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GEOMORPHIC APPLICATIONS OF STREAM-GAGE INFORMATION[†]

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ABSTRACT

In the United States, several thousand stream gages provide what typically is the only source of continuous, long-term streamflow and channel-geometry information for the locations being monitored. In this paper, the geomorphic content of stream-gage information, previous and potential applications of stream-gage information in fluvial geomorphic research and various possible limitations are described. Documented applications include studies of hydraulic geometry, channel bankfull characteristics, sediment transport and channel geomorphic response to various types of disturbance. Potential applications include studies to determine the geomorphic effectiveness of large floods and in-stream habitat change in response to disturbance. For certain applications, various spatial, temporal and data limitations may render the stream-gage information of limited use; however, such information often is of considerable value to enable or enhance geomorphic investigations. Published in 2008 by John Wiley & Sons, Ltd.

KEY WORDS: channel change; disturbance; fluvial geomorphology; hydraulic geometry; sediment transport; stream gage

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INTRODUCTION

Stream gaging in the United States dates back to at least the early 1800s. For example, the flow of the Sandusky River (Ohio) was measured in 1823 (Kolupaila, 1960) and flow records for the Merrimack River at Lowell, Massachusetts, began in 1848 (Liddell, 1927). Today, more than 90% of the nation's stream gages that provide daily streamflow records are operated by the US Geological Survey (USGS) (Hirsch and Costa, 2004). Beginning with the establishment of the first USGS stream gage in 1889 (on the Rio Grande near Embudo, New Mexico) (Wahl *et al*., 1995), the programme grew to a network of more than 7000 active gages by 2004 (Hirsch and Costa, 2004). Several thousand discontinued gages also provide historical information. Access to the streamflow information (historical and near real time) is provided via the internet by the USGS national data system, NWISWeb (http://waterdata.usgs.gov/nwis).

Information from stream gages has been used for a diversity of water-resources management and research purposes. Applications include, but are not limited to, flood forecasting, flood-plain mapping, reservoir design and operation, bridge and culvert design, establishment and monitoring of minimum streamflow requirements, management of water rights, water-use allocation, resolution of interstate and international conflicts, water-quality assessment and protection, investigation of surface- and ground-water interaction, climate-change research and recreation (Wahl *et al*., 1995; Hester *et al*., 2006).

Beyond the hydrologic applications, the data generated from measurements of streamflow at gages have also been used in fluvial geomorphic investigations. Examples include studies to assess the geomorphic response of channels to various types of human disturbance including flow regulation associated with dam construction (Williams and Wolman, 1984; Hirsch *et al*., 1990; Graf, 1996; Juracek, 2000), channelization (Piest *et al*., 1977; Simon, 1994; Juracek, 2004a), sand and gravel extraction (Collins and Dunne, 1989) and hydraulic mining (James, 1991, 1997). Other examples include studies of hydraulic geometry (Leopold and Maddock, 1953; Richards, 1977; Ferguson, 1986) and sediment transport (Andrews, 1986; Simon *et al*., 2004). Where present, stream gages

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typically provide the only source of continuous, long-term streamflow and channel-geometry information. Sediment data are also available for some gages.

The purpose of this paper is to: (1) describe the geomorphic content of stream-gage information, (2) provide an overview of previously published studies that used stream-gage information in fluvial geomorphic investigations, (3) present potential applications for stream-gage information in fluvial geomorphic investigations and (4) describe the limitations of stream-gage information for fluvial geomorphic investigations. This paper is intended to benefit the many users of stream-gage information in various fields including aquatic ecology, engineering, geomorphology, hydrology and water-resources management.

STREAM-GAGING METHODS AND ANCILLARY DATA COLLECTION

According to Rantz *et al*. (1982), the ideal site for a USGS gage meets the following criteria:

1. The stream channel generally is straight for about 100 m upstream and downstream from the gage site.
2. Total flow is confined to a single channel at all stages, and no flow bypasses the site as subsurface flow.
3. The streambed is not affected by scour and fill and is free of aquatic vegetation.
4. Channel banks are permanent, high enough to contain floods and free of brush.
5. Unchanging natural controls are present such as a bedrock outcrop or other stable riffle for low flow and a channel constriction for high flow—or a falls or cascade that is unsubmerged at all stages.
6. A pool exists upstream from the control at extremely low stages to ensure a recording of stage at extremely low flow.
7. The gage site is sufficiently far upstream from the confluence with another stream or from tidal effect to avoid any variable effect the other stream or the tide may have on the stage at the gage site.
8. An acceptable reach for measuring discharge at all stages is available within reasonable proximity of the gage site. (Low and high flows need not necessarily be measured at the same channel cross section.)
9. The site is readily accessible for ease in installation and operation of the gage.

Many gages are located at non-ideal sites because often it is impossible to meet all of the criteria at locations where gages are needed.

Continuous-stage data, known as unit-value data, are collected at USGS gages in intervals that typically range from 5 to 60 min. For each gage, stage is related to discharge through a stage-discharge rating developed by USGS personnel that operate and maintain the gage. Each rating represents a best-fit line through the measurement data (i.e. paired measurements of stage and discharge). In addition to rating display curves, rating tables are prepared.

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). Typically, a discharge measurement involves the measurement of flow width, depth, area and velocity at approximately 25 points along an established channel cross section. The goal of the technician is to represent 5% or less of the total discharge with each point measurement. Low flows are measured by wading across the channel, whereas high flows are measured from a bridge or cableway or by boat. Discharge generally is measured 10–12 times during a water year (i.e. 1 October through 30 September) with the objective being to measure a wide range of flow conditions to obtain an accurate stage-discharge relation (Rantz *et al*., 1982). Measuring discharge is especially important during floods so that the upper end of the stage-discharge rating can be adequately represented. During a flood, multiple follow-up measurements are made as the flow decreases to assess channel conditions and determine if a new rating is needed. The follow-up measurements often are in addition to the usual 10–12 measurements per year.

Requisite for the operation of a stream gage is the establishment of the datum, which serves as the reference elevation for measuring stage. Typically, an arbitrary datum is selected for the convenience of using relatively low numbers for stage. To eliminate the possibility of negative values for stage, the datum initially chosen is several feet below the elevation of zero flow in a channel with natural control (Rantz *et al*., 1982). However, subsequent to gage installation, excessive channel-bed erosion may necessitate lowering the datum to avoid negative stages. Such datum changes may be made one or more times for an individual gage and normally are documented in the station description and (or) station analysis (described below).

