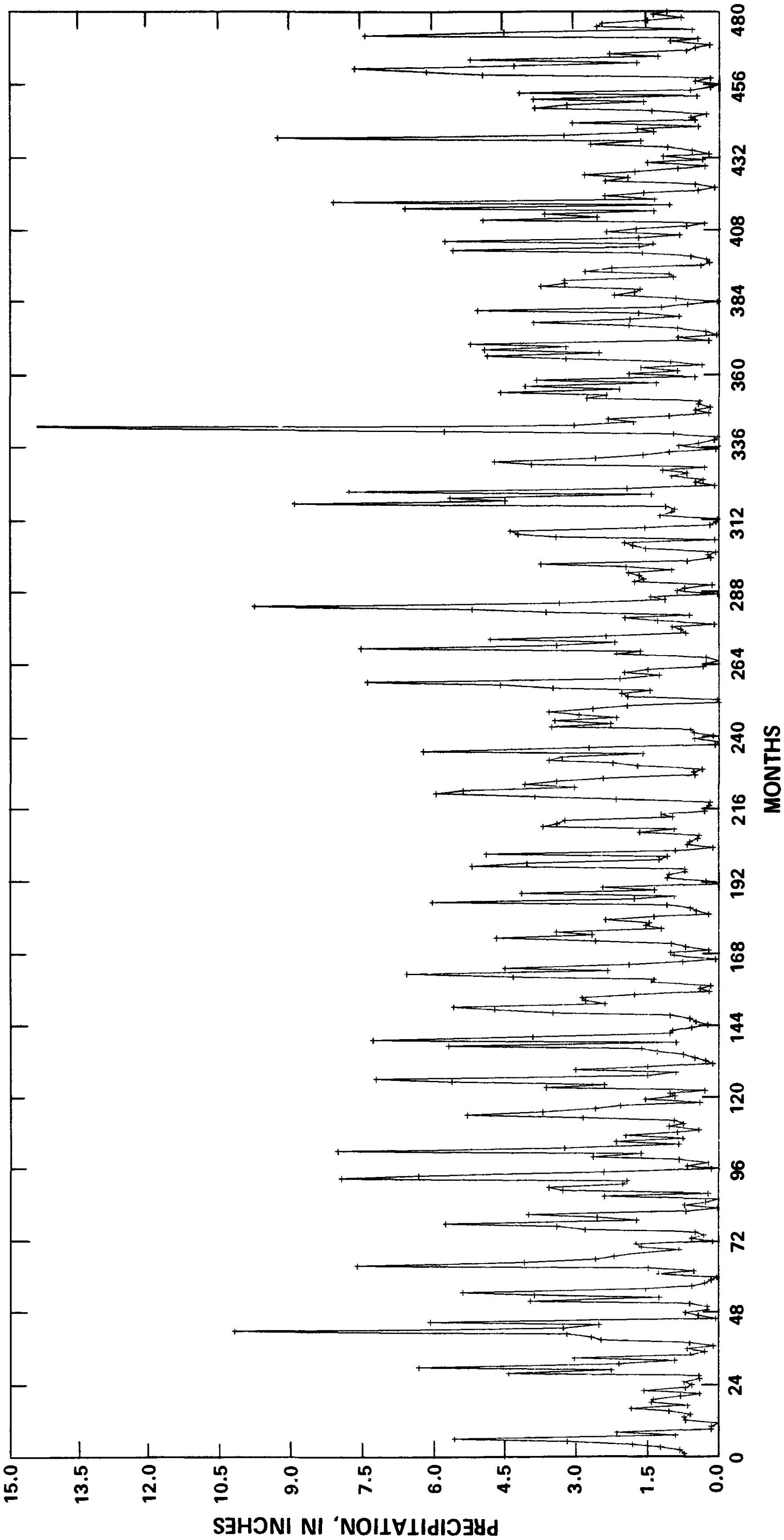


FIGURE 3.—Monthly precipitation at Kearney, January 1, 1939 through December 31, 1978.

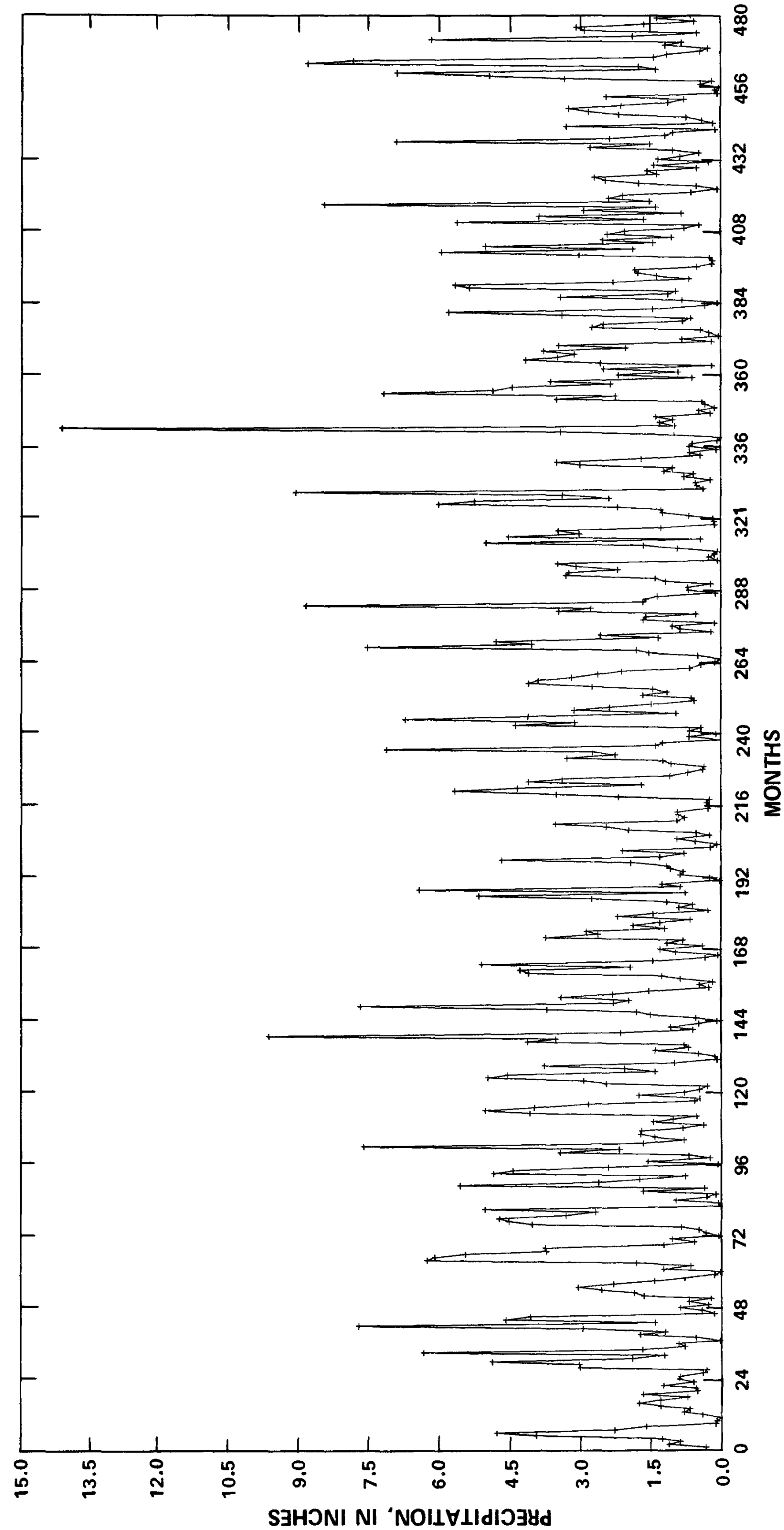


FIGURE 4.—Monthly precipitation at Grand Island, January 1, 1939 through December 31, 1978.

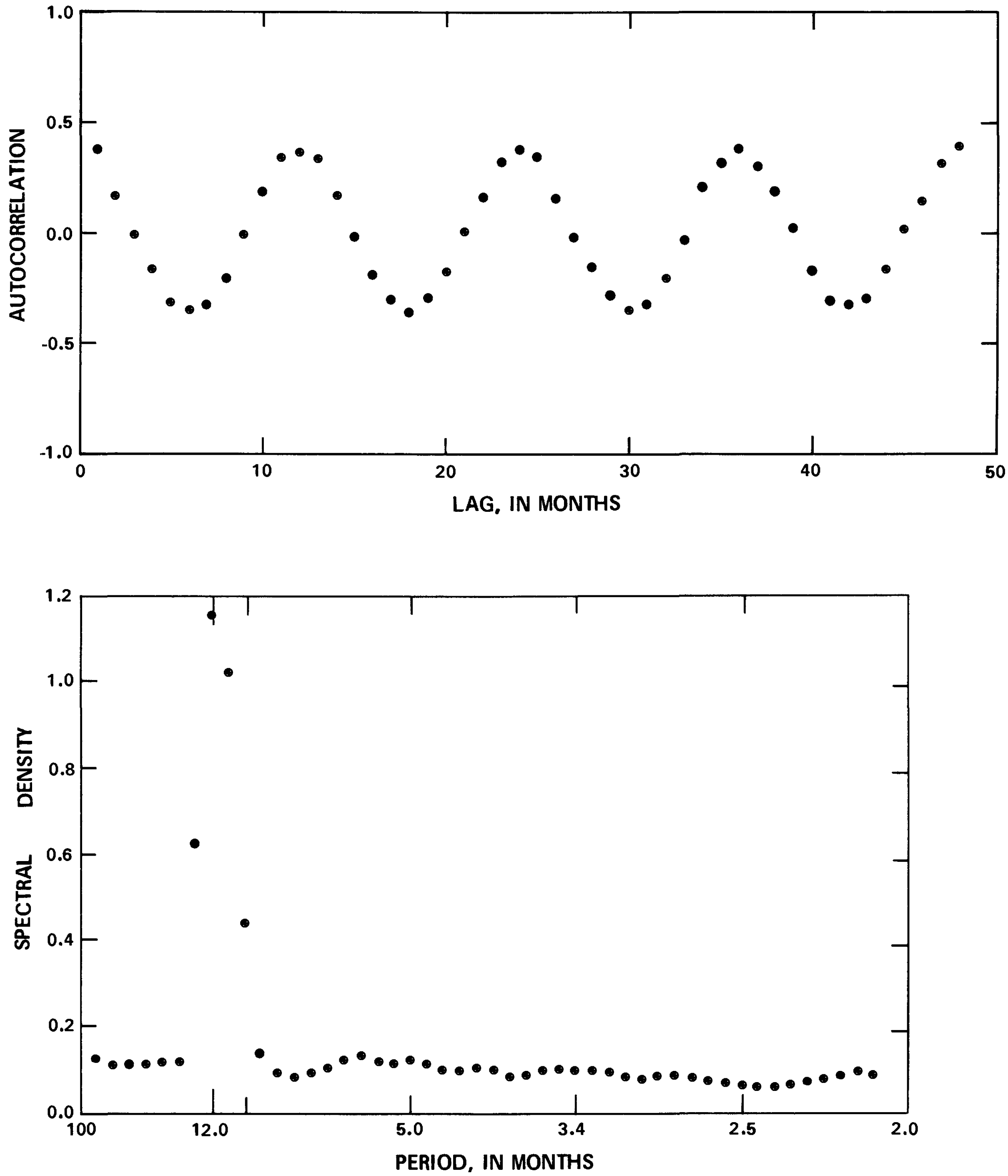


FIGURE 5.—Autocorrelations and spectral density of the monthly precipitation totals at Kearney, January 1, 1939 through December 31, 1978.

Grand Island:

$$Z_t^{(3)}=0.3187-1.117*\cos\frac{2\pi t}{12}+0.1988*\sin\frac{2\pi t}{4}+0.1216*\sin\frac{2\pi t}{6}-0.1097*\sin\frac{2\pi t}{12}+\epsilon_t^{(3)}; \quad (3)$$

where $\{\epsilon_t^{(3)}\}$ are iid normal $(0,0.895^2)$; R^2=45.1 percent.

Residuals from each of the above models were examined to insure that the following assumptions were not violated: (1) The residuals ϵ_t are mutually independent; and (2) ϵ_t is distributed normally, with mean 0 and variance σ^2 for all t. A visual inspection of the graphs of the residuals versus time for each station indicated no

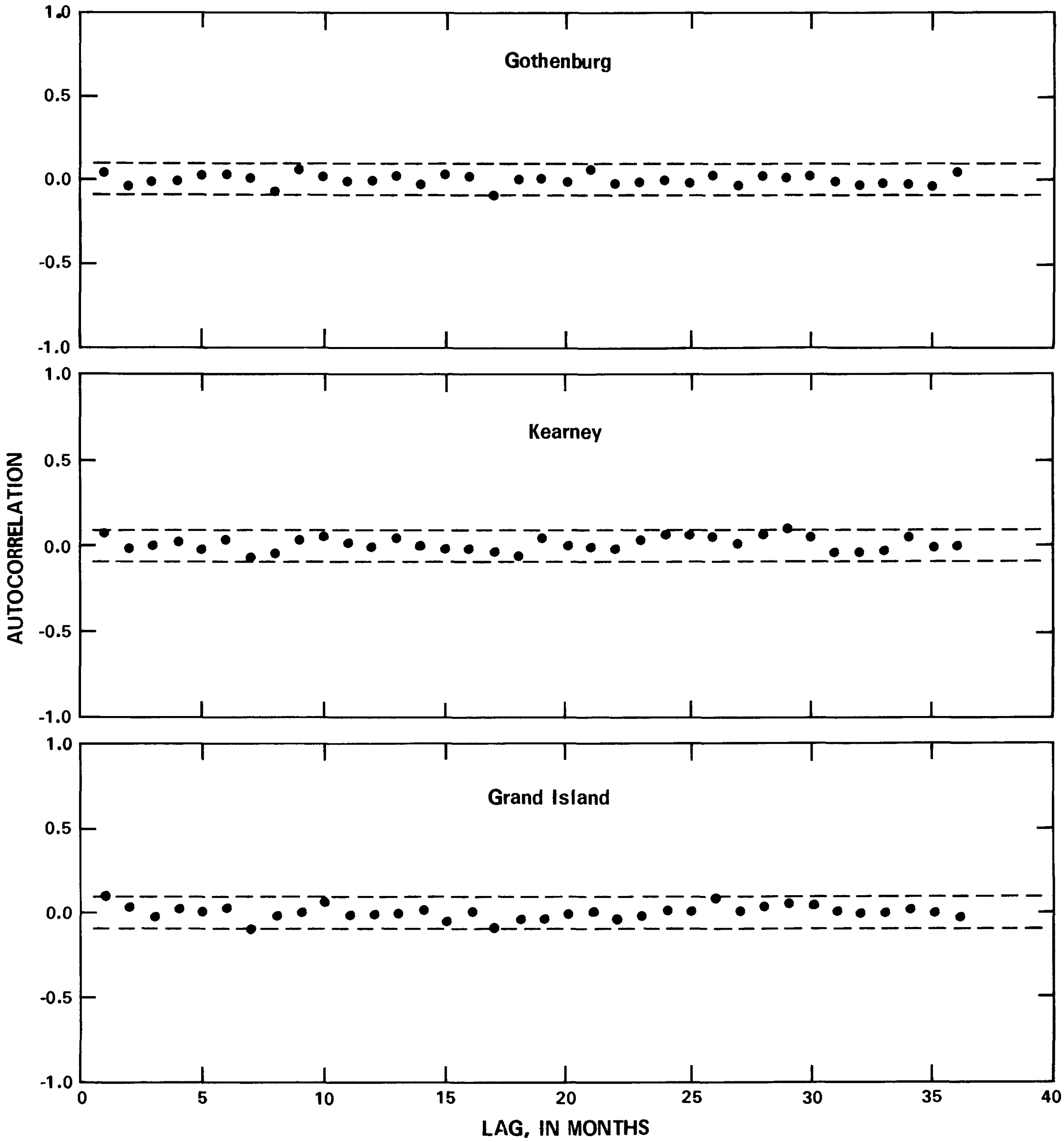


FIGURE 6.—Autocorrelations for residuals at Gothenburg, Kearney, and Grand Island within 95-percent confidence limits.

trends or abnormalities. Graphs of the autocorrelations of the residuals for each station, along with 95-percent confidence limits assuming white noise (fig. 6), show that the residuals have no significant autocorrelation. A histogram of the residuals for Gothenburg and Grand Island (fig. 7), with the series statistics (table 2), show that the residuals appear to be normally distributed, but that some differences exist in the means and standard deviations among the months. The differences were considered minor enough for the model to be used.

COMBINED-STATION MODEL

Models were determined for each station individually. However, if joint probability statements are to be made about the three stations, a multivariate structure must

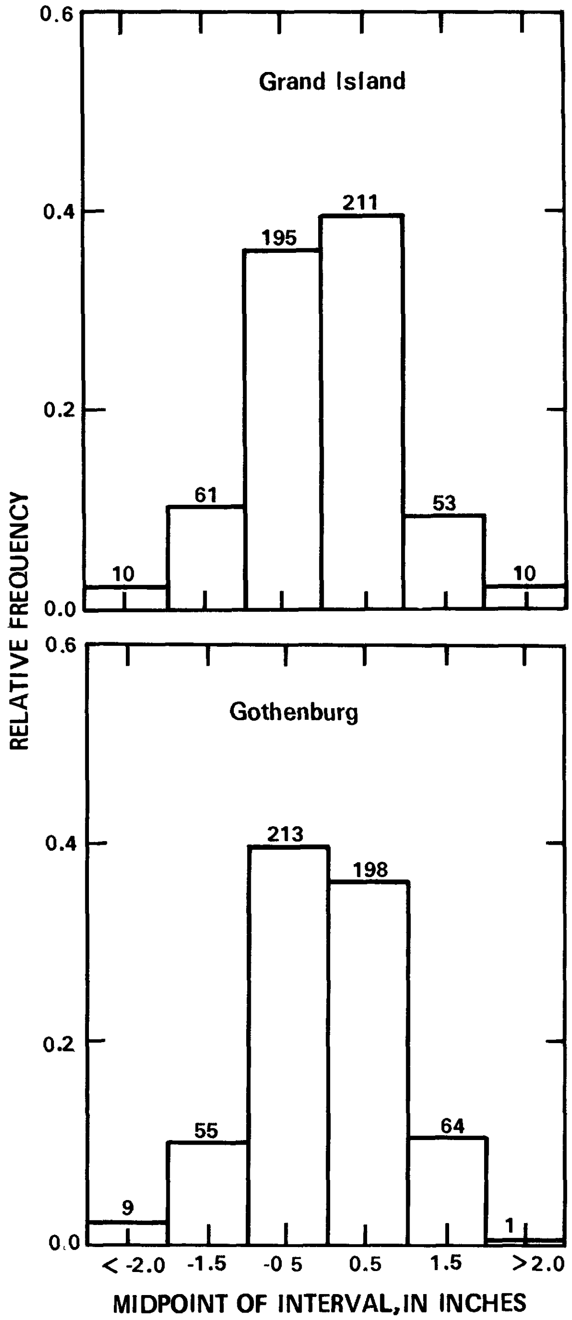


FIGURE 7.—Histograms of residuals for Gothenburg and Grand Island.

be added to the model. Because the stations are geographically near each other, they are assumed to be similar in their precipitation patterns. Therefore, if the error in predicting rainfall at any one station is a large positive number (the rainfall is much greater for that month than the model predicts), then the errors at the other stations should tend to be positive. This is indeed the case, as the estimated covariance matrix of the computed residuals is:

$$\underline{\hat{\Sigma}} = \begin{array}{l} \text{Gothenburg} \\ \text{Kearney} \\ \text{Grand Island} \end{array} \begin{bmatrix} 0.741 & 0.546 & 0.484 \\ .546 & .805 & .622 \\ .484 & .622 & .799 \end{bmatrix}$$

(columns: Gothenburg, Kearney, Grand Island); and the corresponding estimate of the correlation matrix is:

$$\underline{\hat{R}} = \begin{array}{l} \text{Gothenburg} \\ \text{Kearney} \\ \text{Grand Island} \end{array} \begin{bmatrix} 1.0 & 0.706 & 0.628 \\ .706 & 1.0 & .773 \\ .628 & .773 & 1.0 \end{bmatrix}.$$

(columns: Gothenburg, Kearney, Grand Island)

Therefore, the final model for the joint monthly precipitation series at Gothenburg, Kearney, and Grand Island is:

Gothenburg: $Z_t^{(1)} = \mu_t^{(1)} + \epsilon_t^{(1)}$; (4a)

Kearney: $Z_t^{(2)} = \mu_t^{(2)} + \epsilon_t^{(2)}$; (4b)

Grand Island: $Z_t^{(3)} = \mu_t^{(3)} + \epsilon_t^{(3)}$; (4c)

where $\mu_t^{(\cdot)}$ are the deterministic components given in equations 1, 2, and 3 of the previous section and the sequences $\{\underline{\epsilon}_t\} = \left\{\left(\epsilon_t^{(1)}, \epsilon_t^{(2)}, \epsilon_t^{(3)}\right)\right\}$ are independent and identically distributed trivariate normal random vectors, with mean $\underline{0}$ and covariance matrix $\underline{\hat{\Sigma}}$. The deterministic components are periodic functions with period 12 ($t=1$ corresponding to January).

The purpose of the model is to make probability statements about events in the future, not to predict specific future precipitation values. If direct evaluation of the probability of an event from the model is not possible, then a number of future realizations can be generated to determine frequency of the event. The simulation of joint-station precipitation for a particular month proceeds as follows:

1. Generate three independent normal random variates with mean 0 and variance 1, $(\eta_{t1}, \eta_{t2}, \eta_{t3})$, from an existing normal random generator
2. Compute $\epsilon_t^{(1)} = 0.8608 * \eta_{t1}$, $\epsilon_t^{(2)} = 0.6346 * \eta_{t1} + 0.6347 * \eta_{t2}$, and $\epsilon_t^{(3)} = 0.5627 * \eta_{t1} + 0.4167 * \eta_{t2} + 0.5557 * \eta_{t3}$;
3. add the corresponding deterministic components to the residuals of (4) to obtain $Z_t^{(1)}$, $Z_t^{(2)}$, and $Z_t^{(3)}$; and
4. Untransform $Z_t^{(\cdot)}$ to get precipitation in original units:

$$X_t^{(\cdot)} = \left(Z_t^{(\cdot)}/3 + 1\right)^3 - 0.01.$$

TABLE 2.—*Residual statistics for Gothenburg, Kearney, and Grand Island, 1934 to 1978*

Month	Gothenburg		Kearney		Grand Island	
	Mean (inches)	Standard deviation (inches)	Mean (inches)	Standard deviation (inches)	Mean (inches)	Standard deviation (inches)
Jan.	0.059	0.690	-0.054	0.631	-0.120	0.653
Feb.	-.100	.699	-.026	.714	.041	.705
Mar.	-.023	.756	.093	.870	-.003	.848
Apr.	-.030	.947	-.064	.894	-.044	.895
May.	.021	1.017	-.046	1.064	.001	.912
June.	.117	.911	.099	1.003	.105	.915
July.	-.128	.934	-.016	.869	-.099	1.042
Aug.	.169	.718	-.093	.805	.010	.831
Sept.	-.158	1.048	.088	1.056	.125	1.079
Oct.	-.065	1.025	.011	.969	-.234	1.002
Nov.	.074	.887	-.089	1.074	.108	.999
Dec.	.062	.628	.098	.779	.109	.784
Total	0.0		0.0		0.0	

Graphs of 40-year model simulations are presented for Gothenburg (fig. 8), Kearney (fig. 9), and Grand Island (fig. 10).

One method of evaluating model adequacy is to determine how well it reproduces monthly means and standard deviations of past data. Note that the historical record is assumed to be one possible realization from an underlying model driving the system. Therefore, the purpose is not to reproduce past statistics exactly, but to determine that the realization that occurred could have come from the developed model within a reasonable margin of accuracy (which depends on the purpose of the model). Monthly means and standard deviations for the actual data and for 10 model simulations of 40 years each are presented in table 3 (Gothenburg), table 4 (Kearney), and table 5 (Grand Island). A graphical display of the means for Kearney is shown in figure 11. Data in the tables indicate that values for January and February seem too large in the simulations for Kearney and Grand Island, and the September simulations may be slightly distorted. The distribution of values for all of the months combined is another check of the adequacy of the model. Although these values do not represent a random sample from a single distribution, the simulated sequences should closely resemble the past data. Some quantile values of actual versus simulated data are shown in table 6.

CALCULATION OF DROUGHT PROBABILITIES

The discussion in this section shows how the precipitation model can be used: (1) For direct evaluation of the probability of a precipitation shortage of given severity in any particular month; and (2) for determination of the probabilities of multi-station and multi-month events. The probabilities from (1) and (2) are used to determine the likelihood of droughts of given severity and durations over the next 50 years.

Let $Y_n = f\left(\left\{X^{(j)}_{t(n,k)}, j=1,2,3, k=1,2,...,12\right\}\right)$

Where f is any real-valued function of the monthly precipitation values of year n. Under the precipitation model, Y_n and Y_m are independent and identically distributed random variables for all $m \neq n$. This allows easy calculation of probabilities involving the series Y_N, Y_{N+1}, ..., Y_{N+M} (where $N-1$ is the current year) from the cdf (cumulative distribution function) of Y_n, $F_Y(x)=P[Y_m \leq x]$, because $(Y_N, Y_{N+1}, ..., Y_{N+M})$ is a random sample of size $M+1$ from a population with cdf $F_Y(x)$. The calculation of $F_Y(x)$ for two cases proceeds as follows:

1. To evaluate the probability of the rainfall at a particular station in a month k of year n falling below level ℓ, first let $Y_n = X_{t(n,k)}$ (the station index is dropped for convenience). Because the Box-Cox transformation, $Z_{t(n,k)}$, is monotone increasing in $X_{t(n,k)}$, probability statements about $X_{t(n,k)}$ can be directly related to probability statements about $Z_{t(n,k)}$:

$$F_Y(\ell) = P\left[X_{t(n,k)} \leq \ell\right]$$

$$F_Y(\ell) = P\left[Z_{t(n,k)} \leq \{(\ell + .01)^{1/3} - 1\} * 3\right].$$

Letting $\ell' = \{(\ell + .01)^{1/3} - 1\} * 3$, this probability becomes:

$$P\left[Z_{t(n,k)} \leq \ell'\right] = P\left[\left(Z_{t(n,k)} - \mu_{t(n,k)}\right)/\sigma \leq \left(\ell' - \mu_{t(n,k)}\right)/\sigma\right]$$

$$P\left[Z_{t(n,k)} \leq \ell'\right] = P\left[\epsilon_{t(n,k)}/\sigma \leq \left(\ell' - \mu_{t(n,k)}\right)/\sigma\right] \quad (5)$$

where $\mu_{t(n,k)}$ is the deterministic component for season k and σ is the residual standard deviation for the particular station of interest (see the previous section). This probability is easily evaluated from standard normal tables, since $\epsilon_{t(n,k)}/\sigma$ is normally distributed with mean 0 and unit variance. For example, to compute the probability that the rainfall at Grand Island in June of any

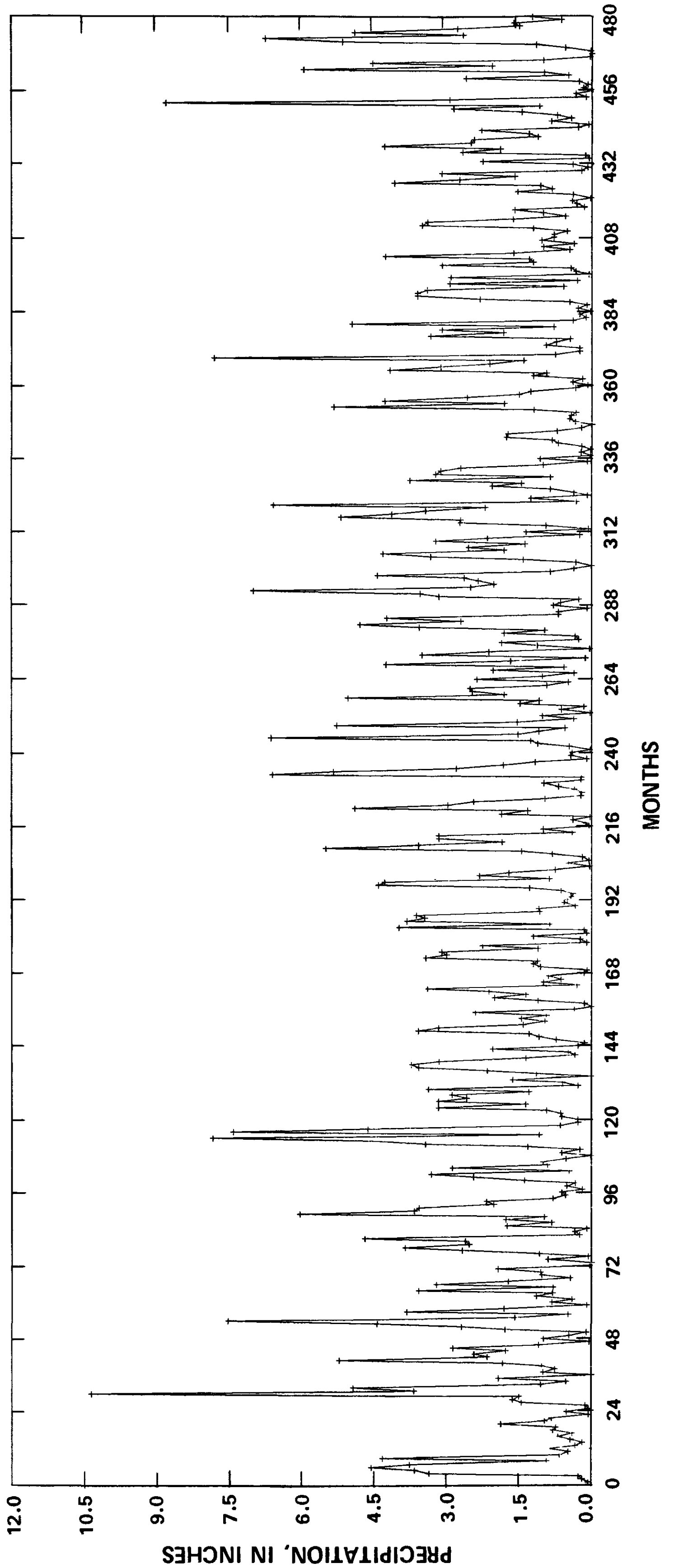


FIGURE 8.—Monthly precipitation simulation of 40 years for Gothenburg.

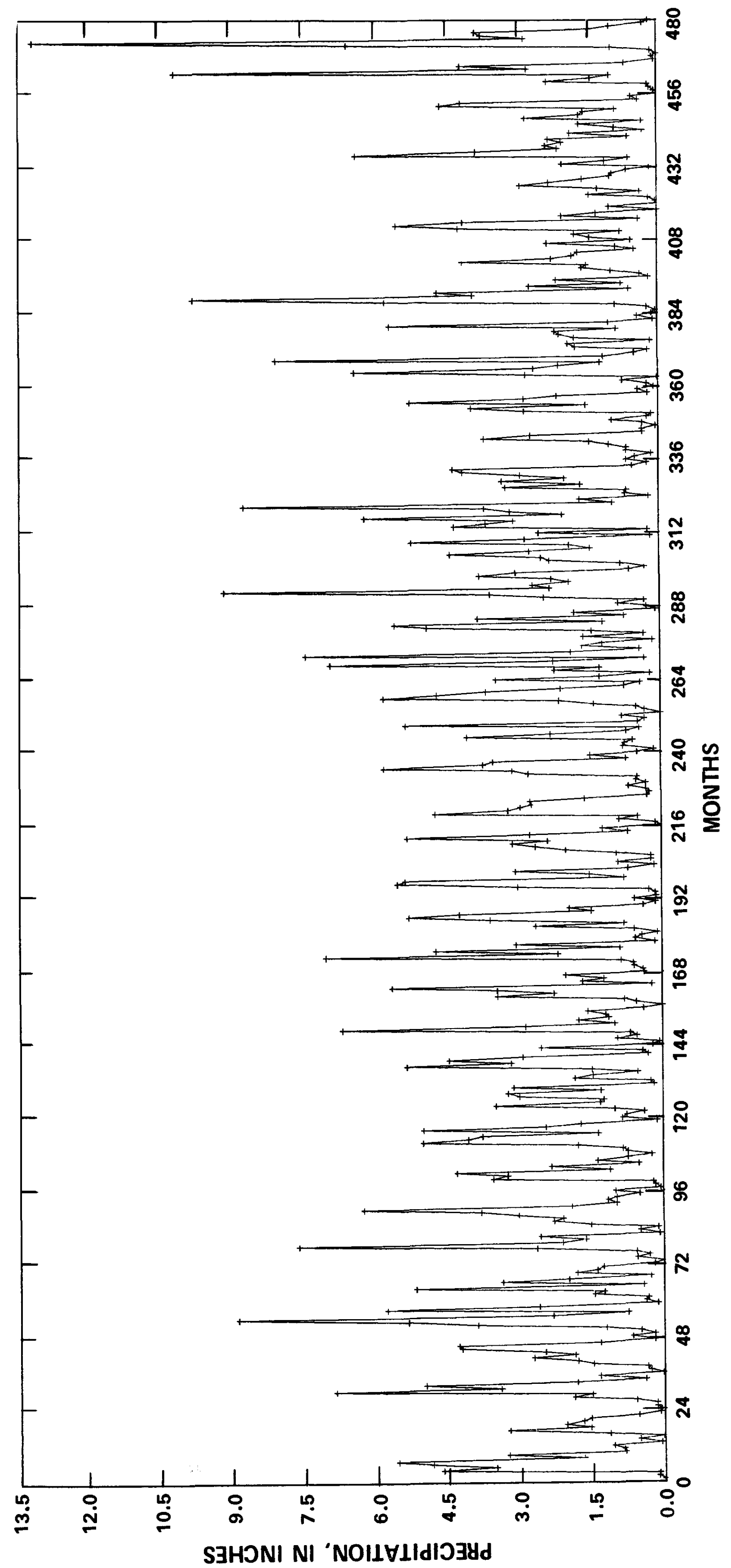


FIGURE 9.—Monthly precipitation simulation of 40 years for Kearney.

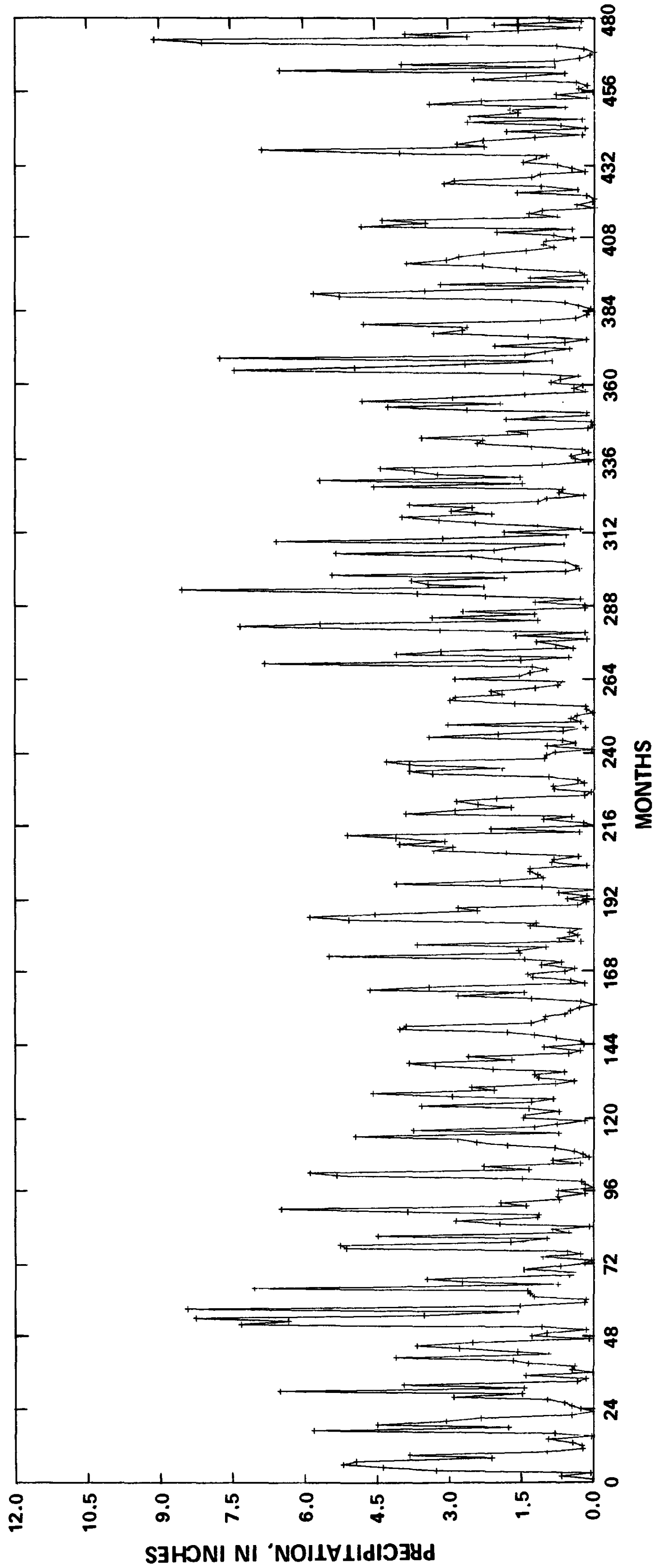


FIGURE 10.—Monthly precipitation simulation of 40 years for Grand Island.

