ASSESSMENT OF THE GEOMORPHIC EFFECTS OF LARGE FLOODS USING STREAMGAGE DATA: THE 1951 FLOODS IN EASTERN KANSAS, USA

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Abstract: Data from 23 U.S. Geological Survey (USGS) streamgages were analyzed to assess the geomorphic effects (short-term change and subsequent recovery) of the record 1951 floods on streams in eastern Kansas. Flood-related, channel-bed elevation change was indicated for 17 gage sites, with substantial deposition at five sites and substantial erosion at two sites. An assessment of post-flood bed elevation recovery was possible for several sites. While recovery to pre-flood channel-bed elevation occurred over a period of months to years at some sites, at other sites recovery was incomplete or absent. Flood-related channel widening with partial recovery was indicated for one site and possible channel widening was indicated for two sites. It was demonstrated that an analysis of streamgage data is a potentially useful technique for assessing the geomorphic effects of a large flood at a site, provided that the gage has a long period of record and is located on an alluvial channel. In the absence of other lines of evidence, streamgage data can provide an estimate of the direction and magnitude (net) of geomorphic change that otherwise might not be available or attainable. [Key words: geomorphic effect, 1951 floods, streamgage, channel-bed elevation, channel width, channel change, channel recovery, Kansas.]

INTRODUCTION

The geomorphic effectiveness of a large flood can be defined as the amount of channel morphological change caused by the flood and the subsequent time required for the channel to recover (Wolman and Gerson, 1978). Geomorphic effects caused by large floods, which may range from negligible to substantial, include channel widening, channel-bed erosion or deposition, and channel straightening (Baker, 1988; Knighton, 1998). Factors that determine geomorphic effectiveness include channel bed and bank composition, channel morphology, channel slope, valley confinement, sediment load, flood duration, stream power, the temporal ordering of floods, climate, and vegetation (Baker, 1988; Kochel, 1988; Costa and O'Connor, 1995; Osterkamp and Friedman, 2000; Emmett and Wolman, 2001; Fuller, 2007).

Various data sources potentially can be used to quantify channel geomorphic effects of large floods, including aerial photography, channel cross-sections, erosion pins, and Light Detection and Ranging (LiDAR); however, each of these data sources

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has limitations. For example, aerial photographs may not be available for the dates needed. Moreover, the channel may be partly or completely obscured by tree cover or high-flow conditions. Channel cross-sections and erosion pins are vulnerable to being lost as a result of the very geomorphic effects that they may have been established to monitor. LiDAR can provide centimeter accuracy to assess the geomorphic effects of large floods (Alho et al., 2009); however, the technology is relatively expensive and the baseline (pre-flood) data may not be available. A limitation common to all of these data sources is that they typically do not provide a continuous, long-term (i.e., decades) source of channel morphology information for the purpose of assessing the geomorphic effects of large floods. For a given river, such information often is limited or unavailable. If available, it also may provide some of the knowledge necessary to predict the geomorphic effects of future large floods.

A potential source to provide additional information on the geomorphic effects of large floods is streamgage data. In the United States, several thousand streamgages (predominantly operated by the U.S. Geological Survey [USGS]) provide what typically is the only source of continuous, long-term streamflow and channel morphology information for the locations being monitored. An advantage of the national USGS streamgage network is that on-site discharge measurements are made frequently using consistent methods. Information from streamgages can be used to investigate changes in geomorphically relevant variables, including channel-bed elevation and channel width (Juracek and Fitzpatrick, 2009).

This paper presents the results of a study to assess the utility of streamgage data for quantifying the geomorphic effects of large floods. The 1951 floods in Kansas (described below) were selected as the test case. Specific objectives were to: (1) estimate flood-related changes in channel-bed elevation; (2) estimate flood-related changes in channel width; (3) determine the time required for post-flood channel recovery; and (4) assess the prospects for using streamgage data to document and possibly predict the geomorphic effects of future large floods.

THE 1951 FLOODS IN KANSAS

The 1951 floods in eastern Kansas were caused by above-normal precipitation in May, June, and July. While some major flooding occurred in May and June, most of the record flooding was associated with the intense rainfall that occurred July 9–13, 1951, a period during which some of the affected areas received more than 40 cm of rainfall (U.S. Geological Survey, 1952) (Fig. 1). In 1951, USGS operated a network of 96 streamgages in Kansas. Of those, 36 recorded the highest flows in 1951 since the time records began, and, for most of these sites, the 1951 flood is still the peak of record.

The 1951 floods caused substantial geomorphic changes to affected river and stream channels and adjacent floodplains (Fig. 2). For example, along the Kansas River, the flooding resulted in substantial bank erosion and channel widening. On the adjoining floodplain, which was submerged to depths of 4.6 to 6.1 m in the vicinity of Lawrence and Topeka, the land surface was scoured to depths of as much as 4.6 m in some places and covered by deposits of sand and silt to thicknesses of as much as 1.2 m in other places (McCrae, 1954).

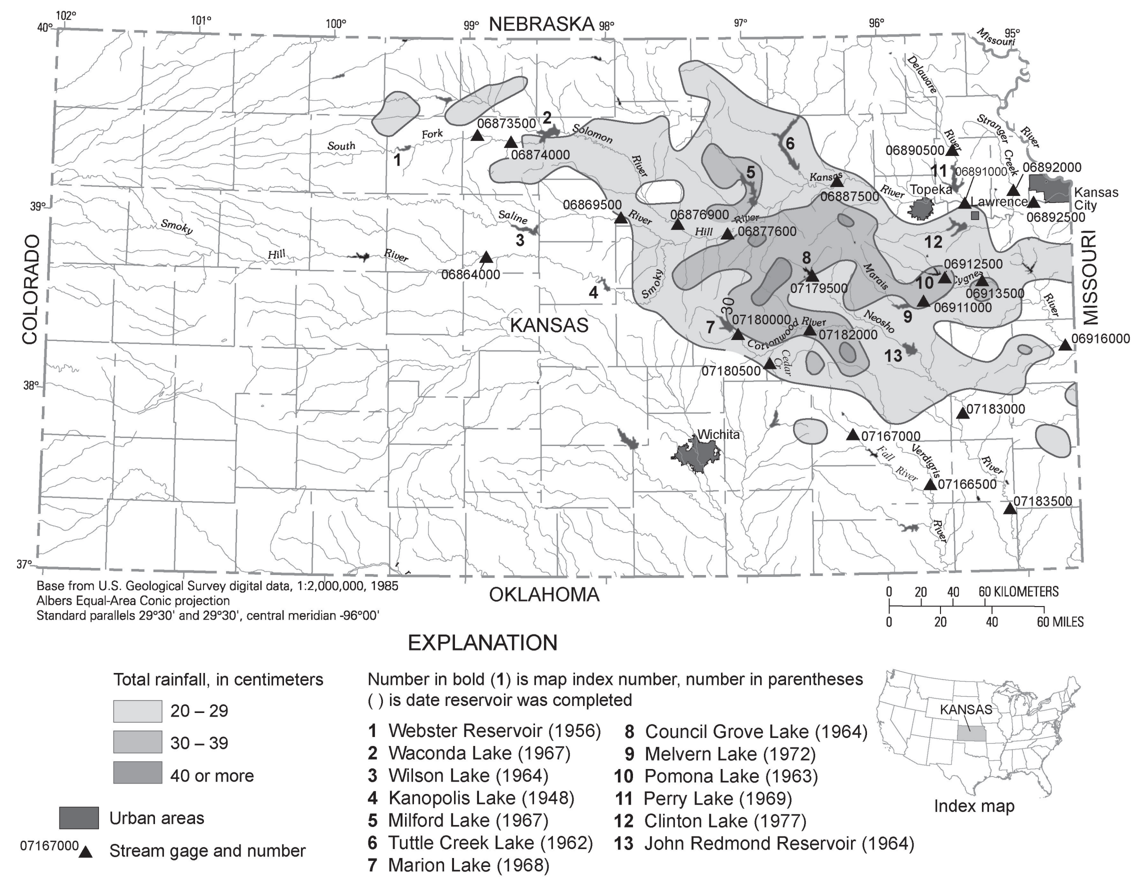

Fig. 1. Location of streamgages included in this study and distribution of rainfall for July 9–13, 1951.