Presently (2008), the information for each discharge measurement is entered directly into the USGS National Water Information System (NWIS) database. Historically, a summary of discharge measurements associated with each gage was recorded on the USGS standard form (SF) 9-207. For each discharge measurement, the SF 9-207 forms include the date of measurement, flow width, flow area, flow velocity and the computed discharge. The SF 9-207 forms also contain stage readings and any gage-height corrections that were done based on results from the discharge measurements. For individual discharge measurement notes, the USGS SF 9-275 form is used to record flow width, depth, area and velocity for approximately 25 points along an established cross section. From these measurements a wetted cross section can be constructed. The SF 9-275 forms also contain the stage height for point of zero flow. The SF 9-207 and SF 9-275 forms are not published, but are available at the USGS Water Science Center (WSC) in each state. Each gage may have multiple stage-discharge rating curves and tables applicable for different time periods (as stage-discharge relations may change with time because of erosion and deposition in the channel). Daily discharges at the active gages are published in annual water data reports by each WSC, and are also available via NWISWeb. In 2006, the USGS began making the unit-value discharge data available on the internet (http://ida.water.usgs.gov). Streamflow summary statistics and characteristics such as flow variability, magnitudes, frequencies, durations, trends, minimums, maximums, means and medians are calculated routinely and available via NWISWeb or other USGS internet sites (e.g. StreamStats, see next section).

Station descriptions traditionally are unpublished and contain information on gage location (including directions to the site), history of equipment and datum changes, site establishment, contributing drainage area, major floods, point of zero flow, location of wading section, channel and control characteristics, flow regulation and accuracy of streamflow records. Elevations and locational descriptions of reference marks and benchmarks are also included. Elevation surveys are done periodically to ensure that the elevation between the water surface and the stage recorder has not changed.

Station analyses are updated annually and traditionally are unpublished. They document the results of study of the data (Rantz *et al*., 1982) collected during a year and include type of equipment, gage-height corrections and rating shifts, channel disturbances in the vicinity of the gage (e.g. ice effects, changes in control, bridge construction, bank sloughing) and descriptions of the quality of the record. Electronic versions of station analyses and station descriptions for recent years are available from the WSCs. Older versions of station analyses and station descriptions typically are available in paper and (or) microfiche at the WSCs.

Sediment data traditionally have been collected through routine and periodic sampling at a small percentage of stream gages by standard direct techniques (Edwards and Glysson, 1999; Nolan *et al*., 2005). Data typically include suspended-sediment concentration and size, with a few gages having bedload and bed material size, and water temperature data. In 2000, NWIS contained sediment data for 15 400 sites in the United States (US), Puerto Rico and other places, of which 12 115 had suspended-sediment concentration data, 238 had bedload discharge data and 3623 had particle-size distribution data for bed material (Turcios and Gray, 2001).

The USGS suspended-sediment database included about 1600 sites in 2007 (http://water.usgs.gov/osw/sediment/index.html). Sites with bedload transport curves are rare. Suspended-sediment samples are usually composite samples collected using depth-integrated samplers from several verticals in a channel cross section (Edwards and Glysson, 1999). Suspended-sediment concentration data are combined with water discharge to compute suspended-sediment discharge or loads (Porterfield, 1972). Bed material and bedload samples typically are collected at several points along a channel cross section (usually at the same verticals sampled for suspended sediment) using a variety of handheld or cable-mounted samplers (Edwards and Glysson, 1999). The amount of sediment captured by the bedload sampler over a known period of time at a given discharge is used to calculate an instantaneous bedload. Particle size, flow and water temperature data are used to estimate bedload by applying appropriate empirically based sediment transport rates (Stevens and Yang, 1989). Techniques for measuring suspended sediment, bedload and bed material, including optical and acoustic methods, are being tested by the USGS and other federal agencies and universities for augmenting or replacing traditional techniques (Gray, 2005; Gray *et al*., 2007). Suspended sediment is easier to measure by direct methods than bedload (Meade *et al*., 1990). The proportion of suspended load to bedload can be highly variable and depends on several factors including sediment sources and supply, physiographic and climatic setting, antecedent conditions, local variations in transport capacity and flow magnitude (Walling and Webb, 1983; Simon, 1989; Leopold and Emmett, 1997; Chalov, 2004).

GEOMORPHIC CONTENT

Information from USGS stream gages typically used in geomorphic studies includes data from individual discharge measurements (i.e. flow width, depth, area and velocity), streamflow and sediment data and statistics, stage-discharge rating curves and tables, station descriptions and station analyses. These data can be used to determine and explain historical changes in channel morphology and can serve as additional lines of evidence for channel changes observed through other geomorphic measurements (e.g. cross sections and aerial photography). Stream-gage records are used to construct plots of discharge exceedence probability, channel-bed elevation and hydraulic geometry that are used to determine changes and trends in floods, channel-bed elevation and channel morphology. Smelser and Schmidt (1998) provide a detailed description of these plots and analyses and how to interpret geomorphic changes from them. Information contained in station descriptions and analyses has been used to document the timing and cause of historical channel morphology changes (Stover and Montgomery, 2001; Juracek, 2004a; Fitzpatrick, 2005).

Depending on the length of historical record, streamflow statistics can be generated for different periods of interest and the data can be analysed for statistically significant changes or trends. These data are useful for determining hydrologic and geomorphic responses to indirect causes of disturbance such as clearing of vegetation cover (e.g. urbanization) on a watershed scale, and direct causes such as dam construction. Typically, peak flow statistics are generated from both continuous and crest-stage (i.e. elevation of flood crest only) gages with more than 10 years of data and are based on instantaneous peak flows from the annual time series (Hydrology Subcommittee, Interagency Advisory Committee on Water Data, 1982). These statistics are used to estimate the magnitude and recurrence interval of flows at ungaged sites by using multiple regression equations that include such variables as drainage area, slope, precipitation intensity, snow cover, soil type and land cover. Instantaneous peaks from partial duration series (i.e. floods above a given threshold discharge) commonly are used to examine the frequency and magnitude of floods with recurrence intervals of 5 years or less. The partial duration series is also useful to examine overbank flows linked with processes of flood-plain formation and vegetation communities. Flow duration statistics above a given stage are useful for linking hydraulic processes to channel and flood-plain morphology, or storage/remobilization of contaminated sediment. There are several automated packages for determining flow statistics including the USGS's StreamStats program (Ries *et al*., 2004; http://water.usgs.gov/osw/streamstats/) and The Nature Conservancy's Indicators of Hydrologic Alteration (Richter *et al*., 1996; http://www.nature.org/initiatives/freshwater/conservationtools/). Also, some WSCs have computed flow statistics and made them available on the internet (e.g. http://ks.water.usgs.gov/Kansas/studies/strmstats/).

GEOMORPHIC APPLICATIONS

Applications of stream-gage information in fluvial geomorphic investigations include the relation of streamflow to channel characteristics, the estimation of process rates, the documentation of channel changes, the reconstruction of historical channel conditions, the determination of causes of channel change and the estimation of future channel changes. In this section, examples of the uses of stream-gage information in published fluvial geomorphic studies are reviewed and several potential applications are presented.