TABLE 3.—*Monthly means and standard deviations for actual precipitation data and 10 model simulations of 40 years each for Gothenburg statistics*

[Mean values (upper number) standard deviations (lower number) in inches]

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
Actual Data												
	0.440	0.500	1.220	2.156	3.431	4.118	2.587	2.493	1.892	1.045	0.597	0.473
	.381	.440	.881	1.516	2.120	2.279	1.610	1.285	1.453	1.163	.588	.344
Simulations												
1	.502	.553	.968	1.842	3.266	4.146	2.825	1.736	2.169	.918	.447	.423
	.569	.585	.632	1.281	2.070	2.271	1.855	1.160	1.696	.978	.404	.423
2	.475	.506	1.434	2.027	3.198	3.802	2.594	2.182	2.407	1.096	.511	.521
	.361	.659	1.264	1.075	1.633	1.806	1.435	1.496	1.383	1.372	.566	.543
3	.545	.735	1.265	2.557	2.950	3.447	2.694	2.702	2.101	1.146	.517	.432
	.523	.671	1.112	1.503	1.531	1.927	1.414	1.656	1.649	.977	.516	.380
4	.404	.632	1.556	2.300	3.617	3.700	2.606	2.209	2.037	.942	.463	.408
	.548	.520	.940	1.646	2.143	1.981	1.862	1.632	1.596	.773	.436	.374
5	.457	.719	1.306	2.158	3.440	3.774	2.728	2.506	1.883	1.045	.631	.588
	.414	.785	1.127	1.721	2.318	2.015	1.613	2.238	1.744	.727	.619	.622
6	.574	.569	1.133	1.940	3.191	4.446	2.317	2.231	2.260	1.045	.596	.496
	.536	.614	1.112	1.323	1.851	2.384	1.455	1.326	1.495	.936	.679	.478
7	.510	.580	1.292	1.992	2.744	4.097	2.508	2.711	2.524	1.101	.581	.410
	.453	.639	.822	1.065	1.703	1.888	1.686	1.832	1.733	.860	.595	.617
8	.405	.579	1.485	2.405	3.256	3.782	3.134	2.249	1.840	.985	.528	.333
	.602	.572	1.132	1.381	1.767	2.406	2.108	1.518	1.186	.880	.581	.399
9	.450	.491	1.320	2.098	3.290	3.661	2.230	2.110	2.249	.977	.697	.721
	.370	.556	.952	1.441	2.159	2.329	1.182	1.568	1.533	.857	.806	.894
10	.499	.626	1.455	1.940	3.575	4.474	3.439	2.591	2.053	.817	.649	.698
	.597	.562	1.312	1.264	1.929	2.691	2.247	1.673	1.108	.788	.707	.832

TABLE 4.—*Monthly means and standard deviations for actual precipitation data and 10 model simulations of 40 years each for Kearney statistics*

[Mean values (upper number) standard deviations (lower number) in inches]

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
Actual Data												
	0.511	0.688	1.357	2.420	3.915	4.141	2.962	2.410	2.451	1.348	0.730	0.576
	.401	.539	1.138	1.670	2.227	2.781	1.911	1.479	1.986	1.262	.849	.473
Simulations												
1	.702	.747	1.081	1.950	.70	3.876	2.868	2.072	2.444	1.122	.591	.372
	.804	.653	.891	1.102	1.863	2.177	1.921	1.482	1.554	.966	.634	.477
2	.730	.635	1.316	2.706	3.878	3.296	3.063	2.829	2.474	1.579	.640	.501
	.570	.780	1.148	1.317	1.776	1.887	1.747	1.663	1.678	1.606	.539	.447
3	.737	.977	1.142	2.960	3.727	3.646	2.915	2.912	2.150	1.506	.713	.457
	.888	1.099	1.142	1.787	2.033	2.122	1.675	1.867	1.432	1.026	.813	.483
4	.537	.663	1.288	2.545	4.208	3.667	3.172	2.387	1.972	1.147	.705	.616
	.827	.589	.799	1.477	2.224	2.157	2.627	1.627	1.402	1.015	.652	.654
5	.629	.927	1.261	2.406	3.936	3.716	2.663	2.710	2.170	1.408	.817	.541
	.663	.992	1.316	1.552	2.163	1.939	1.598	2.237	1.925	1.066	.680	.509
6	.757	.689	1.002	2.422	3.353	4.222	2.951	2.639	2.673	1.283	.904	.530
	.609	.786	1.169	1.530	1.688	2.314	2.100	1.895	2.031	1.453	.739	.509
7	.832	.653	1.176	2.735	3.424	3.835	2.853	2.969	2.636	1.317	.703	.452
	.694	.608	.859	1.605	1.954	1.888	2.056	1.917	1.696	.913	.666	.514
8	.557	.881	1.264	3.065	3.909	3.593	3.274	2.316	1.915	1.038	.644	.396
	.601	.862	.780	1.929	1.801	2.203	2.313	1.417	1.218	1.060	.594	.409
9	.941	.617	1.169	2.483	4.170	4.329	2.569	2.339	2.057	1.233	.659	.728
	1.066	.606	.929	1.531	2.801	2.528	1.494	1.814	1.349	1.171	.655	.948
10	.600	.771	1.379	2.382	4.159	4.568	3.862	2.761	2.330	1.039	.789	.694
	.547	.786	1.179	1.572	1.944	2.870	1.940	1.528	1.580	.840	.794	.733
Combined simnlations												
	.702	.756	1.208	2.567	3.846	3.875	3.021	2.593	2.282	1.267	.717	.529
	.734	.615	1.025	1.537	2.024	2.202	1.952	1.741	1.586	.122	.674	.585
1–10	.109	.092	.153	.229	.302	.328	.291	.260	.236	.182	.100	.087

TABLE 5.—*Monthly means and standard deviations for actual precipitation data and 10 model simulations of 40 years each for Grand Island statistics*

[Mean values (upper number) standard deviations (lower number) in inches]

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
Actual Data												
	0.525	0.786	1.238	2.421	3.864	3.871	2.710	2.447	2.443	1.031	0.787	0.603
	.390	.641	1.067	1.493	2.080	2.331	2.040	1.621	2.153	.951	.837	.550
Simulations												
1	.789	.872	1.241	1.966	3.668	3.559	2.616	1.896	2.249	1.042	.483	.386
	.882	.929	1.051	1.350	2.021	2.217	1.582	1.217	1.541	.904	.506	.457
2	.680	.610	1.435	2.586	3.716	3.148	3.199	2.588	2.432	1.200	.748	.436
	.436	.766	1.239	1.739	2.131	1.761	1.626	1.743	1.491	.937	.687	.350
3	.847	1.086	1.108	2.632	3.323	3.281	3.041	2.770	2.088	1.508	.708	.433
	.712	1.491	.966	1.642	1.943	1.766	1.694	2.023	1.457	1.189	.747	.385
4	.715	.809	1.437	2.287	4.023	3.167	2.682	2.368	1.836	1.130	.704	.650
	1.002	.680	.664	1.364	2.719	1.707	2.128	1.396	1.252	.960	.717	.719
5	.673	1.004	1.276	2.513	3.885	3.124	2.807	2.481	2.034	1.405	.795	.539
	.668	1.108	1.100	1.325	2.292	1.721	1.608	1.880	1.513	1.494	.586	.449
6	.835	.691	1.028	2.349	3.632	3.724	2.555	2.370	2.489	1.132	.888	.607
	.582	.626	1.189	1.529	1.790	2.581	1.797	1.767	1.769	1.009	.723	.565
7	.892	.726	1.298	2.680	3.549	3.721	2.790	2.773	2.319	1.281	.582	.589
	.873	.636	.977	1.413	1.853	1.978	2.221	2.032	1.501	.875	.561	.872
8	.585	.774	1.289	2.724	3.697	3.232	3.084	2.176	1.845	1.188	.711	.421
	.503	.782	.873	1.684	1.481	1.681	1.945	1.171	1.202	1.509	.800	.565
9	.899	.729	1.301	2.716	4.161	4.033	2.383	2.351	2.198	1.118	.817	.742
	.788	.642	1.212	1.944	2.698	2.304	1.186	1.655	1.759	1.023	.819	.070
10	.609	.738	1.191	2.111	3.849	4.065	3.409	2.876	1.964	.933	.816	.719
	.597	.633	.810	1.392	1.992	2.479	2.005	1.765	1.162	.852	.819	.855

year will be less than 1 inch, set $k=6$ and $\ell=1$. Then refer to the model for Grand Island (eq. 3 of the previous section) to obtain:

$$\mu^{(3)}_{t(n,6)}=0.3187-1.1174*\cos\pi+0.1988*\sin 3\pi$$

$$-0.1216*\sin 2\pi-0.1097*\sin\pi=1.4361.$$

With the above result and $\sigma\approx\hat{\sigma}=0.895$ and $\ell'=0.00997$ then:

$$P\left[X^{(3)}_{t(n,6)}\leq 1\right]=P\left[\epsilon^{(3)}_{t(n,6)}/0.895\leq -1.5934\right]$$

$=P\left[\text{Standard normal random variable} \leq -1.5934\right]$ $=0.056$ (see equation 5).

2. For the case when Y_n is a function of several months and (or) stations, such as $Y=$ total precipitation for May through August at Grand Island, direct evaluation of $F_Y(x)$ becomes difficult. However, $F_Y(x)$ can be determined from model simulations. Using the simulation method outlines in the previous section, generate a random sample of Y_n of size L, $(y_1, ..., y_L)$ where L is a large number as determined below. If a certain number, say M, of the values $y_1, y_2, ..., y_L$ are less than or equal to x, and if L is large, than a good estimate of $P[y_m\leq x]$ would be $F_L(x)\equiv M/L$, the proportion of the L values which did not exceed x. To be more precise, define the sample cdf of Y_n, $F_L(x)$, as:

$$F_L(x)=\frac{1}{L}\left(\sum_{i=1}^{L} I^{(y_i)}_{(-\infty,x]}\right) \text{ where}$$

$$I^{(y_i)}_{(-\infty,x]}=\begin{Bmatrix} 1, \text{ if } y_i\leq x \\ 0, \text{ otherwise}\end{Bmatrix}.$$

By the Glivenko-Cantelli theorem (Gibbons, 1971) $F_L(x)$ converges uniformily with probability one to $F_Y(x)$. Therefore, $F_L(x)$ can be used as a approximation to $F_Y(x)$, if L is large enough to achieve accurate estimates for small values of x. As a general rule in this report, the sample cdf will be assumed to adequately estimate the true cdf for all x for which:

$$E\left[\sum_{i=1}^{L} I^{(y_i)}_{(-\infty,x]}\right]\geq 10.$$

This rule can be used to pick L by noting that:

$$E\left[\sum_{i=1}^{L} I^{(y_i)}_{(-\infty,x]}\right]=LF_Y(x).$$

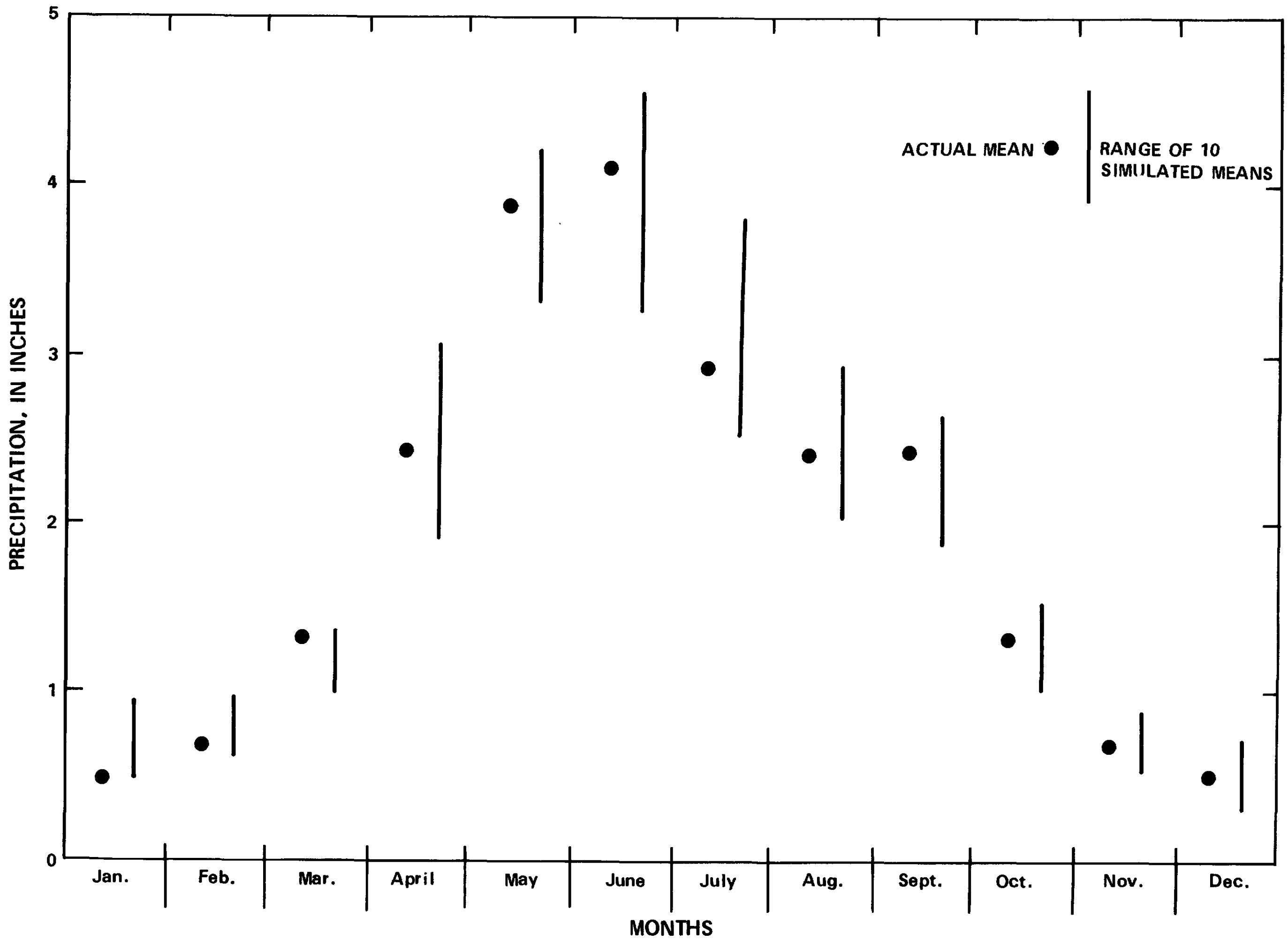


FIGURE 11.—Actual monthly means versus means from 10 simulations for Kearney.

TABLE 6.—*Quantiles (all months combined) of actual data versus simulation*

Rainfall (percent less than tabular values)	Gothenburg		Kearney		Grand Island	
	Actual (inches)	Simulated (inches)	Actual (inches)	Simulated (inches)	Actual (inches)	Simulated (inches)
10	0.16	0.12	0.21	0.15	0.19	0.17
20	.31	.32	.45	.33	.45	.32
30	.58	.50	.70	.56	.68	.60
40	.83	.82	.99	.87	.95	.93
50	1.22	1.07	1.42	1.33	1.30	1.24
60	1.66	1.45	1.79	1.78	1.68	1.58
70	2.19	2.12	2.40	2.32	2.36	2.31
80	2.97	2.97	3.40	3.19	3.26	3.17
90	4.26	3.82	4.71	4.44	4.51	4.31

For example, if a value x_m for which the precipitation exceeds with probability, 0.99 is the smallest x value of interest, then $F_Y(x_m)=0.01$, and L would be 1,000, for one to expect, on the average, that:

$$\sum_{i=1}^{L} I_{(-\infty,x_m]}^{(y_i)}=10.$$

For the drought analyses in this report, 2,000 years of joint monthly precipitation from March through August were simulated for the Gothenburg, Kearney, and Grand Island stations. In addition, the monthly simulations were averaged over the stations to obtain an average precipitation series:

$\overline{X}_{t(n,k)}=\left(X^{(1)}_{t(n,k)}+X^{(2)}_{t(n,k)}+X^{(3)}_{t(n,k)}\right)/3$. The following random variables were computed for each of the 2,000 years of simulated precipitation:

$$U_n^{(j)}=X_{t(n,3)}^{(j)}+X_{t(n,4)}^{(j)}, j=1,2,3\ ;$$

$$V_n^{(j)}=X_{t(n,5)}^{(j)}+X_{t(n,6)}^{(j)}+X_{t(n,7)}^{(j)}+X_{t(n,8)}^{(j)}, j=1,2,3\ ;$$

$$\overline{U}_n=\overline{X}_{t(n,3)}+\overline{X}_{t(n,4)};$$

$$\overline{V}_n=\overline{X}_{t(n,5)}+\overline{X}_{t(n,6)}+\overline{X}_{t(n,7)}+\overline{X}_{t(n,8)}.$$

U corresponds to precipitation totals for March and April (snowmelt season); V corresponds to totals for May through August (seed-germination period). The sample cdf's were computed for each of the above random variables at various values of x (the drought severity levels); they are given in table 7. The values of x were determined as follows: The precipitation record (1934–78) was used to estimate the mean rainfall, μ, for each season-station combination in table 7, and severity levels were defined as μ, $\frac{5}{6}\mu$, $\frac{4}{6}\mu$, $\frac{3}{6}\mu$, and $\frac{2}{6}\mu$. The rationale for using data rather than the model to estimate μ is that it is assumed because of the stationarity of the precipitation present environment in the critical reach was maintained during the period of record. Therefore, changes in precipitation, because of their effect on the river in environment, should be evaluated with reference to historical patterns. A value in table 7 under the column heading "cdf" is an estimate of the probability that the precipitation will fall below the corresponding severity level in any given year (for the corresponding season-station combination). Because L was chosen to be 2,000, cdf values below 0.005 are not very reliable estimates.

The probability of a drought of duration m years or longer during the 50-year planning period can be estimated by using table 7. Suppose a drought is said to occur whenever Y_n is less than a certain amount x, and that the duration of the drought is the number of years in a row that Y_n is less than x. The problem above would reduce to finding distribution of the longest number of successes in a row a sequence of Bernoulli trials, with success probability equal to probability $[Y_n \le x]$. David and Barton (1962) show that if a sample of size r is drawn (with replacement) from an urn consisting of black balls and white balls, then, given that r_1 white and $r_2 = r - r_1$ black balls were selected, the distribution of the longest run K of white balls is:

$$\text{Prob}[K \ge m+1] \equiv P_K(m,r,r_1)=1-\sum_{t=0}^{\infty}\frac{(-1)^t}{t!}(r_2+1)^{(t)}\frac{r_1^{(tm+t)}}{r^{(tm+t)}};$$

where $z^{(t)}=t^{th}$ factorial power of $z=z(z-1)...(z-t+1)$. Let M be the largest number of successes in a row in a sequence of 50 Bernoulli trials with success probability p; then:

$$\text{P}[M \ge m+1]=\sum_{n=0}^{50} P[M \ge m+1|N=n]\cdot P[N=n];$$

where N is the total number of successes in the 50 trials (hence N has a bionomial distribution). Therefore:

$$\text{P}[M \ge m+1]=\sum_{n=0}^{50} P_K(m,50,n)\cdot P[N=n]$$

$$=\sum_{n=0}^{50} P_K(m,50,n)\cdot \binom{50}{n} p^n(1-p)^{50-n}.$$

where $P_k(m,50,n)$ can be evaluated as accurately as desired. Note that the summation in $P_K(m,r,r_1)$ is not really an infinite sum for fixed m, r, and r_1, because the terms become zero, whenever $t > r_2+1$ or $tm+t > r_1$. In this context, the probability of one or more droughts of $m+1$ years or longer during the next 50 years would be:

TABLE 7.—*Drought severity levels and corresponding estimates of cumulative distribution function*

[μ, historical mean of season; cdf, cumulative distribution function]

		Gothenburg		Kearney		Grand Island		Three-station average	
Season	Fraction of mean	Severity level (inches)	cfd	Severity level (inches)	cdf	Severity level (inches)	cdf	Severity level (inches)	cdf
	μ	3.376	0.544	3.777	0.560	3.659	0.541	3.604	0.538
March	5/6 μ	2.813	.416	3.147	.426	3.049	.414	3.003	.392
and	4/6 μ	2.251	.258	2.518	.277	2.439	.267	2.403	.233
April	3/6 μ	1.688	.141	1.888	.145	1.829	.140	1.802	.106
	2/6 μ	1.125	.045	1.259	.053	1.220	.051	1.201	.028
	μ	12.629	.580	13.428	.531	12.892	.556	12.783	.562
May	5/6 μ	10.524	.353	11.190	.312	10.743	.327	10.819	.294
through	4/6 μ	8.419	.139	8.952	.122	8.595	.145	8.655	.105
Aug.	3/6 μ	6.314	.027	6.714	.025	6.446	.026	6.491	.015
	2/6 μ	4.210	.001	4.476	.003	4.297	.002	4.328	.001

$$P[M \geq m+1]$$

where

$p=\text{Prob}[Y_n \leq x]$

and a drought occurs whenever $Y_n \leq x$. The probabilities of some droughts involving $U_n^{(j)}$, $V_n^{(j)}$, $\overline{U}_n$, and $\overline{V}_n$ are presented in tables 8 through 11.

STREAMFLOW MODEL

The streamflow time series consists of monthly average discharges (in cubic feet per second) from September 1942 through August 1979 (September 1942 and water years 1943 to 1979) at the Overton, Odessa, and Grand Island gaging stations (see fig. 1). These series can be obtained from Petsch and others (1980). The streamflow model is a model of 3-season flow series obtained for each station by aggregating the monthly series as follows: Season 1 flows consist of the sum of the monthly series from September through February; season 2 flows consist of the sum of the monthly series of March and April: and season 3 flows consist of the sum of the monthly series from May through August. The year of season 1 will be designated by the year in which it ends (that is, season 1 of 1943 consists of September 1942 through February 1943). Graphs of these 111 seasonal flow totals in the 37-year period from water years 1943 to 1979 for each station are presented in figures 12 through 14. Seasonal statistics for Overton, Odessa, and Grand Island are summarized in table 12. The means and standard deviations appear to be significantly different across seasons (parameters will be included in the models which can account for these differences). Also, the positive skewness and kurtosis coefficients indicate that flows for individual seasons are not normally distributed. This distribution problem is solved by a Box-Cox transformation (see precipitation model) of the original flows to achieve a model in which residuals are nearly normal.

SINGLE-STATION MODELS

Autocorrelations of the flow series will be important in determining the appropriate model to fit to the data. In ordinary autoregressive-moving average (ARMA) time-series modeling, the autocorrelation structure of the series is assumed to be the same for each season, an assumption which does not appear to be true in this case (fig. 15). An explanation of the term seasonal autocorrelations follows. Let $X_{t(n,k)}$, $n=0,1,2,...N-1$, $k=1,2,..., s$, be a seasonal time series, where $t(n,k) = ns+k$; n is the year index (there are s seasons per year); and k is the season index. The lag defined for members of the series $X_{t(n,k)}$ is a seasonal lag and not a yearly lag. For example, $X_{t(n,k)-2}$, where $k=3$, is season number one of year n, and $X_{t(n,k)-4}$, where $k=3$, is season number 2 of year $(n-1)$. The autocorrelation for season k at lag j is defined to be $\rho_{k,j}=$ Corr $\left(X_{t(n,k)}, X_{t(n,k)-j}\right)$ and is assumed throughout to be independent of n. The values graphed in figure 15 are estimates $\hat{\rho}_{k,j}$, $k=1,2,3$, $j=1,2,...$ 6 obtained by using the formula

$$\hat{\rho}_{k,j}=\frac{1}{N}\sum_{n=0}^{N-1}\left(Y_{t(n,k)}\ Y_{t(n,k)-j}\right)$$

where $Y_{t(n,k)}=X_{t(n,k)}-\dfrac{\sum_{n=0}^{N-1}X_{t(n,k)}}{N}$

and $Y_{t(n,k)'-j}=0$ for $t(n,k)-j\leq 0$. The class of periodic autoregression models are useful in modeling time series that have heterogeneous correlation structure among seasons. The models used to describe the single-station series fall under this class, for which a substantial base of theory has been developed (Pagano, 1978; Parzen and Pagano, 1979; Troutman, 1979). Only the statement of the models will be given here. For a complete exposition of the model fitting and parameter estimation, see Vecchia (1981b).

Results for the three stations are summarized in table 13. The notation has been changed slightly by dropping the cumulative time index, t; $X_{n,k}$ denotes the streamflow in season k of year n. The R^2 value for season k is interpreted as the percentage of the variation of the observed data for season k from 1945 to 1979 (allowing for lag considerations), which is accounted for by the nonrandom component of the model. Note that the last season has a low R^2 value. This does not indicate model inadequacy, but rather shows that season 3 variation is nearly random with respect to previous values in the series. However, season 3 is important in predicting season 1 of the following year; hence, it should be included in the model.

It is assumed for each station that $\{\epsilon_n\}$ are iid normal random variables, with $E(\epsilon_n)=0$, and Cov $(\epsilon_n)=D$ (a diagonal matrix), or that the errors are independent from season to season. Residuals from the models from 1945 to 1979 were examined to check these assumptions. Some statistics of the residuals are in table 14, which reveals no obvious deviations from normality, or from the assumption that $E(\epsilon_n)=0$. A graph of the residual series for Odessa from 1945 to 1979 is shown in figure 16; it is observed that no obvious trends are taking place. To check the assumption of no correlation between seasons, lag autocorrelation matrices for the residuals were examined. The lag k autocorrelation matrix of the

TABLE 8.—*Probabilities of some droughts of duration m years or longer for Gothenburg*

[μ, historical mean of drought period, in inches]

Season	Severity level[1]	1	2	3	4	*m* years 5	6	7	8	9
	μ= 3.376	1.000	1.000	0.994	0.908	0.688	0.446	0.262	0.147	0.080
March	5/6 μ= 2.813	1.000	.999	.911	.596	.298	.131	.055	.023	.009
and	4/6 μ= 2.251	1.000	.939	.475	.146	.039	.010	.002	.001	.000
April	3/6 μ= 1.688	.999	.584	.110	.016	.002	.000	.000	.000	.000
	2/6 μ= 1.125	.900	.091	.004	.000	.000	.000	.000	.000	.000
	μ=12.629	1.000	1.000	.998	.951	.788	.562	.363	.221	.130
May	5/6 μ=10.524	1.000	.994	.785	.393	.155	.056	.020	.007	.000
through	4/6 μ= 8.419	.999	.574	.106	.015	.002	.000	.000	.000	.000
Aug.	3/6 μ= 6.314	.745	.034	.001	.000	.000	.000	.000	.000	.000
	2/6 μ= 4.210	.049	.000	.000	.000	.000	.000	.000	.000	.000

[1]The severity level is the value (in inches) that defines the occurrence of a drought.

TABLE 9.—*Probabilities of some droughts of duration m years or longer for Kearney*

[μ, historical mean of drought period, in inches]

Season	Severity level[1]	1	2	3	4	*m* years 5	6	7	8	9
	μ= 3.777	1.000	1.000	0.996	0.929	0.735	0.497	0.305	0.177	0.100
March	5/6 μ= 3.147	1.000	.999	.925	.627	.325	.148	.064	.027	.008
and	4/6 μ= 2.518	1.000	.960	.544	.186	.053	.015	.004	.001	.000
April	3/6 μ= 1.888	.999	.604	.119	.018	.003	.000	.000	.000	.000
	2/6 μ= 1.259	.934	.123	.007	.000	.000	.000	.000	.000	.000
	μ=13.428	1.000	1.000	.992	.887	.649	.405	.231	.125	.066
May	5/6 μ=11.190	1.000	.982	.665	.273	.091	.029	.009	.003	.001
through	4/6 μ= 8.952	.998	.485	.074	.009	.001	.000	.000	.000	.000
Aug.	3/6 μ= 6.714	.718	.029	.001	.000	.000	.000	.000	.000	.000
	2/6 μ= 4.476	.139	.000	.000	.000	.000	.000	.000	.000	.000

[1]The severity level is the value (in inches) that defines the occurrence of a drought.

TABLE 10.—*Probabilities of some droughts of duration m years or longer for Grand Island*

[μ, historical mean of drought period, in inches]

Season	Severity level[1]	1	2	3	4	*m* years 5	6	7	8	9
	μ= 3.659	1.000	1.000	0.994	0.903	0.680	0.436	0.255	0.142	0.077
March	5/6 μ= 3.049	1.000	.999	.909	.589	.292	.128	.053	.022	.009
and	4/6 μ= 2.439	1.000	.950	.508	.164	.045	.012	.003	.001	.000
April	3/6 μ= 1.829	.999	.579	.108	.015	.002	.000	.000	.000	.000
	2/6 μ= 1.220	.927	.122	.006	.000	.000	.000	.000	.000	.000
	μ=12.892	1.000	1.000	.996	.924	.723	.484	.294	.169	.091
May	5/6 μ=10.743	1.000	.988	.712	.315	.112	.037	.012	.004	.000
through	4/6 μ= 8.595	.999	.604	.119	.018	.002	.000	.000	.000	.000
Aug.	3/6 μ= 6.446	.732	.032	.001	.000	.000	.000	.000	.000	.000
	2/6 μ= 4.297	.095	.000	.000	.000	.000	.000	.000	.000	.000

[1]The severity level is the value (in inches) that defines the occurrence of a drought.

TABLE 11.—*Probabilities of some droughts of duration m years or longer for the three-station average*

[μ, historical mean of drought period, in inches]

Season	Severity level[1]	1	2	3	4	*m* years 5	6	7	8	9
	μ= 3.604	1.000	1.000	0.993	0.899	0.671	0.427	0.247	0.137	0.074
March	5/6 μ= 3.003	1.000	.998	.872	.518	.237	.097	.038	.015	.002
and	4/6 μ= 2.403	1.000	.900	.384	.102	.024	.006	.001	.000	.000
April	3/6 μ= 1.802	.996	.397	.050	.005	.001	.000	.000	.000	.000
	2/6 μ= 1.201	.758	.039	.001	.000	.000	.000	.000	.000	.000
	μ=12.983	1.000	1.000	.997	.932	.740	.504	.310	.181	.103
May	5/6 μ=10.819	1.000	.973	.604	.226	.070	.021	.006	.002	.000
through	4/6 μ= 8.655	.996	.392	.049	.005	.001	.000	.000	.000	.000
Aug.	3/6 μ= 6.491	.530	.011	.000	.000	.000	.000	.000	.000	.000
	2/6 μ= 4.328	.049	.000	.000	.000	.000	.000	.000	.000	.000

[1]The severity level is the value (in inches) that defines the occurrence of a drought.

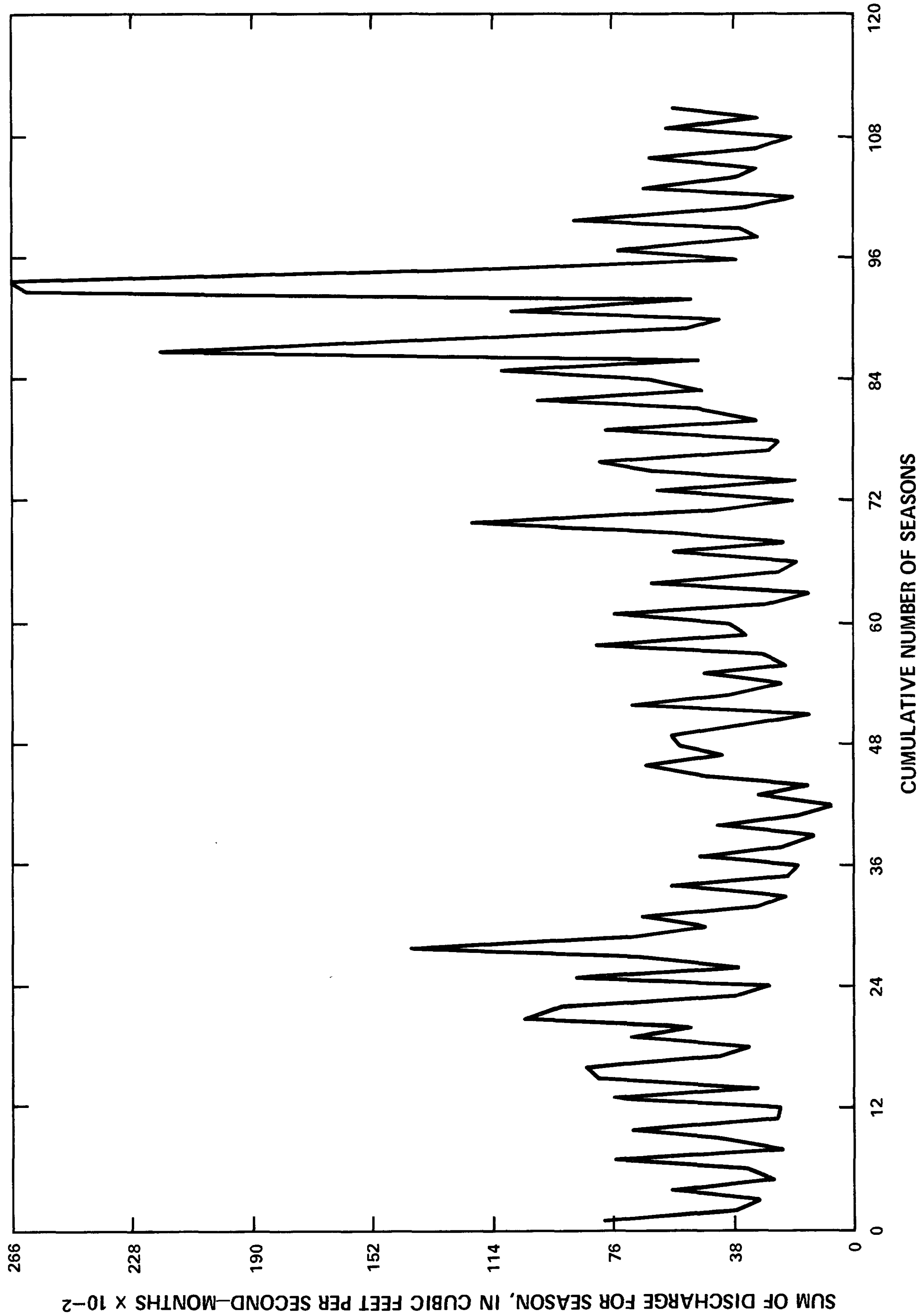


FIGURE 12.—Historical sequence of seasonal discharges at Overton, Nebraska gaging station, water years 1943–1979.

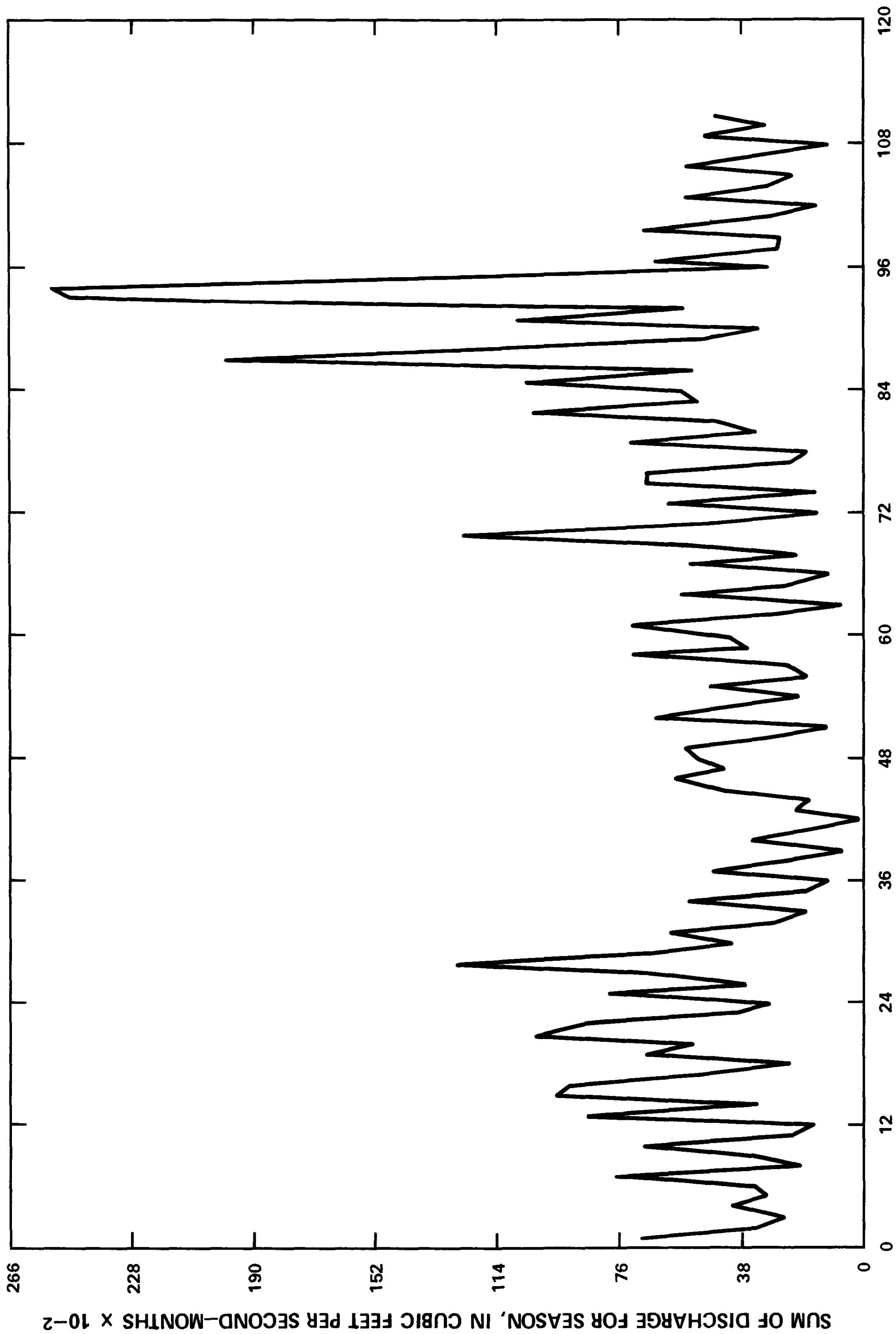


FIGURE 13.—Historical sequence of seasonal discharges at Odessa, Nebraska gaging station, water years 1943–1979.

