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Regional bankfull geometry relationships for southern California mountain streams and hydrologic applications

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ABSTRACT

This study develops and intercompares regional relationships for bankfull channel width, hydraulic depth, and cross-sectional area for southern California mountain streams based on several data sources: surveyed streams, US Geological Survey stream survey reports, and existing literature. Although considerable uncertainty exists in estimating bankfull conditions, the relationships developed from the varying data sources show significant agreement. For small watersheds with drainage area ranging from 15 to ~2000 km^2, the estimates of bankfull top width ranged from 7.2 to 44.5 m and hydraulic depth estimates ranged from 0.35 to 1.15 m. The utility of the developed bankfull geometry regional curves is demonstrated for southern California catchments through (a) the computation of the bankfull discharge and (b) the estimation of the surface runoff response necessary to produce bankfull conditions in the streams at the outlet of these catchments. For selected locations with instantaneous flow records, the occurrence frequency of events exceeding bankfull flow was examined for the available 10–15 year span of observational records. Bankfull discharge estimates for all small watersheds in the region ranged from 1.3 to 74 m^3/s, while the range at the selected gauged stream locations was from 2.6 to 16.4 m^3/s. Stream locations along the Transverse Mountains of southern California showed an average occurrence frequency of less than 1 year, whereas along the Peninsular Mountains the average return period tended to be greater than 1 year.

The application of the regional curves to the estimation of the surface runoff response necessary to produce bankfull conditions at the channel outlets of small catchments may be used as an index for conditions of minor flooding with saturated soils. This surface runoff response index ranges from 2.0 to 5.5 mm for a 3-hour rainfall duration for southern California watersheds greater than 15 km^2 in area. Differences between the values for the Peninsular and Transverse Mountain Ranges are linked to geological, climatic, and geomorphologic differences. The developed regional geometry relationships are suitable for use in various hydrologic modeling applications, including distributed modeling with high resolution pertinent to flash flood forecasting.

1. Introduction

Bankfull discharge is an important and widely used concept in hydrologic science, ecosystem studies, and river restoration design. Bankfull discharge is the flow in a river channel at the level of transition from the active channel to the flood plain (Leopold et al., 1964). It is closely associated with the concept of channel forming or dominant flow, which determines and maintains the channel dimension, and with the effective discharge, which is the flow that carries the highest sediment volume over time (e.g., Leopold, 1994). The concept of bankfull discharge is usually applied to alluvial channels, given the connection with effective sediment transport and erosion. The three terms of bankfull-, effective-, and channel-forming-flow have become strongly interconnected, and often used without clear distinction in the literature. Differences in these flows may become larger in regions where the climate is arid (ephemeral streams) and has strong interannual variability. However, bankfull discharge has become a widely-used surrogate for channel forming flow in many studies because it may be recognized based on morphologic field evidence. As bankfull conditions may be identified by field evidence, the focus in this paper is on bankfull discharge.

The systematic variation of stream channel hydraulic geometric characteristics was first suggested by Leopold and Maddox (1953), who showed the relationship of channel width, mean flow depth, velocity, and suspended sediment load to bankfull discharge in the form:

$$X = a\ Q^b, \tag{1}$$

where X represents the dependent variables (width, depth, velocity, total suspended sediment), Q is the discharge, and a and b are derived parameters. Such relationships are discussed in two contexts: (a) "at-station hydraulic geometry" which describes the variation of cross-

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sectional properties with varying discharge rates at a given location or cross-section, and (b) “downstream hydraulic geometry”, which describes the variation of cross-sectional properties along a length of river for a given flow level, such as the mean annual flow, a selected recurrence interval flow, or bankfull flow. The latter case reflects the variation of discharge and channel dimension with catchment scale. As discharge varies with catchment size, this work has been extended to examine the variation of bankfull discharge and related bankfull channel geometry with catchment area, A, in a similar form (Dunne and Leopold, 1978):

$$X = \alpha A^{\beta}, \quad (2)$$

with α and β being the parameters of this relationship. Within this paper, relationships in the form of Eq. (2) are referred to as regional hydraulic geometry curves (regional curves), and they relate the bankfull channel dimensions and discharge to watershed drainage area. Other physical or climatological watershed characteristics such as main stream length, channel slope, or climatologically average precipitation may also be considered in developing such relationships.

Hydraulic geometry analyses have been performed throughout the U.S. and abroad to empirically derive hydraulic geometry relationships (Eq. (1)) or regional hydraulic geometry curves (Eq. (2)) for a single stream or for several streams in a coherent hydro-physiographical region (e.g., Harvey, 1969; Rhoads, 1991; Dudley, 2004; Lawlor, 2004; Messinger and Wiley, 2004; Chaplin, 2005). Recent work has examined the development of such relationships over a range of hydro-climatic and geologic regions on a continental scale (Wilkerson et al., 2014). As regional hydraulic geometry curves allow for the estimation of bankfull channel dimensions at unsurveyed locations, regional curves have had practical application in a variety of studies of fluvial or channel processes (Merigliano, 1997; Buhman et al., 2002; Stewardson, 2005), river restoration or natural channel design (Rosgen, 1994, 1996; Hey, 2006; Metcalf et al., 2009), habitat assessment and ecosystem studies (Singh and McConkey, 1989; Jowett, 1998), and as flash flood indicators in ungauged basins (Carpenter et al., 1999).