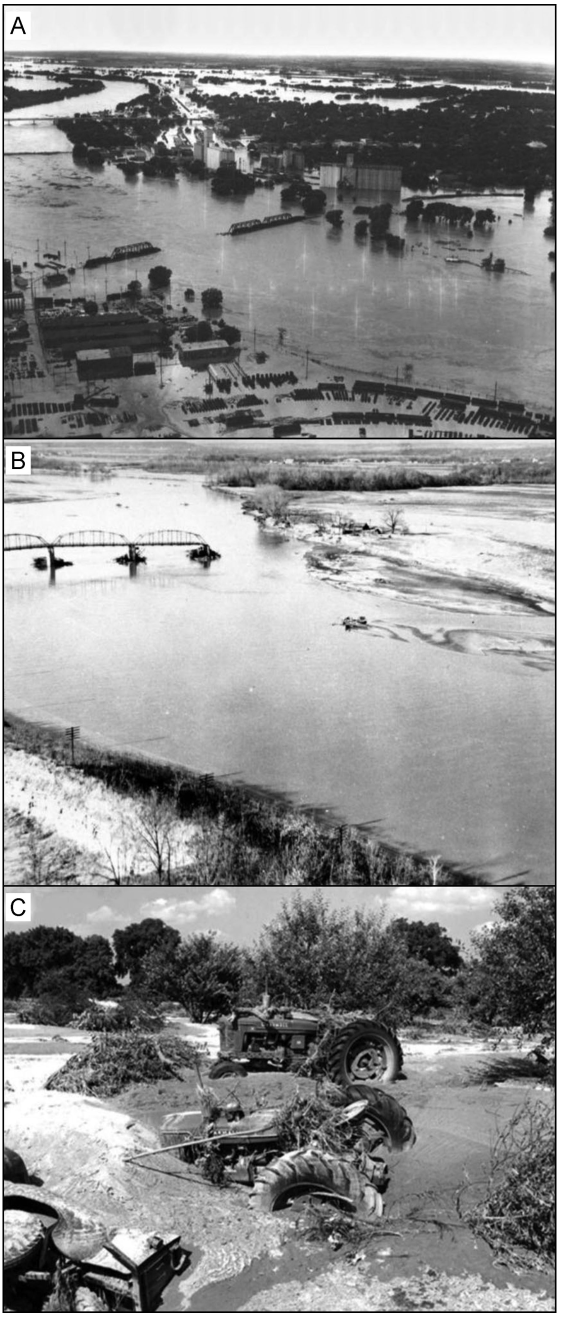

Fig. 2. A. View of the Kansas River at Topeka, Kansas, showing extent of flooding in 1951 (image courtesy of the Kansas State Historical Society). B. Post-flood view of the Kansas River at Lecompton, Kansas, at the site of USGS streamgage no. 06891000, which was included in this study (reproduced from McCrae, 1954). C. Tractors buried by sediment and other debris deposited on the Kansas River floodplain by the 1951 flood near Lawrence, Kansas (image courtesy of the U.S. Department of Agriculture, Natural Resources Conservation Service).

REGIONAL PHYSICAL SETTING

The study area in eastern Kansas includes parts of the Kansas, Marais des Cygnes, Neosho, Verdigris, and Smoky Hill River Basins (Fig. 1), which are within the Flint Hills Upland, Osage Cuestas, and Smoky Hills physiographic sections (Fenneman, 1938; Schoewe, 1949). The study area is underlain primarily by limestone and shale of Pennsylvanian age in the eastern part, Permian age in the central part, and Cretaceous age to the west (Kansas Geological Survey, 2008). Although the region consists of gently rolling hills, in some places topographic relief is considerable. Soils are variable throughout the study area, ranging from thin, clayey soils to thick, sand- and silt-rich soils (Soil Survey Staff, 2009). Channel banks along reaches where streamgages are located are composed predominantly of silty and sandy loams within the Smoky Hill, Kansas, and Verdigris River Basins and clay loams with gravel in the Marais des Cygnes and Neosho River Basins (Soil Survey Staff, 2009). Channel beds range in composition from sand and gravel to bedrock (Osterkamp and Hedman, 1981). Gravel deposits and bedrock-controlled sections are prevalent in the Marais des Cygnes, Neosho, and Verdigris River Basins (Kansas Water Resources Board (KWRB), 1958, 1960, 1961a), whereas gravel deposits are less common and bedrock-controlled sections typically are absent in the Smoky Hill and Kansas River Basins (KWRB, 1959, 1962). Monthly mean temperatures range from about –7° C to 32° C throughout the year, and mean annual precipitation ranges from about 65 cm in the western part of the study area to about 100 cm in the east (High Plains Regional Climate Center, 2009). Potential natural vegetation predominantly consists of Tall Grass Prairie, with Mixed Prairie increasing toward the western part of the study area (Kuchler, 1974). By the 1950s, about 25–45% of the landscape within the river basins had been converted to cropland (KWRB, 1958, 1959, 1960, 1961a, 1961b, 1962).

METHODS

Site Selection

Streamgages selected for this analysis were in the area affected by the 1951 floods in eastern Kansas. Criteria used in the selection of gages required that (1) the peak discharge for the period of record was measured during the 1951 floods; (2) a minimum of five years of record was available before and after the 1951 peak discharge; and (3) the gage was not moved during the aforementioned 10-year period (or, if moved, the distance was minimal). Based on these criteria, 23 gages were selected for analysis (Table 1, Fig. 1). Compared to the mean annual discharge for the period of record, the 1951 peak discharge at the selected gages ranged from about 70 to about 500 times larger (Table 1).

Determination of Channel-Bed Elevation Change

At any given location and time along a stream, a relation exists between stage and discharge. For streamgages, these relations are quantified on rating curves and

Table 1. U.S. Geological Survey Streamgages in Kansas Included in this Study

USGS stream-gage number[a]	USGS streamgage name	Approx. drainage area (km^2)	Period of record analyzed for discharge	Mean annual discharge, period of record (m^3/s)	1951 peak discharge (m^3/s)	Ratio of 1951 peak to mean annual discharge
	Smoky Hill River Basin					
06864000	Smoky Hill River near Russell	18,000	1940–1974	5.9	450	76
06869500	Saline River at Tescott	7,300	1937–2005	6.7	1,348	201
06873500	S. Fork Solomon River at Alton	4,500	1942–1957	3.7	1,498	407
06874000	S. Fork Solomon River at Osborne	5,200	1946–2005	3.1	1,515	489
06876900	Solomon River at Niles	17,500	1934–2006	16.4	4,446	271
06877600	Smoky Hill River at Enterprise	49,900	1934–2005	43.7	5,862	134
	Kansas River Basin					
06887500	Kansas River at Wamego	143,200	1940–2001	166.1	11,129	67
06890500	Delaware River at Valley Falls	2,400	1922–1967	11.0	1,563	142
06891000	Kansas River at Lecompton	151,400	1936–2007	203.7	13,366	66
06892000	Stranger Creek near Tonganoxie	1,100	1939–2006	7.4	549	74
06892500	Kansas River at Bonner Springs	155,200	1934–1960	209.0	13,762	66
	Marais des Cygnes River Basin					
06911000	Marais des Cygnes River at Melvern	900	1940–1974	5.6	1,116	199
06912500	110 Mile Creek near Quenemo	800	1939–2006	5.1	784	154
06913500	Marais des Cygnes River near Ottawa	3,200	1920–2006	19.0	3,794	199
06916000	Marais des Cygnes River at Trading Post	7,500	1929–1958	47.7	3,993	84
	Neosho River Basin					
07179500	Neosho River at Council Grove	600	1940–2006	3.5	963	275
07180000	Cottonwood River near Marion	900	1938–1968	3.2	867	271
07180500	Cedar Creek near Cedar Point	300	1943–1992	1.6	309	193
07182000	Cottonwood River at Cottonwood Falls	3,400	1932–1971	14.7	3,313	226
07183000	Neosho River near Iola	9,900	1917–2006	52.6	9,741	185
07183500	Neosho River near Parsons	12,700	1935–2006	80.5	10,364	129
	Verdigris River Basin					
07166500	Verdigris River near Altoona	2,900	1944–2006	21.4	1,614	75
07167000	Fall River near Eureka	800	1946–1976	5.4	886	164

[a]Location indicated in Figure 1.

updated as necessary to accommodate changes in channel shape, slope, and other factors that affect the relation. Each rating represents a best-fit line through the measurement data (i.e., paired measurements of stage and discharge). Discharge measurements at, and stage-discharge ratings for, USGS gages are made using standard USGS techniques (Buchanan and Somers, 1969; Kennedy, 1984) with a typical accuracy of about ±5% (Kennedy, 1983; Sauer and Meyer, 1992).