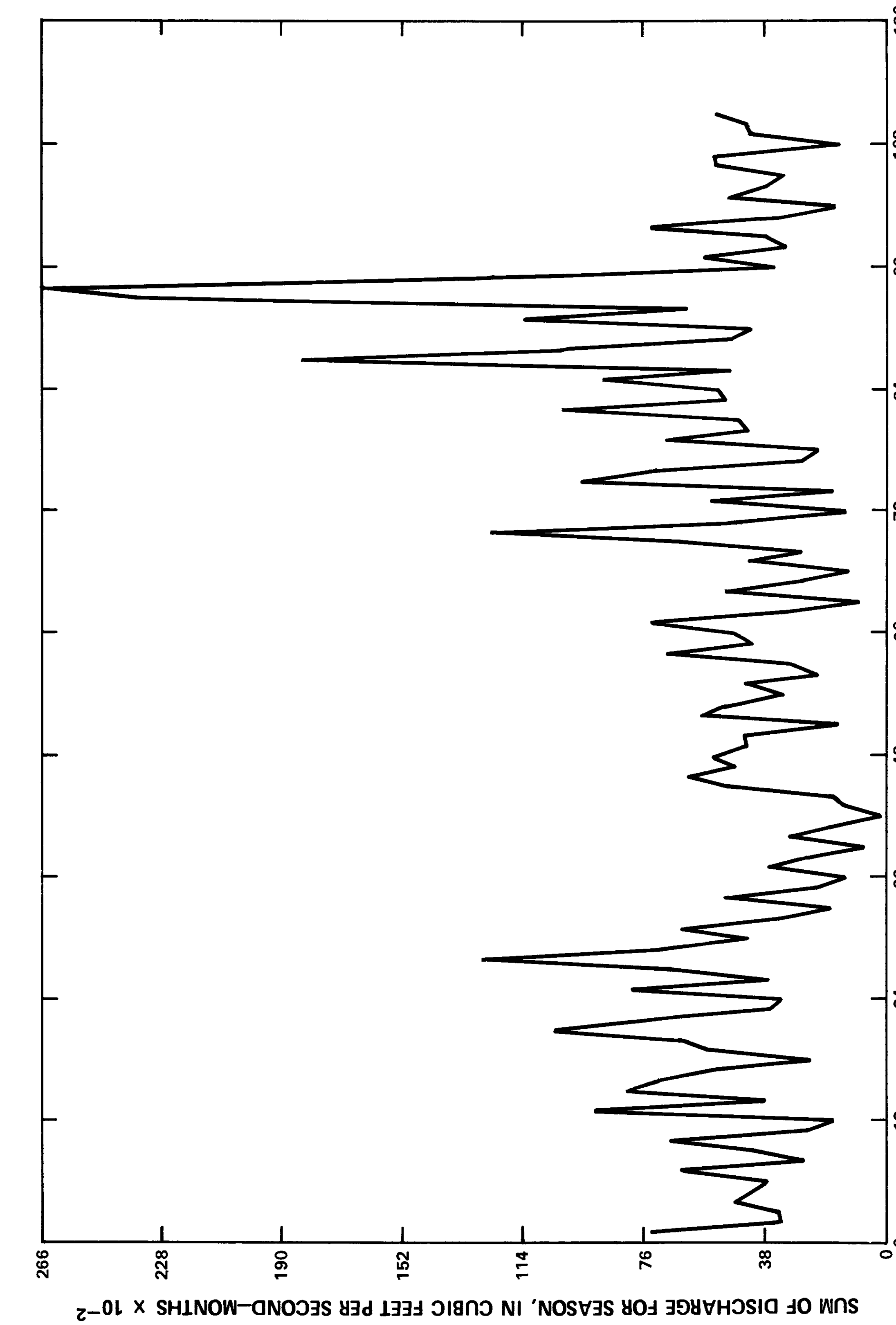


FIGURE 14.—Historical sequence of seasonal discharges at Grand Island, Nebraska gaging station, water years 1943–1979.

TABLE 12.—*Flow statistics for Overton, Odessa, and Grand Island, Nebraska, water years 1943 to 1979*

[ft³/s-months, cubic feet per second-months]

	Season	Average season total (ft³/s-months)	Standard deviation (ft³/s-months)	Skewness	Kurtosis
Overton	1	8093.2	3922.6	2.918	11.068
	2	3641.9	2044.5	3.043	11.927
	3	4809.7	5108.1	2.904	8.554
Odessa	1	7585.5	3864.5	2.676	9.757
	2	3662.9	2062.8	2.618	9.438
	3	4363.8	4960.7	2.669	7.368
Grand Island	1	7219.4	4184.1	2.860	10.962
	2	4068.6	1973.1	2.065	6.564
	3	4653.6	4643.8	2.448	6.456

residual vector ϵ_n is defined as Cov $(\epsilon_n, \epsilon_{n-k})$ (note that lags are now in years). Estimates of these matrices for k=0,1,2,3 appear in table 15. Each estimate is based on about 35 observations, and an approximate standard error of the estimate is $1/\sqrt{35}=0.17$. Therefore, any value below about 0.3 in absolute value can be considered insignificant. The only problem is the lag 1 correlation for season 2 (Corr $(\epsilon_{n,2}\ \epsilon_{n-1,2})$), which is about 0.4 for each station, but drops off to near zero for the remaining lags. This correlation can be preserved in the model by allowing $\epsilon_{n,2}$ to follow a moving-average process of order 1 (Box and Jenkins, 1975). In other words, $\epsilon_{n,2}=\Psi_{n,2}+\Theta\ \Psi_{n-1,2}$ with $\{\Psi_{n,2}, n=0,1,...\}$ a white-noise process. Moment estimates of Θ were determined to be $\hat{\Theta}=0.63$ for Overton, and $\hat{\Theta}=0.5$ for Odessa and Grand Island. A precise statement of the models with moving-average components included will be given in the next section.

As a final check, the models were used to simulate 10 realizations of 37 years each, the same length as the historical series, and the properties of the simulations were compared to the historical series. Some statistics of the simulations are in tables 16, 17, and 18. Care must be taken in interpreting the tables owing to high variability of the skewness and kurtosis coefficients for such short data sets. The standard deviations for most of the simulations are lower than the respective observed standard deviations. This could indicate two things: (1) The observed standard deviation is higher than the long term standard deviation; (2) the standard deviations of model simulations are biased, possibly owing to the inverse transformation of model output. For purposes of this report, these differences did not warrant further investigation. Season 2 and 3 are of primary interest;

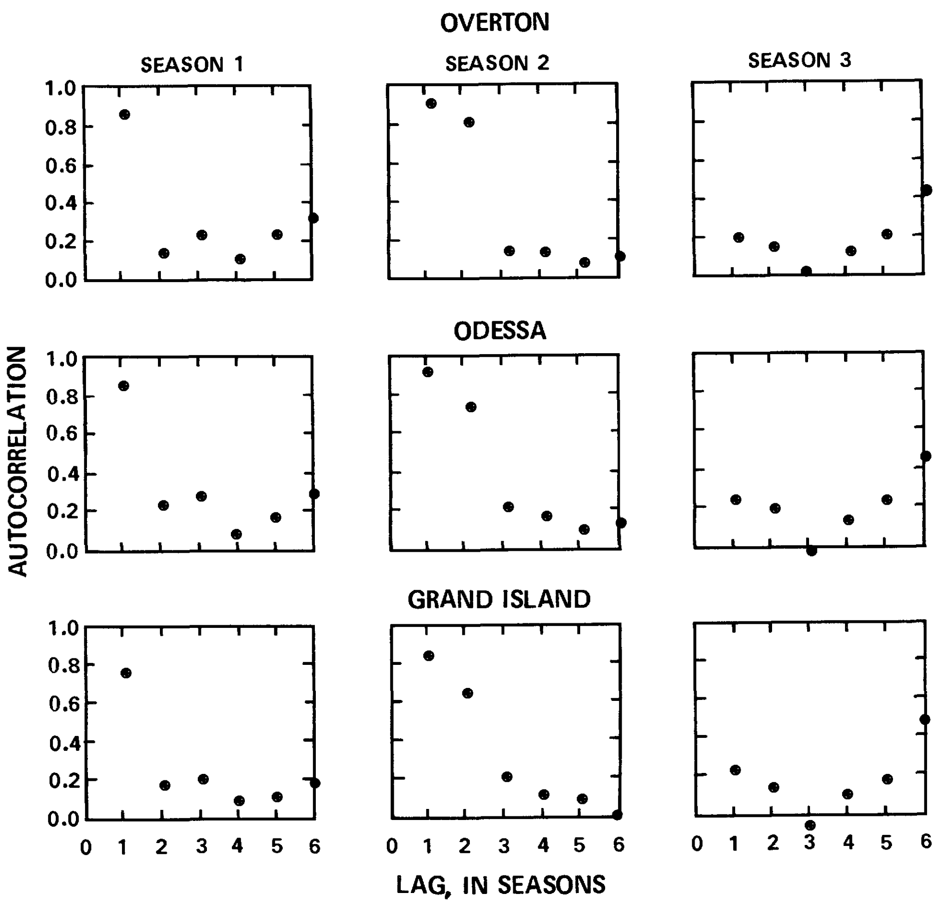


FIGURE 15.—Seasonal autocorrelations.

TABLE 13.—*Individual station streamflow models.*

[Z, transformed streamflow variable X, seasonal streamflow; ϵ_t, residual component: R^2, explained variation due to model]

Overton

$Z_{n,i}=[(X_{n,i}+0.01)^{-.1}-1]/(-0.1)-\mu_i$, $i=1,2,3$

Seasonal mean vector $\mu'=(\mu_1, \mu_2, \mu_3)=(5.9000, 5.548, 5.569)$

$Z_{n,1}=0.3632 * Z_{n-1,3}+0.1449 * Z_{n-1,1}+\epsilon_{n,1}$

$Z_{n,2}=1.0756 * Z_{n,1}+\epsilon_{n,2}$

$Z_{n,3}=0.4646 * Z_{n,2}+0.2631 * Z_{n-2,3}+\epsilon_{n,3}$

Season:	1	2	3	Overall R^2=33 percent
R^2:	67 percent	76 percent	12.4 percent	Cov(ϵ_n)=diag (0.00706, 0.00825, 0.08944)

Odessa

$Z_{n,i}=\log_e(X_{n,i}+0.01)-\mu_i$, $i=1, 2, 3$

$\mu'=(8.8427, 8.0965, 7.9568)$

$Z_{n,1}=0.3423 * Z_{n-1,3}+0.1461 * Z_{n-1,1}+\epsilon_{n,1}$

$Z_{n,2}=0.9168 * Z_{n,1}-0.0982 * Z_{n-1,1}+\epsilon_{n,2}$

$Z_{n,3}=0.7850 * Z_{n,2}+\epsilon_{n,3}$

Season:	1	2	3	Overall R^2=28 percent
R^2:	67 percent	66 percent	12 percent	Cov(ϵ_n)=diag (0.05082, 0.06616, 0.77623)

Grand Island

$Z_{n,i}=\log_e(X_{n,i}+0.01)-\mu_i$, $i=1,2,3$

$\mu'=(8.7668, 8.2185, 8.0729)$

$Z_{n,1}=0.4198 * Z_{n-1,3}-0.0469 * Z_{n-1,1}+0.1284 * Z_{n-2,3}+\epsilon_{n,1}$

$Z_{n,2}=0.6715 * Z_{n,1}-0.0949 * Z_{n-1,1}+\epsilon_{n,2}$

$Z_{n,3}=0.7757 * Z_{n,2}+\epsilon_{n,3}$

Season:	1	2	3	Overall R^2=26 percent
R^2:	68 percent	50 percent	8.2 percent	Cov(ϵ_n)=diag (0.07431, 0.08806, 0.74906)

TABLE 14.—*Statistics of residuals from individual-station models 1945 to 1979 (water years)*

Overton	Sept. to Feb.	March to April	May to Aug.
Mean	0.004	-0.002	0.000
Variance	.007	.008	.089
Skewness	.053	-.055	.253
Kurtosis	-.761	1.216	-.872
Maximum values	-.175	-.261	-.569
Minimum values	.174	.222	.625
Odessa	**Sept. to Feb.**	**March to April**	**May to Aug.**
Mean	0.003	0.000	0.004
Variance	.051	.067	.776
Skewness	.098	-.563	-.045
Kurtosis	-.499	.287	-.107
Maximum values	-.493	-.675	-2.206
Minimum values	.500	.528	1.732
Grand Island	**Sept. to Feb.**	**March to April**	**May to Aug.**
Mean	0.011	-0.002	-0.006
Variance	.074	.088	.749
Skewness	.218	-.110	-.110
Kurtosis	.362	.124	.124
Maximum values	-.658	-.632	-2.259
Minimum values	.610	.654	1.713

however, most of the season 2 skewness and kurtosis coefficients for the Odessa and Grand Island simulations are smaller than the observed values. This problem is not considered serious enough to cast doubt on the validity of the model.

COMBINED-STATION MODEL

Thus far, cross correlations between streamflow stations have not been considered. However, if simulations of more than one station are generated, these simula-

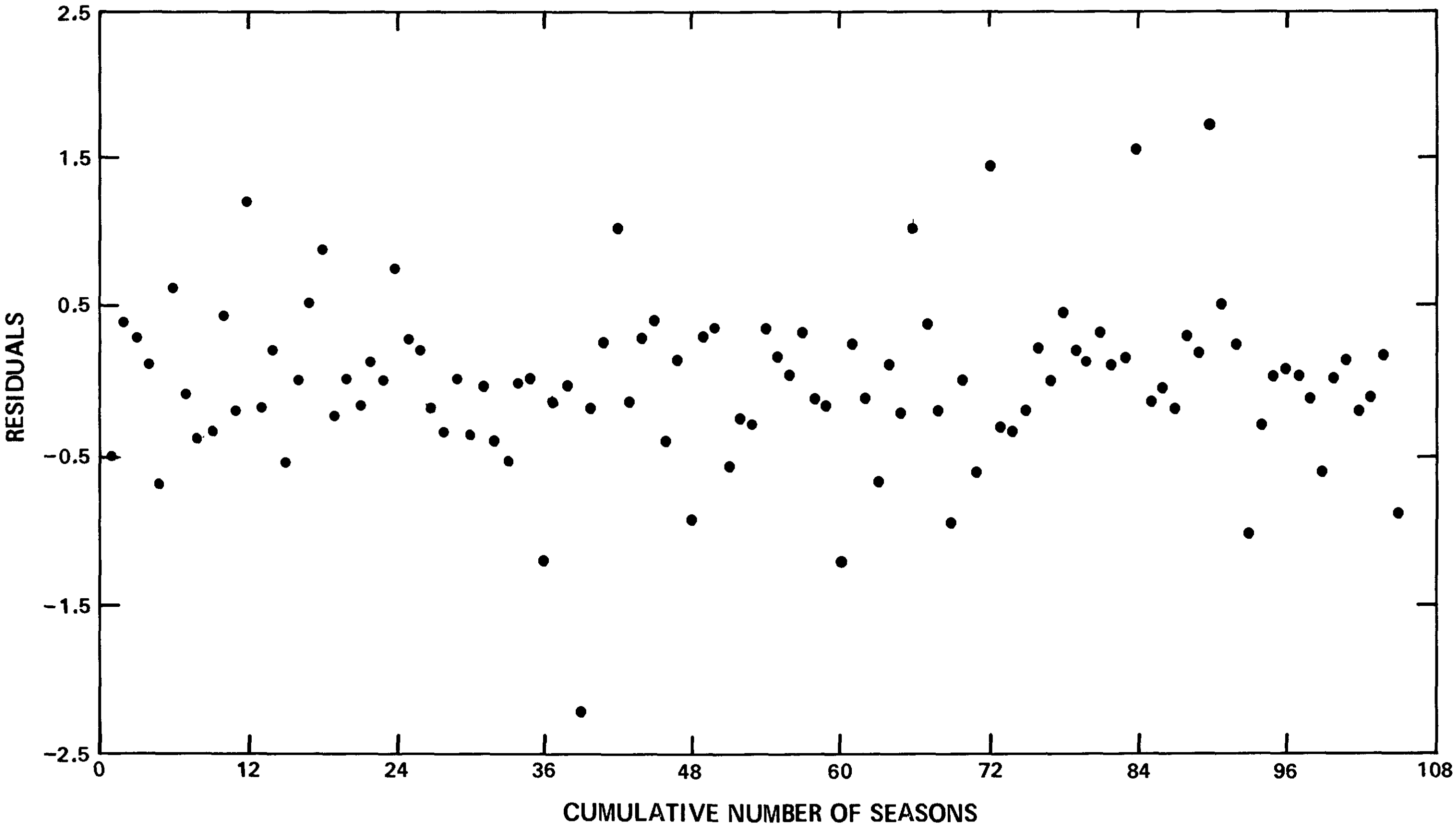


FIGURE 16.—Residuals (synthesized minus observed) for Odessa, Nebraska.

TABLE 15.—*Matrices of autocorrelation of residuals*

Lag (years)	Season	Overton Season 1	Overton Season 2	Overton Season 3	Odessa Season 1	Odessa Season 2	Odessa Season 3	Grand Island Season 1	Grand Island Season 2	Grand Island Season 3
0	1	1.0	-0.053	0.178	1.0	0.064	0.207	1.0	-0.105	0.113
	2	-.053	1.0	-.011	.064	1.0	-.018	-.105	1.0	.016
	3	.178	-.011	1.0	.207	-.018	1.0	.113	.016	1.0
1	1	-.266	-.194	.020	-.214	-.188	-.003	-.117	-.124	.029
	2	-.234	.446	-.150	-.246	.403	-.024	-.243	.396	-.048
	3	-.049	.083	-.070	.047	-.015	-.200	.077	-.046	-.182
2	1	.125	-.247	.032	.024	-.131	.191	-.057	-.074	.099
	2	-.088	.107	-.127	-.178	.110	.004	-.261	-.039	.152
	3	.067	-.058	.045	.119	.059	.231	.102	.160	.214
3	1	-.014	-.197	.006	.024	-.163	.056	.013	-.163	.115
	2	.178	.006	-.204	.120	-.108	-.215	.116	-.097	-.169
	3	.246	-.047	-.042	.200	-.051	-.086	.245	-.104	-.066

tions should maintain continuity between the stations. This will allow simulation of average flow series for two or three of the stations by simulating from the combined-station model and averaging the appropriate values. Station continuity is maintained in the model by allowing the residual vectors, ϵ_n, to be correlated from station to station. Let ξ_n be the residuals for Overton, γ_n the residuals for Odessa, and δ_n the residuals for Grand Island. The results are easier to interpret if the residuals are grouped together by season rather than by station, so define $[\epsilon_n^{(i)}]'=(\xi_{ni}, \gamma_{ni}, \delta_{ni})$ for $i=1,2,3$ and $\epsilon_n'=(\epsilon_n^{(1)\prime}, \epsilon_n^{(2)\prime}, \epsilon_n^{(3)\prime})$. The autocorrelation matrices Corr $(\epsilon_n, \epsilon_{n-k})$ (note that lag values are now in years) were estimated for $k=0,1,2,3$; no significant values were found among the submatrices Corr $(\epsilon_n^{(i)}, \epsilon_{n-k}^{(j)})$, $k=0,...,3$ and $i \neq j$ (a value is considered significant if it is greater than 0.3 in absolute

TABLE 16.—*Seasonal statistics for actual streamflow data and 10 model simulations for the same length for Overton, Nebraska*

[Means and standard deviations are in cubic feet per second-months]

	September through February				March and April				May through August			
	Mean	Standard deviation	Skewness	Kurtosis	Mean	Standard deviation	Skewness	Kurtosis	Mean	Standard deviation	Skewness	Kurtosis
Actual data												
	8093	3923	2.918	11.068	3642	2044	3.043	11.927	4810	5108	2.904	8.554
Simulations												
1	8489	2822	0.194	-0.602	3750	1550	0.990	1.411	4952	4399	3.029	11.913
2	6972	2993	1.146	.764	3399	2172	1.811	2.897	3592	2965	1.757	3.838
3	7796	2730	1.132	.558	3705	1676	1.372	1.591	4017	3456	2.489	6.001
4	7990	3471	.899	-.161	3709	1727	.853	.510	4173	4661	3.216	11.305
5	8972	4044	1.795	4.885	4674	2989	2.830	10.202	5367	3749	1.200	1.293
6	8101	3074	1.085	.826	4006	1936	1.789	4.161	5153	4867	3.274	13.135
7	6902	1825	.426	-.178	3145	1040	.629	-.056	3282	1927	.903	-.251
8	7040	2684	.725	.222	3032	1109	.455	-.104	3630	3752	2.838	9.369
9	8159	4082	.933	.222	3705	1809	1.010	.693	5286	5275	2.022	4.708
10	8398	3396	1.994	5.601	3724	1668	3.605	16.009	4218	3806	3.184	12.057

TABLE 17.—*Seasonal statistics for actual streamflow data and 10 model simulations for the same length for Odessa, Nebraska*

[Means and standard deviations are in cubic feet per second-months]

	September through February				March and April				May through August			
	Mean	Standard deviation	Skewness	Kurtosis	Mean	Standard deviation	Skewness	Kurtosis	Mean	Standard deviation	Skewness	Kurtosis
Actual data												
	8093	3923	2.918	11.068	3642	2044	3.043	11.927	4810	5108	2.904	8.554
Simulations												
1	7325	2612	0.108	-0.785	3423	1469	1.168	2.012	3612	2679	0.984	0.197
2	7645	3642	1.325	1.685	3671	2208	1.438	1.806	4518	4921	2.181	5.366
3	6779	2505	1.189	1.156	3379	1518	.922	.227	3987	6098	4.452	21.502
4	7513	2839	1.638	3.144	3863	1594	1.219	1.180	4645	5465	2.307	4.597
5	7691	2939	1.036	1.075	3526	1705	2.283	7.422	4965	4829	2.079	4.661
6	6533	2666	1.125	.701	3707	1510	1.093	1.422	3349	3755	1.816	2.204
7	7219	3479	1.670	3.358	3487	1839	1.068	.115	3877	4559	3.184	11.803
8	7183	2282	.704	2.169	3311	1340	1.016	1.314	3219	2221	.939	-.153
9	6656	2281	.751	.946	3222	1285	.583	-.084	3483	2695	1.608	2.713
10	6734	1939	.635	-.061	3150	1158	.483	-.616	2833	2103	1.851	3.834

TABLE 18.—*Seasonal statistics for actual streamflow data and 10 model simulations for the same length for Grand Island, Nebraska*

[Means and standard deviations are in cubic feet per second-months]

	September through February				March and April				May through August			
	Mean	Standard deviation	Skewness	Kurtosis	Mean	Standard deviation	Skewness	Kurtosis	Mean	Standard deviation	Skewness	Kurtosis
Actual data												
	7219	4184	2.860	10.962	4068	1973	2.065	6.564	4653	4644	2.448	6.465
Simulations												
1	7670	4679	2.179	5.272	4228	1874	2.005	6.137	4400	4816	2.877	9.581
2	8815	4068	1.153	1.661	4502	1920	.814	.212	6232	4701	1.233	.865
3	7634	3819	1.654	3.667	3440	1472	.704	-.178	8386	4929	1.785	3.398
4	7784	4386	2.818	10.631	4028	1812	1.002	1.162	5502	8219	4.739	23.758
5	6952	3715	1.536	2.913	3638	1851	1.564	3.146	5903	8254	3.608	15.341
6	6865	3160	1.229	1.382	4279	1671	.707	.186	4414	3996	1.582	1.794
7	6750	3355	1.619	2.105	4203	2028	1.164	.783	4896	6069	2.633	6.810
8	7843	4111	.947	-.210	4727	2956	1.770	4.042	6093	8237	3.968	18.084
9	9154	5016	1.391	1.998	4883	2291	1.331	1.867	7523	8093	2.613	7.681
10	7694	3351	.383	-.942	4173	1968	1.073	.758	4941	4364	.995	-.371

value). All correlations between the residuals occur within the same season. Among the matrices Corr $\left(\epsilon_n^{(i)}, \epsilon_{n-k}^{(i)}\right)$, the only significant values occur for $k=0$; $i=1,2,3$; $k=1$; and $i=2$. These matrices are given in table 19.

Recall from the individual models that a moving average component was added to the residuals for the second season. In particular, we have $\xi_{n2}=\xi_n^*+0.63\,\xi_{n-1}^*$, $\gamma_{n2}=\gamma_n^*+0.5\,\gamma_{n-1}^*$, $\delta_{n2}=\delta_n^*+0.5\,\delta_{n-1}^*$ where $\left(\xi_n^*, \gamma_n^*, \delta_n^*\right)$ and $\left(\xi_t^*, \gamma_t^*, \delta_t^*\right)$ are independent for $n \neq t$.

Let $\left(\epsilon_n^{*\prime}\right)=\left(\xi_n^*, \gamma_n^*, \delta_n^*\right)$.

It is straightfoward to show that if

$$\mathrm{Cov}(\epsilon_n^*)=\begin{bmatrix} 0.00591 & 0.01586 & 0.01772 \\ .01586 & .05293 & .05558 \\ .01772 & .05558 & .07045 \end{bmatrix}$$

then

$$\mathrm{Corr}\left(\epsilon_n^{(2)}, \epsilon_n^{(2)}\right)=\begin{bmatrix} 1.0 & 0.893 & 0.864 \\ .893 & 1.0 & .910 \\ .864 & .910 & 1.0 \end{bmatrix}$$

and

$$\mathrm{Corr}\left(\epsilon_n^{(2)}, \epsilon_{n-1}^{(2)}\right)=\begin{bmatrix} 0.450 & 0.428 & 0.414 \\ .339 & .400 & .364 \\ .328 & .364 & .400 \end{bmatrix}$$

It is evident that the lag 1 matrix for season 2 in table 19 can be explained by the moving average components.

It should be noted that the same parameter estimates obtained for the single-station models were used for the combined model rather than estimating the parameters in a multivariate sense. These estimates can easily be shown to correspond to the ordinary least squares estimates. This should not greatly affect the performance of the model for simulation.

The statement of the combined-station model is: Let $\left\{Z_{n,k}^{(Ov)}\right\}$ be the transformed and mean standardized values for Overton; let $\left\{Z_{n,k}^{(Od)}\right\}$ be the transformed and mean standardized values for Odessa; and let $\left\{Z_{n,k}^{(GI)}\right\}$ be the transformed and mean standardized values for Grand Island. (See table 13.) The final model becomes:

Overton

$$Z_{n,1}^{(Ov)}=0.3632*Z_{n-1,3}^{(Ov)}+0.1449*Z_{n-1,1}^{(Ov)}+\xi_{n,1} \quad (6a)$$

$$Z_{n,2}^{(Ov)}=1.0756*Z_{n,1}^{(Ov)}+\xi_n^*+0.63\ \xi_{n-1}^* \quad (6b)$$

$$Z_{n,3}^{(Ov)}=0.4646*Z_{n,2}^{(Ov)}+0.2631*Z_{n-2,3}^{(Ov)}+\xi_{n,3} \quad (6c)$$

Odessa

$$Z_{n,1}^{(Od)}=0.3423*Z_{n-1,3}^{(Od)}+0.1461*Z_{n-1,1}^{(Od)}+\gamma_{n,1} \quad (7a)$$

$$Z_{n,2}^{(Od)}=0.9168*Z_{n,1}^{(Od)}-0.0982*Z_{n-1,1}^{(Od)}+\gamma_n^*+.5\ \gamma_{n-1}^* \quad (7b)$$

$$Z_{n,3}^{(Od)}=0.7850*Z_{n,2}^{(Od)}+\gamma_{n,3} \quad (7c)$$

Grand Island

$$Z_{n,1}^{(GI)}=0.4198*Z_{n-1,3}^{(GI)}-0.0469*Z_{n-1,1}^{(GI)}+0.1284*Z_{n-2,3}^{(GI)}+\delta_{n,1} \quad (8a)$$

$$Z_{n,2}^{(GI)}=0.6715*Z_{n,1}^{(GI)}+0.0949*Z_{n-1,1}^{(GI)}+\delta_n^*+.5\ \delta_{n-1}^* \quad (8b)$$

$$Z_{n,3}^{(GI)}=0.7757*Z_{n,2}^{(GI)}+\delta_{n,3} \quad (8c)$$

TABLE 19.—*Significant cross correlations between residuals from individual-station models*

[Lag, in years]

			Overton	Odessa	Grand Island
Season 1 (September through February)	Lag 0	Overton	1.0	0.941	0.871
		Odessa	.941	1.0	.913
		Grand Island	.871	.913	1.0
Season 2 (March and April)	Lag 0	Overton	1.0	.893	.864
		Odessa	.893	1.0	.910
		Grand Island	.864	.910	1.0
	Lag 1	Overton	.446	.436	.430
		Odessa	.387	.403	.395
		Grand Island	.420	.410	.395
Season 3 (May through August)	Lag 0	Overton	1.0	.945	.918
		Odessa	.945	1.0	.988
		Grand Island	.918	.988	1.0

Let $\left(\epsilon_n^{(1)}\right)'=\left(\xi_{n,1}, \gamma_{n,1}, \epsilon_{n,1}\right)$, $\left(\epsilon_n^{(2)}\right)'=\left(\xi_n^*, \gamma_n^*, \delta_n^*\right)$, $\left(\epsilon_n^{(3)}\right)'=\left(\xi_{n,3}, \gamma_{n,3}, \delta_{n,3}\right)$. Then: $\epsilon_n^{(j)}$, $j=1,2,3$, $n=0,1,...$ are independent normal random vectors with

$$\mathrm{Cov}\left(\epsilon_n^{(1)}\right)=\begin{bmatrix} .00706 & .01782 & .01993 \\ .01782 & .05082 & .05608 \\ .01993 & .05608 & .07431 \end{bmatrix}$$

$$\mathrm{Cov}\left(\epsilon_n^{(2)}\right)=\begin{bmatrix} .00591 & .01586 & .01772 \\ .01586 & .05293 & .05558 \\ .01772 & .05558 & .07045 \end{bmatrix}$$

$$\mathrm{Cov}\left(\epsilon_n^{(3)}\right)=\begin{bmatrix} .08944 & .24913 & .23767 \\ .24913 & .77623 & .75345 \\ .23767 & .75345 & .74906 \end{bmatrix}$$

$E\epsilon_n^{(j)}=0$ for $j=1,2,3$.

Graphs of 50-year simulations from the combined-station model are given in figures 17, 18, and 19. The unusually high discharge values for the 72nd simulated values at Odessa and Grand Island (73,396 ft³/s-months for Odessa and 96,266 ft³/s-months for Grand Island) may seem at first to point to a model inadequacy. However, out of five hundred 50-year combined-station simulations from the next section, only eight contained values greater than 90,000, which indicates that this particular simulation happened to be an extreme case.

SIMULATION AND EVALUATION OF PROBABILITIES

The model of the previous section can easily be used for simulation of 3-station, 3-season flow series over the next 50 years. The complicated dependence structure between seasons and between stations causes direct evaluation of probabilities of most events of interest to be difficult. However, if one obtains N 50-year simulations from the model, n of which exhibit a certain event, then an estimate of the probability of that event occurring over the next 50 years would be n/N, assuming that all simulations are equally likely.

Suppose one has data for years 0, 1,..., t (t corresponds to 1979 here) and wants to simulate from the model for years t+1,..., t+50. Referring to table 13 and to any of the equations of the last section, one would proceed as follows:

1. Obtain the values of the series from years t and $t-1$ that are needed in the chosen equation for year $t+1$; these values are transformed as in table 13.

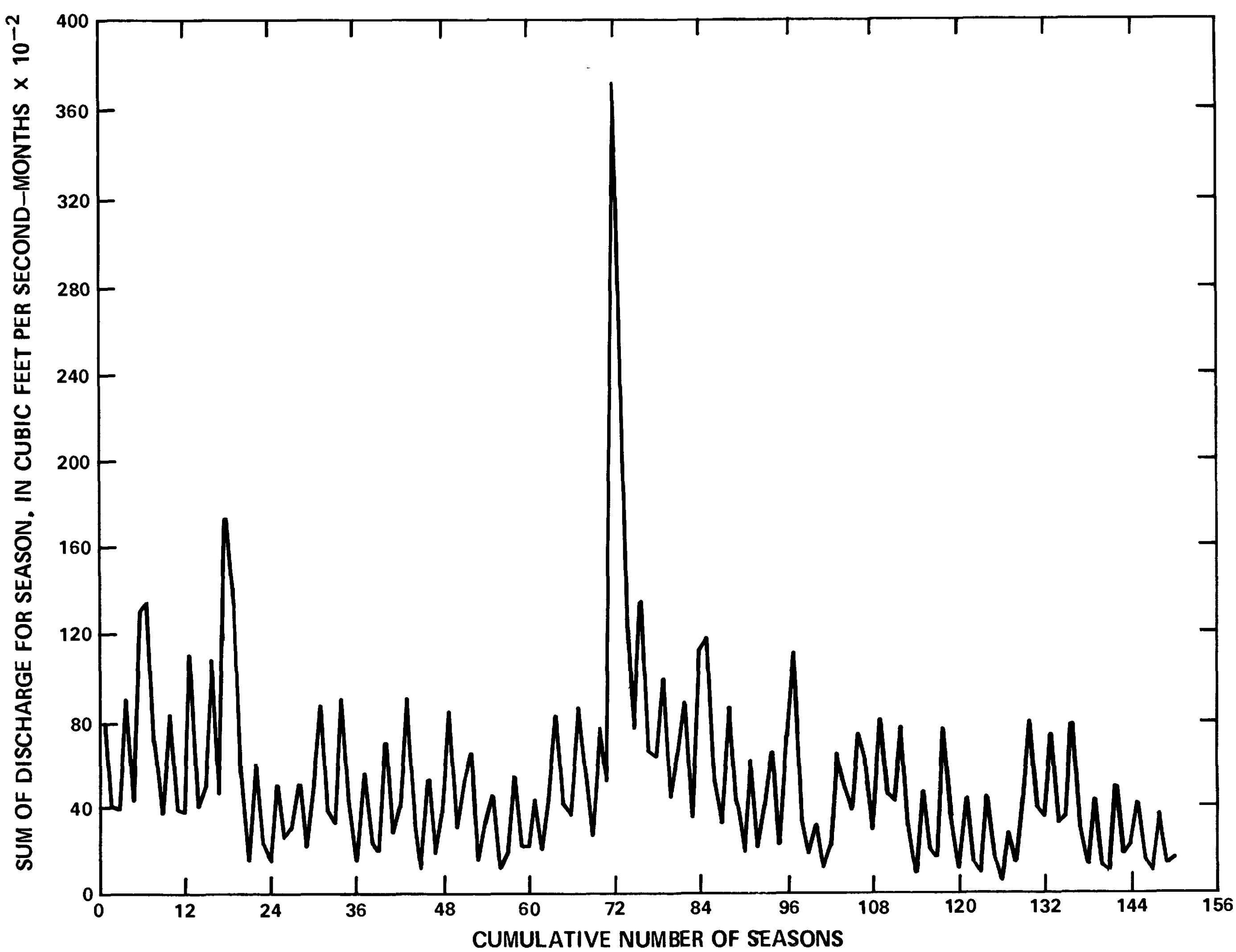


FIGURE 17.—Fifty-year simulation of streamflow at Overton, Nebraska from the combined-station model.