Previous applications

Hydraulic geometry. In an influential paper, Leopold and Maddock (1953) presented a series of relations that they termed 'hydraulic geometry'. The relations, expressed as simple power functions, provide an indication of how flow width, depth and velocity vary with discharge. The functions are as follows:

$$w = aQ^b \tag{1}$$

$$d = cQ^f \tag{2}$$

$$v = kQ^m \tag{3}$$

where w is the flow width, d the mean flow depth, v the mean flow velocity, Q the discharge and a, b, c, f, k and m are numerical constants. Given that $Q = wdv$, it follows that the sum of b, f and m equals 1.0 and the product of a, c and k equals 1.0. The exponents b, f and m represent the respective rates of change for the flow variables w, d and v (Leopold and Maddock, 1953).

Hydraulic geometry provides a basis for investigating alluvial channel response to changing discharge both at a station and in the downstream direction. Whereas at-a-station hydraulic geometry considers temporal variations in flow variables as discharge varies at a cross section, downstream hydraulic geometry is concerned with spatial variations in flow variables for a reference discharge (e.g. mean annual discharge) (Leopold and Maddock, 1953). Since its introduction, considerable research has been devoted to the theory, interpretation and improvement of hydraulic geometry. Review papers include those by Richards (1977) and Ferguson (1986). The global variation in hydraulic geometry exponents has been investigated by Park (1977) and Rhodes (1987).

While generally regarded as a useful tool for understanding river behaviour, concerns have been raised about hydraulic geometry in its original form. For example, a common concern is oversimplification because discharge is the only independent variable and linearity (in log space) is assumed in the bivariate relations (Richards, 1973; Knighton, 1987; Rhoads, 1992). Another concern centres on the data sets used to develop the hydraulic geometry relations. Typically, the relations have been developed for a group of streams within a given area because generally there are not enough gages along individual streams to provide an adequate sample (Knighton, 1998). The appropriateness of using such regionally derived average relations has been questioned (Knighton, 1975; Park, 1977; Rhodes, 1977; Betson, 1979). Other concerns, including indeterminacy and equifinality, were presented by Thornes (1977).

Methods developed for the interpretation and (or) improvement of hydraulic geometry have included the ternary diagram (Park, 1977; Rhodes, 1977, 1987). Basically, this approach involves the plotting of the b, f and m exponents on a common diagram to compare and classify streams and to interpret the direction of adjustment to changing discharge. Alternative statistical approaches presented have included a log quadratic model (Richards, 1973), a log piecewise linear model (Bates, 1990) and compositional data analysis (Ridenour and Giardino, 1991).

Besides discharge, other determinants of channel geometry include sediment load, channel boundary composition, channel slope and vegetation (e.g. Schumm, 1960; Richards, 1982; Knighton, 1998). The importance of these additional variables for predicting channel geometry has been demonstrated by multivariate analyses including those by Hey and Thorne (1986) and Huang and Warner (1995). Osterkamp and Hedman (1982) related discharge characteristics to channel geometry and channel bed and bank composition for the purpose of estimating discharge characteristics at ungaged sites.

Despite some limitations, hydraulic geometry has been used for various purposes. Geomorphic applications have included channel pattern discrimination (Xu, 2004), inference or prediction of channel change (Williams, 1987; Merigliano, 1997), assessment of channel adjustment during a flood (Merritt and Wohl, 2003) and prediction of the direction and rate of tidal channel evolution (Williams *et al*., 2002). Other applications include streamflow monitoring, modelling river recovery, estimation of minimum flow requirements, stream habitat assessment, channel design, estimation of present or past discharges from channel dimensions, water-quality modelling, stream rehabilitation and numerical simulations of landscape evolution (Ferguson, 1986; McConkey and Singh, 1992; Wohl, 2004).

Channel bankfull characteristics. During the past three decades, bankfull discharge or the discharge that fills the channel to the top of the banks before it spills out onto a flood plain, has become a simplified surrogate for the discharge, or range of discharges, most responsible for the major morphologic characteristics of self-formed, alluvial channels (Dunne and Leopold, 1978; Rosgen, 1996; Castro and Jackson, 2001). Channel bankfull dimensions and corresponding bankfull discharge have been related to effective discharge (i.e. the discharge or range of discharges that transports the largest sediment load over a period of years and has the ability to shape the channel) since Wolman and Miller's (1960) and Wolman and Gerson's (1978) well-known publications on the magnitude, frequency and duration of geomorphic forces responsible for channel formation and recovery. Regionally specific empirical equations, describing relations among bankfull channel dimensions of width, depth and area and bankfull discharge are used extensively across the US for geomorphic assessments, stream rehabilitation and channel design (Hedman *et al*., 1974; Dunne and Leopold, 1978; Harman *et al*., 1999; Maner, 1999; Castro and Jackson, 2001). Bankfull discharge for many streams in the US has a recurrence interval of about

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1.5 years, based on the annual mean daily streamflow series at rural USGS gages (Leopold *et al*., 1964; Dunne and Leopold, 1978; Andrews, 1980; Leopold, 1994; Rosgen, 1996; Castro and Jackson, 2001).

The assumptions for equating bankfull discharge, effective discharge, channel-forming flow and 1.5-year flow are best upheld for perennial, alluvial, meandering streams in humid areas with gentle slopes, well-developed point bars and no watershed disturbance. Effective discharge, or the discharge that transports the most sediment load, may deviate from the bankfull discharge, especially in gravel-bed streams (high bedload), arid streams, channels dominated by debris flows and high-energy mountain streams (Wolman and Gerson, 1978; Osterkamp and Hupp, 1984; Emmett and Wolman, 2001). A single relation between the frequency and magnitude of one discharge and bankfull channel morphology may be an oversimplification of the many frequencies, magnitudes and durations responsible for the complex features that define channel morphology. For example, many channels have multiple geomorphic surfaces below the flood-plain elevation that are shaped by flows more common than the 1.5-year event (Osterkamp and Hupp, 1984). Instead of a simple relation with flood magnitude, geomorphic effectiveness may better relate to stream power, flood duration, thresholds for erosion, potential for vegetative recovery and position within a watershed (Wolman and Gerson, 1978; Costa and O'Connor, 1995).