By computing the stage that relates to a reference discharge for each rating curve developed during the entire period of record of a gage (and correcting to a common datum, if necessary), trends in the elevation of the channel bed can be inferred by plotting the resulting time-series data. This method was called specific gage analysis by Blench (1969). Ideally, the reference discharge selected is a relatively low flow that is sensitive to change. Use of a low discharge minimizes the effects of variations in channel width on flow depth (Simon and Hupp, 1992). Juracek (2004) used the mean annual discharge for the period of record, whereas Williams and Wolman (1984) used the discharge exceeded 95% of the time. In this study, the mean annual discharge for the period of record was used as the reference discharge to investigate possible flood-related changes in channel-bed elevation. The mean annual discharge was selected because it is a relatively low discharge that typically covers the entire channel bed.

If the stage for the reference discharge (hereafter referred to as the reference stage) has a downward trend, it may be inferred that the channel-bed elevation has decreased with time because of erosion. Conversely, if the reference stage has an upward trend, it may be inferred that the channel-bed elevation has increased with time as a result of deposition. An abrupt increase or decrease in reference stage may be indicative of a relatively rapid change in channel-bed elevation. In addition to the deposition or erosion of sediment, another possible contributing factor for changes in reference stage is the accumulation or removal of woody debris. The absence of a pronounced change or trend in reference stage indicates that the channel bed essentially has been stable.

Flood-related change at each gage site was estimated as the difference in reference stage between the rating curve that immediately preceded the 1951 flood and the rating curve that immediately followed the 1951 flood. For this study, bed-elevation change caused by the 1951 floods was considered substantial if it was at least two times larger than the mean absolute bed-elevation change for the period of record. Only gages for which substantial bed-elevation change was indicated are presented and discussed in the results.

Determination of Channel-Width Change

Discharge and water-surface width data available for individual discharge measurements were used to investigate whether the 1951 floods caused pronounced changes in channel width. For each site, discharge-width relations were grouped into approximate five-year successive intervals (to get a representative range of in-channel flow conditions; Juracek, 2000) such that the first interval immediately preceded and the second interval immediately followed the 1951 floods. Effects of the floods were determined by plotting the data. If a substantial post-flood change in channel width (i.e., at least 20%) was indicated, additional five-year intervals were included to assess the time required for channel recovery. Use of a range of in-channel flows potentially can provide an indication of channel-width changes at multiple heights within the channel (as opposed to using only the water-surface width for one selected flow such as the mean annual discharge or bankfull discharge).

Limitations of Streamgage Data

Several possible limitations may restrict or prevent the use of streamgage data to assess the geomorphic effects of large floods. First, for an area of interest, there may be an inadequate number of gages with a sufficiently long period of record. Second, an existing gage may not be ideal because it is in a reach that is unrepresentative or essentially stable as a result of one or more natural or human-caused conditions. Third, discharge measurements made at different cross-sections (locations) may be a concern because the potential variability introduced may affect interpretation of geomorphic change. For a comprehensive discussion of the potential limitations of using streamgage data for geomorphic applications, see Juracek and Fitzpatrick (2009).

CHANNEL-BED ELEVATION CHANGE

Of the 23 streamgages investigated, 17 indicated channel-bed elevation change as a result of the 1951 floods (Table 2). Deposition was indicated at nine gage sites and ranged from 0.03 to 0.64 m, whereas erosion was indicated at eight sites and ranged from 0.02 to 0.46 m. Only seven gages documented substantial channel-bed deposition (five sites) or erosion (two sites). These sites are described below.

Saline River at Tescott

The streamgage at Tescott (USGS gage no. 06869500) is in central Kansas about 110 km upstream from the confluence with the Smoky Hill River (Fig. 1). Mean annual discharge for the period of record (1937–2005) was 6.7 m^3/s, with a maximum peak discharge of 1348 m^3/s recorded during the 1951 flood (Table 1). A change in reference stage indicated 0.58 m of material was deposited at this site as a result of the flood (Table 2, Fig. 3A).

A comparison of reference stage before and after the 1951 flood indicated possibly greater variability in channel-bed elevation following the flood. Before the 1951 flood (1937–1951), the reference stage did not exhibit any trends. Rather, it fluctuated within 0.3 m of the mean stage of 2.52 m (Fig. 3A). Reference stage was more variable following the flood and exhibited a downward trend for approximately 20 years, indicating that channel-bed elevation steadily declined with time because of erosion. This downward trend continued until the early 1970s, when stage increased as a result of several lower-magnitude floods, and reached a maximum stage of 3.02 m immediately following a high-magnitude flood in 1973. The downward trend in reference stage resumed following the 1973 flood as a result of removal of flood-deposited sediment. Reference stage was relatively stable during the 1980s. In the 1990s, the downward trend in reference stage indicated additional channel-bed degradation (Fig. 3A).

Table 2. U.S. Geological Survey Streamgages in Kansas That Indicated Channel Change Following the 1951 Floods[a]

USGS stream-gage number[b]	USGS streamgage name	Mean absolute reference stage change[c] (m)	1951 reference stage change[d] (m)
	Smoky Hill River Basin		
06869500	**Saline River at Tescott**	**0.13**	**0.58**
06873500	*S. Fork Solomon River at Alton*	*0.09*	*0.08*
06874000	**S. Fork Solomon River at Osborne**	**0.06**	**0.17**
06877600	**Smoky Hill River at Enterprise**	**0.13**	**0.64**
	Kansas River Basin		
06887500	**Kansas River at Wamego**	**0.09**	**–0.45**
06890500	Delaware River at Valley Falls	0.03	0.05
06891000	*Kansas River at Lecompton*	*0.09*	*–0.03*
06892000	Stranger Creek near Tonganoxie	0.15	–0.06
06892500	**Kansas River at Bonner Springs**	**0.12**	**–0.40**
	Marais des Cygnes River Basin		
06911000	Marais des Cygnes River at Melvern	0.05	–0.05
06912500	110 Mile Creek near Quenemo	0.11	–0.02
06916000	*Marais des Cygnes River at Trading Post*	*0.04*	*0.03*
	Neosho River Basin		
07179500	Neosho River at Council Grove	0.04	0.06
07180000	**Cottonwood River near Marion**	**0.03**	**0.09**
07180500	**Cedar Creek near Cedar Point**	**0.04**	**0.10**
07182000	Cottonwood River at Cottonwood Falls	0.02	–0.02
	Verdigris River Basin		
07167000	Fall River near Eureka	0.11	–0.02

[a]Bold indicates substantial reference stage change. Italics indicates substantial channel widening.
[b]Location indicated in Figure 1.
[c]The mean absolute reference stage change was computed as the average of the absolute values of all changes in reference stage for the period of record.
[d]The 1951 reference stage change was the change in reference stage for the rating curve that immediately followed the 1951 flood compared to the rating curve that immediately preceded the 1951 flood.