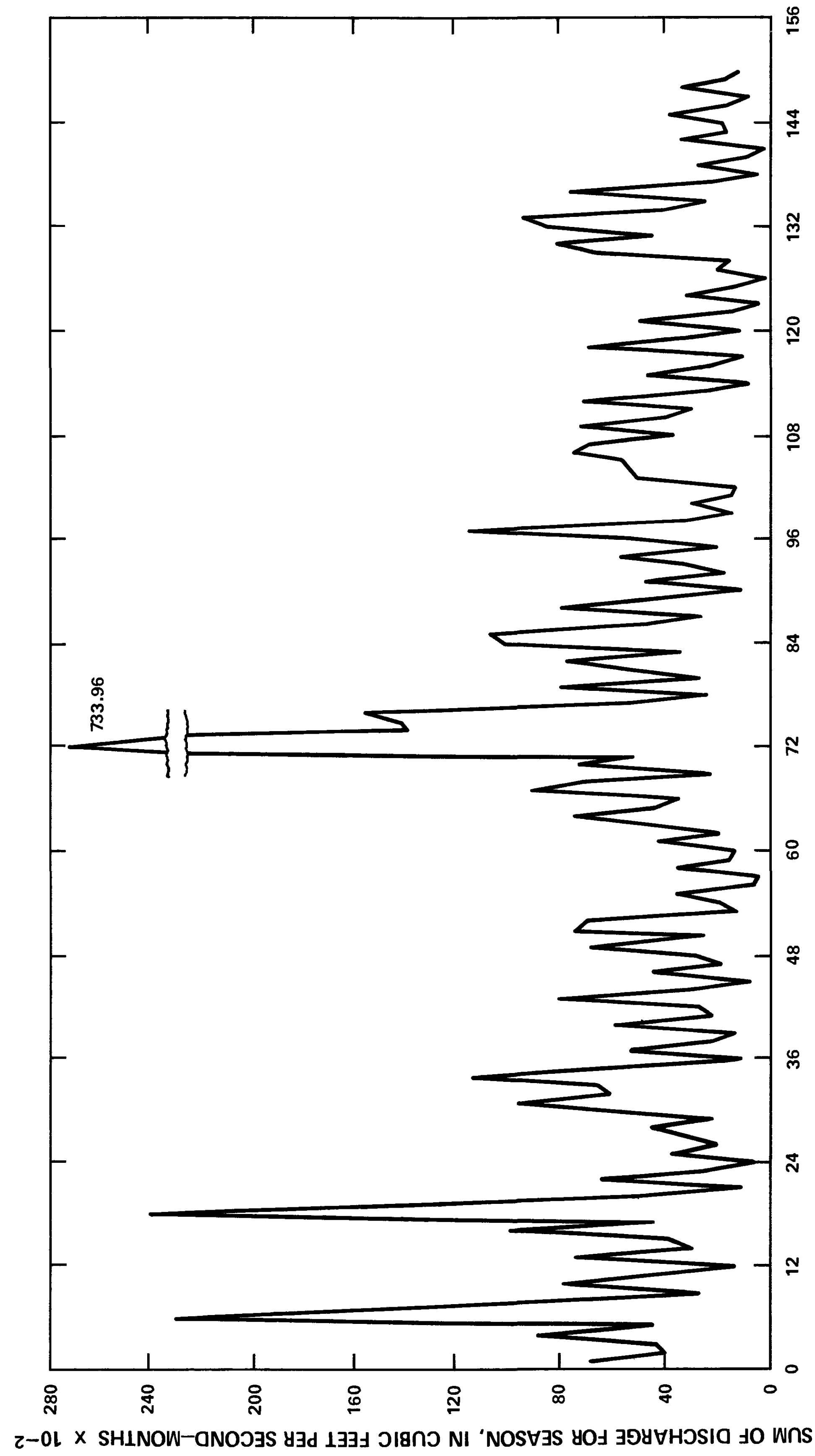


FIGURE 18.—Fifty-year simulation of streamflow at Odessa, Nebraska from the combined-station model.

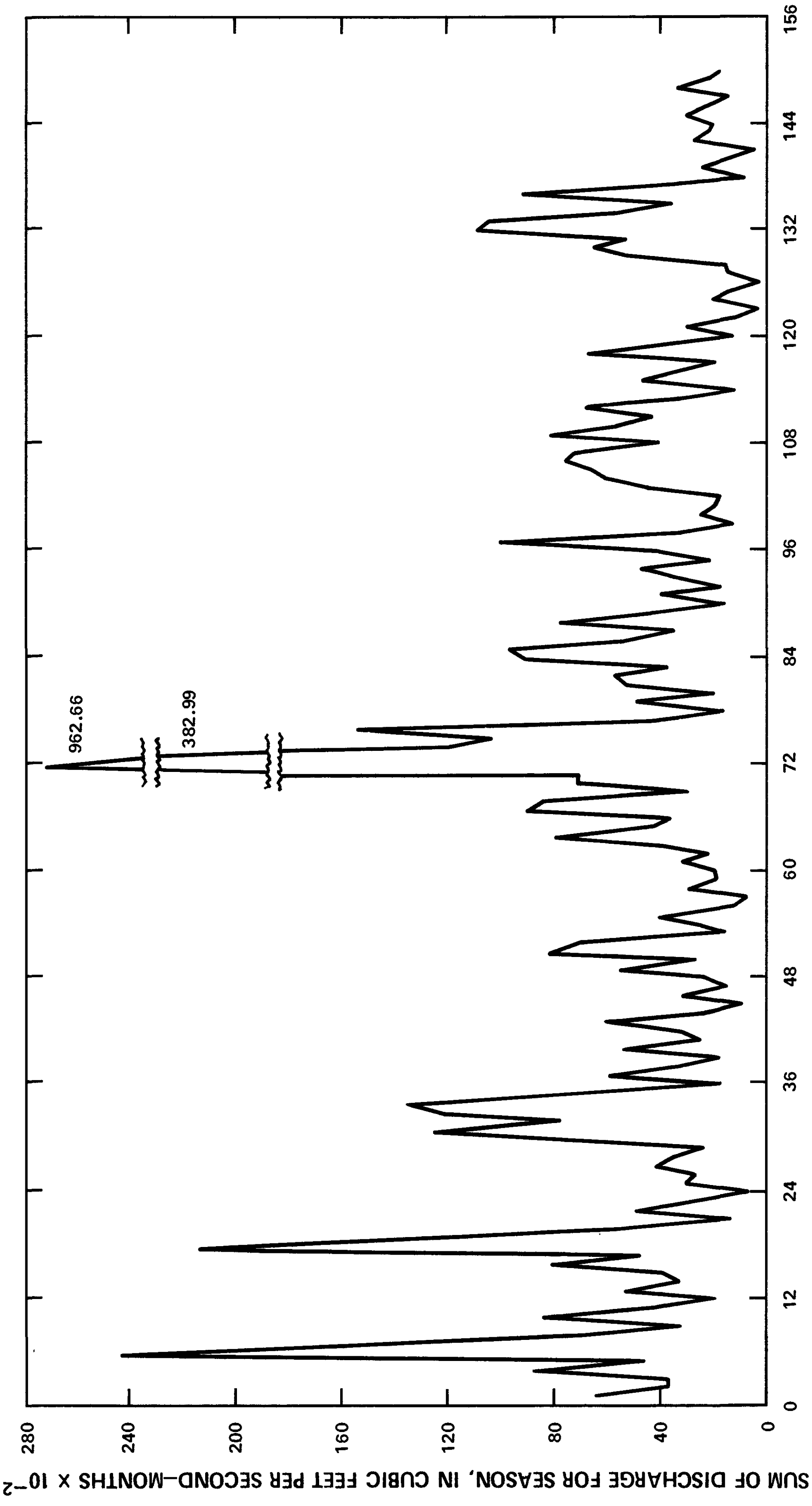


FIGURE 19.—Fifty-year simulation of streamflow at Grand Island, Nebraska from the combined-station model.

2. Generate random vectors $\epsilon^{(1)}_{t+j}, \epsilon^{(2)}_{t}, \epsilon^{(2)}_{t+j}, \epsilon^{(3)}_{t+j}$, $j=1,2, ..., 50$. The easiest way to do this is to generate a vector of three independent standard normal random variables for each season and each year and then transform them to obtain the desired covariance matrices. For instance, if Cov $(\epsilon^{(j)}_t)=\Sigma_j$, then Σ_j can be written as $\Gamma'_j \Gamma_j$, where Γ_j is 3×3 of rank 3. Hence, if $e^{(j)}_{t+1}$ is a 3×1 standard normal random vector $(\mathrm{Cov}\,(e^{(j)}_{t+1})=I)$, then $\Gamma'_j e^{(j)}_{t+1}=\epsilon^{(j)}_{t+1}$ is a normal random vector, with covariance matrix $\Gamma'_j \Gamma_j=\Sigma_j$. Γ'_j for $j=1, 2, 3$ is shown in table 20.

   Note that for season 2, $\epsilon^{(2)}_t$ is not observable from the past series. The following is observable:

$$\xi^*_t+0.63\,\xi^*_{t-1}, \gamma^*_t+0.5\,\gamma^*_{t-1}, \delta^*_t+0.5\,\delta^*_{t-1}.$$

   There are ways to estimate $\epsilon^{(2)}_t$ from the available data, but since the initial effect of $\epsilon^{(2)}_t$ on the simulations will die off quickly and the simulations are so long, the effect of using $\epsilon^{(2)}_t$ generated as above will be negligible.
3. Now all the quantities necessary for the generation of Z_{t+1} for each station are secured. Using the chosen equation, generate $Z_{t+1,1}$ followed by $Z_{t+1,2}$ and $Z_{t+1,3}$ for each station. Once Z_{t+j} is generated, Z_{t+j+1} can be generated by using Z_{t+j} and $\epsilon^{(k)}_{t+j+1}$, $k=1, 2, 3$.
4. Untransform the simulated values to get the series in terms of the original units.

Results of a simulation study involving some flow events for season 2 (March through April) and season 3 (May through August) are presented in table 21. The flow events represent a range of discharges that can be related to certain habitat characteristics.

Based on a study by R. T. Hurr (1981) it was found that ground-water levels at Mormon Island would rise to within 8 inches of the land surface if the discharge in the channels was 3,000 ft³/s. For season two, this is equivalent to a seasonal sum of 6,000 ft³/s-months. A seasonal value of 8,000 ft³/s-months would raise the levels to within about 4 inches of land surface, while a value of 4,000 ft³/s-months would drop the levels to about one foot below land surface. These values are assumed to encompass the critical ground-water levels necessary for an acceptable wet-meadow habitat in this area. Probability values based on these flows are presented also for Overton and Odessa, although the ground-water streamflow relationships regarding possible wet-meadow complexes in these areas have not been determined.

TABLE 20.—*Full-rank decompositions of seasonal-covariance matrices*

$[(\Sigma_j=\Gamma'_j\Gamma_j)]$

Season 1	Γ'_1	=	0.08402	0	0
			.21208	.07643	0
			.23719	.07557	.11108
Season 2	Γ'_2	=	.07688	0	0
			.20631	.10182	0
			.23050	.07883	.10538
Season 3	Γ'_3	=	.29906	0	0
			.83303	.28686	0
			.79471	.31873	.12612

Season 3, May through August, is the seed-germination period within the critical habitat reach. If the process of channel maintenance is to occur during this period, the flows should be sufficient to prevent seedling establishment, as well as to transport the sediment necessary for erosional processes of channel formation. Channel-geometry plots from Eschner (1981) show that a width of 500 feet near Odessa is associated with an instantaneous discharge of approximately 3,000 ft³/s. This width is estimated as the minimum unobstructed width necessary for suitable crane habitat. Therefore, as an approximation for each reach, seasonal streamflow means of 4,000, 12,000, and 20,000 ft³/s-months were chosen as channel-maintenance discharge reference points for calculation of exceedence probabilities. These streamflow means are presented as seasonal values because of limited model resolution. They do not imply that these discharges are necessary throughout season 3 to maintain the channel; in fact, flows listed in table 10 are probably necessary for no more than 15 percent of season 3 to maintain the channel.

Critical discharge levels for maintenance of both wet meadows and channel cross sections can be compared to the probabilities of achieving these levels over the next 50 years using table 21. This comparison guide should assist habitat managers and water users in the area to plan effective utilization of available flows to satisfy projected water demands. Five hundred 50-year simulations were generated; probabilities of the events of table 21 were evaluated by counting the number, n, of the 500 simulations that satisfied the event, and taking n/500 as an estimate of the probability. To achieve an approximate estimate for the variability of these probability estimates, assume that each of the simulations is independent of the others. This assumption is not quite valid since the observed streamflow values for 1978 and 1979 were used as input to start each of the simulations. However, this transience will not significantly affect the results presented here. If p is the true probability of the event A (A could be any event involving the future of the streamflow series), and n is the number out of 500

TABLE 21.—*Estimates of the probability of level* χ *being surpassed at least m times over the next 50 years*
[ft³/s-month, cubic feet per second-month]

Season	χ ft³/s-month	Station m:	1	2	3	4	5	6	7	8	16	20	24	30
2	4,000	Overton	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.96	0.49	0.25	0.07	0.01
		Odessa	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.56	.25	.06	.00
		Grand Island	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.94	.71	.34	.04
2	6,000	Overton	0.93	0.83	0.67	0.52	0.39	0.27	.17	.09	.00	.00	.00	.00
		Odessa	.98	.91	.79	.66	.47	.34	.23	.14	.00	.00	.00	.00
		Grand Island	1.0	.99	.91	.90	.80	.67	.54	.43	.00	.00	.00	.00
2	8,000	Overton	.60	.31	.13	.06	.02	.01	.00	.00	.00	.00	.00	.00
		Odessa	.68	.38	.17	.06	.02	.01	.00	.00	.00	.00	.00	.00
		Grand Island	.83	.59	.37	.20	.09	.04	.02	.01	.00	.00	.00	.00
3	4,000	Overton	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.80	.56	.31	.05
		Odessa	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.71	.35	.09	.00
		Grand Island	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.89	.54	.21	.00
2	12,000	Overton	.89	.69	.49	.28	.16	.12	.06	.03	.00	.00	.00	.00
		Odessa	.96	.83	.62	.40	.22	.12	.06	.02	.00	.00	.00	.00
		Grand Island	.97	.90	.71	.53	.33	.18	.11	.06	.00	.00	.00	.00
3	20,000	Overton	.43	.18	.06	.02	.01	.00	.00	.00	.00	.00	.00	.00
		Odessa	.61	.27	.09	.04	.01	.00	.00	.00	.00	.00	.00	.00
		Grand Island	.68	.36	.12	.05	.02	.00	.00	.00	.00	.00	.00	.00

simulations in which A is observed, then, under the independence assumption:

$$\mathrm{Var}\left[\frac{n}{500}\right]=\frac{p\,(1-p)}{500}$$

PRECIPITATION-STREAMFLOW CORRELATION

The precipitation and streamflow models are intended as tools for simulation and calculation of probabilities of specific precipitation and streamflow conditions. The streamflow model can be used with channel-geometry models and stream discharge-ground-water level models to evaluate future wildlife-management alternatives. The precipitation model is useful in estimating probabilities of drought severity and duration that otherwise could not directly be estimated because of the short record.

Because of the presumed interrelationship between precipitation and streamflow, the joint effects of precipitation and streamflow on water use, including ground-water pumping, can only be determined from more extensive data collection and more sophisticated modeling procedures. Nevertheless, the correlation between precipitation and streamflow may allow initial estimates to be made of the effects of changes in precipitation on channel characteristics.

Some estimated correlations between precipitation in each of the 12 months, and streamflow (in average cfs) in the same month and 12 subsequent months, are presented in the Gothenburg and Grand Island precipitation stations, with the Overton streamflow station (table 22) and the Grand Island streamflow station (table 23). Data used for the estimations consists of monthly precipitation tables from September 1941 to August 1978, and monthly streamflow series from September 1942 to August 1978, at the respective stations. Values below 0.3 in absolute value can be considered statistically insignificant. The same series as above were aggregated over the three streamflow seasons (September through February, March and April, and May through August), and used to estimate correlations between precipitation in each of the seasons and streamflow in the same season and six following seasons. Results are presented in tables 24 and 25. Once again, absolute values below 0.3 are considered insignificant. There seems to be essentially no correlation of precipitation in seasons 2 and 3 with streamflow in subsequent seasons.

Significant correlations observed in tables 22 and 23 indicate that monthly precipitation could be used effectively as a predictor of monthly streamflow. However, tables 24 and 25 indicate that the advantage of a joint precipitation-streamflow model for evaluation of streamflow probabilities would be lost when model output is aggregated over seasons.

SUMMARY

This report presents the development of stochastic precipitation and streamflow models for a critical wildlife-habitat reach of the Platte River. The habitat, defined as the reach of the Platte River from Lexington to Grand Island, Nebraska, is assumed to be adequately represented in terms of precipitation by basing the relevant models on data collected at Gothenburg, Kearney,

TABLE 22.—*Estimated correlations between monthly precipitation at Gothenburg (A) and at Grand Island (B) with monthly streamflow at Overton*

Streamflow lead (in months)	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.
						A. Gothenburg						
0	−0.44	0.07	0.39	0.28	−0.08	0.04	0.22	0.26	0.18	0.50	0.28	−0.09
1	.32	.12	.33	.34	−.02	−.08	.31	.11	.16	.27	.28	−.11
2	.38	.06	.28	.42	−.02	.03	.30	−.13	.08	.02	.23	−.09
3	.37	.06	.24	.39	.01	.01	−.12	.02	.20	−.11	.32	−.14
4	.31	.08	.22	.05	.04	−.06	.13	.03	.23	−.05	.27	−.09
5	.36	.10	.29	.09	.20	−.26	.24	−.02	.35	−.01	.21	−.03
6	.42	.05	.21	.10	−.13	−.24	.31	.00	.25	−.00	.27	−.07
7	−.08	.10	.07	.23	.08	−.21	.28	.14	.24	.02	.32	−.20
8	−.11	.38	.51	.19	.20	−.18	.27	.15	.40	.00	.29	−.01
9	.02	.07	.24	.18	−.04	−.14	.14	.12	.33	−.05	−.07	.05
10	−.05	−.04	.26	.13	.12	−.09	.18	.10	.22	−.12	−.10	.27
11	−.09	−.02	.27	.06	−.03	−.13	.23	.04	−.00	.00	−.05	−.01
12	−.17	−.08	.16	−.06	−.12	−.15	.28	−.03	−.11	.02	.11	.10
						B. Grand Island						
0	0.66	0.21	0.41	0.35	−0.16	0.01	0.08	−0.07	0.14	0.49	0.07	−0.04
1	.53	.25	.36	.40	−.05	−.06	.50	−.17	.06	−.01	−.05	−.15
2	.59	.22	.37	.40	−.01	.30	.40	−.05	.16	−.17	−.00	−.14
3	.53	.21	.38	.38	.11	.33	−.07	.04	.15	−.23	.13	−.04
4	.43	.22	.39	.23	.16	.13	.28	−.07	.24	−.18	.02	−.05
5	.49	.17	.23	.16	.33	−.03	.55	−.12	.39	−.11	.00	−.03
6	.57	.09	.20	.04	−.01	−.02	.60	−.12	.33	−.12	.07	−.04
7	.16	.15	.16	.19	.11	−.00	.50	−.04	.28	−.20	.01	−.05
8	.10	.50	.42	.35	.06	.21	.45	−.01	.43	−.21	−.02	−.02
9	−.02	.29	.28	.30	.02	.23	.36	.00	.39	−.27	.02	.07
10	−.01	.14	.25	.23	.10	.26	.43	−.05	.23	−.31	.06	−.01
11	−.01	.07	.22	.24	.05	.28	.58	−.08	.15	−.29	.16	−.20
12	−.00	.08	.18	.19	.00	.21	.60	.08	.10	−.14	.16	−.15

TABLE 23.—*Estimated correlations between monthly precipitation at Gothenburg (A) and at Grand Island (B) with monthly streamflow at Grand Island*

Streamflow lead (in months)	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.
						A. Gothenburg						
0	0.50	0.22	0.39	0.45	−0.06	0.14	0.26	0.29	0.24	0.48	0.43	−0.01
1	.41	.14	.25	.39	.14	.01	.35	.09	.19	.28	.26	−.05
2	.40	.00	.32	.50	.09	.02	.27	−.13	.18	.02	.25	−.03
3	.42	.03	.23	.34	.05	−.03	−.10	−.09	.27	−.10	.31	−.20
4	.27	.05	.20	.03	.05	.03	.10	−.01	.25	−.05	.34	−.07
5	.26	.14	.30	.11	.10	−.16	.21	−.07	.39	.04	.08	−.06
6	.39	.04	.20	.05	−.23	−.21	.28	−.08	.21	−.09	.24	−.05
7	−.11	.11	−04	.21	.05	−.20	.26	.02	.18	.04	.36	−.17
8	−.11	.29	.40	.16	.03	−.16	.19	.05	.40	.09	.29	−.05
9	.01	.00	.16	.19	−.04	−.04	.14	.08	.25	−.09	−.06	.11
10	−.05	−.10	.21	.13	.07	−.18	.16	.06	.21	−.13	−.11	.30
11	−.17	−.08	.22	.09	−.00	−.08	.17	.08	−.01	−.02	−.10	.06
12	−.18	−.06	.17	−.01	−.10	−.19	.27	.02	−.14	.05	.15	.16
						B. Grand Island						
0	0.70	0.35	0.51	0.51	−0.16	0.14	0.16	−0.01	0.13	0.46	0.31	0.02
1	.61	.23	.36	.47	.08	−.07	.54	−.17	.09	−.00	−.04	−.13
2	.56	.19	.40	.47	.07	.26	.37	−.08	.15	−.16	.04	−.09
3	.57	.21	.42	.36	.12	.24	−.06	−.12	.22	−.23	.14	−.08
4	.40	.29	.37	.21	.20	.23	.23	−.06	.28	−.19	.07	−.00
5	.38	.21	.25	.15	.29	.09	.52	−.14	.46	−.11	.07	−.05
6	.50	.07	.19	.03	−.08	.01	.58	−.11	.29	−.22	.12	−.02
7	.15	.15	.06	.24	.09	−.01	.47	−.08	.26	−.20	.12	−.04
8	.06	.40	.32	.32	.03	.20	.44	.04	.45	−.17	.03	−.05
9	−.06	.22	.18	.30	−.03	.27	.42	.03	.38	−.33	.03	.02
10	−.08	.29	.20	.23	.15	−.02	.40	−.02	.27	−.34	.06	.10
11	−.08	.02	.17	.32	−.01	.28	.46	−.07	.16	−.31	.14	−.31
12	.02	.10	.19	.28	.01	.14	.58	.08	.09	−.11	.17	−.11

TABLE 24.—*Estimated correlations between seasonal precipitation at Gothenburg (A) and at Grand Island (B) with seasonal streamflow at Overton*

Streamflow lead (in seasons)	Season 1	Season 2	Season 3
A. Gothenburg			
0	0.42	-0.02	0.09
1	.42	.23	.19
2	.11	.12	.18
3	-.02	.13	-.09
4	.02	-.19	-.02
5	.17	-.03	-.00
6	.14	-.02	.03
B. Grand Island			
0	0.59	-0.05	-0.03
1	.55	.13	-.00
2	.29	.21	-.04
3	.22	.27	-.11
4	.21	-.15	.10
5	.09	-.13	.07
6	.14	-.12	.09

TABLE 25.—*Estimated correlations between seasonal precipitation at Gothenburg (A) and at Grand Island (B) with seasonal streamflow at Grand Island*

Streamflow lead (in seasons)	Season 1	Season 2	Season 3
A. Gothenburg			
0	0.49	0.02	0.17
1	.45	.21	.19
2	.09	.05	.21
3	-.05	.20	-.10
4	-.01	-.16	-.00
5	.18	.05	.05
6	.10	.05	.08
B. Grand Island			
0	0.64	0.10	0.66
1	.61	.12	.03
2	.24	.21	.05
3	.18	.31	-.13
4	.16	-.16	.16
5	.12	-.07	.08
6	.08	-.13	.09

and Grand Island. The streamflow models are developed using data collected at Overton, Odessa, and Grand Island.

For modeling purposes, three seasons were defined to correspond approximately to periods of significantly different flows and vegetation development. Season 1, comprising the months September through February, represents the base flow period. Season 2, March and April, represents the period of high flows from snowmelt in the Rocky Mountains. Season 3, from May through August, represents the approximate time of seed drop by riparian vegetation, and, consequently, the period of seedling germination and establishment.

Each hydrologic variable, defined as the seasonal value at the appropriate station, is modeled both independently of the other stations for the particular variable, and as part of a combined station model. The combined station model allows for expression of the interrelationship between stations for the given variable.

The precipitation models are used primarily in this report to estimate probabilities of droughts of given severities and durations. Drought severities are defined relative to the historical mean at the stations and the durations are presented as consecutive years. The streamflow models are used to estimate exceedence probabilities for specified levels of flows that are related to the maintenance of channel characteristics and wet meadow environments.

It is recognized that streamflow may not be independent of precipitation in the study reach. Although the interrelationship was not modeled, tables of the correlation between precipitation and streamflow (tables 22–25) may allow initial estimates of the effects of changes in precipitation on streamflow to be made.

Because the resolution for both the precipitation and streamflow models allows only seasonal estimation, the models are intended as initial screening tools for evaluating management alternatives for the habitat. In order to more exactly evaluate consequences of operating rules of water releases or diversions of water for proposed development, models allowing finer estimation of the hydrology would have to be developed. The development of these models, however, would require a more extensive data collection and model development research effort.

SELECTED REFERENCES

Box, G. E. P., and Cox, D. R., 1964, An analysis of transformations: Journal of the Royal Statistical Society, Ser. B, 26, p. 211–252.

Box, G. E. P., and Jenkins, G. W., 1975, Time series analysis, forecasting and control: San Francisco, Calif., Holden-Day, p. 67–70.

David, F. N., and Barton, D. E., 1962, Combinatorial chance: New York, Hafner, p. 228–231.

Eschner, T. R., 1981, Morphologic and hydrologic changes of the Platte River, south-central Nebraska: Fort Collins, Colorado State University, MS Thesis, 269 p.

Gibbons, J. D., 1971, Nonparametric statistical inference: New York, McGraw-Hill, p. 75.

Graybill, F. A., 1976, Theory and application of the linear model: North Scituate, Mass., Duxbury Press, p. 310–324.

Hurr, R. T., 1981, Ground-water hydrology of the Crane Meadows wildlife area, near Grand Island, Hall County, Nebraska: U.S. Geological Survey Open-File Report 81-1109, 43 p.

Pagano, Marcello, 1978, On periodic and multiple autoregressions: Annals of Statistics, v. 6, no. 6, p. 1310–1317.

Parzen, E., and Pagano, M., 1979, An approach to modeling seasonally stationary time series: Journal of Econometrics, v. 9, p. 137–153.

Petsch, H. E., Jr., Rennick, K. B., and Nordin, C. F., Jr., 1980, Statistical summaries of selected streamflow data, South Platte River in Colorado and Nebraska: North Platte and Platte Rivers in Nebraska, U.S. Geological Survey Open-File Report 80-679, 278 p.

Stidd, C. K., 1970, The nth root normal distribution of precipitation: Water Resources Research, v. 6, no. 4, p. 1095-1103.

Troutman, B. M., 1979, Some results in periodic autoregression: Biometrika, v. 66, no. 2, p. 219-228.

Vecchia, A. V., Jr., 1981a, Precipitation model for the Platte River valley from Gothenburg to Grand Island, Nebraska: U.S. Geological Survey Open-File Report 81-130, 44 p.

Vecchia, A. V., Jr., 1981b, A stochastic streamflow model of the Platte River at Overton, Odessa, and Grand Island, Nebraska: U.S. Geological Survey Open-File Report 81-1188, 42 p.

Simulated Hydrologic Effects of Possible Ground-Water and Surface-Water Management Alternatives in and Near the Platte River, South-Central Nebraska

By ALAN W. BURNS

HYDROLOGIC AND GEOMORPHIC STUDIES OF THE PLATTE RIVER BASIN

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1277-G

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1983

CONTENTS

ILLUSTRATIONS

TABLES

METRIC CONVERSIONS

Inch-pound units used in this report may be converted to metric (SI) units by using the following conversion factors:

Multiply inch-pound units	*By*	*To obtain*
acre	0.0040	square kilometer
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
cubic foot per second (ft^3/s)	0.2832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
foot squared per day (ft^2/d)	0.093	meter squared per day

SIMULATED HYDROLOGIC EFFECTS OF POSSIBLE GROUND-WATER AND SURFACE-WATER MANAGEMENT ALTERNATIVES IN AND NEAR THE PLATTE RIVER, SOUTH-CENTRAL NEBRASKA

By ALAN W. BURNS

ABSTRACT

Digital-computer models were developed and used to simulate the hydrologic effects of hypothetical water-management alternatives on the wetland habitat area near Grand Island, Nebr. Areally distributed recharge to and discharge from the aquifer system adjacent to the Platte River between Overton and Grand Island were computed for four hypothetical water-management alternatives: (1) Current methods; (2) increasing the acreage irrigated by surface water about 270,000 acres; (3) increasing the acreage irrigated by ground water by about 270,000 acres, replacing as much subirrigated area as possible; and (4) increasing the acreage irrigated by ground water by about 270,000 acres without replacing subirrigated areas. Using stream-aquifer response functions, the stream depletions resulting from the computed aquifer recharge and discharge, averaged over a 50-year planning period, were 125,000, 53,000, 174,000, and 177,000 acre-feet per year, respectively.

Frequency curves of the stage in the river near the wildlife habitat area were computed from the 50-year sequences of monthly streamflows for each of the management alternatives. The differences in the stage-frequency curves were minimal for the four water-management alternatives.

For comparative purposes, three additional water-management alternatives were simulated which had direct effects on the streamflow entering the study area: (1) Assume an importation of 240,000 acre-feet per year for irrigation of 100,000 acres downstream from the study area; (2) assume a diversion of 240,000 acre-feet per year for irrigation of 100,000 acres upstream from the study area; and (3) assume a reservoir or diversion which would store or divert any incoming monthly streamflow greater than 2,000 cubic feet per second. The average streamflow for the current-conditions simulation was 1,274 cubic feet per second, whereas the average for each of these hypothetical management alternatives was 1,606, 1,045, and 1,102 cubic feet per second, respectively. Translating these different streamflow sequences to stage-frequency curves indicates a much greater change in stream stage than the four water-management alternatives previously evaluated.

INTRODUCTION

This study is part of the Platte River Study, a multidisciplinary study being conducted by agencies of the U.S. Department of the Interior concerned with the critical habitat of the whooping crane and other migratory waterfowl along the Platte River in central Nebraska. Hydrologic investigations have been an important subset of the Platte River Study and have attempted to identify the hydrologic system as it relates to the habitat, and thus how water-management alternatives could affect the habitat. This particular report presents the simulations of the hydrologic effect on the river caused by potential water-management alternatives in and near the Platte River between Overton and Grand Island, Nebr.

PURPOSE AND SCOPE

The purpose of the part of the Platte River Study described in this report was to determine the range of effects on the streamflow and stage of the river near the habitat area due to possible water-management practices in a 70-mile reach of the river upstream from the habitat area. The analysis considered only hypothetical water-management alternatives rather than actual proposed projects. A 50-year planning period was used to be compatible with the rest of the Platte River Study. The area of analysis was limited to the reach of the Platte River between the two gaging stations at Overton and Grand Island (fig. 1). The area extended outward from the river to a distance at which the effects of water management would be negligible during the 50-year period. This report does not consider the effect of water managment on the habitat areas directly, nor does it directly consider effects of additional ground-water diversions upstream from Overton. However, it does provide information that can be used with other reports in this study to do such an evaluation.

The primary objective of this substudy was to determine the effects of possible ground-water development between Overton and Grand Island on the streamflow of the Platte River. Secondary objectives were to compare the effects of possible ground-water developments to similar irrigation developments using surface water and to compare the effects of these possible developments, which are transmitted through the aquifer system to the river, to the effects of developments which would directly affect the incoming streamflow at Overton. This report is a brief discussion of a rather brief and general analysis for a topic that could involve considerably greater effort to evaluate in more detail.

BACKGROUND AND APPROACH

The hydrologic system in this reach of the Platte River is typical of the entire Platte River drainage system throughout the Great Plains. Surface water is hydraulically connected to the ground water in the adjacent aquifers. The diversion of streamflow for irrigation, the withdrawal of ground water for irrigation, the return flow of excess irrigation applications, and the ground-water use by native and agricultural phreatophytes are components of this highly complex and integrated hydrologic system. Within a certain area of influence controlled by geologic boundaries, ground-water withdrawals that are consumptively used will deplete the streamflow in the Platte River either by reducing return flow or by inducing infiltration from the river to the aquifer. Recharge in excess of withdrawals will augment streamflow either by increasing return flow or by reducing infiltration from the river to the aquifer.

Based on information available from previous studies, the study area was partitioned into subareas, each of which can be characterized by the response of the river to changes in water-management practices that are transmitted through the aquifer system. Scenarios of possible water-management alternatives then were selected, and the effects of those alternatives on the river were simulated.

DESCRIPTION OF STUDY AREA

The study area for this report is shown in figure 1. It includes those areas for which land-use data were available and where water use will affect the flows in the Platte River. Much of this area is on the south side of the Platte River where both the surface water and ground water flow away from the Platte River. This area is included in the study area because there is no hydrologic boundary which would prevent water withdrawals or accretions from affecting the flows of the Platte River. This area is generally flat. Normal precipitation is about 23 in/yr, with almost half of that occurring from April through June. The primary use of the land is for agriculture, with corn being the predominant crop.

The Platte River flows through this region, providing an important source of water for both agricultural use and for wildlife. The river-bottom area is wide, and the river generally is shallow and extensively braided in sandy channels through the bottom area. These features contribute to a closely connected stream-aquifer system. Other prominent surface waters in this region include the Wood River and the many irrigation canals that tend to parallel the Platte River.

Large volumes of ground water occur in the Quaternary deposits adjacent to the Platte River and in the underlying Tertiary Ogallala Formation. The Quaternary deposits include various units of alluvial and eolian deposits. The Ogallala Formation, which contains an extensive aquifer from Texas to South Dakota, underlies most of the Quaternary deposits in this area. Below the Ogallala Formation is the Cretaceous Pierre Shale or the Niobrara Formation, which serves as the bottom of the aquifer system.

All of these deposits can be considered a single unconfined aquifer system (Lappala and others, 1979, p. 18), consisting of clay, silt, sand, and gravel. The saturated thickness of the aquifer ranges from 100 to 360 ft. The transmissivity ranges from 5,000 to 30,000 ft^2/d, and the specific yield probably ranges from about 0.10 to 0.20.

Irrigation is an important aspect of agriculture in this area. Surface water diverted from the Platte River is delivered to the farms by extensive canal systems. In many areas, the water table is close enough to land surface for natural subirrigation to occur. In these areas, roots of the crops (or native riparian vegetation) grow deep enough to get water directly from the aquifer. In other areas, ground water is pumped for irrigation from wells using high-capacity pumps.

STREAM-AQUIFER INTERACTION

The effects of losses from the ground-water system by pumpage or subirrigation and the effects of gains by recharge from precipitation or excess irrigation applications are transmitted through the aquifer system to the river as accretions or depletions to streamflow. Withdrawals from the aquifer do not necessarily cause direct losses of water from the river; for example, ground-water withdrawals may not cause river water to enter the aquifer but rather may just reduce the amount of ground water that previously had been entering the river.