Recent publications on the relations among bankfull channel dimensions, effective discharge and streamflow characteristics indicate that practitioners of channel design concepts for stream rehabilitation require more than simple regional relations between bankfull discharge and drainage area (Dudley, 2004; Sherwood and Huitger, 2005; Doyle *et al*., 2007). Dudley (2004), using information from 10 gages, examined streamflow duration, as well as frequency characteristics, for describing channel morphology of central and coastal Maine streams. Sherwood and Huitger (2005), using information from 40 gages, developed regional bankfull curves and simple regression equations for relating bankfull characteristics (discharge, width, depth, cross-sectional area) to drainage area. They also developed multiple regression equations for relating bankfull characteristics to drainage area and several other variables including main-channel slope, local-channel slope, average main-channel elevation and median bed-material particle size. Doyle *et al*. (2007) recommended that a cumulative sediment discharge curve was needed to determine effective discharge and also provided insights to geomorphic processes and better prediction capabilities for channel change related to watershed disturbance.

Sediment transport. Geomorphic characteristics of channels and flood plains are affected by the magnitude and frequency of the interwoven processes of water and sediment movement; therefore, channel and flood-plain dimensions may be useful indicators of sediment transport processes. Alterations in sediment supply may cause changes in channel planform, geometry and elevation. Channel-morphology recovery after high-magnitude flow events is dependent on vegetation growth and sediment supply (Wolman and Gerson, 1978).

Several studies have linked channel changes to alterations in streamflow regime and sediment loads caused by watershed-scale land cover or vegetation change (agriculture, urbanization, logging, wildfire), flow regulation (dams, diversion) and climate change (Andrews, 1986; Keown *et al*., 1986; Knox, 1987; Jacobson and Primm, 1997; Van Steeter and Pitlick, 1998; Knox, 1999; Moody and Martin, 2001). Andrews (1986) illustrated how dam-related decreases in the duration of large discharges on the Green River (a tributary to the Colorado River) reduced annual sediment discharge by about 50%, and resulted in a bankfull channel width decrease of about 10%. Jacobson and Primm (1997) related channel disturbance and channel-bed elevation changes for Ozark streams to increased runoff and sediment yields from agricultural practices within the context of flood occurrence. In another study, Jacobson (1995) used long-term, channel-bed elevation data from 23 gages to assess spatial controls on land-use-induced stream disturbance and infer the passage of sediment waves for several Ozark streams.

Discharge, depth and velocity data from gages, as well as slope data from a subset of gages, have been used extensively for estimating potential flow competence, reconstructing past flood stages and estimating scour potential related to channel stability or aquatic habitat (Gilbert and Murphy, 1914; Colby, 1964; Baker and Ritter, 1975; Costa, 1983; Buffington and Montgomery, 1997; Lorang and Hauer, 2003; Fitzpatrick *et al*., 2005). Flow competence data from gages are spatially limited to points along the measurement section, which may or may not provide a good representation for possible longitudinal variations. Data from gages have also been used indirectly to investigate relations among sediment loads, flood characteristics and flood-plain sedimentation. Increased overbank sedimentation affects stage-discharge relations and the potential for flooding on flood plains and low terraces. Studies conducted more than 60 years ago by Happ (1944) indicated that accelerated overbank sedimentation along the Kickapoo River, a tributary to the Upper Mississippi River in Wisconsin, caused increased flood heights and subsequently increased the potential for flooding to downstream reaches by 40%, especially for frequent, low magnitude events. Excessive overbank sedimentation in some Tennessee streams during the early 20th century resulted in enlarged channels and widespread downstream flooding (Wolfe and Diehl, 1993). In New Zealand, rapid, episodic vertical accretion during large floods along the Waipaoa River affected channel morphology; the floods were dated using flood history from a nearby gage (Gomez *et al*., 1998). An unsteady, one-dimensional model of flood-plain vertical accretion was developed by Moody and Troutman (2000) for the Powder River, Montana and Wyoming, from partial-duration flood frequency probability distributions, the average number of floods per year that exceed the flood-plain stage, stage-discharge relations and estimates of net sediment discharge for a flood.

Short-term records (decades or less) of suspended-sediment load and bedload collected at gages have been used with geomorphic, paleohydrologic and sediment-source information to determine long-term (decadal to millennial) sediment budgets and yields (Walling and Webb, 1983; Walling, 2003). Sources of geomorphic, paleohydrologic and sediment-source information include aerial photographs, alluvial stratigraphy, flood-plain elevation surveys, soil development, reservoir surveys, geologic setting and history, flood scour lines and drainage topography and density (Madej, 1995; Fitzpatrick and Knox, 2000; Knox and Daniels, 2002; O'Connor *et al*., 2003). The combination of data sources can be used to estimate long-term episodic rates of erosion, sedimentation and sediment storage throughout a watershed. In addition, Fitzpatrick and Knox (2000) used a combination of total sediment-discharge rating curves with a flood-event model to predict varying sediment loads for historical land-cover scenarios.

Simon *et al*. (2004) used suspended-sediment concentration and streamflow data from more than 2900 gages to develop national suspended-sediment transport rates for 1.5-year recurrence flows. Many rehabilitation projects use the 1.5-year flow to determine channel size. In their study, suspended-sediment transport rates for 1.5-year flow were used to characterize and compare long-term sediment-transport conditions at background or 'reference' sites and disturbed sites among ecoregions.

Channel response to disturbance. Stream-gage information has been used in several ways to investigate the geomorphic response of stream channels to various types of disturbance. A relatively common application, which dates back to at least the early 1900s (Gilbert, 1917), is the determination of channel-bed elevation changes with time. At any given location and time along a stream, a relation exists between stage and discharge. For gages these relations are quantified on rating curves and updated as necessary to accommodate changes in channel shape, slope and other factors that affect the relation.

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. For example, Williams and Wolman (1984) used the discharge exceeded 95% of the time and Juracek (2004a) used the mean annual discharge for the period of record. Use of a low-flow discharge minimizes the effect of variations in channel width on flow depth (Simon and Hupp, 1992).

If the stage for the reference discharge has a downward trend, it may be inferred that the channel-bed elevation has declined with time because of erosion. Conversely, if the stage for the reference discharge has an upward trend, it may be inferred that the channel-bed elevation has risen with time as a result of deposition. An absence of trend indicates that the channel bed has essentially been stable.

As part of a study to assess the downstream effects of dams on alluvial river channels, Williams and Wolman (1984) used stage-discharge relations for 14 rivers to determine post-dam channel-bed elevation changes. Without exception, the results indicated that the channel beds were relatively stable before dam construction and began degrading soon after the dams were built (a consequence of the sediment-depleted or 'hungry' water released from the dams). For some of the rivers, a control gage tens of kilometres upstream from the dam was used to confirm that the downstream channel-bed degradation was a result of the changes imposed by the dam. In each case, the post-dam stage-discharge relation at the control gage did not change substantially.