South Fork Solomon River at Osborne

The streamgage at Osborne (USGS gage no. 06874000) is in central Kansas approximately 44 km upstream from the confluence with the North Fork Solomon River (Fig. 1). From 1946 to 2005 the gage recorded a mean annual discharge of 3.1

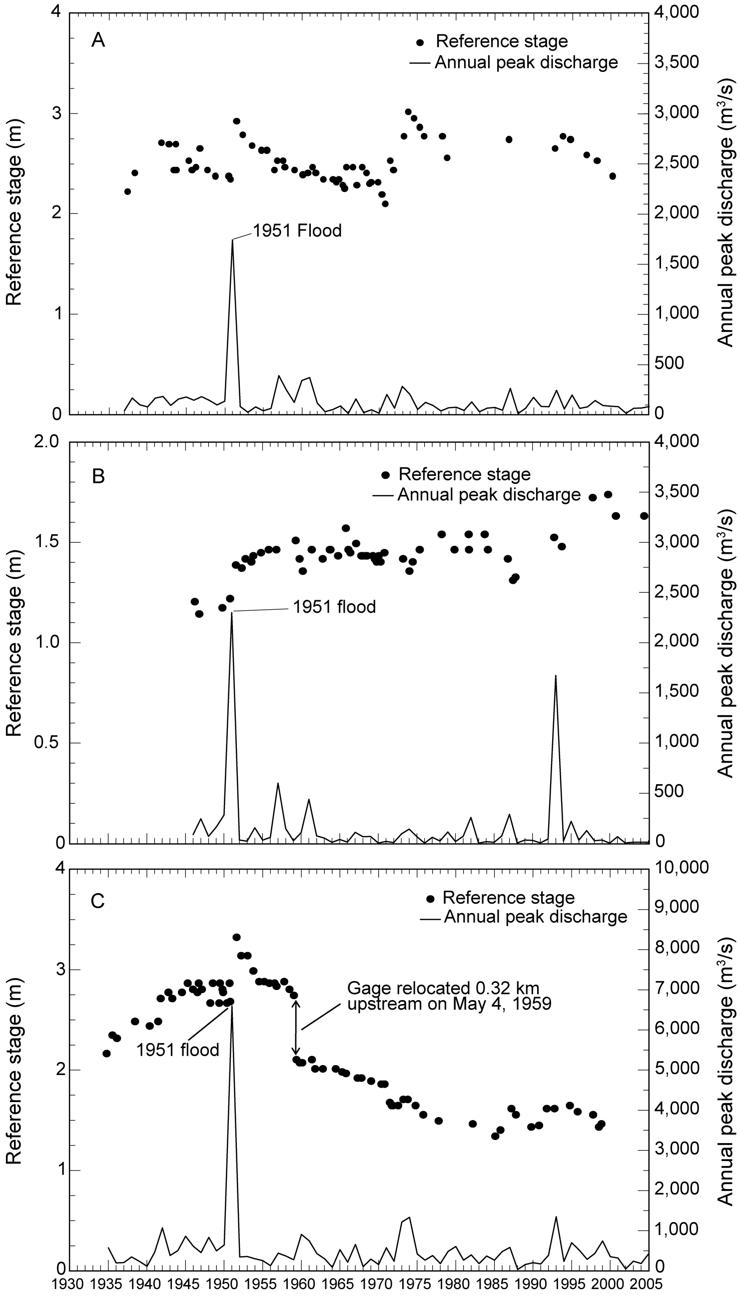

Fig. 3. Variation in stream stage for mean annual discharge and annual peak discharges at (A) Saline River at Tescott streamgage from 1937 to 2005 (USGS gage no. 06869500, mean annual discharge = 6.7 m^3/s), (B) South Fork Solomon River at Osborne streamgage from 1946 to 2005 (USGS gage no. 06874000, mean annual discharge = 3.1 m^3/s), and (C) Smoky Hill River at Enterprise streamgage from 1934 to 2005 (USGS gage no. 06877600, mean annual discharge = 43.7 m^3/s). The location of the streamgages is shown in Figure 1.

m^3/s and a 1951 peak discharge of 1515 m^3/s (Table 1). A change in reference stage indicated that channel-bed elevation increased 0.17 m as a result of the 1951 flood (Table 2, Fig. 3B).

Reference stage had been relatively stable for at least five years before the 1951 flood. Following the flood, reference stage had increased from 1.22 to 1.39 m. Subsequent changes in reference stage indicated aggradation of an additional 0.12 m through 1960, after which time it varied about ±0.1 m at the higher post-1951-flood elevation until at least 1993 (Fig. 3B). Between 1993 and 1997 reference stage increased 0.25 m, the cause of which apparently was the accumulation of a large woody debris pile downstream from the gage site (B. J. Dague, hydrographer, USGS, written comm., February 26, 1999).

Smoky Hill River at Enterprise

The streamgage at Enterprise (USGS gage no. 06877600) is in central Kansas about 70 km upstream from the confluence with the Republican River (Fig. 1). The gage at this site was active since 1934 with a mean annual discharge of 43.7 m^3/s through 2005. The highest discharge on record, 5862 m^3/s, was recorded during the 1951 flood (Table 1).

Reference stage primarily exhibited an upward trend through 1945 and then fluctuated before the 1951 flood, increasing from 2.16 m in 1934 to 2.87 m in 1950. Reference stage decreased slightly just before the 1951 flood, then increased substantially to the peak reference stage on record of 3.32 m as a result of the flood (Fig. 3C). This pronounced increase in reference stage indicated that about 0.64 m of material was deposited by the flood (Table 2). Following the flood, reference stage exhibited a steady, downward trend, as flood deposits gradually were eroded (Fig. 3C). In 1959, the gage was relocated 0.32 km upstream, and a new datum established. After the relocation, the downward trend in reference stage continued until 1987, at which time a smaller-scale flood deposited material that resulted in an increase in reference stage of 0.21 m. Following the 1987 flood, a fluctuating stage indicated that the channel bed was relatively stable until at least 2001.

Kansas River at Wamego

The streamgage at Wamego (USGS gage no. 06887500) is in northeast Kansas about 200 km upstream from the confluence with the Missouri River (Fig. 1). Mean annual discharge for the period of record (1940–2001) was 166.1 m^3/s, with a peak discharge of 11,129 m^3/s recorded during the 1951 flood (Table 1).

Before the 1951 flood, reference stage exhibited a downward trend followed by relative stability with a net decrease from 2.30 m in 1940 to 2.10 m in early 1951. Immediately following the 1951 flood, reference stage had decreased to 1.65 m, indicating the erosion of 0.45 m of material from the channel bed (Table 2, Fig. 4A). During the next 10 years, reference stage progressively increased by 0.21 m and then remained steady for nearly 30 years. In 1988, scour by iceflows resulted in a decrease in reference stage of 0.17 m (J. R. Barnard, hydrographer, USGS, written comm., December 9, 1988). In 1993, deposition during a large flood resulted in an

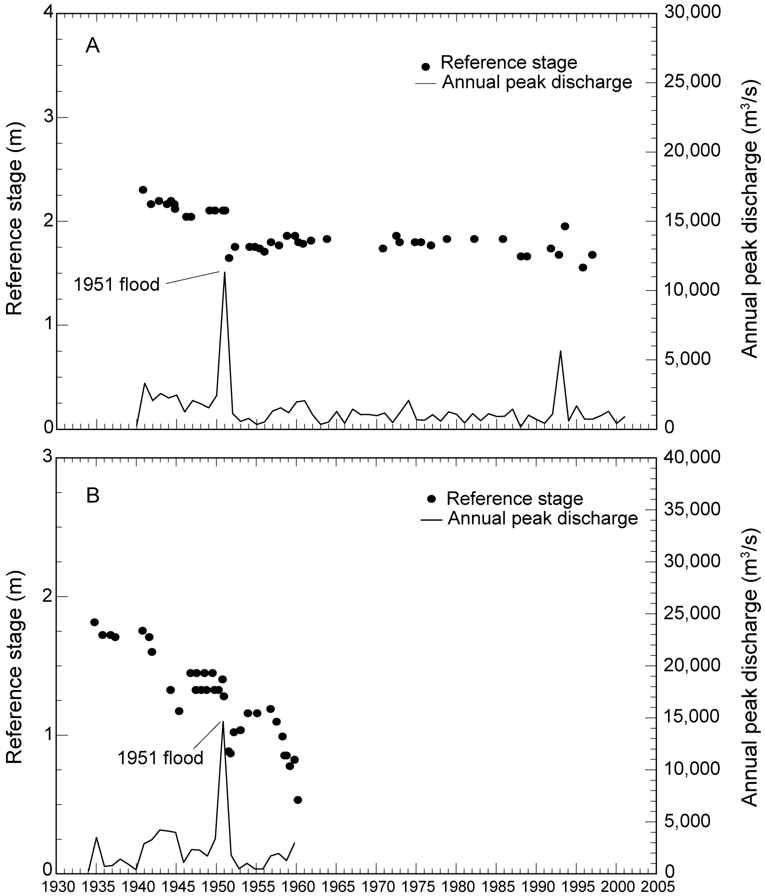

Fig. 4. Variation in stream stage for mean annual discharge and annual peak discharges at (A) Kansas River at Wamego streamgage from 1940 to 2001 (USGS gage no. 06887500, mean annual discharge = 166.1 m^3/s) and (B) Kansas River at Bonner Springs streamgage from 1934 to 1960 (USGS gage no. 06892500, mean annual discharge = 209 m^3/s). The location of streamgages is shown in Figure 1.

increase in reference stage of 0.27 m. Sediment deposited during the 1993 flood, plus an additional 0.18 m of sediment, was eroded from the channel bed by 1995. Then, following modest deposition in 1996, reference stage remained stable until at least 2001 (Fig. 4A).