The magnitude and timing of the effects of these stresses (pumpage or recharge) which are transmitted

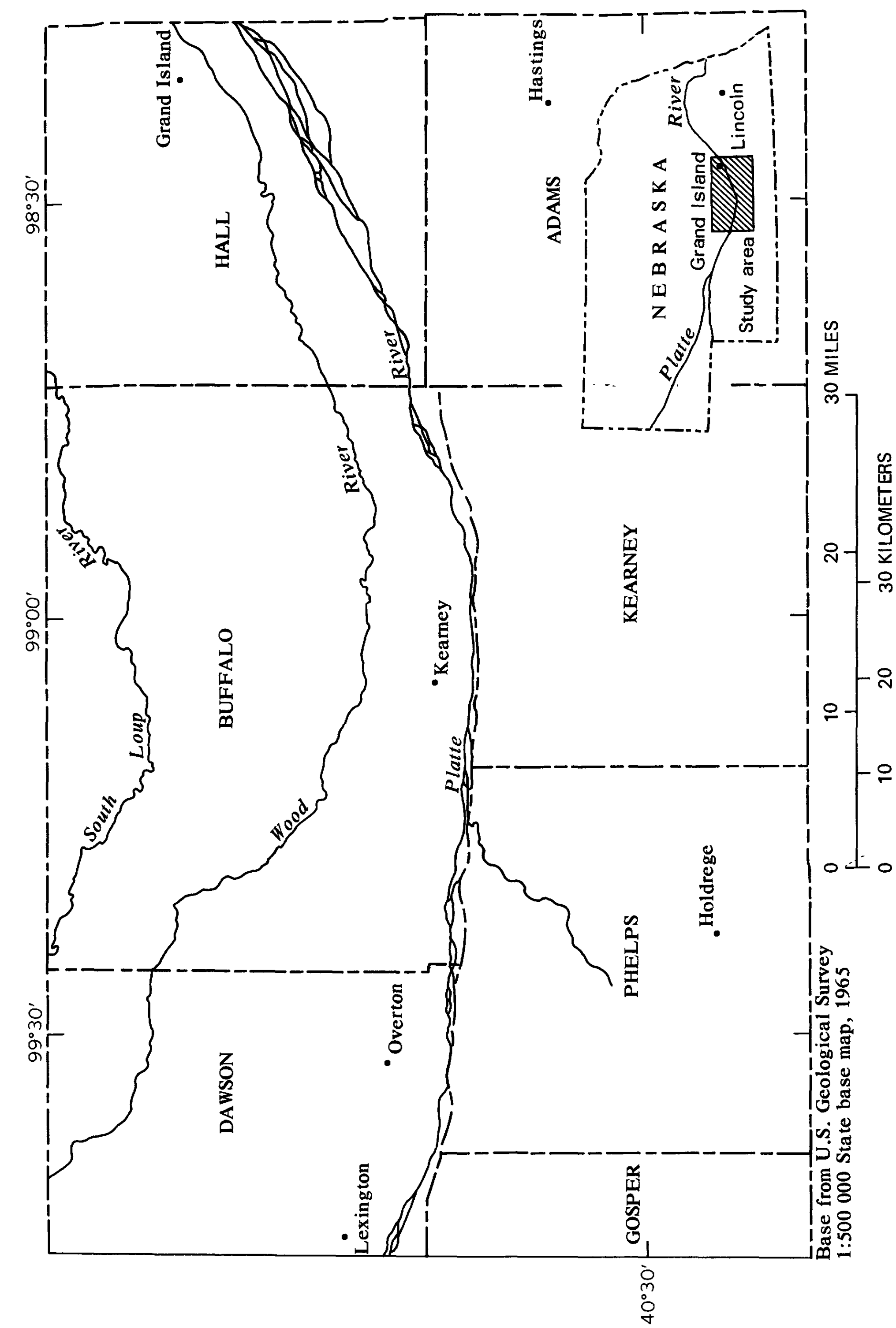


FIGURE 1.—Location of study area.

through the aquifer to the river depend upon the transmissive properties of the aquifer (transmissivity); the storage properties of the aquifer (specific yield for this water-table aquifer); the hydraulic connection between the stream and aquifer; and the distance from the point of stress to the stream. Procedures to describe these response functions can be derived from the theory of ground-water hydraulics. The general form of a response of a straight stream in perfect connection to an ideal aquifer to a stress on the ground-water system is:

$$q/Q=erfc\ \frac{x^2S_y}{eTt} \tag{1}$$

where:

q is the instantaneous rate of depletion or accretion from the stream measured at time t, in cubic feet per second;

Q is the rate of stress on the ground-water system, in cubic feet per second;

$erfc$ is the complementary error function;

x is the distance from the point of stress to the stream, in feet;

S_y is the specific yield of the aquifer under water-table conditions;

T is the transmissivity of the aquifer in feet squared per day; and

t is the time since the stress was commenced, in days.

The assumptions necessary in the derivation of this function and the definition of an ideal aquifer are:

(1) The aquifer is semi-infinite, homogeneous, and isotropic;
(2) the transmissivity is constant with time;
(3) the water is released instantaneously from storage;
(4) the stream is straight, hydraulically connected to the aquifer, and fully penetrating;
(5) the water temperature is the same in the stream and aquifer and is constant with time;
(6) the stress is continuous and steady; and
(7) the stress affects the entire saturated thickness instantaneously.

A curve illustrating this response function for a given set of parameters is shown in figure 2. This curve indicates that the rate of stream depletion (accretion) would be 25 percent of the pumping (injection) rate after 6 months, 50 percent after 18 months, and 75 percent after 80 months.

Equation 1 is typically integrated over time to evaluate the volume of stream response to the volume of the stress. The solution of this integration is:

$$\frac{v}{Qt}=\left(\frac{x^2S_y}{2Tt}+1\right)erfc\left(\sqrt{\frac{x^2S_y}{4Tt}}\right) - \sqrt{\frac{x^2S_y}{4Tt}}\frac{2}{\sqrt{\pi}}e-\left(\frac{x^2S_y}{4Tt}\right) \tag{2}$$

where v is the volume depleted from the stream through time t.

Jenkins (1968a) has developed a "lumped" parameter known as the SDF (stream-depletion factor), that uniquely characterizes a response curve. The SDF is equal to the distance squared times the specific yield divided by the transmissivity (x^2S_y/T) for the idealized assumptions stated earlier. Response curves of the integrated equation (2) for different SDF values are shown in figure 3. These curves indicate the percent of the volume pumped (or injected) that comes from (or goes to) the stream. Using an SDF value of 100 as an example, streamflow would be depleted by about 8 percent of the first month's pumpage, by about 40 percent of the first 6-months' pumpage, by about 65 percent of the first 30-months' pumpage, and by about 92 percent of the first 50 years of pumpage.

The SDF becomes a very important parameter when evaluating stream-aquifer interactions for large regions. Using a detailed, distributed parameter, digital ground-water flow model, arbitrary points within the model can be stressed and the response of the stream to those stresses can be simulated. Using a type-curve analysis similar to that used in fitting aquifer-test data to theoretical curves, a theoretical curve is fit to the simulated stream-depletion values and the respective SDF values are assigned to each of the points in the model. Thus all the vagaries of boundary conditions, variable transmissivities, and a sinuous river can be accounted for with the SDF parameter within the limits of resolution of the corresponding digital model.

The curves in figures 2 and 3 are for a continuous stress. A representation of the response data which proves more useful for analysis with time-varying stresses are discrete *unit* response functions (figs. 4–8) for unit periods of stress, such as a month. These step functions represent the percent by volume that stream depletion (or accretion) is of a monthly stress and the continuing future effects beyond the termination of the stress. Notice the differences between the magnitude of the peak of the response curves for different SDF values (see fig. 9, which demonstrates the differences in scales of figs. 4–8) and the differences in time when the peak occurs. Using an SDF value of 10, for example, streamflow would be depleted by about 50 percent of the

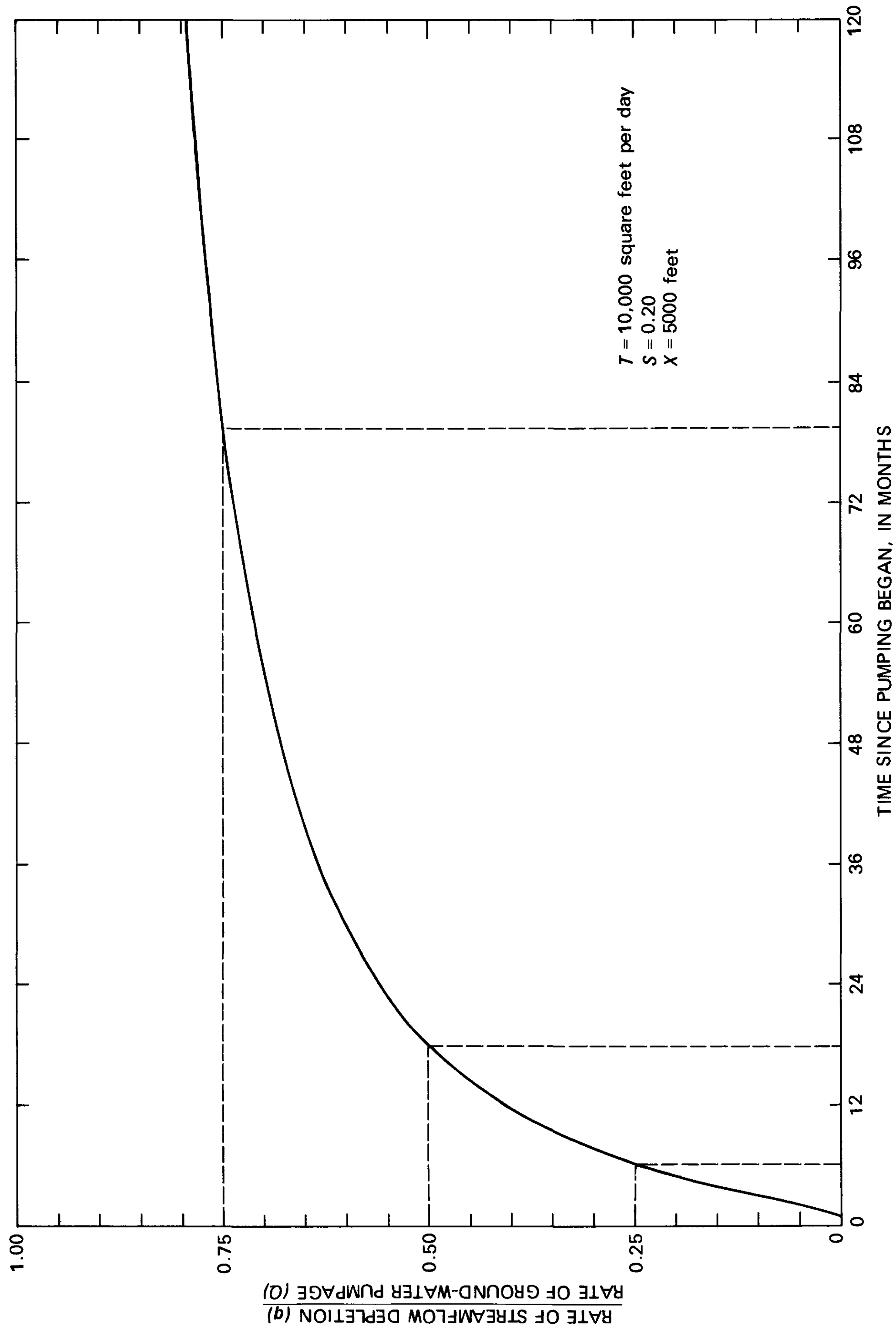
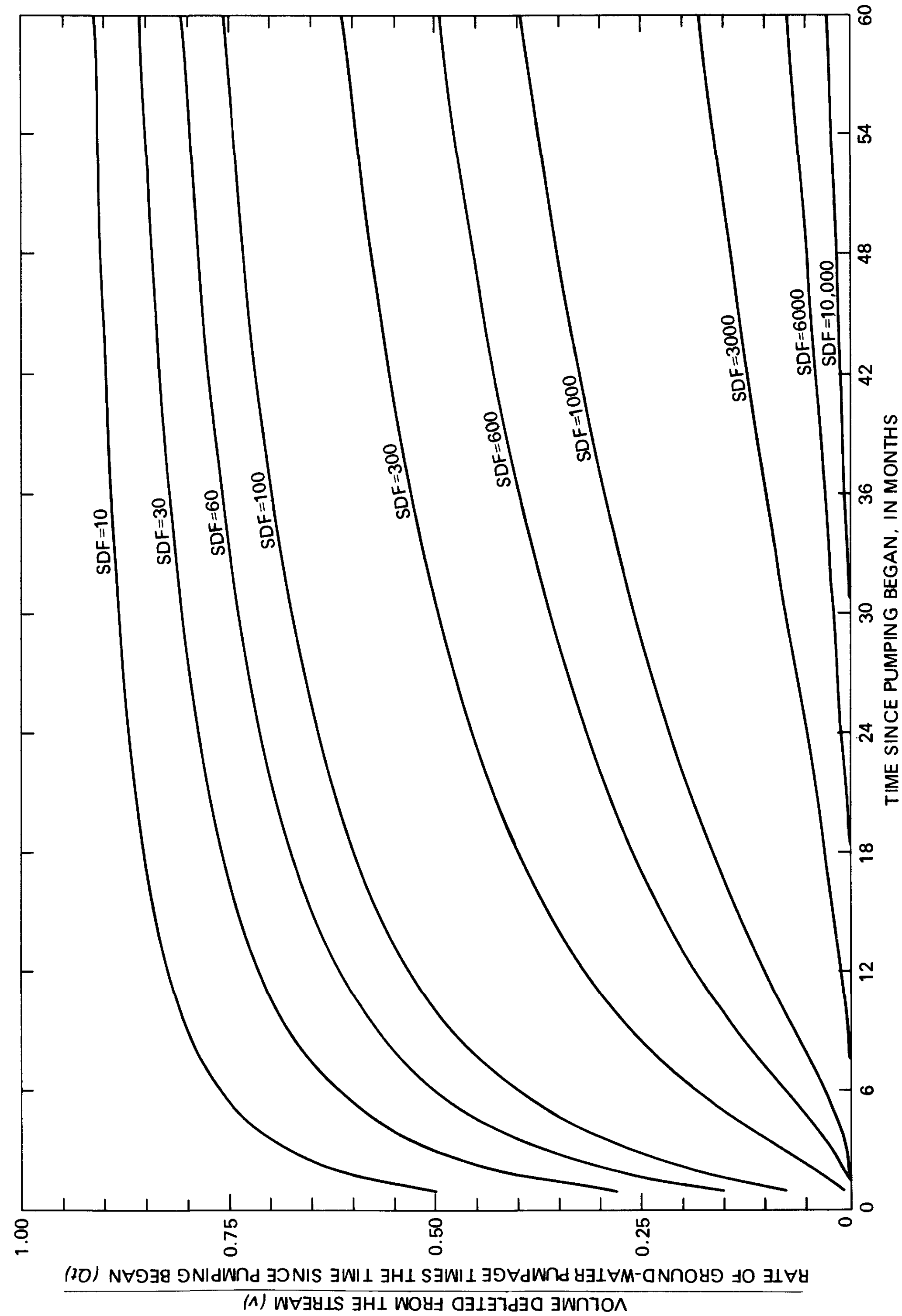


FIGURE 2.—Stream-aquifer response function.


RATE OF GROUND-WATER PUMPAGE TIMES THE TIME SINCE PUMPING BEGAN (Qt)
VOLUME DEPLETED FROM THE STREAM (v)
1.00
0.75
0.50
0.25
0
TIME SINCE PUMPING BEGAN, IN MONTHS
0
6
12
18
24
30
36
42
48
54
60
SDF=10
SDF=30
SDF=60
SDF=100
SDF=300
SDF=600
SDF=1000
SDF=3000
SDF=6000
SDF=10,000

A. Months

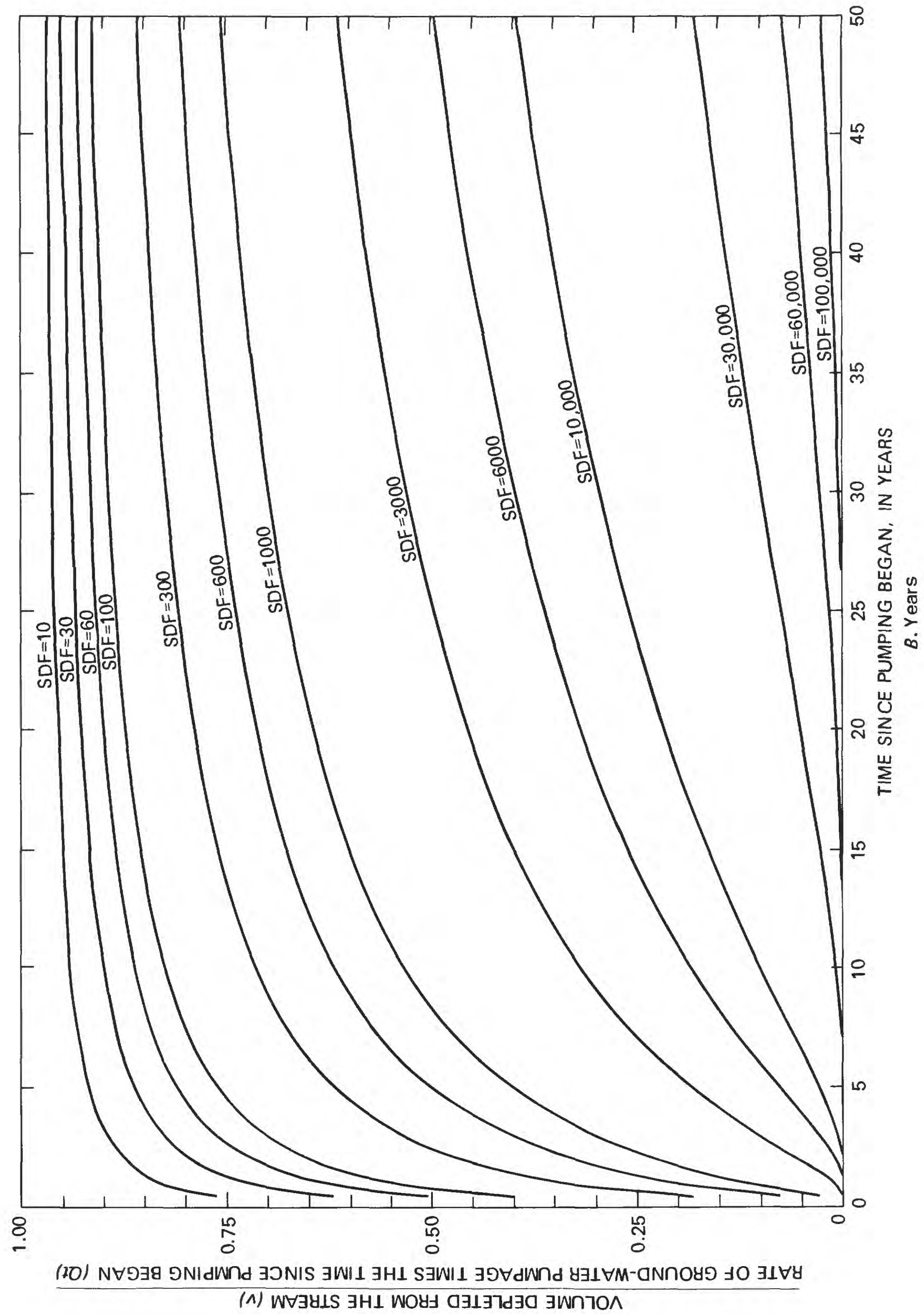


FIGURE 3.—Stream-depletion factor (SDF) response functions; *A*, Months; *B*, Years.

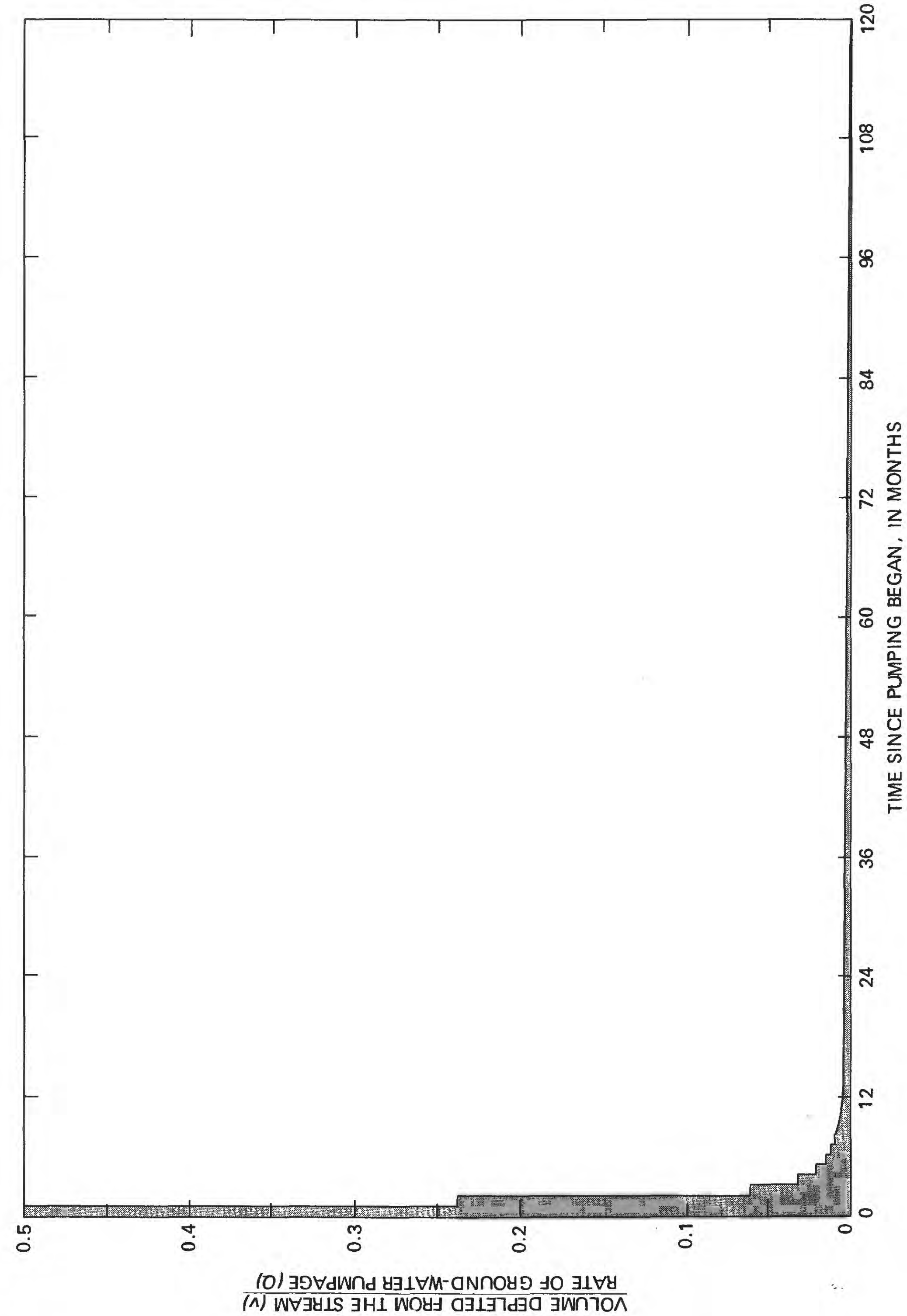


FIGURE 4.—Unit response function for stream-depletion factor (SDF)=10 days.

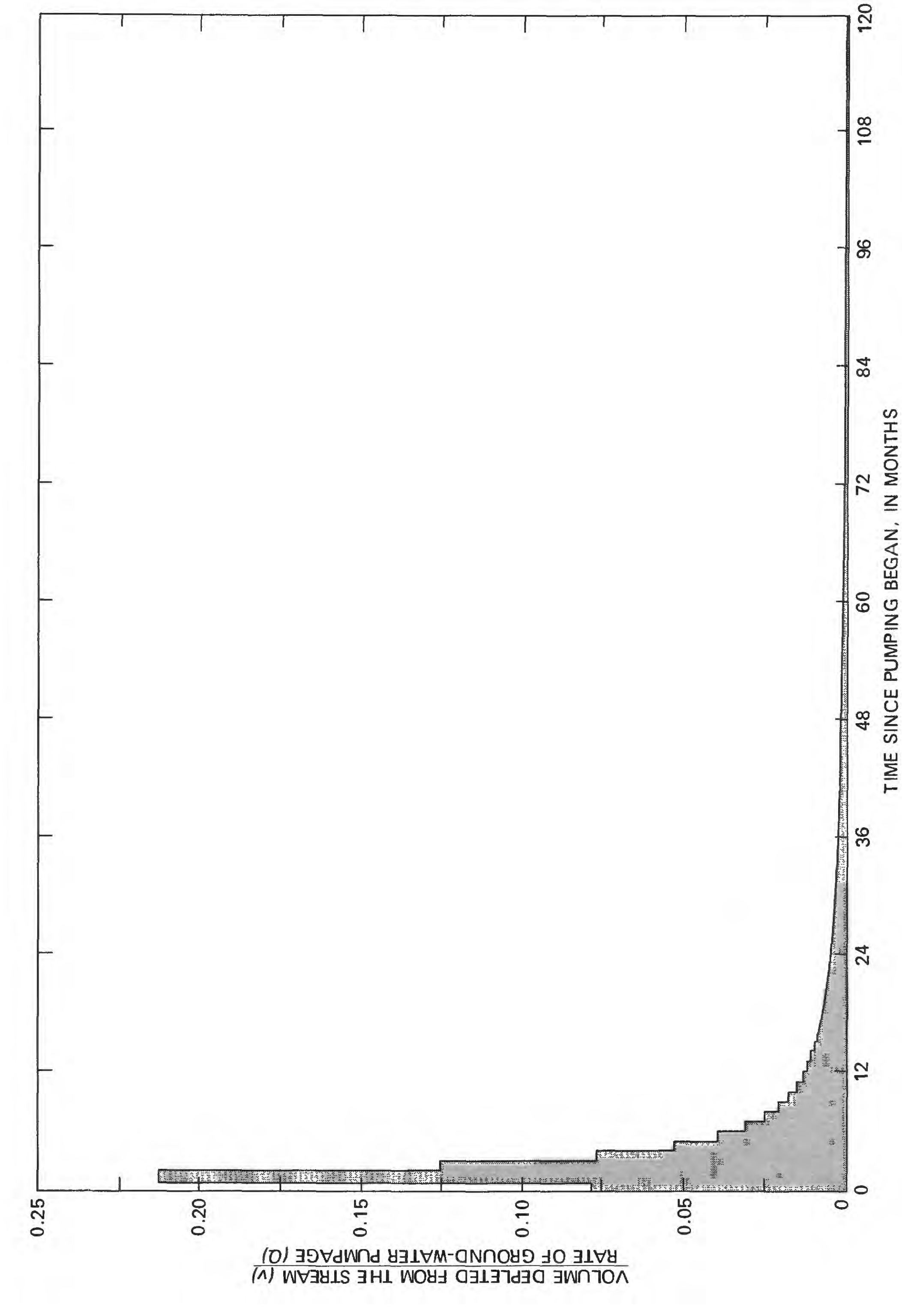


FIGURE 5.—Unit response function for stream-depletion factor (SDF)=100 days.

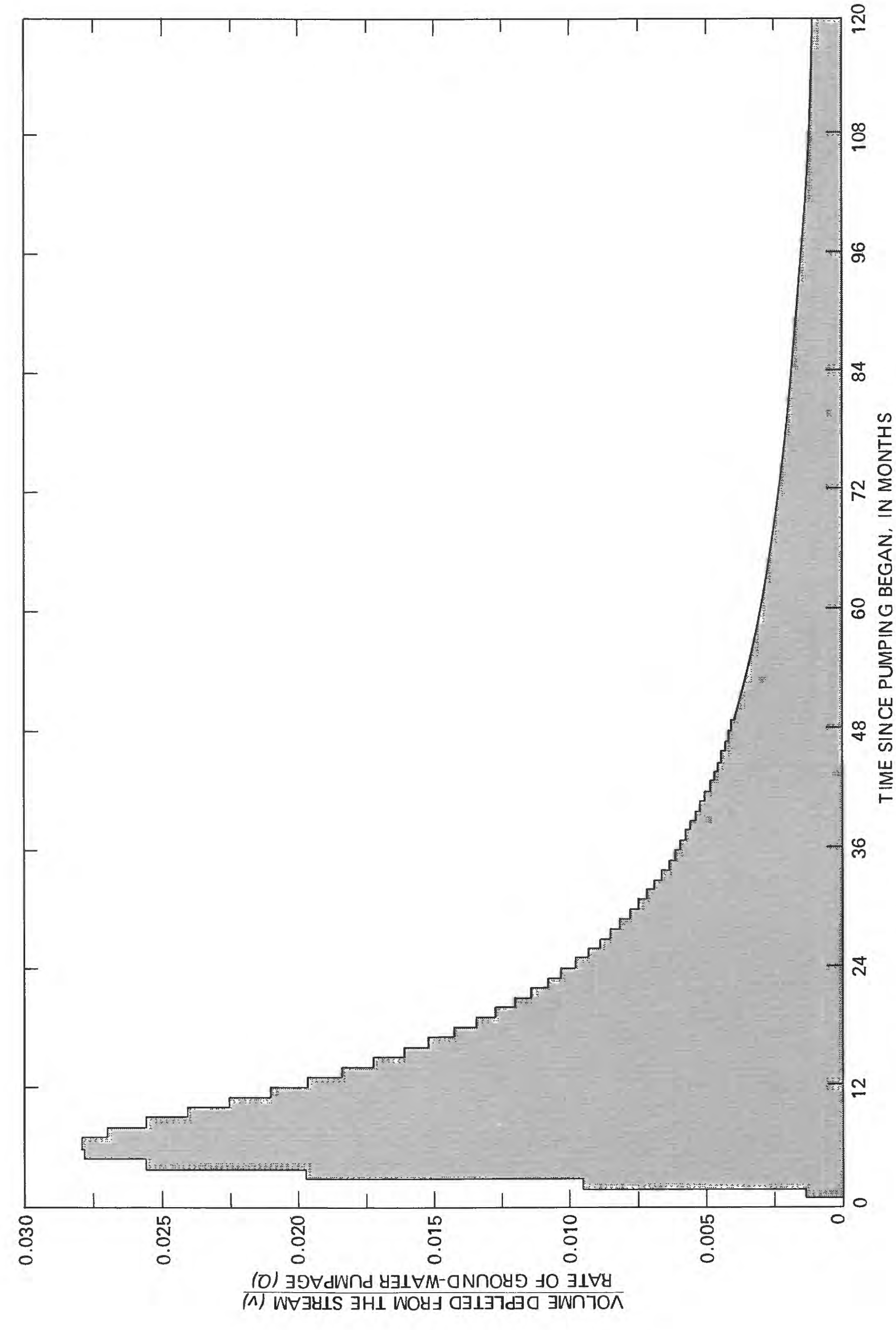


FIGURE 6.—Unit response function for stream-depletion factor (SDF)=1,000 days.

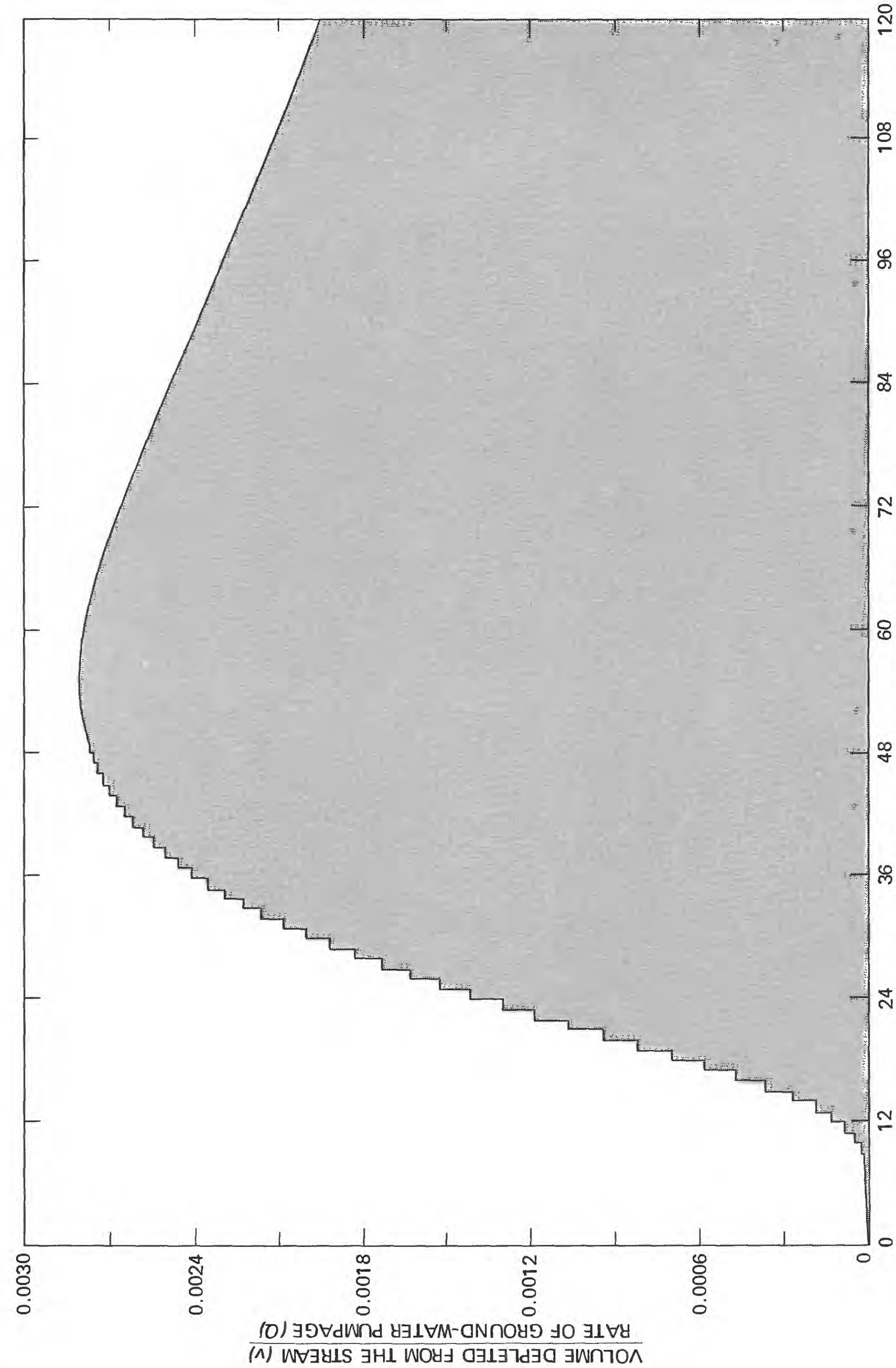


FIGURE 7.—Unit response function for stream-depletion factor (SDF)=10,000 days.

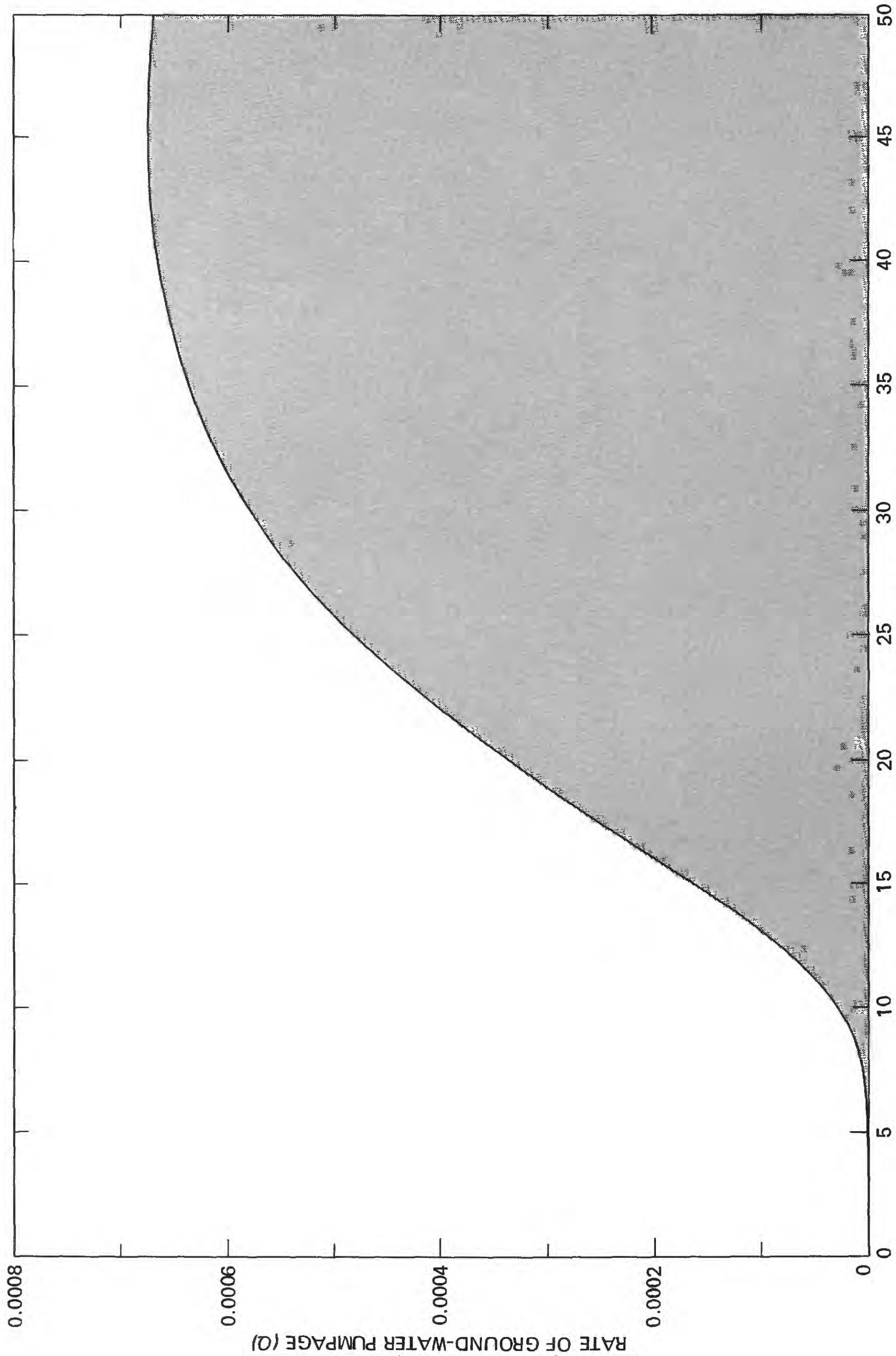


FIGURE 8.—Unit response function for stream-depletion factor (SDF)=100,000 days.