Collins and Dunne (1989), as part of a study to assess the effects of gravel extraction on the Humptulips, Satsop and Wynoochee Rivers in Washington, analysed stage-discharge relations for six gages. Channel-bed degradation was documented at several sites, the timing of which indicated that gravel extraction was the cause. Additionally,

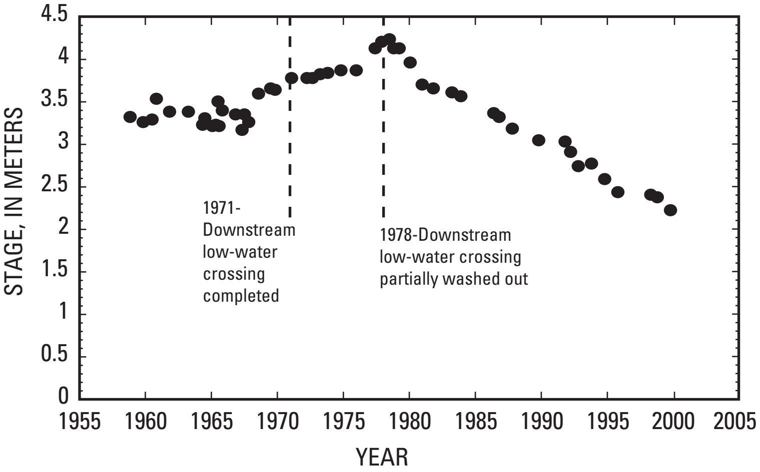

Figure 1. Variation in stream stage for mean annual discharge (2.8 $m^3 s^{-1}$) at Soldier Creek stream gage near Delia, Kansas (USGS stream gage 06889200), 1958–1999. Channel-bed degradation caused by downstream channelization began in 1978 (source: Juracek, 2004a)

the computed average annual rate of channel-bed degradation (along with the average river bed width) was used to estimate the average annual volume of gravel eroded from the affected river reaches.

As a component of studies to assess the recovery of the Bear and American Rivers in California from aggradation caused by hydraulic gold mining in the 1800s, James (1991, 1997) analysed stage-discharge relations for several gages. Specifically, time series of stage-discharge regression residuals were used to assess changes in channel-bed elevation. Results provided independent confirmation of substantial channel incision documented by cross sections and elaboration on the timing of the changes. The bed-elevation changes indicated scour during floods, deposition during low flows and large volumes of bed material transported through the reach. The onset of bed-elevation fluctuations possibly dated the initiation of severe channel migration upstream (James, 1991).

Biedenharn and Watson (1997), as part of a study of stage adjustments along the lower Mississippi River, used peak stage-peak discharge plots at several sites to increase the spatial density of the stage-discharge records. The peak stage-peak discharge plots also served to confirm the results of the stage-discharge analyses.

Using channel-bed elevation as the primary indicator variable, Juracek (2004a) investigated the effects of multiple disturbances on Soldier Creek, Kansas. In this study, stage-discharge relations for eight gages were analysed. Results included a determination of the timing, magnitude and rate of substantial channel-bed degradation in the downstream part of the basin that primarily was caused by channelization (Figure 1). Also, the upstream migration rate of the channelization-caused knickpoint was estimated. In the upstream part of the basin, the stage-discharge relations enabled documentation of the deposition, and subsequent erosion, of a flood-related sediment deposit.

An alternative approach for assessing channel-bed elevation change involves using the original discharge measurement notes to construct and compare channel cross sections. Such an approach was used by Stover and Montgomery (2001) in a study of channel change along the Skokomish River in Washington. In this study, gage data were used to determine that increased flooding on the main-stem Skokomish River was caused by channel aggradation without an increase in peak discharges.

Pinter and Heine (2005) used long-term data from five gages to investigate the hydrologic and geomorphic response of the lower Missouri River to engineering (i.e. channelization, levee and wing dam construction). In addition to analysing stage-discharge relations, they analysed other variables that are known to co-vary with discharge (i.e. channel width, channel cross-sectional area, flow depth and flow velocity) and for which information routinely is collected during discharge measurements. Results indicated that stages for given flood discharges have risen during the period of record because of decreased flow velocity or reduced cross-sectional area. Previously, Pinter *et al*. (2000) used stage-discharge relations for three gages to assess the effects of levee construction and channelization on the middle Mississippi River.

As shown, stream-gage information has multiple applications for studies concerned with channel-bed elevation change (i.e. degradation, aggradation, knickpoint migration). Additionally, information from gages has been used to assess changes in channel morphology based on variations in channel width, channel cross-sectional area, flow depth and flow velocity.

Juracek (2000) used information from two gages to assess channel change along the Neosho River (Kansas) downstream from a reservoir. For each gage, long-term information on channel width, channel cross-sectional area and flow velocity representing a range of in-channel flows was plotted against discharge in successive 5-year intervals. For the near-dam gage, an initial period of modest channel widening followed by stability was indicated. At the downstream gage, no change in width was evident; however, a decrease in channel cross-sectional area associated with an increase in flow velocity was apparent.

In addition to documenting channel incision, James (1991) used gage data to assess changes in Bear River (California) channel morphology as evidenced by changes in channel width and width–depth ratio. Mean depths were computed as flow cross-sectional area divided by channel-top width. The analysis indicated that the Bear River channel narrowed as it incised.

Gage data have also been used for verification purposes. For example, a question that sometimes arises is whether or not a decrease in stage with time for a specific discharge is caused by channel-bed degradation, channel widening or increased flow velocity. In the case of Soldier Creek, Kansas (Juracek, 2004a), the pronounced channel-bed degradation indicated by progressive changes in the stage-discharge relation (Figure 1) was confirmed by an assessment of temporal changes in the width-discharge relation for a range of in-channel flows. Specifically, a substantial decrease in the widths associated with the higher discharges (Figure 2) indicated that the channel had entrenched.

Long-term continuous streamflow records have been used to document the timing, frequency, magnitude and duration of floods and to infer associated geomorphic effects. Juracek (2004b) used long-term streamflow data, in combination with cesium-137 and total organic carbon data from sediment cores, to identify and date flood-deposited sediment in reservoirs. A similar approach was used by Fitzpatrick (2005) for the Wolf River in Wisconsin. Flood units from an impounded reach, from backwater side channels and from vertical accretion in the flood plain were dated using a combination of cesium-137 and flood records from a nearby gage. Flood stages from the gage record that were capable of overtopping nearby flood-plain areas were identified and compared to the alluvial chronologies.