Development of regional hydraulic geometry curves relies on estimates of channel geometric characteristics and flow from detailed field surveys and field identification of bankfull conditions (e.g., see Leopold (1994) for principal field indicators of bankfull stage). Uncertainty or differences in estimates of bankfull level have been noted (Williams, 1978; Johnson and Heil, 1996; Radecki-Pawlik, 2002; Navratil et al., 2006; Harman et al., 2008; Xia et al., 2010). Williams (1978) cites 11 variations on the definition of “bankfull”, based on morphologic evidence including various sedimentary surfaces, vegetation and geomorphic boundary features. Such variations may lead to different estimates of the bankfull level at a single cross-section. Xia et al. (2010) discuss difficulties in identifying and estimating bankfull level based on field evidence in the complex and braided channel network of the Lower Yellow River in China. Indeed, there may also be variation in channel morphology over relatively short stream reach distances which influence the selection of bankfull elevation. Recommendations to improve reliability of field-based bankfull stage estimates include the use of multiple indicators at a single cross-section, and evaluation of multiple locations within a short stream reach.

After identifying the bankfull elevation, varying methods exist for computing the associated discharge. These methods may involve the use of observed streamflow records and at-station rating curves (i.e., stage-discharge relationships), existing at-station hydraulic geometry relationships, flood frequency information or empirical flow relationships (Williams, 1978). Williams (1978) and Johnson and Heil (1996) give 16 estimates of bankfull discharge at selected stream locations to examine variation in the estimates. Such studies often examine the definition of bankfull in the context of estimating the recurrence interval of bankfull flow (Williams, 1978; Petit and Pauquet, 1997; Castro and Jackson, 2001; Navratil et al., 2006). Leopold's definition of the bankfull discharge as having a 1.5-year return period is frequently cited (Leopold, 1994). Some studies show good agreement with this period; for example, Castro and Jackson (2001) report recurrence intervals of 1–3.1 years with an average of 1.4 years for streams in the Pacific Northwest United States. Other studies report larger variability in the recurrence interval. The early study of Williams (1978) reported a range of bankfull recurrence intervals from less than 1 year to more than 30 years. In another example, Petit and Pauquet (1997) report a range of values from 0.7 year to 5.3 years for streams in Belgium, with variation in the recurrence interval further classified by catchment size and by permeability of stratum.

The concept of bankfull discharge and the development of hydraulic geometry relationships have historically been applied for alluvial, and often low-gradient, streams. Until recently, such relationships for streams with more erosionally-resistant channel bed, including bedrock substrate, and colluvial processes have received little attention (Wohl and Wilcox, 2005). Wohl et al. (2004) found relatively poor correlation in downstream hydraulic geometry relationships for a high-gradient stream in Colorado, but correlation improved with the addition of reach-scale controls such as channel gradient. In contrast, Wohl and Wilcox (2005) found well-developed downstream hydraulic geometry relationships for two high-gradient streams in New Zealand, and with exponent values in the relationship commensurate with those originally suggested by Leopold and Maddox (1953). Montgomery and Gran (2001) explore variation in hydraulic geometry relationships of the form of Eq. (2) for five mountain streams that included both alluvial and bedrock reach sections. They found good agreement among the exponents of the channel width to drainage area relationships between bedrock reaches and alluvial reaches, with the exception of a small drainage basin ($A < 1$ km^2) in Oregon. Wohl and David (2008) also examined the similarity in hydraulic geometry relationships between alluvial and bedrock channels. The exponent values found were also in agreement with the reported exponent values for alluvial streams. Wohl and Merritt (2008) examined an extensive collection of data from 335 mountain stream reaches throughout the western continental United States, Alaska, Panama, New Zealand, and Nepal. There was agreement among the exponents of the hydraulic geometry relationships for channel width and depth (as functions of bankfull discharge) with reference values for alluvial streams, but with variation in the relationships considered for different channel form types (e.g., pool-riffle, step-pool). These recent studies suggest that regional hydraulic geometry curves may be produced for mountain streams, and that the exponent values of the relationships are similar to those found in the wealth of literature on alluvial streams. Other work (e.g., Wohl, 2004) has looked for limitations in the hydraulic geometry relationship, finding poorly developed relationships are marked by the relationship between stream power and sediment characteristics.

This paper develops regional bankfull geometry relationships for streams in southern California utilizing stream survey data from different sources. This region is used given the proximity of the mountainous and foothill streams of the Transverse and Peninsular Mountains to the southern California coast, yielding relatively short and steep streams prone to flash flood occurrence. The first data source is from a set of field surveys that were conducted by an NSF-funded study following significant hydrometeorologic events in January 2005. This dataset contains channel cross-sectional survey data with estimates of channel hydraulic depth and width measurements based on field indicators of bankfull conditions. The second data source is derived from two types of stream survey reports from the U.S. Geological Survey (USGS). These reports include field notes from regular discharge measurements and post-event reports of significant flood events. Both USGS reports provide detailed channel cross-section survey data from which bankfull conditions were estimated based on cross-section shape only. From each survey data source, regional relationships for the channel width, hydraulic depth, and channel cross-sectional area at bankfull conditions were developed as functions of drainage area.