Kansas River at Bonner Springs

The streamgage at Bonner Springs (USGS gage no. 06892500) is in northeast Kansas about 34 km upstream from the confluence with the Missouri River (Fig. 1). This gage was activated in 1934 and relocated in 1960 (to a site 0.8 km downstream); thus, only data from 1934 to 1960 were examined. During this period, mean annual discharge was 209 m^3/s, and maximum discharge was recorded during the 1951 flood at 13,762 m^3/s (Table 1).

Overall, from 1934 to 1960, reference stage exhibited a downward trend with imbedded periods of partial recovery and relative stability (Fig. 4B). Reference stage decreased from 1.81 m in 1934 to 1.28 m by early 1951. As a result of the 1951 flood, the reference stage dropped to 0.88 m, indicating the erosion of 0.40 m of channel-bed material (Table 2). During the next five years, it increased to 1.18 m. Beginning in 1957, it decreased by 0.65 m in less than three years to 0.53 m in 1960, the lowest reference stage recorded before the gage was relocated (Fig. 4B). Channel-bed elevation at this site also may have been affected by in-channel sand dredging (Joshua Marx, U.S. Army Corps of Engineers, written comm., August 19, 2009).

Cottonwood River near Marion

The streamgage near Marion (USGS gage no. 07180000) is in central Kansas approximately 200 km upstream from the confluence with the Neosho River (Fig. 1). The gage was only active from 1938 to 1968. Mean annual discharge for this period was 3.2 m^3/s, and the 1951 peak discharge was 867 m^3/s (Table 1). A change in reference stage indicated that about 0.09 m of material was deposited at this site as a result of the 1951 flood (Table 2, Fig. 5A).

Before the flood, reference stage had progressively declined from 0.88 m in 1938 to 0.76 m in 1950. Immediately following the flood, it increased to 0.85 m. Reference stage remained constant at 0.85 m during the next five years before decreasing to 0.78 m in 1962. Then it increased until 1968, when the gage was discontinued (Fig. 5A).

Cedar Creek near Cedar Point

The streamgage near Cedar Point (USGS gage no. 07180500) is in central Kansas about 15 km upstream from the confluence with the Cottonwood River (Fig. 1). Mean annual discharge was 1.6 m^3/s from 1943 to 1992; peak discharge in 1951 was 309 m^3/s (Table 1). A change in reference stage indicated that 0.10 m of material was deposited on the channel bed as a result of the 1951 flood (Table 2, Fig. 5B).

Reference stage was variable before and after the 1951 flood; however, change was minimal and absolute mean change was only 0.04 m throughout the entire period of record (Table 2, Fig. 5B). The 0.10 m of deposition attributed to the 1951 flood was the second largest adjustment of the channel bed during the period of record. As indicated by a change in reference stage, more than one-half of the flood-deposited material was eroded within three months. Subsequently, reference stage remained constant until 1957 when disturbance caused by heavy equipment in the channel possibly caused 0.07 m of channel-bed erosion (P.S. Marshall, hydrographer, USGS, written comm., October 4, 1957). Reference stage then was stable until 1965, when an increase of 0.14 m indicated deposition caused by a flood. Post-1965 reference stage was characterized by relative stability with modest fluctuations until at least 1992 (Fig. 5B).

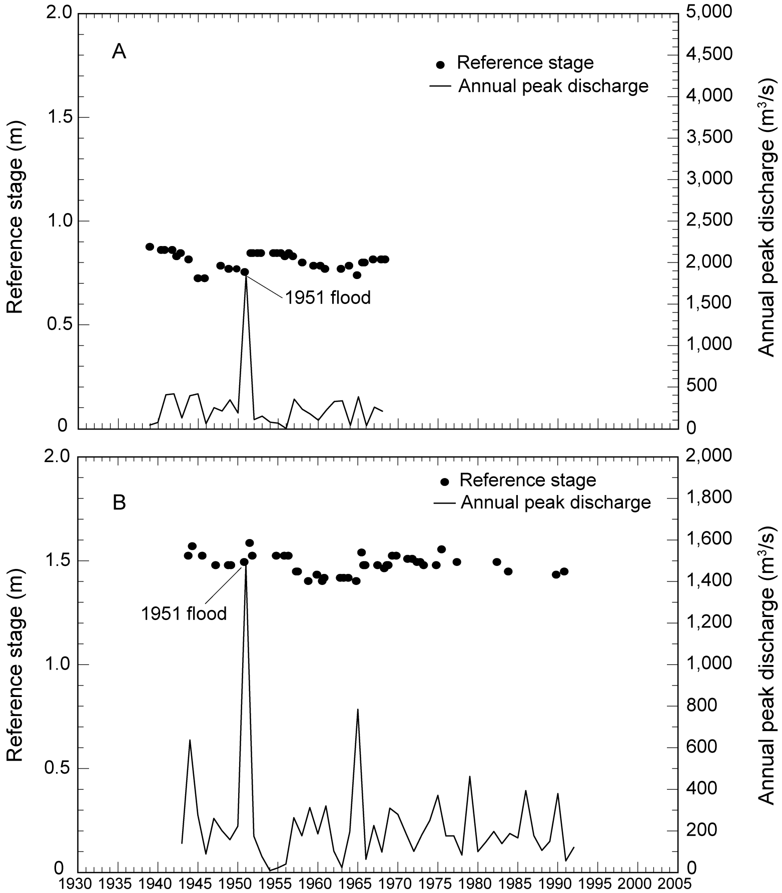

Fig. 5. Variation in stream stage for mean annual discharge and annual peak discharges at (A) Cottonwood River near Marion streamgage from 1938 to 1968 (USGS gage no. 07180000, mean annual discharge = 3.2 m^3/s) and (B) Cedar Creek near Cedar Point streamgage from 1943 to 1992 (USGS gage no. 07180500, mean annual discharge = 1.6 m^3/s). The location of streamgages shown in Figure 1.

CHANNEL-WIDTH CHANGE

The 23 streamgages investigated for channel-bed elevation changes also were examined for channel-width changes caused by the 1951 floods. Of the gages analyzed, approximately one-half had documented channel-width increases that appeared to be a result of the floods. However, most gages lacked post-flood data for a range of in-channel flow conditions because of widespread, long-term drought during the mid-1950s. Thus, the ability to assess channel-width change and post-flood recovery was constrained. Nevertheless, a pronounced increase in channel width immediately following the 1951 floods was indicated at three gage sites that are described below.