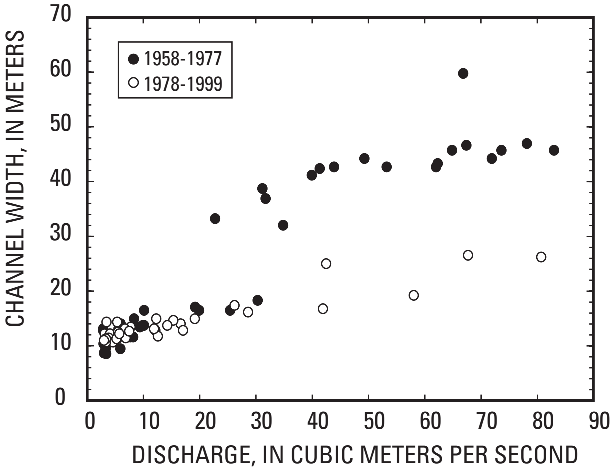

Figure 2. Relation between discharge and channel width at Soldier Creek stream gage near Delia, Kansas (USGS stream gage 06889200), 1958–1999. Decreased channel width for the higher discharges in the 1978–1999 period indicated entrenchment (source: Juracek, 2002)

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Potential applications

Emerging areas of applied and potential research in geomorphology include river rehabilitation, assessments of river ecosystem disturbance processes, understanding of processes in resistant-boundary channels (i.e. channels with bed and (or) banks of bedrock or other erosion-resistent material), and elucidation of feedback mechanisms among climate, erosion and tectonic processes (Montgomery and Wohl, 2003). In this section, potential geomorphic applications of stream-gage information are discussed in the context of these major themes. It is possible that one or more of the following applications is not new, but simply underutilized or underreported as it was not discovered in a search of the literature. Nevertheless, each of the following applications is presented because it merits further research to assess its utility for geomorphic studies.

The geomorphic effectiveness of large floods is a research topic that could potentially benefit from further application of stream-gage information. Here, geomorphic effectiveness is defined as the amount of morphological change caused by a flood and the subsequent time required for the channel to recover (Wolman and Gerson, 1978). Previous studies have reported geomorphic effects of large floods that ranged from minimal to dramatic (Baker, 1988). Among the various factors that can determine geomorphic effectiveness are climate, vegetation, channel bed and bank composition, channel slope, channel morphology, sediment load, flood duration, stream power and the temporal ordering of floods (Baker, 1988; Kochel, 1988; Costa and O'Connor, 1995; Osterkamp and Friedman, 2000; Emmett and Wolman, 2001). Whereas progress has been made, the understanding of the spatial and temporal variability of geomorphic effectiveness is not complete, and the ability to predict it remains a challenge.

Stream-gage information may prove useful for predicting the effectiveness of large floods to cause geomorphic change. Specifically, within a given environment, gage-derived information on flood magnitude, duration, geomorphic effects (e.g. channel-bed elevation change, channel widening, change in width–depth ratio), recovery time and the time since the last large flood potentially could be used to predict the geomorphic effectiveness of subsequent large floods. Moreover, gage-derived information could be used to evaluate the accuracy of the prediction based on post-flood channel changes. One component of such analyses ideally would involve using individual discharge measurements that include the minimum channel-bed (thalweg) elevation. A time series of these data potentially could be used to quantify channel-bed scour and fill associated with a flood (Smelser and Schmidt, 1998). The use of gage data to predict geomorphic effectiveness likely would have the best opportunity to be useful for alluvial streams that are susceptible to change, have experienced multiple large floods and have one or more gages with a long period of record (i.e. several decades). At a minimum, the use of gage data should provide an indication of the direction of change (e.g. channel-bed erosion or deposition) and a conservative estimate of the magnitude of change. Related research topics, which may benefit from the extended use of stream-gage information, include the investigation of the seasonality of geomorphic effectiveness and the geomorphic effectiveness of comparable floods (e.g. same recurrence interval) in different environments.

Another potential application is an assessment of the effects of multiple small impoundments in a drainage basin. In the United States, several million small impoundments have been constructed during the past several decades (especially in agricultural regions) and these impoundments are a major sediment sink (Renwick *et al*., 2005). Information from long-term gages may be used to investigate the possible cumulative effects of these impoundments on flow characteristics and channel morphology. For example, an analysis of channel-bed elevation and channel width changes may indicate whether or not sediment stored by multiple upstream impoundments has resulted in increased channel erosion downstream.

An important research and management issue is the effect of various natural and human disturbances on streamflow and channel characteristics as relating to habitat availability and associated species abundance and diversity. Historical information (recorded on USGS SF 9-275 forms) from individual discharge measurements of similar magnitude (i.e. flow depth and velocity data for the component vertical sections) can be used to reconstruct in-channel conditions and assess habitat change with time at gage sites. For example, such information can be used to investigate temporal change in various aspects of in-stream habitat including: (1) the percentage of channel width that has shallow water depth; (2) the percentage of channel width that has deep, slow-moving water; (3) the percentage of channel width that has deep, fast-moving water; (4) maximum depth; (5) position of the thalweg; (6) mean and median depth and (7) mean and median velocity. In addition to documenting historical changes, such

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analyses may be useful for the prediction of future habitat conditions (Zelt, US Geological Survey, personal communication, 2006).

Other new applications may result in response to developments in streamflow measurement and data dissemination. One development is the use of acoustic Doppler current profilers (ADCPs) for measuring streamflow. Compared to traditional techniques, the use of ADCPs decreases the time required to make discharge measurements while providing similar accuracy. Use of an ADCP precludes use of the traditional USGS SF 9-275 forms but provides much more detailed temporal and cross-sectional views of flow velocity and structure in the channel (Hirsch and Costa, 2004). Also, ADCPs can provide information on channel bathymetry as well as an indication of suspended-sediment concentration and movement, and bedload transport (Rennie and Millar, 2004; Dinehart and Burau, 2005). A second development is the increasing availability of unit-value discharge data from USGS internet sites. Both of these developments may enable new applications in fluvial geomorphic research, such as the detailed analysis of individual high-flow events.

LIMITATIONS

The previous and potential applications of stream-gage information in fluvial geomorphic investigations are numerous. However, depending on the application, one or more limitations may affect the usefulness of the information. For the purposes of this paper, possible limitations were grouped into three general categories—spatial, temporal and data.

Spatial considerations

Spatial limitations can be categorized as geographic and site specific. Geographically, the limitations are concerned with the number and location of gages within an area of interest. The possible limitations are presented as questions. The answer to each question depends on the application.

First, are one or more gages operated along the stream, or within the basin, of interest? Typically, USGS gages with a meaningfully long period of record (e.g. 10 or more years) were established for purposes other than geomorphic studies. In Figure 3, the active USGS national stream-gaging network (as of 2004) is shown as categorized into eight basin-size classes. At a glance, the network appears to be well represented by gages with small- and medium-sized basins. However, the gages with small basins are not uniformly distributed and in many areas small streams and basins are under- or unrepresented. In gaged basins throughout the United States, there is a general tendency for gages to be located mostly or exclusively along main-stem streams. Thus, for a given study area, the number of gages may be none, one or multiple. For each state, the locations of all current and historical USGS gages are available via NWISWeb.