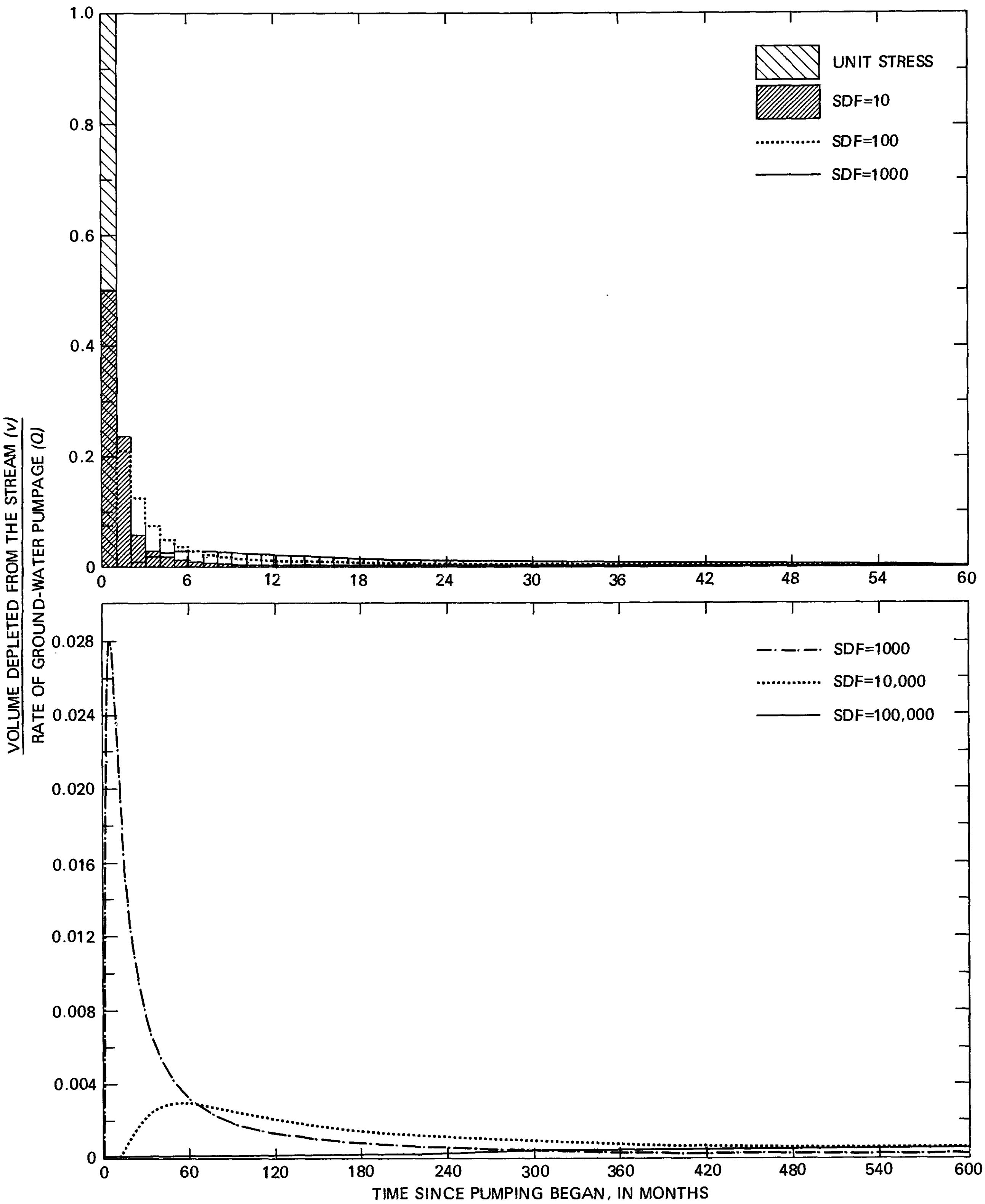


FIGURE 9.—Relative scales for various values of the stream-depletion factor (SDF).

monthly pumpage during the month that the pumpage occurred and by about 24 percent of the pumpage (which has now ceased) during the following month. On the other hand, for an SDF value of 1,000, the maximum monthly stream depletion would be only about 3 percent of the pumpage, and it would occur about 5 months after the pumpage had ceased. The extreme example is for an SDF of 100,000, in which the maximum monthly stream depletion would be only about 0.07 percent of the pumpage and would occur about 45 years after the 1 month of pumping.

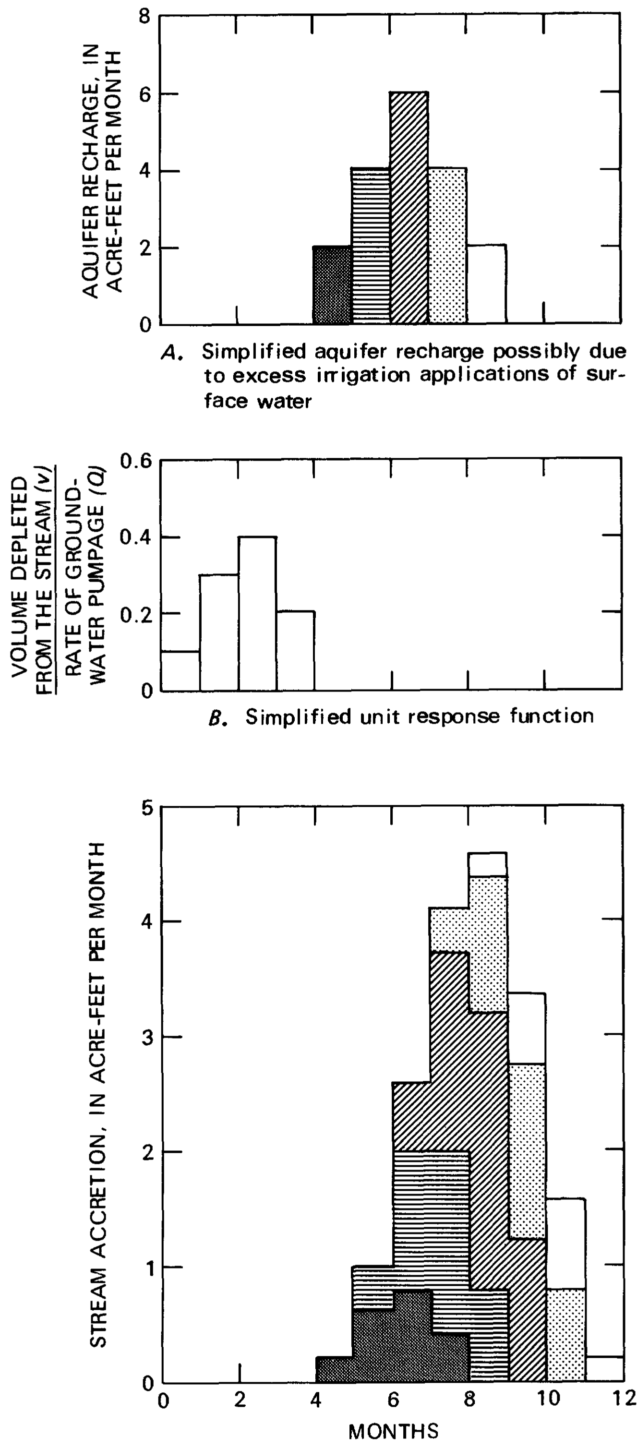
The unit response function $[U(k)]$ and a time series of aquifer stresses $[Q(k)]$ are used with the discretized version of the convolution equation (Eagleson and others, 1966, p. 756–757) to compute the time series of stream depletions (or accretions) $[q(i)]$ at time i:

$$q(i) = \sum_{k=1}^{i} Q(k) \cdot U(i-k+1). \tag{3}$$

This computation is shown in figure 10, where the time series of stream accretions due to aquifer recharge for each month are added to the stream accretions due to the aquifer recharge in each subsequent month, resulting in the total stream accretions.

COMPUTATION OF STREAM DEPLETIONS

The SDF values computed for this study were primarily based on the ground-water model used for the Missouri River Basin Commission Level B Study (Lappala and others, 1979). The model of the Middle Platte reach of the Upper Platte subbasin of the Level B Study extended east and west beyond the area of interest for this current study, using a constant grid network with nodes 2.5 mi by 2.5 mi. For the Level B Study, the southern extent of the modeled area was the approximate ground-water divide between the Platte River and the Republican River or the Blue River. To account for this arbitrary boundary, the Level B model maintained a constant gradient along the boundary. The effect of this assumption was simulation of equal rates of development (withdrawal or recharge) on both sides of the boundary of the modeled area. This current study considered a more realistic distribution of potential development in the area south of the ground-water divide and thus could not use the arbitrary boundary previously used for the Level B Study. The constant gradient boundary conditions in the Level B model were removed and the data set for that model was used with another similar ground-water flow model (Taylor, 1971) for this study.



C. Stream accretion due to A. convolution of aquifer recharge and B. unit response

FIGURE 10.—Illustration of the convolution of aquifer recharge with unit response function to yield stream accretion.

Taylor's model simulates the stream response to a single pumping well, and fits the simulated response to the theoretical response at the point where the response is 28 percent of the pumpage. This point is where the pumping period is equal to the SDF value on the theoretical curve (see Jenkins, 1968b). The SDF values for the study area south of that covered by the Level B data set were computed for three cross sections. Aquifer characteristics were estimated based on the geologic cross sections published by Johnson (1960). These cross sections were extended south beyond the limit of land-use data such that the arbitrarily chosen no-flow boundary would have minimal effect on the SDF values computed along the cross section. The SDF values were then contoured and bands of equal SDF values were assigned the mean SDF value between the contour intervals (fig. 11).

Data enumerating the total acreage, number of wells, acreage irrigated by surface water, soil type, irrigable acreage, and subirrigated acreage for quarter townships (5,760 acres for most quarter townships) were provided by the U.S. Bureau of Reclamation (F. J. Otradovsky, written commun., 1981). An SDF-band value was assigned to each quarter township. When discretizing the area by quarter townships, the distances were such that no SDF value less than 1,000 existed except within quarter townships which intersected the river. An assumed distribution of SDF values was assigned to each quarter township which is intersected by the river. This assumed distribution was based on an average location of the river within a quarter township. This assumed distribution was the same for every quarter township which intersected the river, and thus the acreages and number of wells for some of the bands in table 1 are identical.

TABLE 1.—*Well and acreage data by stream-depletion factor (SDF) bands*

Band	SDF value	Total acreage	Wells	Acreage irrigated with surface water	Irrigable acreage	Sub-irrigated acreage
1	10	17,000	114	314	7,400	15,200
2	30	8,800	55	157	3,700	7,600
3	60	8,800	55	157	3,700	7,600
4	100	19,000	123	340	8,000	16,500
5	300	29,400	191	523	12,300	25,400
6	600	29,400	191	523	12,300	25,400
7	1,000	35,000	248	419	17,400	28,200
8	3,000	176,000	1,260	6,630	102,000	59,200
9	6,000	97,900	719	1,210	64,400	21,200
10	10,000	248,000	1,600	29,700	182,000	8,900
11	30,000	488,000	2,480	62,400	309,000	1,600
12	60,000	445,000	1,990	3,220	190,000	6,400
13	100,000	319,000	954	926	77,200	8,200

To compute the depletion of streamflow from the Platte River between the Overton gage and Grand Island gage due to stresses in the aquifer, the net ground-water recharge for the area within each SDF band was calculated. A computer model (see appendix) was developed to calculate the monthly net ground-water recharges within each SDF band and then convolute them with their respective response functions. The amount of net ground-water recharge in an area is a function of the soil type, available soil moisture, the amount of irrigation water applied and precipitation on the land surface, the plants' consumptive use, and the amount of water withdrawn from the aquifer. To determine the amount of water recharged to or withdrawn from the aquifer, four basic land-irrigation categories were identified within the study area: Dryland (for nonirrigated land), irrigated land using surface water, irrigated land using ground water, and subirrigated areas.

The amount of land characterized by each of these land categories was determined for each SDF band and each of four soil types (see table 2 for brief description) from the data which were summarized in table 1. Net ground-water recharge rates (in feet per month) were computed for each of the four soil types by the U.S. Bureau of Reclamation (Fred Otradovsky, written commun., 1981), using a soil-moisture model. Lappala and others (1979) described the soil-moisture model as follows:

> Net ground-water recharge was computed with a water-balance model of the soil zone developed by the Nebraska Reclamation Office, U.S. Bureau of Reclamation, Grand Island, Nebr. The model operates on a monthly basis and is adapted from the daily irrigation scheduling program developed by Jensen and others (1969). The soil zone was modeled as a lumped system for a given topography, soil type, and crop distribution. Inputs and outputs from the soil zone are shown in figure 12. Inputs to the model are monthly values of precipitation and potential evapotranspiration (ET). Potential ET was computed using the Jensen-Haise method (Jensen and others, 1969). Runoff was abstracted from precipitation using monthly rainfall-runoff relationships derived from data obtained by the Agricultural Research Service at Rosemont, Nebr. (U.S. Department of Agriculture, 1956–68). These relationships considered soil type, slope, crop cover, and farming practices.
>
> Outflow from the soil zone consisted of gravity drainage and ET. Gravity drainage, or assumed recharge to the water table, occurred when infiltration from precipitation and applied irrigation water exceeded ET plus soil-moisture-retention capacity. Net ground-water recharge for land irrigated with ground water was equal to recharge from precipitation plus irrigation seepage minus total ground-water withdrawal. For land irrigated with surface water, net ground-water recharge was equal to recharge from precipitation plus seepage losses. Potential ET was computed for Grand Island, Nebr., by using air temperature and solar radiation (Jensen and others, 1969). Relative humidity, elevation, and crop type were used to adjust potential ET to obtain actual consumptive use. Four major crop types were used for this study: Row crops, small grains, alfalfa, and pasture. Annual net recharge to the water table and ground-water withdrawals were computed using typical cropping patterns for these crops under dryland conditions and irrigation with ground water and surface water.

Annual average net ground-water recharge rates for each soil type and land category computed from these data are shown in table 2. Data provided by the U.S. Bureau of Reclamation (table 1) had to be supplemented with additional soil data and well-pumping data. Soil types for much of the southern part of the study area

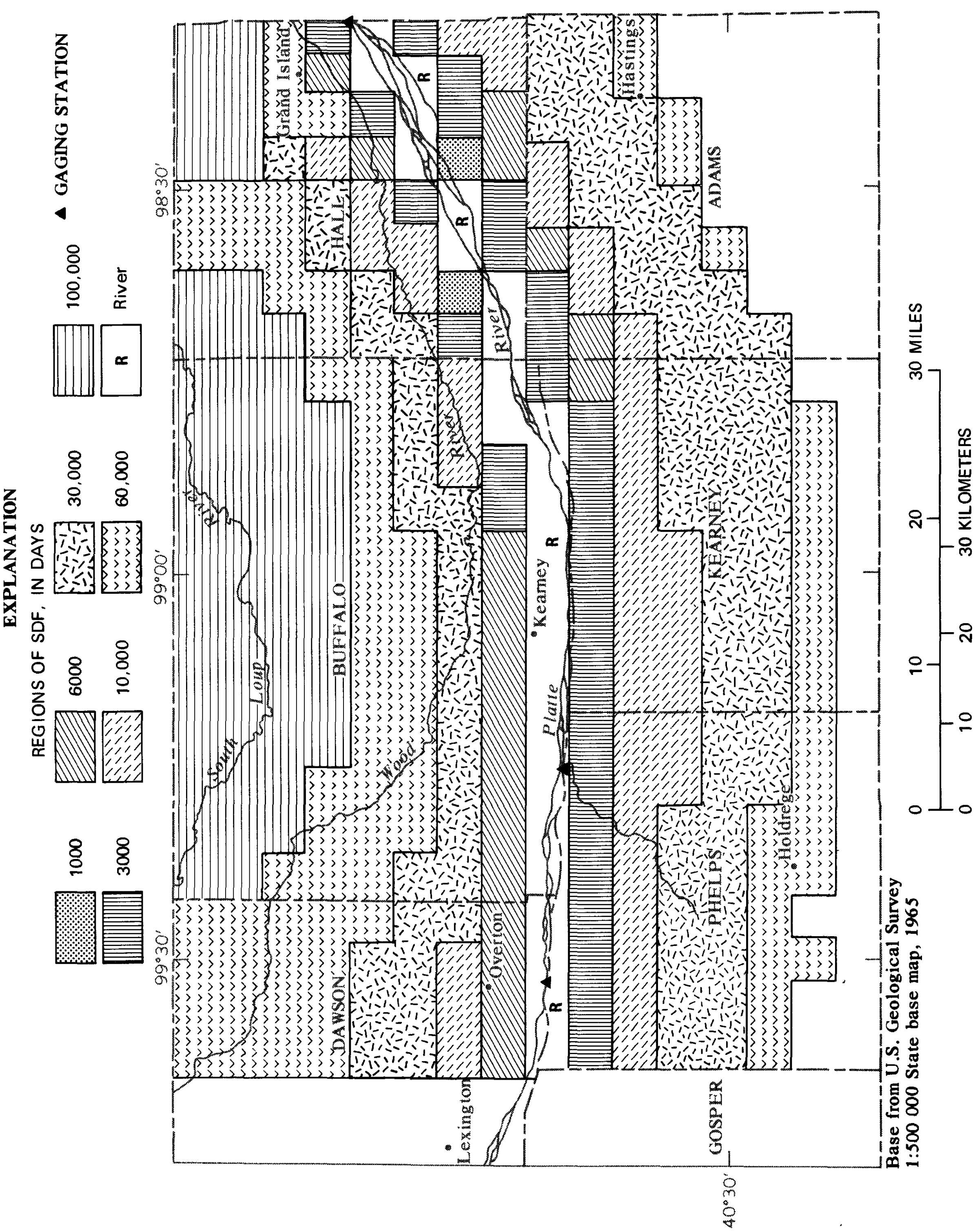


FIGURE 11.—Stream-depletion factor (SDF) regions, in days.

TABLE 2.—*Average net ground-water recharge rates, by irrigation category and soil type, 1941-77*

[Computed from U.S. Bureau of Reclamation soil-moisture model. Data are in feet per year]

Soil type	Dryland	Land irrigated with		Subirrigated land
		Ground water	Surface water	
Bottomland --	0.27	−0.42	1.10	−1.05
Terrace land --	.13	−.47	.62	----
Silty uplands -	.13	−.81	.56	----
Sandy uplands	.40	−.27	.83	----

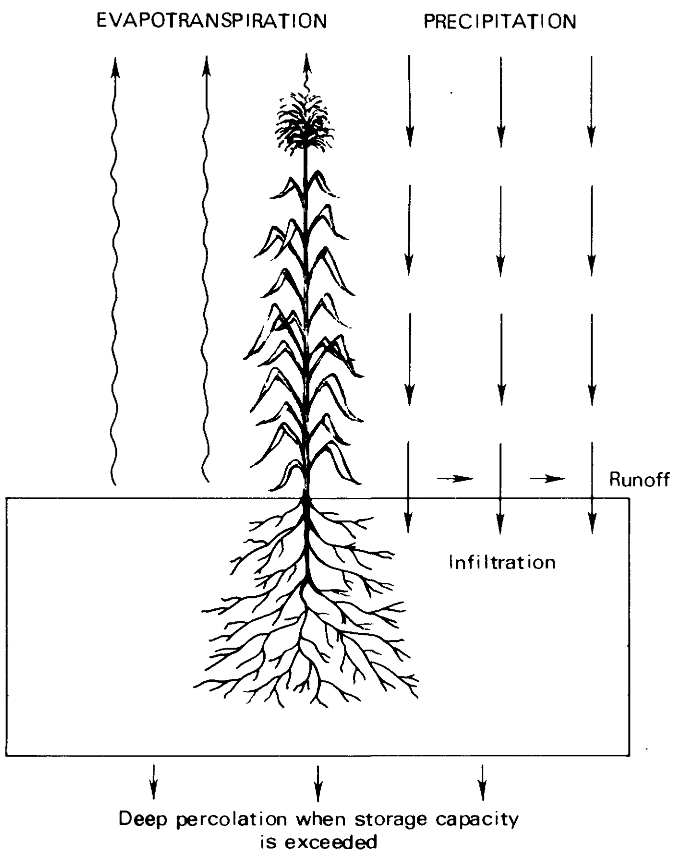


FIGURE 12.—Simulated components of the soil zone.

were assigned using the Soil Conservation Service maps for Phelps (U.S. Department of Agriculture, 1973) and Adams (U.S. Department of Agriculture, 1974) Counties. To compute acreage irrigated by ground water, the acreage irrigated per well was needed. This acreage value was assumed to vary according to SDF band and county (table 3) and was computed to match countywide data provided by the U.S. Bureau of Reclamation.

The 37 years of net ground-water recharge rates provided by the U.S. Bureau of Reclamation had to be extended to provide the needed 50 years of data. This extension was computed by multiple regression using two terms for the sine and cosine of time to compute a seasonality factor and monthly precipitation at

TABLE 3.—*Acres irrigated per well, by SDF band and county*

[SDF, stream-depletion factor; USBR, U.S. Bureau of Reclamation]

SDF band	Acres north of river	Acres south of river
1-6 ----	40	40
7-9 ----	40	80
10-13----	50	100

County	Acres computed using SDF band data	Acres computed using USBR county data
Adams ----	98	92
Buffalo ----	47	61
Dawson ---	46	46
Hall ------	47	56
Kearney ---	93	92
Phelps ----	93	77

Kearney. The model then was run for two consecutive 50-year periods to generate estimates of current streamflow depletions. The first 50-year sequence (an approximation of 1880-1930 conditions) was based on the assumption that there was no ground-water pumpage, no surface-water irrigation on the south side of the river, and that all of the quarter townships intersected by the river were naturally subirrigated. Also, subirrigated acreage was increased from current conditions in all other SDF bands. The second 50-year sequence (an approximation of 1930-80 conditions) was based on the assumption of instantaneous implementation of the Tri-County project, which is on the south side of the river and accounts for most of the acreage irrigated by surface water in the study area. The number of wells was assumed to increase linearly from zero to the present total, and the number of subirrigated acres was assumed to decrease linearly to the present number. Estimates of the net ground-water recharge over the study area and the resultant stream depletion are shown in figure 13. Estimates of streamflow depletion were computed by averaging the last 5 years of data and are shown on the first line of table 4. The average stream depletion of 32, 300 acre-ft/yr compares favorably with the 38,800 acre-ft/yr computed for the 1931-78 point-flow study of the U.S. Bureau of Reclamation (F. J. Otradovsky, written commun., 1981).

Four water-management alternatives for the area between Overton and Grand Island were simulated to identify possible ranges of future streamflow depletions: (1) Continue current management practices, (2) irrigate all remaining irrigable land with surface water, (3) irrigate all remaining irrigable land with ground water, replacing areas of subirrigation, and (4) irrigate all remaining irrigable land with ground water, without replacing subirrigated areas. Each of these conditions was assumed to start instantaneously and was modeled for a 50-year period following the 100-year sequence discussed earlier. The distribution of acreage, the average stream depletion, and the average monthly stream

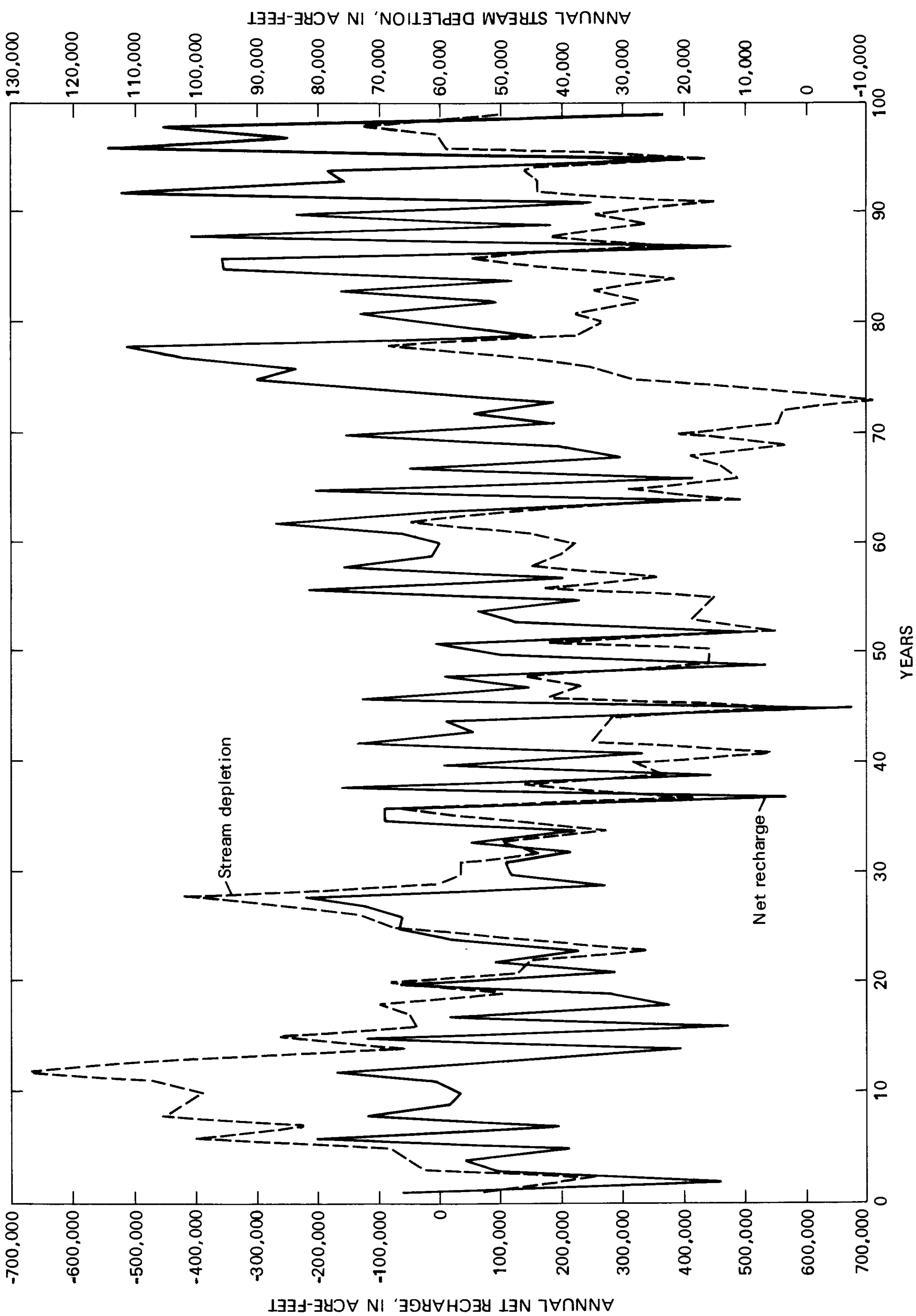


FIGURE 13.—Annual net ground-water recharge and annual stream depletion.

TABLE 4.—*Acreages and stream depletion for current and predicted conditions*

Water management activity	Areas, in acres				Average streamflow depletion for the last 5 years, in thousands of acre-feet													50-year average
	Dryland	Surface-water irrigated	Ground-water irrigated	Subirrigated	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total	
1930–1980 conditions.	(1)	(1)	(1)	(1)	3.9	3.1	2.3	0.9	1.1	3.2	7.0	9.1	8.8	7.9	6.4	5.1	59.1	32
Continue current practices.	944,000	106,000	617,000	197,000	10.4	9.5	8.8	7.4	7.6	9.6	13.3	15.4	15.0	14.1	12.6	11.4	135	125
Surface-water development.	716,000	378,000	617,000	154,000	3.1	2.6	1.9	.5	.4	1.8	4.4	5.9	5.8	.3	4.4	3.7	39.8	53.2
Ground-water replacing subirrigation.	742,000	106,000	889,000	128,000	16.6	15.8	15.1	13.5	13.3	15.0	19.2	21.8	21.2	20.0	18.6	17.6	207.7	174
Ground-water development.	716,000	106,000	889,000	154,000	16.9	16.0	15.4	13.8	13.6	15.3	19.6	22.2	21.6	20.4	19.0	17.9	212	177

[1]Varies with time.

depletion occurring in the last 5 years of the 50-year sequence are shown in table 4 for each alternative.

The four alternatives simulated resulted in a range of stream depletions. If the current water-management practices continue, the predicted 50-year average stream depletion would be 125,000 acre-ft/yr. If the available 270,000 acres of irrigable land were irrigated with some imported source of water, the average depletions would be reduced to 53,200 acre-ft/yr. If that same acreage were irrigated with ground water, replacing where possible subirrigated acreage, the depletions would average 174,000 acre-ft/yr. If the existing subirrigated areas were not replaced by the new irrigated acreage, the stream depletion would average 177,000 acre-ft/yr.

EFFECTS OF WATER-MANAGEMENT ALTERNATIVES ON STREAM STAGE

Changes in the streamflow and stage of the Platte River will affect ground-water levels in wildlife-refuge areas along the Platte River (Hurr, 1981). To relate the effects of changes in stream discharge due to management practices to the stream stage along the habitat area, a relationship between stream discharge and stream stage was developed. The stage-discharge rating tables for the gaging stations, Platte River near Cozad, near Overton, near Odessa, and near Grand Island were all fit to regression lines. The general form of the equation is:

$$h=aQ^b \tag{4}$$

where:

h is river stage above zero flow, in feet;

Q is river discharge, in cubic feet per second; and

a and b are regression coefficients.

The relationship for the Cozad station differed from the other sites because two channels are present there, but the regression coefficients for the other sites (table 5) were remarkably similar. Based on these results, a generalized description of the stage-discharge relationship for the habitat area was modeled as:

$$h=0.033Q^{0.5}. \tag{5}$$

TABLE 5.—*Regression coefficients for stage-discharge relationships for the Platte River*

Station	Regression coefficients a	Regression coefficients b
Platte River near Overton	0.038	0.479
Platte River near Odessa	.040	.484
Platte River near Grand Island	.020	.549
Platte River near Cozad (channel 1)	.414	.333
Platte River near Cozad (channel 2)	.186	.382

As a tool to evaluate the effects of various water-management alternatives, a frequency curve of predicted stream stage along the habitat area was computed. The historical streamflow data for the Platte River near Overton were used for the period 1941–77. To extend this record to the same 50-year sequence used for the net ground-water recharge rates (see section on "Computation of Stream Depletions"), the monthly flows were regressed with the monthly flows for the South Platte River at Julesburg, Colo. Historically, flow diversions between the gages near Overton and Grand Island have been made by the Kearney Canal and Elm Creek Canal. The Elm Creek Canal, abandoned in 1963, was not considered in this analysis of future conditions. Much of the water diverted to the Kearney Canal is used for power production and is returned to the river. The net amount diverted, as modeled, was based on the monthly average data provided by the U.S. Bureau of Reclamation point-flow study (F. J. Otradovsky, written commun., 1981). Thus the streamflow used to compute the frequency curve of stream stage along the habitat area is the historical Overton streamflow (1,270 ft^3/s average), less the average Kearney Canal diversion (23,000 acre-ft/yr), less the stream depletion computed for each water-management activity (see table 4) for 50-year average. The frequency curves were computed not only for the entire year (fig. 14), but also for the different "hydrologic seasons" applicable to the habitat area. These seasons include September through February (fig. 15), March through April (fig. 16), and May through August (fig. 17). As can be seen in these figures, the various management alternatives have only minimal effect on the stage of the river.

Some hypothetical water-management alternatives which would affect streamflow directly were selected to compare their effects with the effects of the four water-management alternatives previously discussed. The possible water-management alternatives which affect the upstream inflow to the study area include: (1) Increase current flows in the Platte River by importing the water needed to irrigate 100,000 acres (average flow is 1,610 ft^3/s); (2) decrease current flows in the river by diverting the water needed to irrigate 100,000 acres (simulated flow is 240,000 acre-ft/yr; average flow is 1,040 ft^3/s); and (3) decrease current flows in the river by storing or diverting all monthly flow that exceeds 2,000 ft^3/s (average flow is 1,100 ft^3/s). All of these flows were adjusted by subtracting the monthly average Kearney

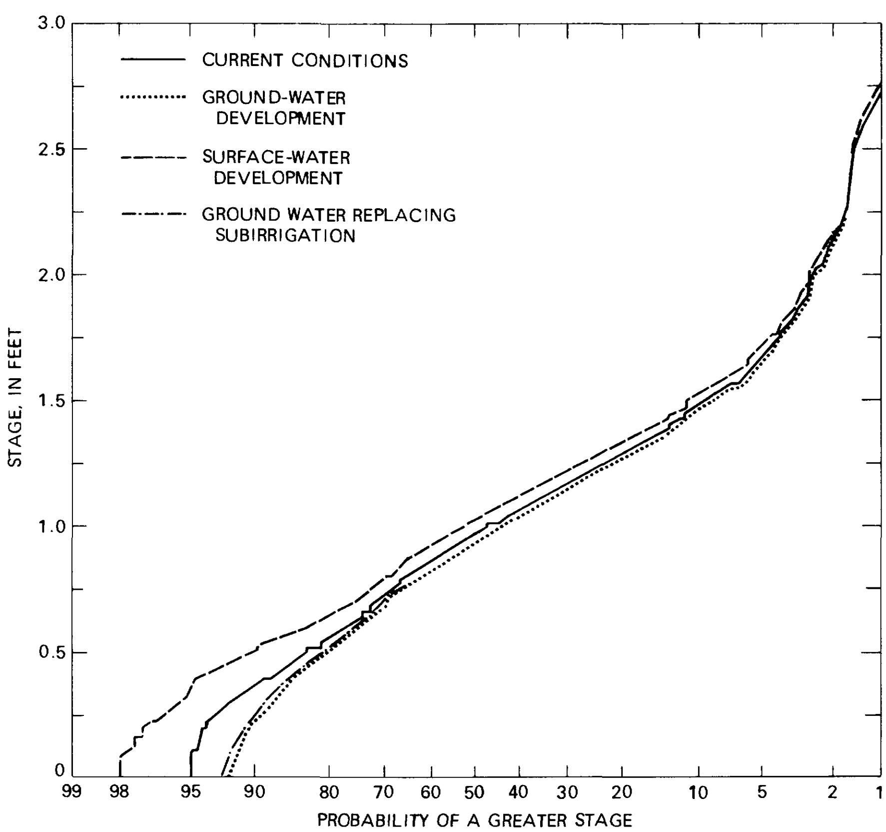


FIGURE 14.—Annual stream-stage frequency curves for four water-management alternatives affecting stream depletion.

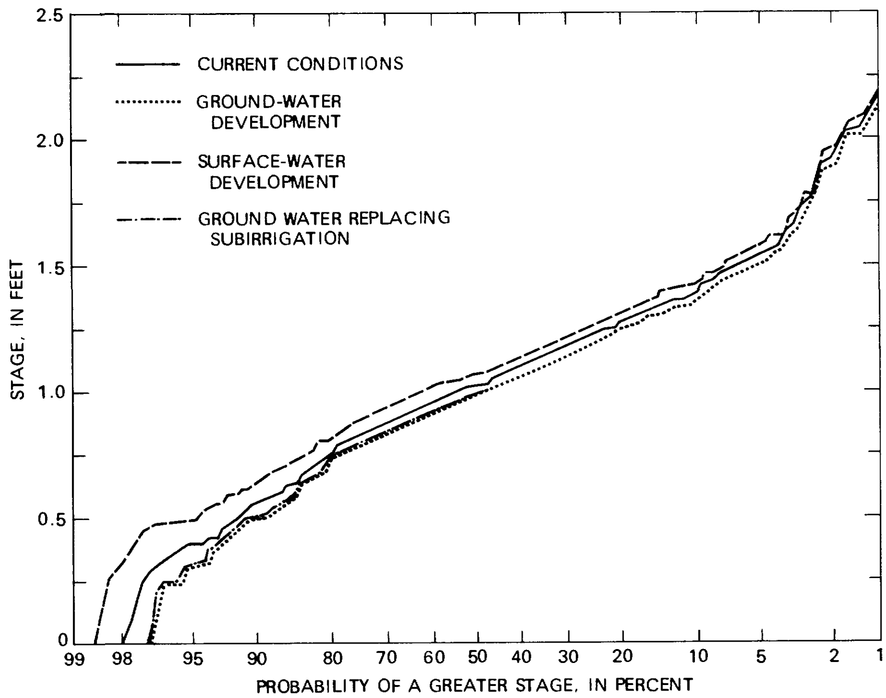


FIGURE 15.—September through February stream-stage frequency curves for four water-management alternatives affecting stream depletion.