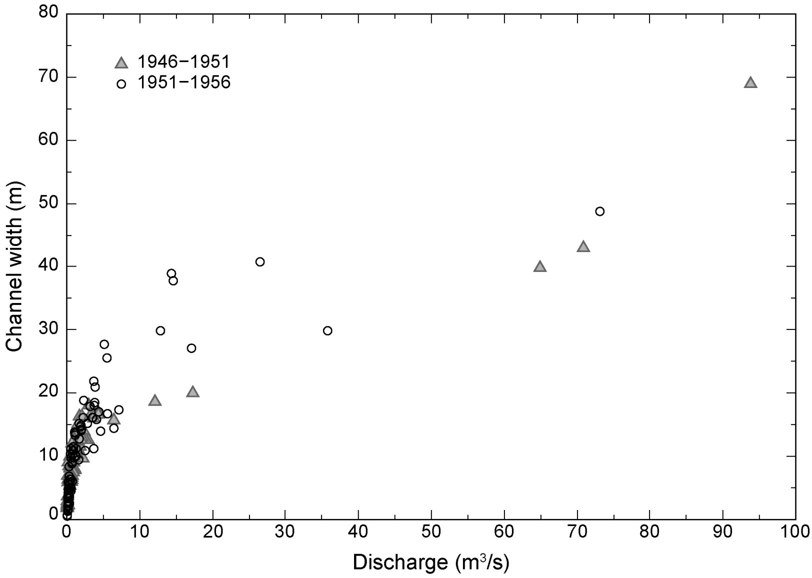

Fig. 6. Discharge-width relations at South Fork Solomon River at Alton streamgage (USGS gage no. 06873500, Fig. 1), 1946–1951 and 1951–1956.

South Fork Solomon River at Alton

The streamgage at Alton (USGS gage no. 06873500) was in north-central Kansas (Fig. 1). Bankfull stage at this site was 3.7 m with a bankfull discharge of 99 m^3/s. The gage was active from 1942 to 1957. Thus, the five-year periods preceding (1946–1951) and following (1951–1956) the 1951 flood were compared. Channel widening of as much as 10 to 20 m (an increase of about 50–100%) was indicated between flows of about 5 to 30 m^3/s (Fig. 6), although the indicated increase in channel width may have been caused, in part, by discharge measurements made at different locations. No change in channel width was apparent at lower or higher flows. However, the ability to effectively assess channel-width change for higher in-channel flows was constrained by a lack of post-flood measurements.

Kansas River at Lecompton

The streamgage at Lecompton (USGS gage no. 06891000) is in northeast Kansas approximately 103 km upstream from the confluence with the Missouri River (Fig. 1). Bankfull stage and discharge were 5.8 m and 2679 m^3/s, respectively. The gage has been active since 1936 and channel response and recovery were assessed in four- to five-year intervals beginning in 1946 and continuing until 2007.

The 1951 flood resulted in substantial channel widening at this site. During the flood, the north section of the bridge at this site was completely washed away (Fig. 2B). Channel width ranged from approximately 220 to 245 m for flows greater than

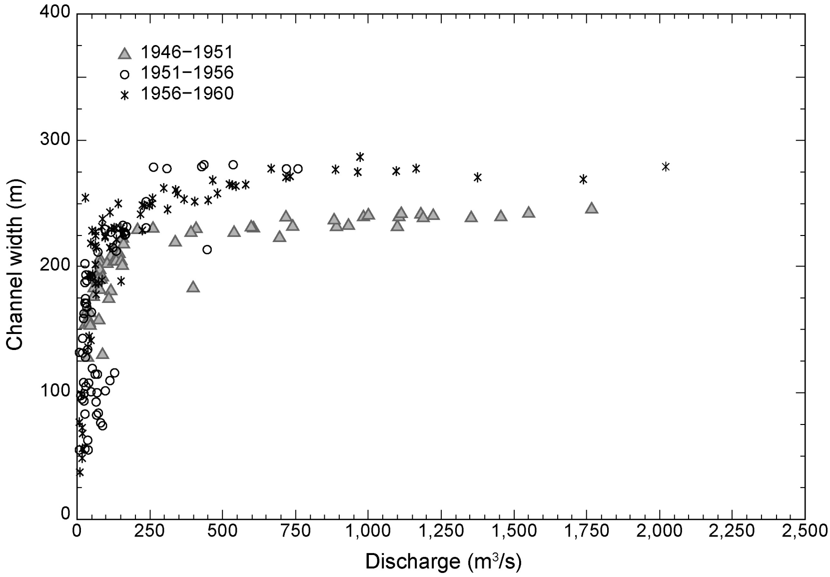

Fig. 7. Discharge-width relations at Kansas River at Lecompton streamgage (USGS gage no. 06891000, Fig. 1), 1946–1951, 1951–1956, and 1956–1960.

225 m^3/s during the five-year period before the 1951 flood. For the five-year period following the flood, channel widening of as much as 50 m for flows between 225 and 765 m^3/s was indicated (Fig. 7). An assessment of channel-width change for flows higher than 765 m^3/s was not possible because of a lack of data for this period; however, data from 1956–1960 indicated that the widening had occurred at higher flows. The 1956–1960 data also indicated that channel width had decreased for flows between 225 and 565 m^3/s by as much as 15 to 25 m. However, at lower flows channel width was nearly identical for the two periods (1951–1956 and 1956–1960) (Fig. 7). Channel width remained stable for the duration of the monitoring period (i.e., 1960–2007). There was no observable change in channel width following major floods in 1973 and 1993.

Marais des Cygnes River at Trading Post

The streamgage at Trading Post (USGS gage no. 06916000) was in east-central Kansas approximately 6 km upstream from the Kansas-Missouri state line (Fig. 1). Bankfull stage and discharge at this site were 7.3 m and 340 m^3/s, respectively. The gage was active from 1929 to 1958. Thus, five-year periods preceding (1946–1951) and following (1951–1956) the 1951 flood were compared.

This gage recorded a wide range of in-channel flow conditions before and after the flood. Thus, channel changes for a range of flow conditions were well documented. For flows greater than approximately 85 m^3/s, channel-width increases of as much as 30 to 40 m (about 75–80%) were indicated. For discharges less than 85 m^3/s, pre- and post-1951 flood channel widths were nearly identical (Fig. 8). In August 1951

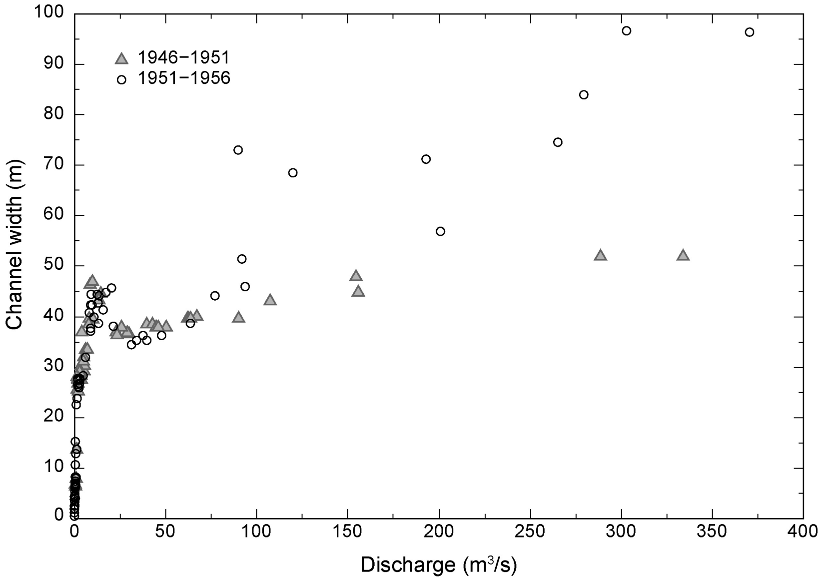

Fig. 8. Discharge-width relations at Marais des Cygnes River at Trading Post streamgage (USGS gage no. 06916000, Fig. 1), 1946–1951 and 1951–1956.

the gage was relocated to a new bridge about 60 m upstream from the former site. It is possible that all or part of the indicated changes in channel width were a result of the gage relocation rather than actual geomorphic changes caused by the 1951 flood (E. R. Leeson, hydrographer, USGS, written comm., February 12, 1954).

DISCUSSION

Geomorphic effects, including channel-bed erosion and deposition and channel widening, were indicated within several drainage basins throughout eastern Kansas as a result of the 1951 floods. Of the 23 USGS streamgages assessed, 17 exhibited a geomorphic response to the floods (Table 2). Substantial channel-bed elevation change was evident at seven sites (Figs. 3–5), and channel widening was indicated at three sites (Figs. 6–8).