Second, is a single gage useful or are multiple gages required? A single gage provides streamflow and geomorphic information that is representative for the vicinity of the gage and, frequently, for a considerable distance upstream and downstream from the gage. In studies of the downstream geomorphic response of a channel to reservoir construction, a single gage provides site-specific information on the magnitude and rate of channel-bed elevation change with time. However, a series of gages is required to assess the downstream progression rate and longitudinal extent of channel-bed elevation change. For such a study, the requisite information could be obtained from gages and (or) resurveys of monumented cross sections.

Third, is the gage location optimal for the geomorphic study? Criteria used to determine whether or not a gage is optimally located may include, but are not limited to, the following: (1) Is the gage upstream or downstream from the site of disturbance as required for the study? (2) Is the distance between the gage and the site of disturbance acceptable? (3) Is the gage in a representative reach? and (4) Is the gage location free of unwanted affects (e.g. tributary inflows, backwater, in-channel structures, bedrock)? Location is fundamental for determining the value of stream-gage information for a given study.

Fourth, has the gage remained at the same location during the period of record? Sometimes, a gage must be moved to a new location that may range from less than a hundred metres to several kilometres upstream or downstream from the previous location. The reasons for moving a gage include washouts; bridge removal, repair or

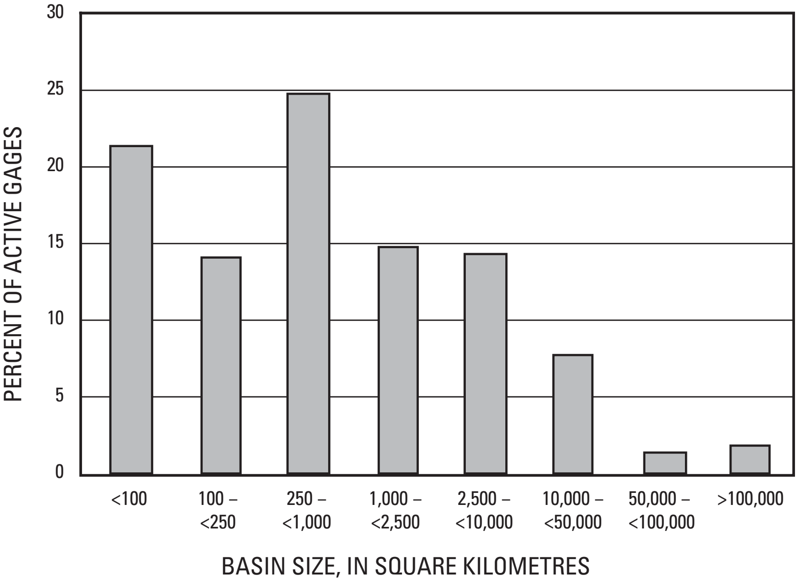

Figure 3. Percentage of active USGS stream gages (as of 2004) in the United States as categorized into eight basin-size classes (source: Stewart *et al*., 2006)

replacement; hydrologic conditions; channel-pattern changes; accessibility; safety; vandalism and property owner request.

In cases where a gage has been relocated one or more times, care must be taken in deciding how the information is used. If no significant tributaries contribute flow between the former and present gage site (and the drainage area changes by less than 5%), it may be acceptable to regard the streamflow information as being representative of a single site for the period of record. However, the presence of one or more intervening tributaries that contribute substantial flow would necessitate that the two sites be treated separately.

Geomorphically, the compatability of the information between a former and subsequent gage site must be carefully evaluated before an analysis. Ideally, such evaluation includes on-site inspection to assess the comparability of channel conditions (e.g. channel control, composition of bed and banks, slope, vegetation, human disturbance, tributary influence) between the two sites. Depending on the application, relocation of a gage may or may not decrease the geomorphic utility of the information. For example, in a study to assess the upstream migration of channel-bed degradation caused by a downstream drop in base level, the relocation of the gage from an alluvial reach to an upstream bedrock-controlled reach would effectively limit the useful part of the record to that associated with the former site. However, if the gage was relocated a short distance (e.g. less than 100 m) upstream or downstream along a uniformly alluvial channel (with no major tributary effect), the information may be useful for the entire period of record. In many cases, gage relocation includes a change in datum that requires calibration between the two sites.

Site-specific limitations are concerned with the physical characteristics of the gage site. Preferentially, the sites chosen for USGS gages should have stable beds and banks and stable stage-discharge relations. Such sites, though ideal hydrologically, would have limited geomorphic value as the channel would not readily adjust in response to changing conditions. Examples of an ideal site include a gage in a bedrock channel or at a weir. Fortunately, from the standpoint of fluvial geomorphology, many gages are at non-ideal sites out of necessity. In many regions of the country, all streams have unstable beds and banks and, therefore, continually changing stage-discharge relations. Gages at such non-ideal sites can provide information of considerable geomorphic value. However, it is important to keep in mind that channel characteristics at gage sites may not be representative of randomly selected locations at any point along the entire length of a stream (Smelser and Schmidt, 1998; National Research Council, 2004). In addition to natural variability, the geomorphic information derived from gages may be affected by artificial influences (e.g. flow constriction at a bridge site). Thus, knowledge of gage-site conditions is necessary before interpretations of the geomorphic information are made.

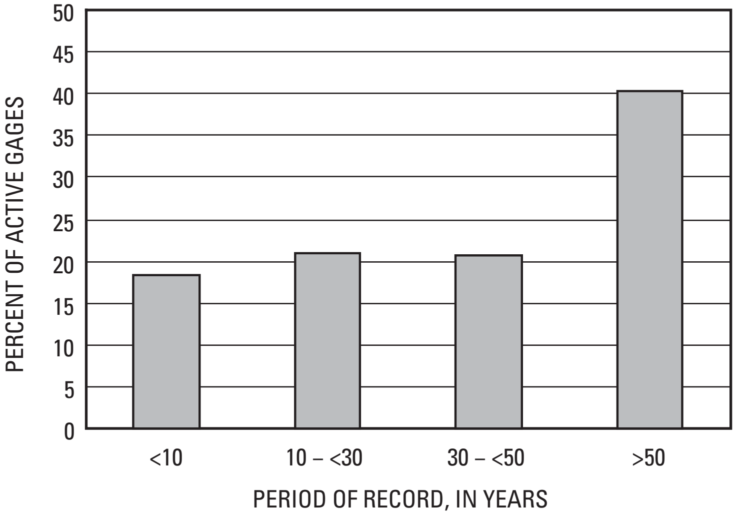

Figure 4. Percentage of active USGS stream gages (as of 2004) in the United States as categorized into four period-of-record classes (source: Stewart *et al*., 2006)

Temporal considerations

Temporal limitations concern the period of record of a gage in absolute and relative terms. In absolute terms, important considerations include the length and continuity of the period of record. Ideally, the period of record is sufficiently long (e.g. decades) and uninterrupted to provide representative information for the purpose of assessing short- and long-term changes. The value of the hydrologic and geomorphic information for a gage site is directly related to the length of the period of record. Gaps in the period of record decrease the value of the information as important hydrologic events may have been missed. In Figure 4, the active USGS national stream-gaging network (as of 2004) is shown as four period-of-record classes. About 60% of the gages have a period of record of at least 30 years; of those, most have a record of 50 years or more. Thus, the majority of the gages provide several decades of data that may be of considerable geomorphic value. Moreover, some discontinued gages provide historical record that spans decades and may be useful.