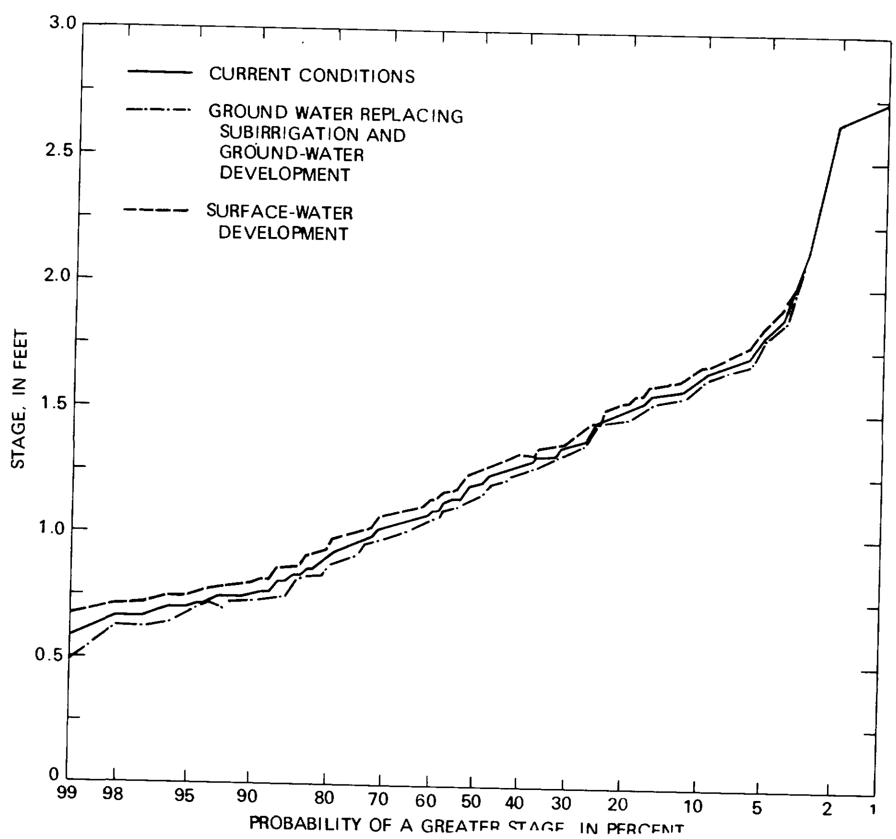


FIGURE 16.—March through April stream-stage frequency curves for four water-management alternatives affecting stream depletion.

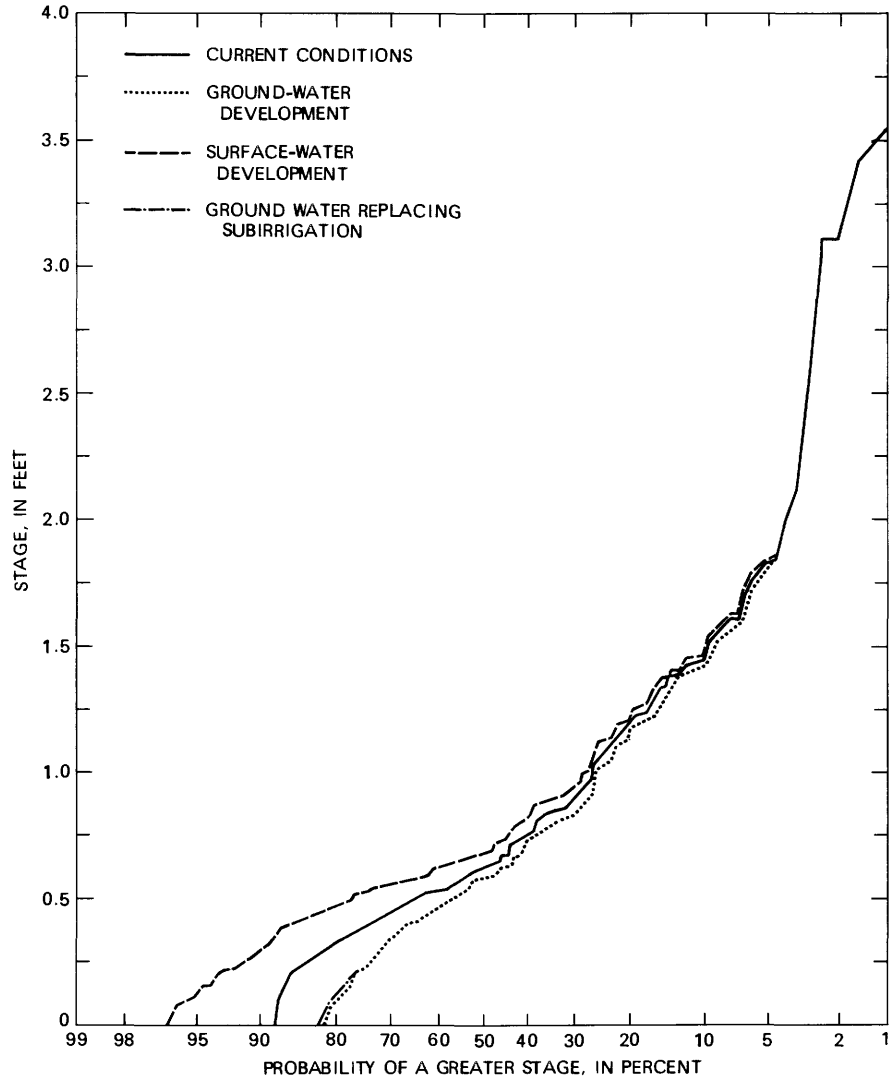


FIGURE 17.—May through August stream-stage frequency curves for four water-management alternatives affecting stream depletion.

Canal diversion and the predicted stream depletion based on current conditions, previously discussed in the section on "Computation of Stream Depletions," to compute the frequency curves of stream stage. The annual frequency curves are shown in figure 18, and the frequency curves for the three hydrologic seasons—September through February, March through April, and May through August—are shown in figures 19, 20, and 21, respectively. Though no quantitative analysis of the stage-frequency curves was made, it is obvious that there is a much greater deviation among these sets of curves than for the previous sets of curves.

CONCLUSIONS

The effects of water-management practices in the area of the Platte River between Overton and Grand Island caused an average of about 32,300 acre-ft/yr of simulated stream depletion over the last 50 years. This depletion would increase to about 124,900 acre-ft/yr over a 50-year period, even if no changes occur in the water-management activities due to the delayed effects of the historical increase in ground-water pumpage to the current level. Adding about 270,000 acres of new surface-water irrigated acreage would reduce the depletions to

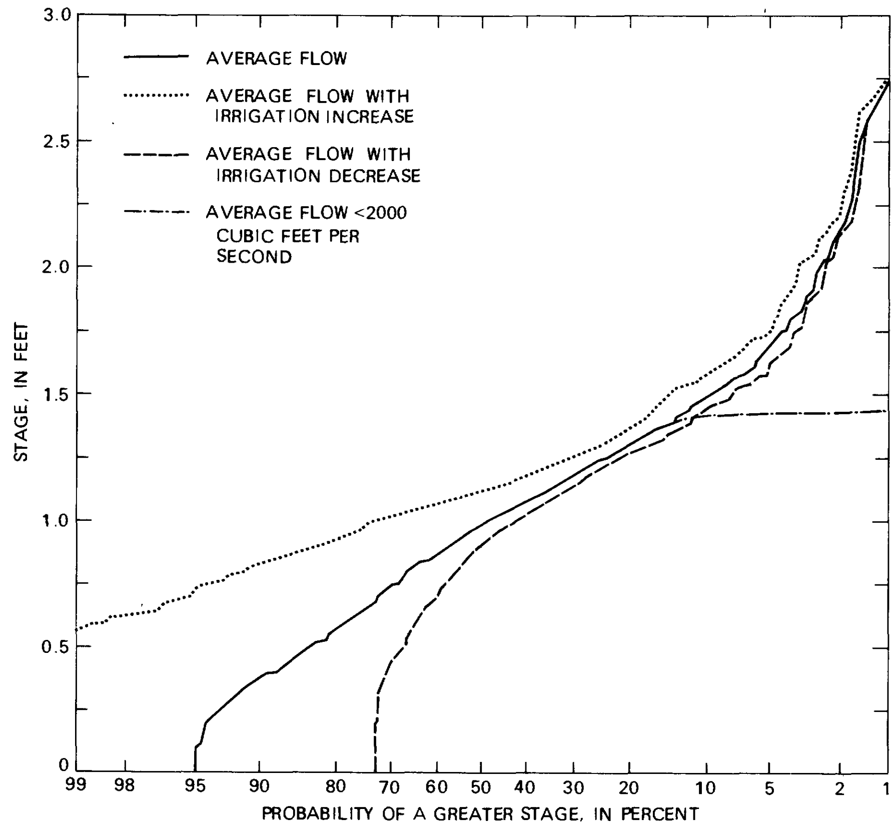


FIGURE 18.—Annual stream-stage frequency curves for four water-management alternatives directly affecting upstream flow.

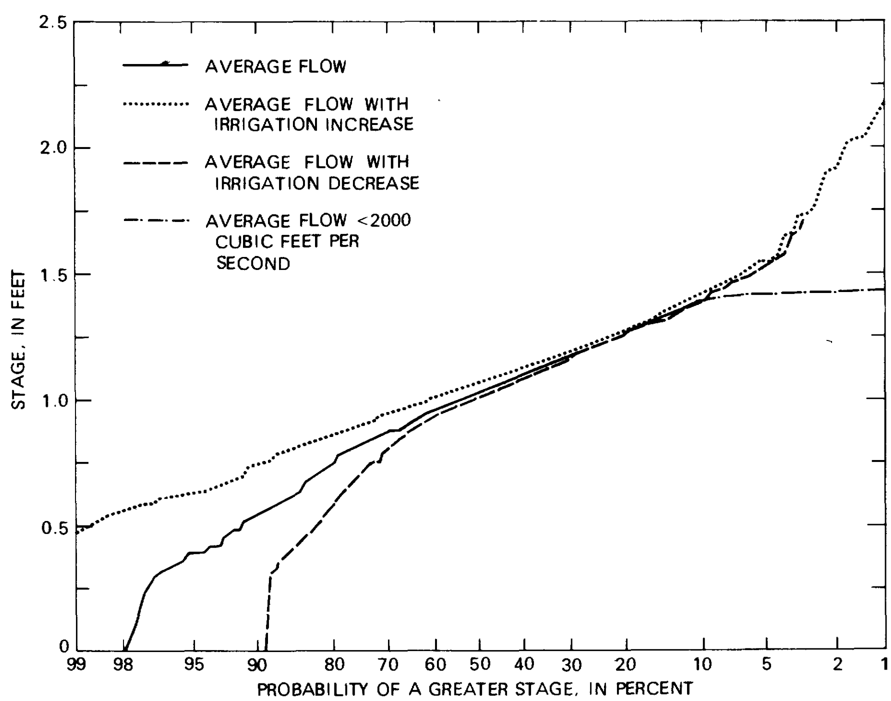


FIGURE 19.—September through February stream-stage frequency curves for four water-management alternatives directly affecting upstream flow.

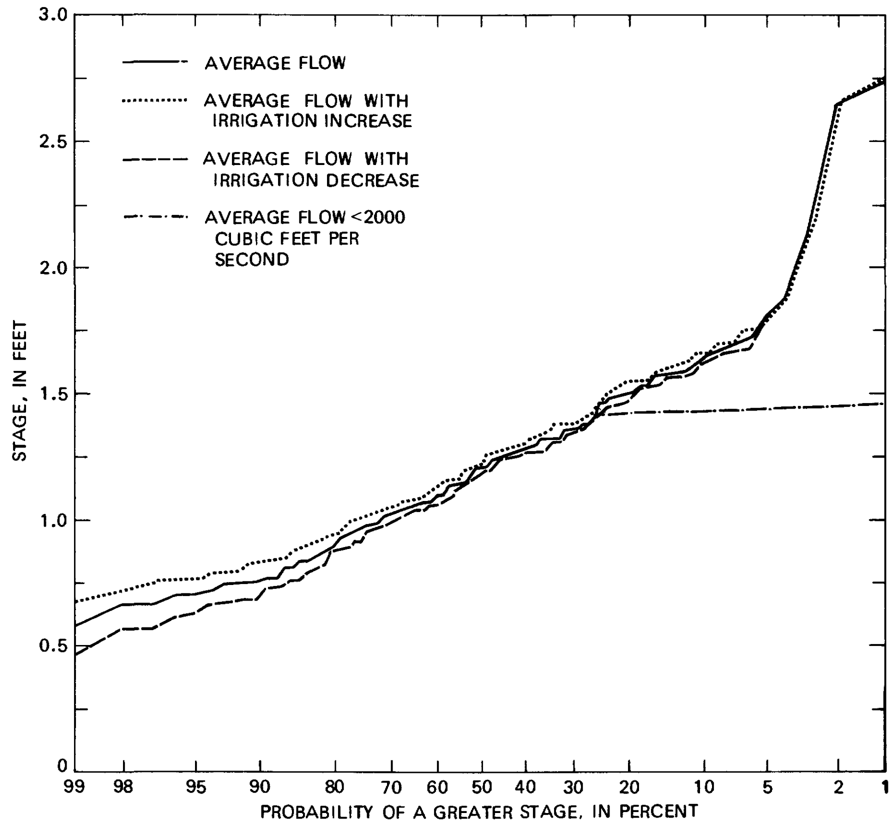


FIGURE 20.—March through April stream-stage frequency curves for four water-management alternatives directly affecting upstream flow.

an average of 53,200 acre-ft/yr over a 50-year period. If ground water were used to irrigate about 270,000 acres of irrigable land, some in areas of current subirrigation, the computed 50-year average depletion would be increased to 174,000 acre-ft/yr. If the increased ground-water irrigated areas did not replace subirrigated areas, the computed 50-year depletion would average 177,000 acre-ft/yr. The hydrologic effect of these possible water-management alternatives would be minimal on the stage of the river along the habitat area, as shown by the frequency curves. The effects of importing or diverting the 240,000 acre-ft/yr necessary to irrigate 100,000 acres, or storing or diverting all high flows in excess of 2,000 ft³/s, would be much more significant to the river stage, as shown in the frequency curves.

REFERENCES CITED

Eagleson, P. S., Mejia-R, Ricardo, and March, Frederic, 1966, Computation of optimum realizable unit hydrographs: Water Resources Research, v. 2, no. 4, p. 755-764.

Hurr, R. T., 1983, Ground-water hydrology of the Mormon Island Crane Meadows wildlife area, near Grand Island, Hall County, Nebraska: U.S. Geological Survey Professional Paper 1277-H, 12 p.

Jenkins, C. T., 1968a, Computation of rate and volume of stream depletion by wells: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 4, Chapter D1, 17 p.

______1968b, Electric-analog and digital-computer model analysis of stream depletion by wells: Ground Water, v. 6, no. 6, p. 27-34.

Jensen, M. E., Wright, J. C., and Pratt, B. J., 1969, Estimating soil moisture depletion from climate, crop, and soil data: American Society of Agricultural Engineers Paper 69-941.

Johnson, C. R., 1960, Geology and ground water in the Platte-Republican Rivers watershed and the Little Blue River basin above Angus, Nebraska: U.S. Geological Survey Water-Supply Paper 1489, 142 p.

Lappala, E. G., Emery, P. A., and Otradovsky, F. J., 1979, Simulated changes in ground-water levels and streamflow resulting from future development (1970-2020) in the Platte River basin, Nebraska: U.S. Geological Survey Water-Resources Investigations 79-26, 82 p.

Taylor, O. J., 1971, A shortcut for computing stream depletion by wells using analog or digital models: Ground Water, v. 9, no. 2, p. 9-11.

U.S. Department of Agriculture, 1956-68, Hydrologic data for experimental watersheds in the United States, annual reports: Agricultural Research Service, Rosemont, Nebr., miscellaneous publications.

U.S. Department of Agriculture, Soil Conservation Service, 1973, Soil survey of Phelps County, Nebraska: 88 p.

______1974, Soil survey of Adams County, Nebraska: 102 p.

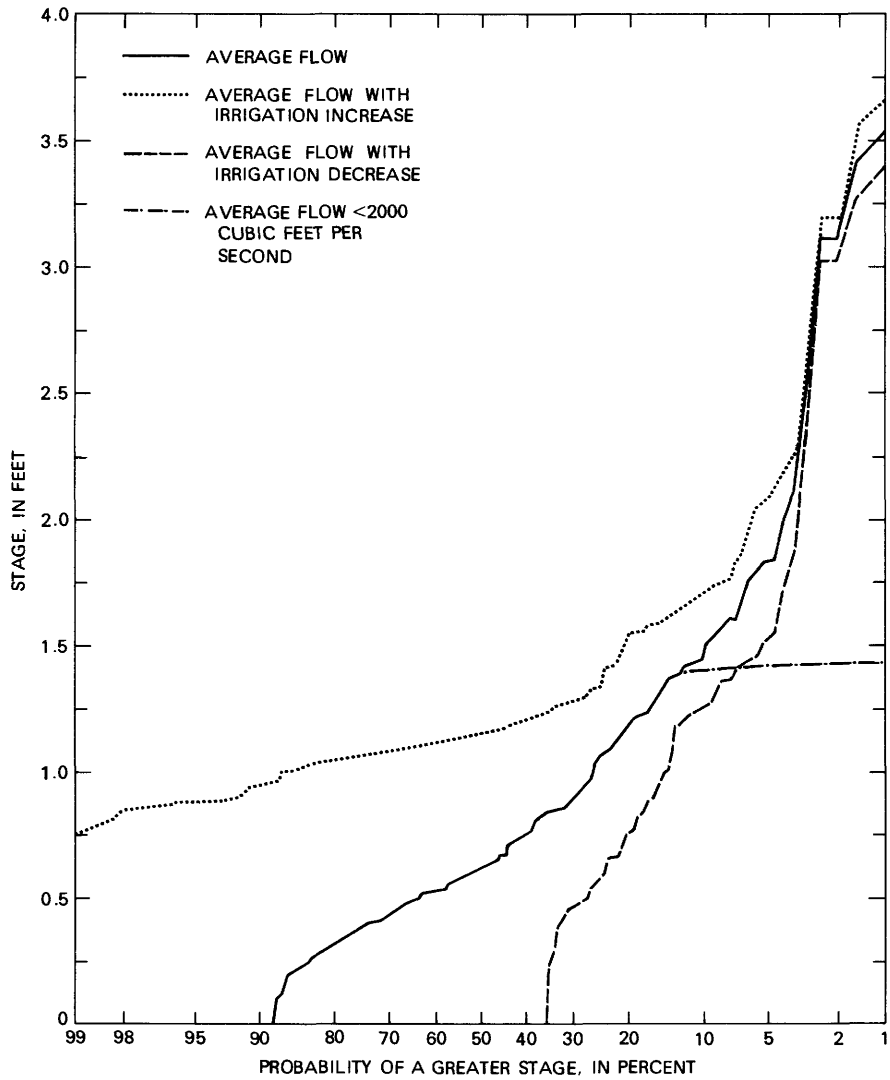


FIGURE 21.—May through August stream-stage frequency curves for four water-management alternatives directly affecting upstream flow.

APPENDIX
FORTRAN MODEL TO COMPUTE STREAM DEPLETION

```
      PROGRAM PLTRSP(INPUT,OUTPUT,TAPE1,TAPE2,TAPE3,TAPE4,
     1 TAPE5=INPUT,TAPE6=OUTPUT)
C
      DIMENSION IBAND(125),ISOIL(125),KOUNTY(125),ACRES(125),NWS(125),
     1 CANALS(125),SUBS(125)
      DIMENSION ETDRY(600,4),ETSW(600,4),ETGW(600,4),ETSUB(600)
      DIMENSION PERSUB(13),ACPRWL(6,13),PRESNT(12),FIX(12)
      DIMENSION UNIT(13,600)
      DIMENSION STRMDP(601)
C
C          ETDRY  - NET RECHARGE FOR DRYLAND
C          ETSW   - NET RECHARGE FOR SURFACE WATER IRRIGATION
C          ETGW   - NET RECHARGE FOR GROUND WATER IRRIGATION
C          ETSUB  - NET RECHARGE FOR AREAS OF SUBIRRIGATION
C
C          PERSUB - PERCENTAGE ADJUSTMENT OF SUBIRRIGATED AREAS (BY BAND)
C          ACPRWL - ACREAGE PER WELL (BY BAND AND COUNTY)
C          PRESNT - 5 YEAR AVERGE OF CURRENT MONTHLY STREAM DEPLETION
C
C          UNIT   - STREAM RESPONSE TO AQUIFER STRESS (BY MONTH AND BAND)
C          STRMDP - FUTURE STREAM DEPLETION
C
C          IBAND  - SDF BAND NUMBR
C          ISOIL  - SOIL TYPE NUMBER
C          KOUNTY - COUNTY NUMBER
C          ACRES  - TOTAL ACREAGE
C          NWS    - NUMBER OF WELLS
C          CANALS - ACREAGE IRRIGATED BY SURFACE WATER
C          SUBS   - ACREAGE THAT IS SUBIRRIGATED
C
      DATA PRESNT /12*0./
      DATA DPMAX /15./ , AVGULD /10./ , AVGBLD /5./
      DATA FIX /1.,1.,1.,1.,1.,1.,.9,.8,.9,1.,1.,1./
C
      READ (5,1000) NMONTH,N
      READ (5,1010) PERSUB
      DO 5 I = 1,6
    5 READ (5,1010) (ACPRWL(I,J),J=1,13)
C
      DO 10 I = 1,N
      READ (1,1020) IBAND(I),KOUNTY(I),ISOIL(I),ACRES(I),NWS(I),
     1 CANALS(I),SUBS(I)
   10 CONTINUE
C
      DO 12 J=1,4
   12 READ (2,1030) (ETDRY(I,J),I=1,NMONTH)
      DO 14 J=1,4
   14 READ (2,1030) (ETGW(I,J),I=1,NMONTH)
      DO 16 J=1,4
   16 READ (2,1030) (ETSW(I,J),I=1,NMONTH)
      READ (2,1030) (ETSUB(I),I=1,NMONTH)
      DO 18 I = 1,NMONTH
      IM = (I-1)/12
      IM = I - IM*12
```

```
   18 ETSUB(I) = ETSUB(I)*FIX(IM)
C
      READ (3) UNIT
C
C         MODEL THE PERIOD 1879-1928
C
      DO 80 IMONTH = 1,NMONTH
      R = 0.
      DRY = 0.
      SW = 0.
      SB = 0.
      GW = 0.
      DO 60 I = 1,N
      DEPTH = AVGULD
      TTLAC = ACRES(I)
      CANAL = 0.
      IF (KOUNTY(I) .EQ. 5 .OR. KOUNTY(I) .EQ. 6) GO TO 20
      CANAL = CANALS(I)
      TTLAC = TTLAC - CANAL
   20 IB = IBAND(I)
      IF (IB .LT. 8) GO TO 30
      SUB = SUBS(I)*PERSUB(IB)
      IF (SUB .GT. TTLAC) GO TO 30
      GO TO 40
   30 SUB = TTLAC
      DEPTH = AVGBLD
   40 TTLAC = TTLAC - SUB
      IS = ISOIL(I)
      DEPTH = DPMAX - (DPMAX-DEPTH)*SUB/ACRES(I)
      RCHGNT = TTLAC*ETDRY(IMONTH,IS) + CANAL*ETSW(IMONTH,IS) +
     1 SUB*ETSUB(IMONTH)*(DPMAX-DEPTH)/DPMAX
      R = R + RCHGNT
      DRY = DRY + TTLAC
      SW = SW + CANAL
      SB = SB + SUB
      DO 50 IK = 1,NMONTH
      STRMDP(IK) = STRMDP(IK) - RCHGNT*UNIT(IB,IK)
   50 CONTINUE
   60 CONTINUE
      WRITE (6,2000) IMONTH,DRY,SW,GW,SB,R,STRMDP(1)
      DO 70 IK = 1,NMONTH
      STRMDP(IK) = STRMDP(IK + 1)
   70 CONTINUE
   80 CONTINUE
C
C         MODEL THE PERIOD 1929-1978
C
      DO 150 IMONTH = 1,NMONTH
      R = 0.
      DRY = 0.
      GW = 0.
      SW = 0.
      SB = 0.
      DO 120 I = 1,N
```

```
      DEPTH = AVGULD
      K = KOUNTY(I)
      TTLAC = ACRES(I)
      CANAL = CANALS(I)
      TTLAC = TTLAC - CANAL
      IB = IBAND(I)
      IGW = (IMONTH -1)/12
      XGW = IGW + 1
      GWAC = (XGW/50.)*NWS(I)*ACPRWL(K,IB)
      IF (GWAC .GT. TTLAC) GWAC = TTLAC
      TTLAC = TTLAC - GWAC
      IF (IB .LT. 8) GO TO 90
      SUB = SUBS(I)*PERSUB(IB)**((50.-XGW)/49)
      GO TO 100
   90 SUB = SUBS(I) - (TTLAC-SUBS(I))*(XGW-50.)/49.
      DEPTH = AVGBLD
  100 IF (SUB .GT. TTLAC) SUB = TTLAC
      TTLAC = TTLAC - SUB
      IS = ISOIL(I)
      DEPTH = DPMAX - (DPMAX-DEPTH)*SUB/ACRES(I)
      RCHGNT = TTLAC*ETDRY(IMONTH,IS) + CANAL*ETSW(IMONTH,IS) +
     1 GWAC*ETGW(IMONTH,IS) + SUB*ETSUB(IMONTH)*(DPMAX-DEPTH)/DPMAX
      R = R + RCHGNT
      DRY = DRY + TTLAC
      SW = SW + CANAL
      GW = GW + GWAC
      SB = SB + SUB
      DO 110 IK = 1,NMONTH
      STRMDP(IK) = STRMDP(IK) - RCHGNT*UNIT(IB,IK)
  110 CONTINUE
  120 CONTINUE
      IM = IMONTH + NMONTH
      WRITE (6,2000) IM,DRY,SW,GW,SB,R,STRMDP(1)
      IF (IMONTH .LT. 541) GO TO 130
      IJ = (IMONTH-1)/12
      IJ = IMONTH - IJ*12
      PRESNT(IJ) = PRESNT(IJ) + STRMDP(1)
  130 DO 140 IK = 1,NMONTH
      STRMDP(IK) = STRMDP(IK + 1)
  140 CONTINUE
  150 CONTINUE
      DO 160 IMONTH = 1,12
      PRESNT(IMONTH) = PRESNT(IMONTH)/5.
      WRITE (6,2000) IMONTH,PRESNT(IMONTH)
  160 CONTINUE
      WRITE (4) STRMDP
      STOP
 1000 FORMAT (2I5)
 1010 FORMAT (13F4.0)
 1020 FORMAT (I4,2I7,F10.0,I6,F9.0,11X,F12.0)
 1030 FORMAT (4X,12F7.2)
 2000 FORMAT (I5,5F8.0,G15.7)
      END
```

Ground-Water Hydrology of the Mormon Island Crane Meadows Wildlife Area Near Grand Island, Hall County, Nebraska

By R. THEODORE HURR

HYDROLOGIC AND GEOMORPHIC STUDIES OF THE PLATTE RIVER BASIN

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1277-H

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1983

CONTENTS

ILLUSTRATIONS

CONVERSION FACTORS

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

Multiply inch-pound unit	*By*	*To obtain SI unit*
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
gallon per minute	6.309×10^{-2}	liter per second
foot squared per day	1.075×10^{-6}	meter squared per second

National Geodetic Vertical Datum of 1929: A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level.

GROUND-WATER HYDROLOGY OF THE MORMON ISLAND CRANE MEADOWS WILDLIFE AREA NEAR GRAND ISLAND, HALL COUNTY, NEBRASKA

By R. THEODORE HURR

ABSTRACT

In and near the Mormon Island Crane Meadows wildlife area in south-central Nebraska, the Platte River flows generally eastward in a broad, flat valley. The river banks and many areas adjacent to the river support thick stands of cottonwood, elm, and willow trees. Brush, grass, pastureland, and cultivated fields occupy most of the remaining area. Seasonally, much of the lower, non-cultivated areas are wetlands due to a high water table. This is the habitat for many types of wildlife that live in the area or stop over in the area during annual migrations. Sandhill cranes and whooping cranes are part of the annual migrations. There is concern that water-management changes, such as changes in surface-water diversions or ground-water withdrawals for irrigation, may adversely affect the hydrologic environment of the wetland areas and be harmful to the wildlife habitat.

In order to determine some of the possible effects changes in water management might have on ground-water levels in the wetland areas, detailed data were collected from Mormon Island Crane Meadows wildlife area, which is on an island in the Platte River, 8½ miles south of Grand Island, Nebr., and which is representative of other wetland areas along the Platte River in south-central Nebraska. The island is approximately 10 miles long and 1 mile wide. Ground-water levels and river stage were monitored for 7 months in 1980 to determine the relationships between ground water and surface water for the alluvial aquifer-river system.

Ground-water levels beneath the island respond to changes in river stage, to recharge from snowmelt and precipitation, and to evapotranspiration by riparian vegetation and from areas where the water table is close to the land surface. The data for the island show that ground-water levels in the general area along the Platte River respond rapidly to changes in river stage—usually within 24 hours in areas along the river's edge as much as 2,500 feet wide. Thus, temporary changes in river stage due to changes in surface-water diversions will have an almost immediate effect on ground-water levels, and the change in ground-water level will be maintained as long as the change in river stage exists. There will be no long-term residual effect on ground-water levels if the river is returned to its original stage.

Changes in ground-water withdrawals will have the simultaneous effects of (1) directly changing ground-water levels due to water-level declines beneath habitat areas and (2) indirectly changing ground-water levels due to changes in river stage caused by the depletion of streamflow. Due to the aquifer characteristics and the distance of withdrawals from the habitat areas, the effects of the withdrawals will develop slowly and be long lasting, perhaps weeks or months. If most of the changes in withdrawal occur farther than 2,500 feet from the river, however, the resulting change in ground-water levels within 2,500 feet of the river probably will average less than 1 or 2 feet. These changes could be modified on a short-term basis by controlling the river stage through controlling diversions and reservoir releases.

INTRODUCTION

In and near the Mormon Island Crane Meadows wildlife area in south-central Nebraska, the Platte River flows generally eastward in a broad, flat valley. Braiding of the river channel creates numerous islands of various sizes. The river banks and many areas adjacent to the river support thick stands of cottonwood, elm, and willow trees. Brush, grass, pastureland, and cultivated fields occupy most of the remaining area. Seasonally, much of the lower, non-cultivated areas are wetlands due to a high water table. This is the habitat for many types of wildlife that live in the area or stop over in the area during annual migrations. Sandhill cranes and whooping cranes are part of the annual migrations which include ducks, geese, and other nongame birds. There is concern that water-management changes, such as changes in surface-water diversions or ground-water withdrawals for irrigation, may adversely affect the hydrologic environment of the wetland areas and be harmful to the wildlife habitat.

PURPOSE AND SCOPE

It is the purpose of this report to describe some of the possible effects that management changes would have on the ground-water system of the habitat area. The objectives of the study were to determine the relationship between ground water and surface water so that the effects of any increase or decrease in surface-water diversion or ground-water withdrawal that changes river flow and the resulting river stage or ground-water level directly can be used to predict the changes in ground-water levels in habitat areas. These predictions of changes in ground-water levels can be used by botanists and wildlife biologists to determine the effects on the habitat in terms of depth, area, and duration of standing water, and in the assemblage and vigor of plant communities. Rather than study the entire valley, the U.S. Geological Survey selected a typical area, the Mormon Island Crane Meadows wildlife area on an island in the Platte River near Grand Island, Nebr., for detailed study (fig. 1). Although the study area takes its name from Mormon Island, it is not actually on Mormon Island. It was beyond the scope of this study to discuss or evaluate particular management plans or the effects any given plan might have on ground-water levels or river flow.

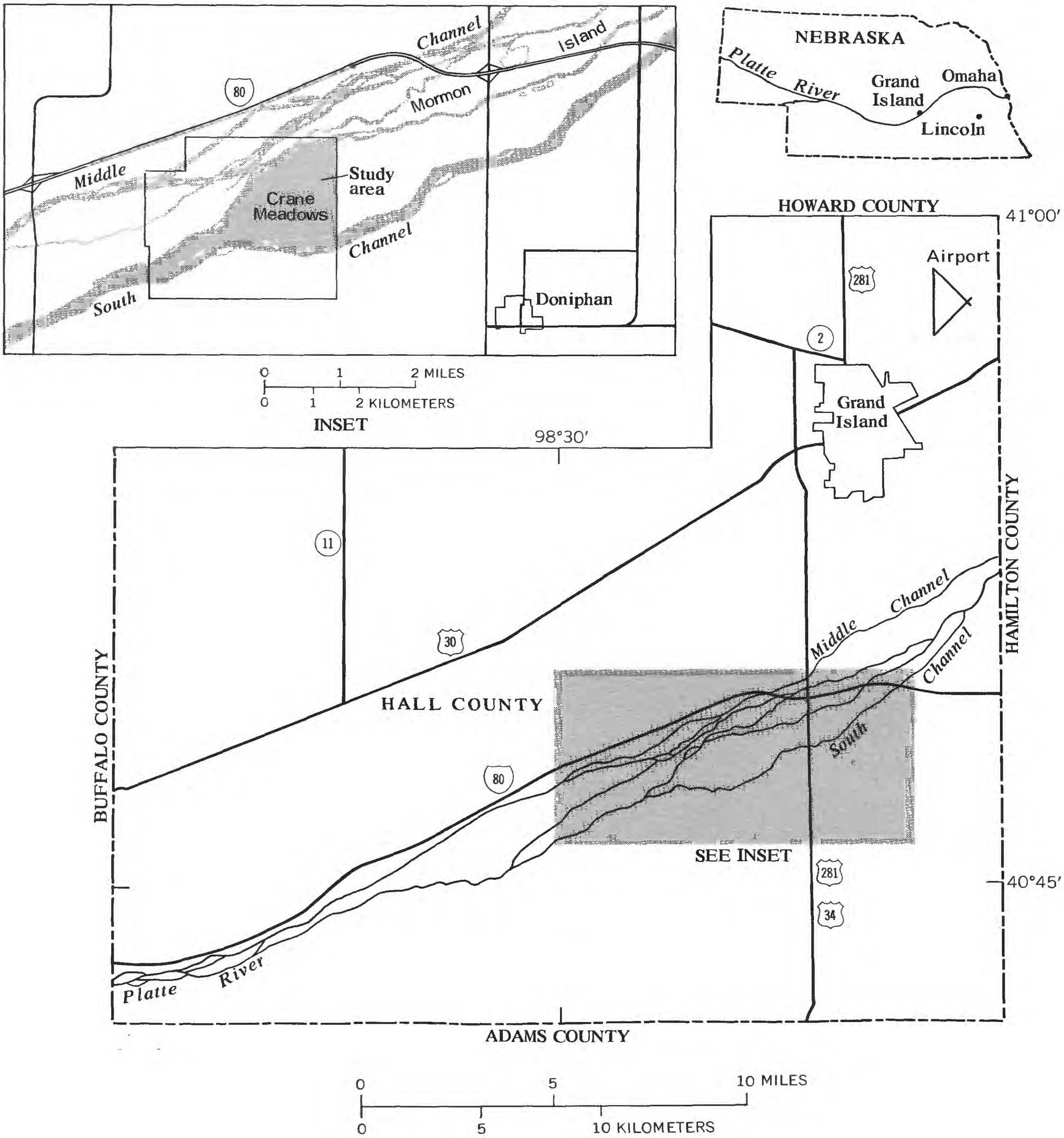


FIGURE 1.—Location of study area.

METHODS OF INVESTIGATION

Previously published reports by the U.S. Geological Survey and the Conservation and Survey Division, University of Nebraska, have defined the general geologic and hydrologic framework of the area. Detailed data on the Mormon Island Crane Meadows study area were obtained by drilling 60 test holes into the alluvium of the island to determine the lithology. These test holes were cased and used as either observation wells or piezometers in order to monitor water levels. Three of the six wells and piezometers equipped with continuous water-level recorders provided continuous water-level records. Fifty-four wells and piezometers were measured manually on a weekly basis (fig. 2). Two river-stage recorders were installed—one on either side of the island (fig. 2). Ground-water levels and river stage were monitored for approximately 7 months, beginning in April and ending in November 1981.

The data were analyzed to quantitatively determine the relationship between river stage and ground-water levels. The analysis included comparing measured ground-water-level fluctuations with measured river-stage fluctuations, and by comparing calculated with measured ground-water-level fluctuations. Ground-water-level fluctuations were calculated both analytically and by digital-model simulation of a generalized vertical section.

ACKNOWLEDGMENTS

Mormon Island Crane Meadows wildlife area is owned by the Platte River Whooping Crane Critical Habitat Maintenance Trust and is managed by the Nature Conservancy. Farming and ranching operations are leased to Quirk Land and Cattle Co., of Hastings, Nebr. The cooperation of these organizations in allowing the U.S. Geological Survey to drill test holes and to collect data is appreciated. Weekly water-level measurements were made under contract by Mr. and Mrs. Russ Hettinger, who manage the farming and ranching operations. Their contribution to this study is greatly appreciated.