Approximately one-half of the 23 gage sites investigated likely experienced channel-width increases. However, a widespread and prolonged drought following the 1951 floods reduced streamflows and prevented a detailed analysis of pre- and post-flood channel-width change for a range of in-channel flow conditions at most sites. Three gage sites, however, had a sufficient range of flows during the five years preceding and following the 1951 floods to enable an assessment of channel-width changes (Figs. 6–8).

Following the 1951 floods, channel recovery may have been affected by several human disturbances. For example, several large flood-control reservoirs were constructed mostly in the 1960s in the affected basins (Fig. 1). Immediately downstream, typical effects of a large reservoir include an increase in sediment load during dam construction followed by a pronounced reduction of the sediment load (most of which is trapped and stored upstream from the dam) and a modified flow regime (i.e., reduced peak flows and frequently increased low flows) once the dam is completed (Williams and Wolman, 1984). Channel-bed and/or bank erosion is a common geomorphic response downstream from large reservoirs. Upstream, the artificial base level caused by a reservoir may result in deposition in the channel. Both downstream and upstream effects decrease with increasing distance from the reservoir. Whereas reservoirs may have affected post-flood recovery at the gage sites where substantial flood-related changes were indicated, such effects were assumed to be relatively minor given that the reservoirs typically were completed several years after the 1951 floods and/or were located tens of kilometers from the gage sites. Other post-flood human disturbances that possibly affected channel recovery at a given gage site included levee construction and channel straightening upstream or downstream of the gage site.

For discussion purposes, the gages were grouped by basin in the following sections.

Smoky Hill River Basin

The Saline and Solomon Rivers are tributaries of the Smoky Hill River, which forms the Kansas River at its confluence with the Republican River (Fig. 1). Soils and geology are variable throughout the Smoky Hill River Basin, but are similar in the area affected by the 1951 floods. Soils in the vicinity of streamgages are dominated by silt loams; however, along the South Fork Solomon River, fine sandy loams are prevalent (Soil Survey Staff, 2009). Bedrock outcrops are not common, and floodplains primarily are underlain by silty alluvium with local areas composed of gravelly, sandy, and clayey alluvium. Only the eastern part of the basin was substantially affected by the 1951 floods (KWRB, 1961b).

A pronounced geomorphic response to the 1951 floods was indicated by four gages in the eastern one-half of the Smoky Hill River Basin. Substantial sediment deposition was indicated at the Saline River at Tescott, the South Fork Solomon River at Osborne, and the Smoky Hill River at Enterprise gage sites (Fig. 3). Possible channel widening was indicated at the South Fork Solomon River at Alton gage site (Fig. 6), which was ~30 km upstream from the gage at Osborne.

Flood-related, channel-bed elevation changes recorded within the basin likely were caused by scour and fill cycles (Leopold et al., 1964; Knighton, 1998). During the rising stage of the flood, increased velocity and bed shear stress resulted in bed scouring. As stage fell, sediment was deposited on the channel bed. Although it is likely that a cycle of scour and fill occurred along the above three reaches, only the net geomorphic response within the channels was detectable using streamgage data.

Channel widening possibly was indicated at the South Fork Solomon River at Alton gage site. Channel banks at this site were composed of easily erodible loamy, fine sand (Soil Survey Staff, 2009). Increased shear stress during the rising limb and/

or liquefaction of channel banks during the falling limb of the storm hydrograph were likely causes of the channel widening (Knighton, 1998).

It was difficult to assess channel recovery following the floods because of several complicating factors. Whereas 1951 was the wettest year on record at the time, 1952 was the driest year on record and the five-year period following the 1951 floods was a prolonged period of drought. In addition, major initiatives such as reservoir construction, levee construction, and channel straightening began shortly following the floods (KWRB, 1959, 1962). Furthermore, the gage on the Smoky Hill River at Enterprise was relocated in 1959 and the gage on the South Fork Solomon River at Alton was discontinued in 1957.

Nevertheless, channel-bed recovery was assessed for the Saline River at Tescott, the South Fork Solomon River at Osborne, and the Smoky Hill River at Enterprise gage sites. At the Saline River site, channel flood deposits steadily were eroded and the channel bed recovered to its pre-flood elevation in about 10 years (Fig. 3A). At the South Fork Solomon River site, the channel bed never recovered to its pre-flood elevation. Instead, the deposition that occurred as a result of the 1951 flood was followed by continual aggradation until ~1960, after which time channel-bed elevation fluctuated until the present (Fig. 3B). It appears that a new post-flood equilibrium was established at the higher channel-bed elevation at this site. At the Smoky Hill River site, the channel bed recovered to its pre-flood elevation within eight years (Fig. 3C).

Kansas River Basin

The Kansas River flows eastward from the confluence of the Smoky Hill and Republican Rivers in central Kansas to the confluence with the Missouri River at Kansas City. The most intense precipitation that produced the July 1951 floods occurred near the Kansas-Neosho Basin divide, southwest of the Kansas River (Fig. 1). Kansas River floodplain soils predominantly are sandy or silty loams formed in alluvium (O'Connor, 1960). Soils in the vicinity of the streamgages were mostly sandy and silty loams (Soil Survey Staff, 2009). Limestone and shale outcrop only along the valley walls (KWRB, 1959). Thus, in general, the Kansas River is an alluvial river with erodible bed and banks that adjust to changing flow conditions.

The basin exhibited pronounced geomorphic response along three reaches of the main-stem river, and minor change along two tributaries, following the 1951 floods (Table 2). Substantial channel-bed erosion was indicated at the Kansas River gage sites at Wamego and Bonner Springs (Fig. 4), and substantial channel widening was indicated at the Kansas River at Lecompton gage site (Fig. 7). Although channel width increased substantially as a result of the flood, only minor channel-bed erosion was indicated at the Lecompton site (Table 2); yet a long-term trend of gradual aggradation persisted for nearly 15 years after the flood (data not shown).

McCrae (1954) examined the geomorphic effects of the 1951 flood on the Kansas River from Topeka to Lawrence (i.e., a reach located between the Wamego and Bonner Springs gage sites and including the Lecompton gage site) and observed considerable geomorphic changes because of widespread scouring by intense turbulent flows within the channel and on the floodplain. Sediment deposition primarily was limited to the floodplain in areas of reduced local velocity. He identified three types of channel-bank erosion and stated that macro-turbulence with eddies rotating on a vertical axis scoured concave banks on straight reaches, and outer banks of meander bends were eroded either by undercutting of the banks or tangential overbank scour. Substantial bank erosion and channel widening were observed at several locations (McCrae, 1954).

Channel recovery assessments within the basin were complicated by many of the same factors identified for the Smoky Hill Basin (i.e., reservoir construction, levee construction, channel straightening, drought, gage relocation). Low flows in the Kansas River persisted for several years following the 1951 flood. In fact, more water was discharged at Bonner Springs during the July 1951 flood than during the entire period from June 1952 through May 1957 (KWRB, 1959). Despite these limitations, channel-bed elevation recovery was assessed for the Kansas River gage sites at Wamego and Bonner Springs and channel-width recovery was assessed for the Kansas River at Lecompton.

At the Wamego site, the channel bed never recovered to its pre-flood elevation. Instead, a new equilibrium was established by 1960 at an elevation that was about 0.25 m lower than the pre-flood elevation. Since then, the channel-bed elevation has been relatively stable (Fig. 4A). Likewise, downstream at the Bonner Springs site, the channel bed never recovered to its pre-flood elevation. Following some initial post-flood redeposition and a brief period of stability, the channel bed eroded substantially in the late 1950s. The removal of sand by in-channel dredging was a possible contributing factor at this site (Joshua Marx, U.S. Army Corps of Engineers, written comm., August 19, 2009). At the Lecompton site, channel-width recovery was analyzed in four- to five-year intervals following the 1951 flood to present. For 1956 to 1960, channel width had decreased by as much as 15 to 25 m for discharges between 225 m^3/s and 565 m^3/s, but was unchanged at higher and lower flows (Fig. 7). A possible explanation is that as riparian vegetation re-established, episodic pulses of moderately high flow and sediment load resulted in deposition of fine-grained material along the channel margins that narrowed the channel (Baker, 1988). Channel width at this site attained a new equilibrium within this five-year period and remained stable until at least 2007. Thus, at this site, the channel did not fully recover to its pre-flood width. Even though the mid-1950s were characterized by widespread drought, channels attained a new, stable equilibrium within several years of the 1951 flood. This is not surprising because previous research has indicated that alluvial rivers in humid regions recover quickly, often in less than one year (Kochel, 1988).