In relative terms, the question is whether or not the period of record sufficiently covers the period of interest for a given geomorphic study. For example, for a study to assess the geomorphic response (i.e. initial impact and subsequent recovery) of a river to an historic flood, the period of record will ideally extend many years before and after the flood. The pre-flood record provides the requisite 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, stream-gage information 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 river channel to multiple floods. If the period of record for the gage of interest is inadequate, it may be possible to extend the streamflow record by correlation using a nearby long-term gage (Hirsch, 1982). The extended record provides context that may help explain geomorphic changes that occurred during the originally available period of record.

Data considerations

As previously stated, discharge measurements at, and stage-discharge ratings for, USGS gages have a typical accuracy of about ±5% (Kennedy, 1983; Sauer and Meyer, 1992). The accuracy of the width, depth, area and velocity measurements, which are components of the discharge measurements, is likewise within 5%.

Variability in the relations between discharge and associated flow characteristics (i.e. width, depth, area, velocity and stage) is caused, in part, by physical factors including changes in channel morphology, slope and roughness (Leopold and Maddock, 1953; Knighton, 1977). Variability also may result, in part, from measurement error. For example, low-flow measurements made by wading may not be made at exactly the same cross section each time

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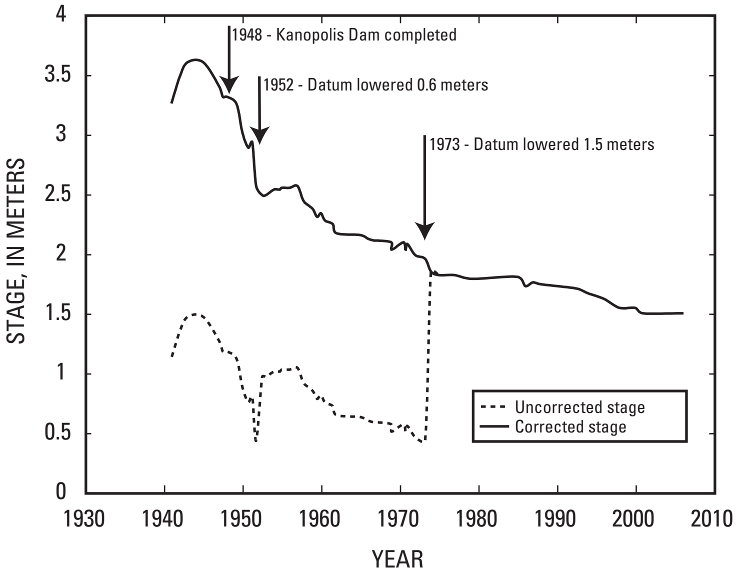

Figure 5. Variation in river stage for mean annual discharge (8.5 $m^3 s^{-1}$) at Smoky Hill River stream gage near Langley, Kansas (USGS stream gage 06865500), 1940–1997. The variation in river stage represents the history of channel-bed elevation changes with and without corrections to account for datum changes (source: Juracek, 2001)

(Leopold and Maddock, 1953). Moreover, the location of discharge measurements may vary with stage (Jacobson, 1995). Wolman (1955) determined that measurements made at different cross sections located close together within a stream reach can result in considerable scatter in the relations of width, depth and velocity to discharge.

The combined use of discharge measurements made at different cross sections (including the mixed use of bridge or cableway and wading measurements) is a concern for geomorphic applications because the potential variability introduced may affect an interpretation of change. The seriousness of such variability will depend on the channel characteristics in the vicinity of the gage and the geomorphic question being addressed. The variability can be minimized with a careful selection and analysis of the available gage data. For example, in an analysis to determine channel-bed elevation change with time, using the mean annual discharge as the reference discharge typically will result in the exclusive use of bridge or cableway measurements for which the cross section is fixed.

Datum changes must be accounted for to avoid erroneous interpretations of channel-bed elevation change. For example, Figure 5 shows the variation in stage for the mean annual discharge for the Smoky Hill River near Langley, Kansas. At this location, the sand bed of the Smoky Hill River has persistently eroded since the completion of Kanopolis Dam 0.2 km upstream in 1948. In Figure 5, the solid line correctly represents the history of channel-bed elevation change for the period of record with stage values adjusted to account for respective lowerings of the datum by 0.6 and 1.5 m in 1952 and 1973. The solid line indicates a net lowering of the channel bed of 1.8 m. However, using the uncorrected stage data represented by the dashed line, a different and inaccurate history is indicated. Errors of particular note include the abrupt 1.5-m increase in bed elevation in 1973 and a net increase in bed elevation of 0.4 m. Thus, the importance of accounting for datum changes is evident.

SUMMARY AND CONCLUSIONS

In the United States, several thousand stream gages provide what typically is the only source of continuous, long-term streamflow and channel-geometry information for the locations being monitored. In addition to various hydrologic uses, the information collected at stream gages has been useful in fluvial geomorphic investigations.

The geomorphic content of stream-gage information includes streamflow characteristics, channel-morphology characteristics, sediment characteristics (for a small number of sites) and related documentation (including channel disturbances) provided in station descriptions and station analyses. Geomorphic applications of stream-gage information have included the relation of streamflow to channel characteristics, the estimation of process rates, the documentation of channel changes, the reconstruction of historical channel conditions, the determination of causes of channel change and the estimation of future channel changes. Specific examples include studies of hydraulic geometry, channel bankfull characteristics, sediment transport and channel response to disturbance. Potential applications include investigation of the geomorphic effectiveness of large floods and changes in habitat conditions caused by disturbance. Moreover, additional new applications may be realized with the use of ADCP as well as the increasing availability of unit-value discharge data.

Despite the diversity of documented and potential applications, caution is warranted as to the use of stream-gage information in fluvial geomorphic investigations. Depending on the application, various spatial, temporal and data limitations may render the information of limited value. However, in many cases, the information is useful and can enable or enhance a geomorphic investigation. The value of stream-gage information could be increased by additional periodic geomorphic measurements at USGS stream gages, such as benchmarked channel cross sections, slope and streambed particle size. Combined with traditional stream-gage information, these data would result in a uniquely powerful national data set that could provide linkages among hydrologic conditions, channel morphology and geomorphic processes.

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