REGIONAL DESCRIPTION

GEOGRAPHY

The Platte River in south-central Nebraska is in a broad, flat valley. The habitat along the river generally includes the river itself, wetland or wet meadows on the islands or areas adjacent to the river, and dry pastures and cultivated fields. Much of the bottomland near and adjacent to the river is covered with cottonwood and willow trees as well as smaller scrub vegetation and brush. Although some birds, such as the sandhill crane, may feed in fields considerably distant from the river, the habitat area that can be affected by water-management changes generally is restricted to within about half a mile on either side of the river.

GEOLOGY

The Platte River in south-central Nebraska is underlain by alluvial clay, silt, sand, and gravel of Quaternary age deposited in a series of broad troughs eroded into the underlying clay, silt, sand, and gravel of Tertiary age and shales and limestones of Cretaceous age. The Tertiary formation is the Ogallala Formation. The Cretaceous rocks are the Pierre Shale and the Niobrara Formation.

The Quaternary alluvium contains the principal aquifer in the area and consists of interfingering lenses and beds of unconsolidated clay, silt, sand, and gravel. The lower one-half of this unit is predominantly clay or silt and the upper one-half is predominantly sand and gravel with some beds of clay or silt.

The Ogallala Formation consists of interfingering beds of clay, silt, sand, and gravel. The material in the sand and gravel beds is fine to medium grained, poorly sorted, and arkosic. The lithology can vary laterally and vertically within short distances. Sandstone beds are common. Calcium carbonate cement forms widespread distinctive "mortar beds," and locally, secondary silica has cemented the sand into quartzite (Dreeszen and others, 1973). Sand, gravel, and some sandstones in the Ogallala Formation are both porous and permeable, and transmit water and supply water to wells.

The Pierre Shale is a gray to black marine shale, which locally contains very thin layers of bentonite. The Niobrara Formation is predominantly gray to orange, argillaceous chalk and limestone with some interbedded chalky shale. Within the area both the Pierre Shale and the Niobrara Formation are relatively impermeable and form the lower boundary to the flow system of the shallow alluvial aquifer.

HYDROLOGY

The Platte River is the principal river in the area. Its flow is the result of the combined flows of the North Platte and South Platte Rivers, runoff from precipitation, surface-water diversions and return flows, and ground-water seepage to or from the river. The Wood River is tributary to the Platte River 20 miles east of

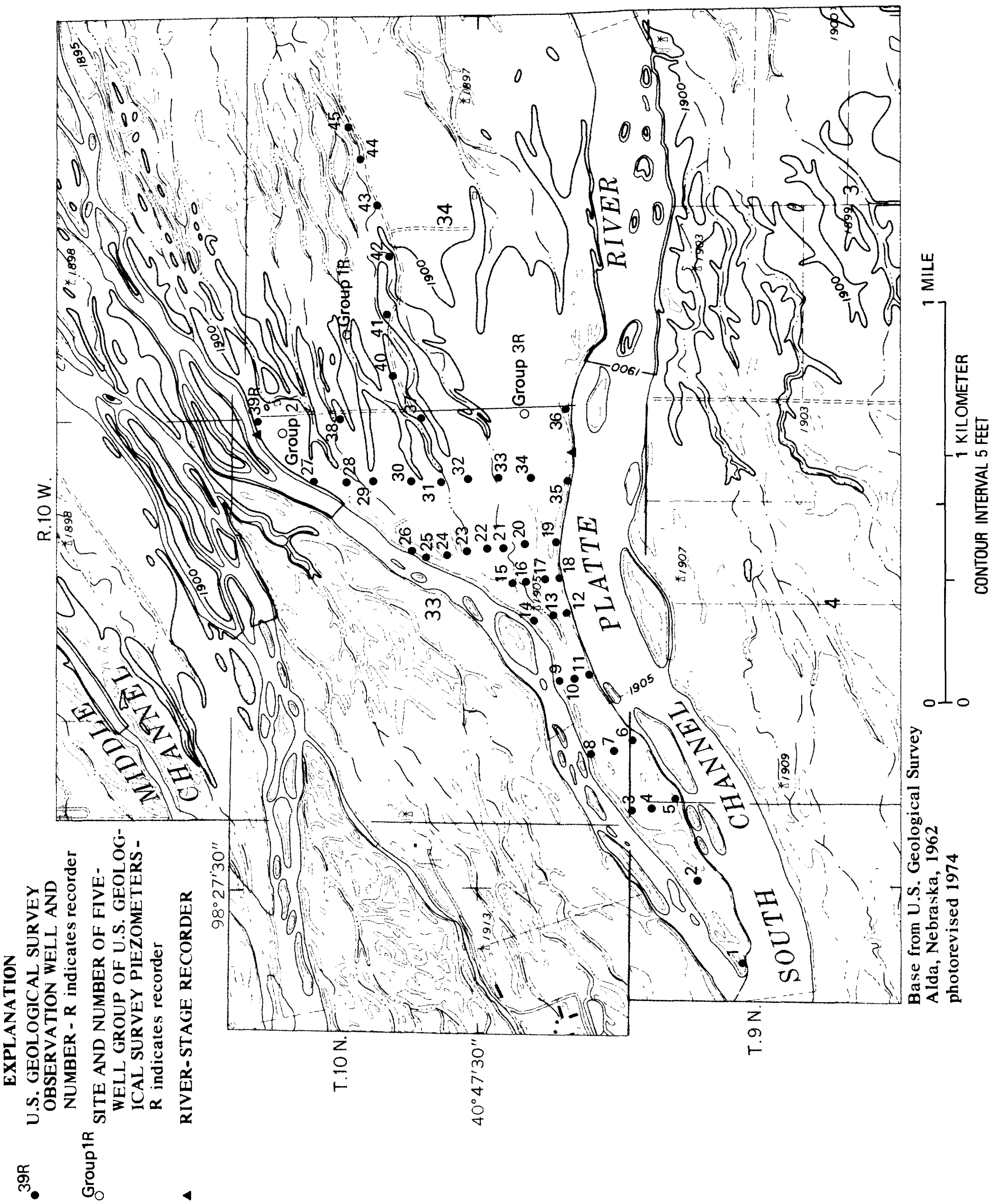


FIGURE 2.—Location of observation wells, including recorder wells, and river-stage recorders.

and downstream from Grand Island. The Loup River is tributary another 45 miles further downstream.

The flow of the North Platte River is regulated by releases from Lake McConaughy, a large, on-channel reservoir in western Nebraska. The flow of the South Platte River is largely the result of seasonal fluctuations, and surface-water diversions and return flows.

Recharge to the alluvial aquifer along the Platte River is from rainfall, snowmelt, applied irrigation water, and seepage from the Platte River. Precipitation in Hall County averages about 24 inches per year, most of which occurs in the spring and summer. The average annual snowfall is 25 inches, most of which falls during February and March (Keech and Dreeszen, 1964).

Ground-water movement is generally to the east throughout the area. Upstream from Kearney, Nebr., which is about 35 miles west of and upstream from Grand Island, ground water contributes to the flow of the Platte River as indicated by the configuration of the water table (Gutentag and Weeks, 1980). From Kearney downstream past Grand Island to about the confluence with the Wood River, the ground water has a component of flow away from the Platte River towards the Wood River on the north and towards the Blue River system on the south (Freethey, 1973; Gutentag and Weeks, 1980).

Discharge from the alluvial aquifer is by ground-water seepage to streams, by evapotranspiration by phreatophytes and from areas of shallow depth to the water table below land surface, and by withdrawal by wells.

DESCRIPTION OF STUDY AREA

GEOGRAPHY

The unnamed island on which the Mormon Island Crane Meadows wildlife area is located is in the Platte River 8½ miles south of Grand Island in Hall County, south-central Nebraska (fig. 1). Mormon Island, from which the study area gets its name, is immediately to the north of the unnamed island and is separated from it by a channel of the Platte River. The unnamed island is approximately 10 miles long by 1¼ miles wide and is one of the many permanent islands within the braided channel of the Platte River. The land surface of the island is nearly flat, as is the land on both sides of the river. Along the edges of the island, the banks of the river channels are nearly vertical. The altitude of the center of the island is several feet lower than the margins of the island.

Most of the Crane Meadows study area is pastureland with various types of grasses. Some land is cultivated and planted with row crops, such as corn. Cottonwood, willow, and varous scrub vegetation and brush grow around the edges of the island.

GEOLOGY

Beneath the study area both the Ogallala Formation and the Pierre Shale were removed by erosion prior to the deposition of the Quaternary alluvium. The Niobrara Formation is the base of the shallow hydrologic system in the area (Keech and Dreeszen, 1964). The Quaternary alluvium is approxiamtely 270 to 275 feet thick, of which the lower 120 to 150 feet is clay or silt. This lower part, although probably saturated with water, is not considered to be a significant part of the aquifer system. The upper part is 120 to 155 feet thick and consists of interfingering beds and lenses of sand and gravel with some clay and silt. The sand is medium to very coarse, and subrounded. The gravel is very fine to medium, and subrounded. The grains of the sand and gravel are mostly quartz with some feldspar and granitic fragments. In the study area this material is saturated to within a few feet of the land surface and supplies water to wells, including irrigation wells. The aquifer, which is part of this alluvium, is in hydraulic connection with the Platte River when water is present in one or more of the channels.

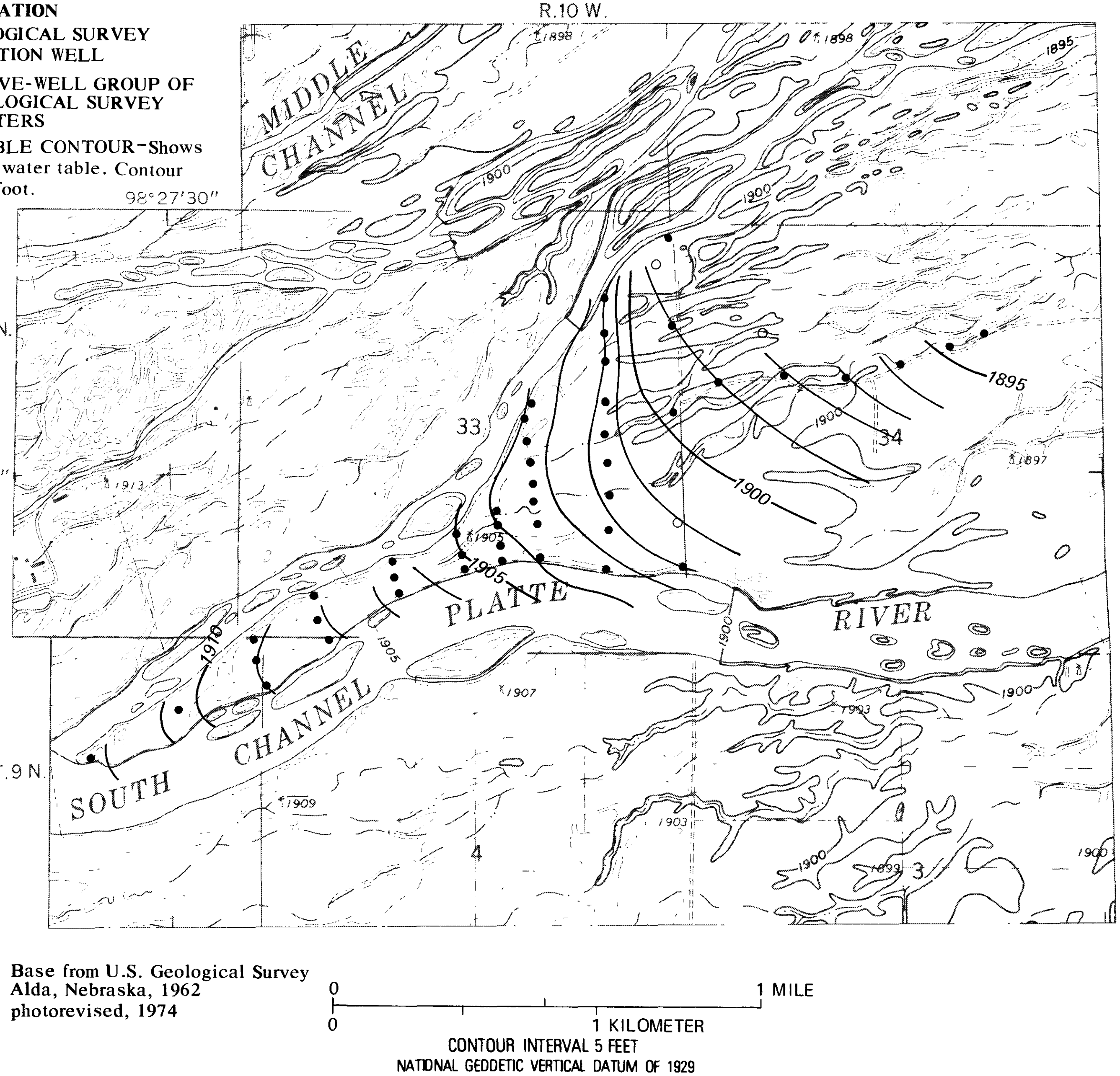
HYDROLOGY

The island on which the study area is located is bounded on the south by South Channel Platte River, which is the main channel of the river, and is bounded on the north by interconnecting channels between South Channel and Middle Channel Platte River. Middle Channel is ¼ to ½ mile north of the study area. The flow of the river usually is highest in the spring due to snowmelt and rainfall runoff. The flow decreases during the summer due to upstream diversions for irrigation and decreasing runoff. Frequently, the flow of Middle Channel and the interconnecting channels ceases altogether. Occasionally, even South Channel goes dry. In the fall when irrigation diversions stop altogether, the flow of the river increases and remains approximately steady or decreases only slightly through the winter to the next spring.

Water in the alluvial aquifer is in hydraulic connection with the river when water is present in the river. The ground-water level is controlled by the presence and altitude of the river as it passes by the island. The direction of ground-water movement beneath the island, as inferred from the water-table contours (fig. 3), is to the

EXPLANATION

- • U.S. GEOLOGICAL SURVEY OBSERVATION WELL
- ○ SITE OF FIVE-WELL GROUP OF U.S. GEOLOGICAL SURVEY PIEZOMETERS
- —1900— WATER-TABLE CONTOUR–Shows altitude of water table. Contour interval 1 foot.



Base from U.S. Geological Survey Alda, Nebraska, 1962 photorevised, 1974

Figure 3.—Water-table configuration beneath the study area, June 1, 1980.

northeast parallel to the principal direction of flow of the river. North and south of the river adjacent to the study area, the ground water has a slight component of flow away from the river as water from the river recharges the aquifer (Freethey, 1973; Gutentag and Weeks, 1980).

Changes in river stage will alter the direction of ground-water flow locally. When the river stage is high, the direction of flow of ground water immediately adjacent to the river will tend to become more perpendicular to the river's edge as water flows from the river into the aquifer. When the river stage is low, the direction of ground-water flow will tend to become more parallel to the river's edge, although flow still continues to be from the river into the aquifer. In general the ground-water level beneath the island and beneath the land adjacent to the river in the vicinity of the island is lower than the level of water in the river. This is due mostly to evapotranspiration by riparian vegetation and from areas where the water table is close to land surface as observed during the period of this study. North and south of the river it is also due, probably even during wintertime, to (1) natural flow away from the Platte River to other, lower river systems, such as the Wood River and the Blue River systems (Freethey, 1973), and (2) to ground-water withdrawals by wells in areas adjacent to the river.

The aquifer beneath the island supplies water to one irrigation well, two domestic wells, and several stock wells. The irrigation well is seldom used. No water is diverted from the river for irrigation in this area.

GROUND-WATER HYDROLOGY

WATER LEVELS

Water levels in the aquifer beneath Mormon Island Crane Meadows wildlife area range from land surface to approximately 7½ feet below land surface, depending on the location and the time of year. Water levels are highest in the late spring or early summer. During this time, when there is water in the channels on both sides of the island, recharge from the river enters the ground-water system along the edges of the island and flows toward the center of the island, curving northeastward along the downstream trend of the island (fig. 3). Most of this water never returns to the river. It either is consumed by evapotranspiration or flows back to the north after the channel on the north side of the island becomes dry during mid- to late summer. The water-table configuration of the area in August 1980 when the channel on the north side of the island was dry is shown in figure 4. Recharge from the river was still occurring along the south side of the island. Along the north side of the island, the channel had dried up, recharge had stopped, ground-water levels were below the bottom of the channel, and the direction of ground-water flow was northward and eastward in response to more regional flow conditions.

The altitude of the Platte River at the stage recorder on South Channel (fig. 2) is shown in figure 5. The altitudes of ground-water levels at three sites across the width of the island (see fig. 2 for location) are shown in figures 6, 7, and 8. Comparisons between these hydrographs show rises in ground-water levels attributed to recharge from snowmelt (fig. 6, April 1–3, 1980) and rainfall (figs. 6 and 7, May 16 and May 31, 1980), with little or no change in river stage; general rises and declines in ground-water levels that are in direct response to changes in river stage; and diurnal fluctuations in ground-water levels that are caused by diurnal changes in the rate of evapotranspiration.

At three sites on the island (fig. 2), groups of piezometers were installed to monitor the hydraulic head at different depths within the aquifer. Each group consisted of five piezometers drilled within a circle of 25-foot radius. The piezometers were set at five different depths, approximately 30 feet apart, starting at a depth of 25 feet. Piezometers are different from observation wells in that piezometers are only open to the aquifer at a specific depth and provide a measure of the pressure or hydraulic head at that specific depth.

Water levels in each of these piezometer groups showed only a slight difference in hydraulic head from the top of the aquifer to the bottom. The maximum difference in hydraulic head was less than 0.2 foot higher near the top of the aquifer than near the bottom. This difference occurred during the maximum water-level stage (May 31 to June 1, 1980).

ANALYSIS OF DATA

The response of ground-water levels to changes in river stage is rapid. Measured changes of water levels in the piezometers at piezometer group 1, about 2,500 feet from the nearest channel of the river, occur within 24 hours of a change in river stage. Trial-and-error comparison of measured ground-water changes with calculated changes indicated a hydraulic diffusivity for the aquifer (transmissivity divided by specific yield) of approximately 200,000 feet squared per day. The calculated changes were obtained by using estimated values of transmissivity and specific yield in the analytical drain formula (Stallman, 1962) and by using a cross-sectional ground-water flow model.

It was not possible to calculate changes in ground-water levels that exactly duplicated the measured

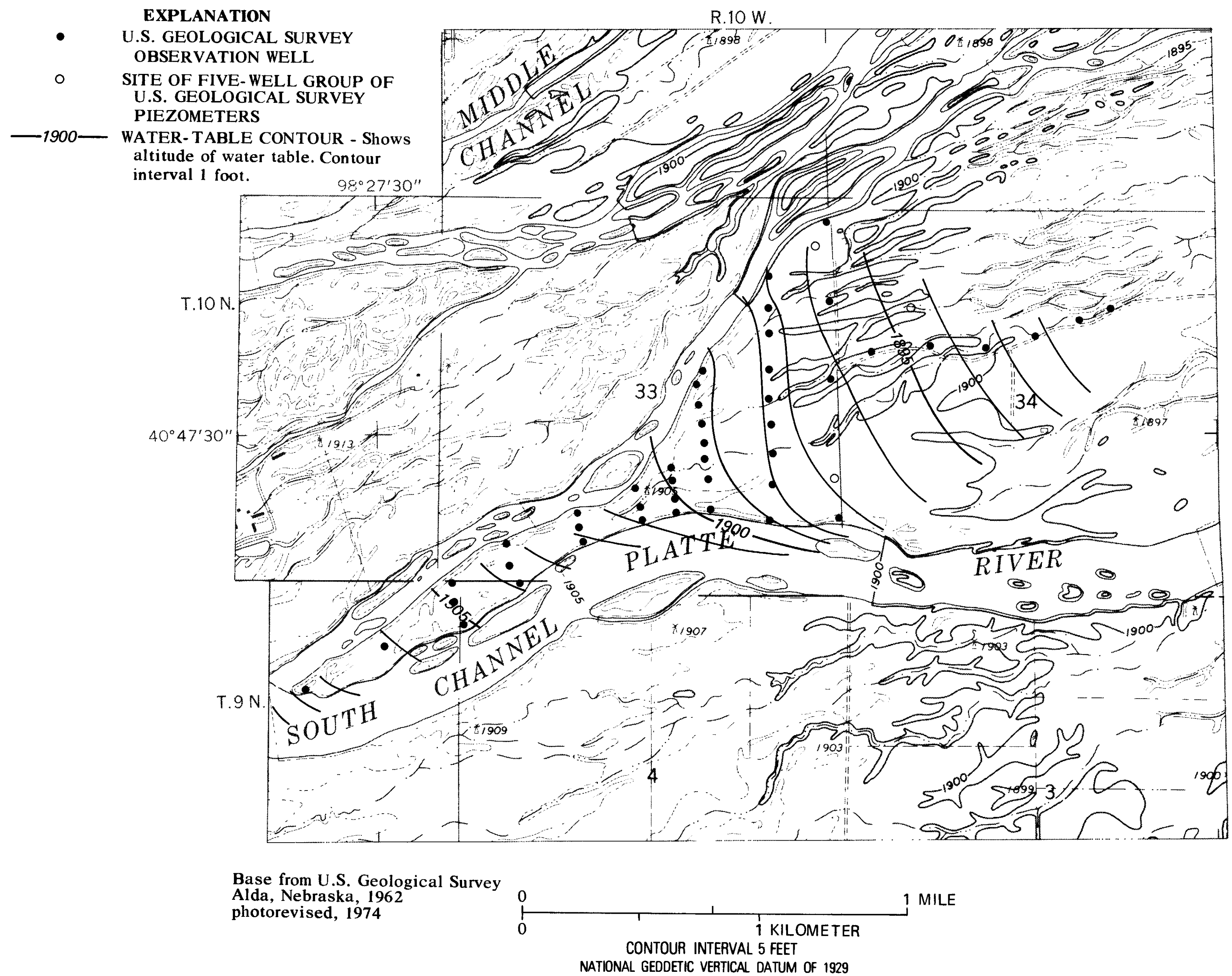


FIGURE 4.—Water-table configuration beneath the study area, August 10, 1980.

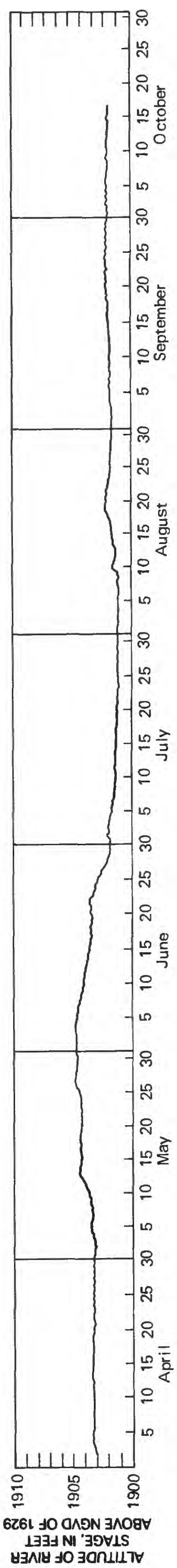


FIGURE 5.—Hydrograph showing river stage, South Channel Platte River.

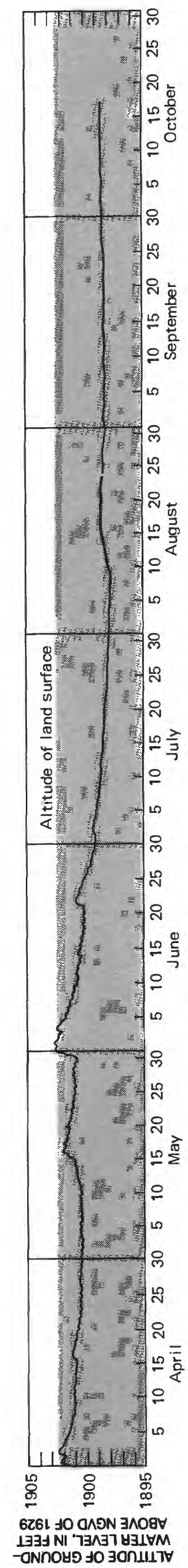


FIGURE 6.—Hydrograph showing ground-water levels in well 5, piezometer group 3.

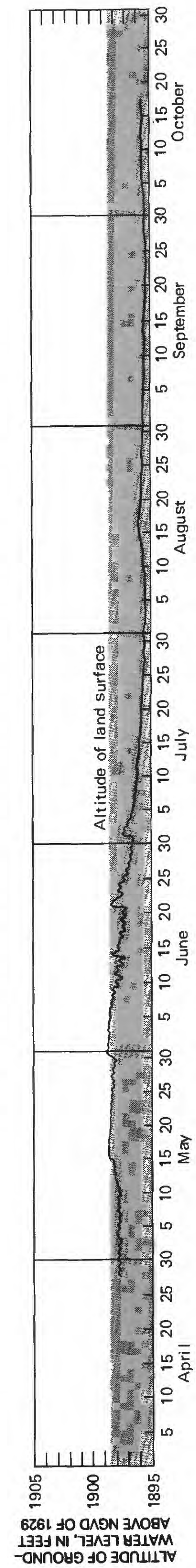


FIGURE 7.—Hydrograph showing ground-water levels in well 5, piezometer group 1.

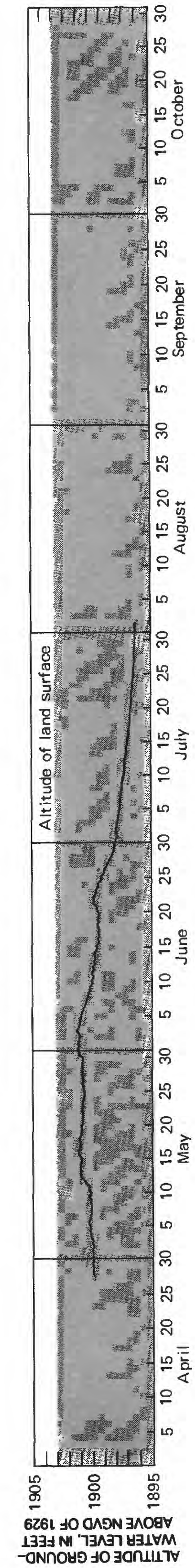


FIGURE 8.—Hydrograph showing ground-water levels in well 39.

change because of some complicating factors. Much of the land surface in the interior of the island is below the altitude of the river, even at low stage. Consequently, the ground-water level can rise only so high—just until the water table intersects and rises slightly above land surface—before ground water begins to run off as surface-water flow in the topographic lows and sloughs that drain the interior of the island. Also, the response of ground-water levels to changes in river stage is mitigated by changes in the rate of evapotranspiration as the depth to water below land surface changes.

Evapotranspiration causes diurnal fluctuations in the ground-water level which range from zero to approximately 0.3 foot, depending on weather conditions, time of the year, and the depth to water below land surface.

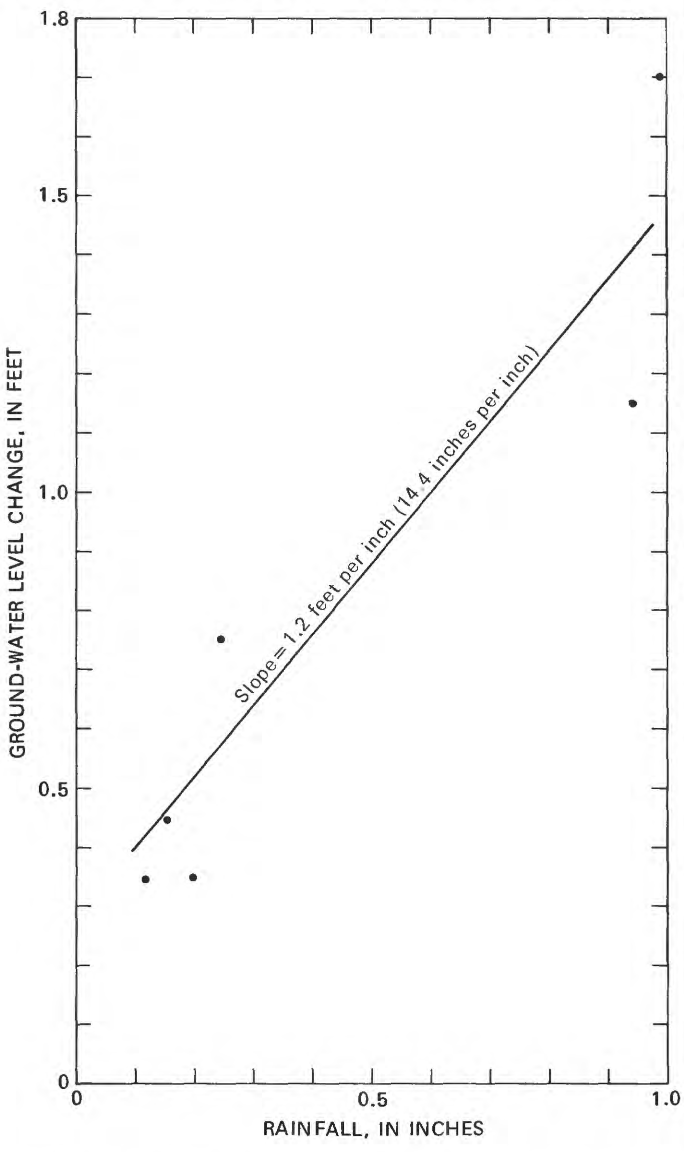


FIGURE 9.—Relationship between rainfall and change in ground-water level.

A 0.3-foot change and an estimated daily evapotranspiration of 0.03 foot (F. J. Otradovsky, U.S. Bureau of Reclamation, oral commun., 1981) would indicate the specific yield for the upper few feet of the aquifer to be 0.10.

The river-stage hydrograph for South Channel (fig. 5) also shows diurnal fluctuations. The magnitude of these fluctuations is smaller than the magnitude of the fluctuations in ground-water levels, indicating that the river is not the cause of the ground-water fluctuations. In fact, the reverse is probably the case: the river-stage fluctuations are the combined result of direct evaporation from the water surface of the river and the loss of streamflow to the ground-water system to replace the water lost by evapotranspiration from the aquifer.

Direct recharge to the aquifer from precipitation is shown by the hydrograph of ground-water levels in figure 6. Sharp rises in ground-water levels on May 16, 18, 20, and 31, and June 2 and 22 correspond to smaller rises in river stage. Rainfall measured at the Grand Island Airport for these dates plotted against the change in ground-water levels is shown in figure 9. If the same rainfall occurred on the island as was measured at the airport and if all of the rainfall was recharge to the aquifer and distributed uniformly over the aquifer, the rise would indicate a specific yield of 0.07.

The transmissivity of the aquifer in the vicinity of the island is approximately 20,000 feet squared per day, based on the diffusivity and specific-yield value of 0.10. This is the transmissivity for the upper part of the alluvial aquifer beneath the island. A test hole showed this part to be 135 feet thick. Below this the formation became much finer grained, mostly silt and clay. This lower, fine-grained part of the aquifer does not contribute to the short-term ground-water responses measured in the upper part of the aquifer.

EFFECTS OF WATER-MANAGEMENT CHANGES

Ground-water levels affect the wet-meadows environment in two ways. The first way is by directly controlling the depth and areal extent of standing and slow-moving water where the water table intersects and stands above the land surface. The second way is the effect that the water level has on plant communities where the water level is below land surface. The depth to water, and, therefore, the water available to the root systems, is a factor in determining the types and varieties of plants in the community and the vigor with which they can grow.

Any change in water-management practices that affects the flow of the river, and consequently the river stage, will have a rapid and almost direct effect on the ground-water level beneath Mormon Island Crane Meadows study area and adjacent areas. The change of ground-water level will occur within approximately 24 hours in areas along the river's edge as much as 2,500 feet wide. A rise in river stage will produce a rise in ground-water levels that is somewhat decreased in magnitude, due to an increase in the rate of evapotranspiration from the water table that is closer to the land surface. A decline in river stage will produce a decline in ground-water levels that is smaller in magnitude due to a decreased rate of evapotranspiration. The degree to which evapotranspiration will modify the magnitude of water-level change depends on the evapotranspiration-depth relationship and the seasonal evapotranspiration rate.

These changes in ground-water levels will last only as long as the change in river stage is maintained. There would be no long-term effects on the ground-water levels if the river were to be returned to its original stage.

Changes in net ground-water withdrawals also would have the effect of changing water levels in the aquifer because of increased or decreased drawdown related to the change in rate of net withdrawal. In general, however, this effect would only occur in areas adjacent to the main river channels, and not in areas or islands between the channels, where there is very little ground-water withdrawal by wells. The areas or islands between channels, however, would be affected only by changes in river stage caused by changes in river flow resulting from the decrease or increase in ground-water withdrawal.

Ground water withdrawn by wells is derived from change of storage within the aquifer, salvage of water from evapotranspiration, and depletion of streamflow. Because most of the ground-water pumpage along the Platte River is at distances greater than 2,500 feet from the river, the greatest drawdowns and changes in ground-water storage due to increases in net ground-water withdrawals will occur beyond that distance from the river. These changes in water levels will have little effect on any wildlife habitat because little habitat that is affected by depth to water exists beyond 2,500 feet from the river. The effect of increases in net ground-water withdrawals at distances closer to the river than 2,500 feet will be to salvage evapotranspiration by lowering the water table and to increase streamflow depletion by increasing the gradient away from the river. Estimates and calculations of these quantities indicate that an average change in water level of not more than 1 or 2 feet should provide enough water from these sources to satisfy anticipated increases in net ground-water withdrawals for irrigation. Depletion of streamflow also would change the stage of the river, which would have the same effect on ground-water levels as previously discussed for changes in surface-water management.

Increases or decreases in ground-water withdrawals would have effects on water levels and river flow that develop more slowly and last longer than the effects caused by increases or decreases in surface-water diversions. The magnitude, occurrence, and duration of the effect from changes in ground-water withdrawals would depend on the magnitude of the change, the distance from the river, and the properties of the aquifer. The rise or decline of ground-water levels adjacent to the river could be decreased on a short-term basis by upstream control of diversions and reservoir releases.

SUMMARY AND CONCLUSIONS

Ground-water levels in the alluvial aquifer beneath the island and areas adjacent to the Platte River are controlled by the presence and stage of the Platte River in its various channels, by evapotranspiration by vegetation and from areas of shallow depth to water, by regional effects of pumpage and recharge, and by ground-water flow to lower river systems. Changes in the stage of the river rapidly affect ground-water levels. Ground-water responses to changes in river stage occur within 24 hours for areas along the river's edge as much as 2,500 feet wide. These water-level changes will exist as long as the change in river stage is maintained. Once the river is returned to its original stage, the ground-water level will quickly return to its original level. The only permanent effects may be on the plant communities if water levels are changed for prolonged periods of time.

Increases or decreases in the rate of net ground-water withdrawal from the aquifer in areas adjacent to the Platte River will have two simultaneous effects on the ground-water levels adjacent to the river. First, ground-water levels will decline or rise due to increased or decreased net withdrawal itself. Due to the aquifer characteristics and the distance of withdrawals from the habitat areas, the effects of the withdrawals will develop slowly and be long lasting, perhaps weeks or months. If most of the increase or decrease in withdrawal occurs farther than 2,500 feet from the river, the average ground-water level change within 2,500 feet of the river will be less than about 1 or 2 feet. Ground-water levels beneath islands and areas between flowing river channels will not be affected directly unless, of course, the withdrawals are on the islands themselves. Second, ground-water levels will respond to the changes in river stage as the flow of the river increases or decreases due to changes in ground-water pumpage. This change in river stage will affect ground-water levels adjacent to the river as well as beneath islands and between channels. Some of these rises or declines in ground-water levels will be decreased by accompanying increases or decreases in rates of evapotranspiration as the depth to ground water below land surface decreases or increases. Some water-level changes can be decreased by controlling the stage of the river on a short-term basis.

SELECTED REFERENCES

Dreeszen, V. H., Reed, E. C., and Burchett, R. R., 1973, Bedrock geologic map showing thickness of overlying Quaternary deposits, Grand Island quadrangle, Nebraska and Kansas: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-819.

Freethey, G. W., 1973, Configuration of the water table, 1971, Grand Island quadrangle, Nebraska: Lincoln, University of Nebraska, Conservation and Survey Division, scale 1:250,000.

Gutentag, E. D., and Weeks, J. B., 1980, Water table in the High Plains aquifer in 1978 in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-642, scale 1:250,000,000.

Keech, C. F., and Dreeszen, V. H., 1964, Availability of ground water in Hall County, Nebraska: U.S. Geological Survey Hydrologic Investigations Atlas HA-131.

Lappala, E. G., Emery, P. A., and Otradovsky, F. J., 1979, Simulated changes in ground-water levels and streamflow resulting from future development (1970-2020) in the Platte River basin, Nebraska: U.S. Geological Survey Water-Resources Investigations Open-File Report 79-26, 82 p.

Stallman, R. W., 1962, Channel methods—Line sink or line source, constant head, *in* Ferris, J. G., Knowles, D. B., Brown, R. H., and Stallman, R. W., Theory of aquifer tests: U.S. Geological Survey Water-Supply Paper 1536-E, 174 p.

☆U.S. GOVERNMENT PRINTING OFFICE:1983—776-041 / 4001