Marais des Cygnes, Neosho, and Verdigris River Basins

The Marais des Cygnes River Basin is in eastern Kansas and is bounded to the north by the Kansas River Basin (Fig. 1). To the west it is bounded by the Neosho River Basin, which extends south into Oklahoma. Most of the Marais des Cygnes Basin lies within Missouri. The Verdigris River Basin is immediately west of the Neosho River Basin and also extends into Oklahoma. All three basins are within the Osage Cuestas section of the Osage Plains physiographic province (Fenneman, 1938; Schoewe, 1949). The Osage Cuestas consist of a series of east-facing limestone escarpments with surfaces that dip gently to the west. Soils within these basins typically are thinner and clayier compared to soils within the Kansas River Basin. Shallow stony and gravelly soils also are more common (KWRB, 1958, 1961a; Soil Survey Staff, 2009). The soils surrounding streamgages predominantly are silt loams and silty clay loams (Soil Survey Staff, 2009).

Three of the four streamgages investigated within the Marais des Cygnes Basin and five of the eight within the Neosho and Verdigris Basins indicated channel-bed elevation change as a result of the 1951 floods. Channel-bed elevation change was modest within the Marais des Cygnes Basin and along the main stem of the Neosho River, but substantial deposition was indicated along two tributaries of the Neosho River (Table 2). Within the upper part of the Cottonwood River and Cedar Creek, a tributary of the Cottonwood River, an increase in reference stage of ~0.1 m indicated possible deposition (Table 2). Channel filling that may have occurred likely was the endproduct of a scour and fill cycle, similar to that indicated elsewhere. The channel bed at the Cottonwood River near Marion gage site eroded to its pre-flood elevation in about 10 years before modest deposition occurred (Fig. 5A). Channel-bed elevation at this site essentially was stable for the first five years following the 1951 flood, possibly because of a lack of erosive flows during the drought (Fig. 5A). Another possibility is that channel-bed adjustment may have been temporarily prevented by an accumulation of woody debris in the channel that eventually was flushed downstream. At the Cedar Creek near Cedar Point gage site, the channel bed nearly recovered to its pre-flood elevation within three months, as most of the flood-deposited material was quickly removed (Fig. 5B). Disturbance caused by heavy equipment in the channel in 1957 may have initiated a period of channel-bed erosion at the Cedar Point site.

Channel widening was not indicated within the Neosho or Verdigris River Basins, but possible widening of as much as 30 to 40 m was indicated at the Marais des Cygnes River at Trading Post gage site (Fig. 8). This represented a nearly twofold increase in channel width during moderate to high flows compared to the pre-flood channel. Aggradation along this reach began in 1947, and by 1951 channel depth was reduced nearly 0.5 m. Aggradation may represent a pulse of sediment migrating through the reach in relation to an unknown local upstream disturbance. Another possibility is that low-flow stages were affected by the accumulation of woody debris in the channel (H. P. Brooks, hydrographer, USGS, written comm., March 1, 1951). Channel widening may be related to woody debris in the channel deflecting flow toward channel banks and/or widening may be a response to aggradation. Research by Schumm (1969) indicated that increases in discharge and bed load result in wider, shallower channels (Knighton, 1998). Aggradation indicates at least a local increase in bed load, and when coupled with a high-magnitude flood discharge, may have caused a response similar to that predicted by Schumm (1969). The gage was discontinued in 1958, so recovery could not be assessed.

The relative lack of geomorphic response to the 1951 floods in these three basins likely was related, in part, to the resistant materials encountered. Bedrock frequently is at or near the surface, and gravelly and clayey soils beneath the floodplains are prevalent (KWRB, 1958, 1960, 1961a). Juracek (2000) identified several reaches along the Neosho River where the channel bed was resistant to erosion because of bedrock control and armoring by coarse gravel.

Utility of Streamgage Data for Assessing the Geomorphic Effects of Large Floods

An assessment of the utility of streamgage data for the purpose of determining the geomorphic effects of large floods requires answers to several questions. An initial question concerns gage availability. Are one or more gages located along the stream, or within the basin, of interest? For each state, the locations of all current and historical USGS gages are available via the Internet from the USGS national data system, NWISWeb (http://waterdata.usgs.gov/nwis).

A second question is fundamental and readily answered. That is, can streamgage data be used to detect flood-related geomorphic changes? As shown in this study, the answer is a qualified yes. Whereas streamgage data can provide an indication of geomorphic change, interpretation of the change needs to be carefully considered within the context of local conditions. In this study, streamgage data were shown to be particularly useful for assessing flood-related changes in channel-bed elevation.

A third important question is more complex and more challenging to answer. That is, how representative are the geomorphic effects evidenced by streamgage data? This question has spatial and temporal aspects. Spatially, a gage provides geomorphic information that is representative for the vicinity of the gage and, frequently, for some distance upstream and downstream from the gage. How far upstream and downstream will depend on the local conditions. Ideally, the gage is in a representative reach that is free of unwanted affects (e.g., backwater, in-channel structures). On-site inspection is essential to assess the representativeness of a particular gage site. It is important to recognize that channel characteristics at gage sites may not be representative of randomly selected locations at any point along the length of a stream (Smelser and Schmidt, 1998; National Research Council, 2004).

Temporally, there are both short- and long-term issues. In the short term, the question is how representative are the geomorphic changes evidenced by streamgage data as compared to the actual geomorphic changes that occurred during the flood. Case in point, because changes in channel-bed elevation are inferred from post-flood measurements made during relatively low-flow conditions, the documented changes provide an indication of net change (i.e., a pre- vs. post-flood comparison). Thus, scour that occurred during the flood may be partially obscured by subsequent fill that occurred as the flood receded and before post-flood measurements were made. It follows that the channel-bed elevation change indicated by streamgage data may provide a conservative estimate of the actual magnitude of change that occurred during the flood. This issue merits further research.

In the long term, the question is whether or not the period of record adequately covers the period of interest. For example, in a study to determine the geomorphic effects (i.e., short-term change and subsequent recovery) of an historic flood, the period of record ideally extends many years before and after the flood. The pre-flood record provides the necessary baseline information for quantifying the magnitude of the channel changes relative to background variability, whereas the post-flood record provides information for assessing channel recovery. Thus, streamgage data may be of limited value for this type of study if the period of record is not sufficiently long before and/or after the flood. An additional benefit of a long period of record is that information may be available to compare the geomorphic response of a channel to multiple floods.

In sum, the utility of streamgage data to estimate the geomorphic effects of large floods depends on several factors including gage location, site conditions, flood characteristics, and the length and continuity of the gage record. Beyond documentation, streamgage data possibly may be used to predict the geomorphic effects of future large floods on alluvial channels. That is, for a given site, estimates of past flood-related changes may provide the basis for estimates of future flood-related changes. Moreover, streamgage data may enable an assessment of the recovery potential for a given river or stream. These possibilities will require additional investigation.

CONCLUSIONS

In this study it was demonstrated that streamgage data—specifically, the reference stage—can provide an indication of the direction and magnitude of channel-bed elevation change caused by a large flood. For a small number of sites, changes in channel width also were indicated. In addition, an assessment of post-flood channel-bed elevation or channel-width recovery was possible for several sites. In sum, it was determined that the use of streamgage data to assess the geomorphic effects of large floods is a potentially useful technique with the best prospects for success being for gages with a long period of record (i.e., several decades) that are located on alluvial channels. Ideally, streamgage data are best used in combination with other lines of evidence (e.g., aerial photographs, cross-section data) to provide a more complete assessment of the geomorphic response of a channel to a large flood. However, the several thousand gages operated throughout the United States often are the only sources of continuous, long-term streamflow and channel morphology data for the locations being monitored. In the absence of other lines of evidence, streamgage data can provide an estimate of the direction and magnitude (net) of geomorphic change that otherwise might not be available or attainable.

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