Middle States Geographer, 1998, 31:1-14

SPATIAL VARIABILITY IN STABILITY THRESHOLDS, VERDE RIVER, ARIZONA

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ABSTRACT: *This study documents the pattern of spatial variability of channel stability, as represented by stability thresholds, along a mid-sized dryland stream, the Verde River in central Arizona. Examining variations in stream competence (as represented by shear stress) and resistance (as represented by the size of sediments comprising various geomorphic surfaces) within the stream channel and along the entire river shed light on the nature of variations in sediment transport. Under this shear stress approach to stability, a threshold exists, dividing conditions of stability and little sediment motion, from conditions of instability and sediment mobility. Channel morphology and sediment data, combined with calculations of discharge and shear stress, facilitate the creation of stability thresholds for 14 cross-sections representing reaches of the Verde River. Different geomorphic surfaces exhibit different stability thresholds: most low-flow channels and flood plains are unstable at the discharge with a two year recurrence interval, while only a few side bars are unstable. At moderate flows (discharges with a ten year recurrence interval), most of the surfaces within the study cross-sections are unstable, implying that within-channel shifting and channel change may occur on average every ten years. These results imply that during more frequent, lower flow events, the sediment transport system of the Verde River is highly fragmented, with localized areas of sediment entrainment and areas of sediment storage. During moderate to high flow events, however, the river is more integrated, variations in stability largely disappear, and sediment moves perhaps more predictably through the system.*

INTRODUCTION

Rivers and their channels express the balance between the force generated by flowing water and the resistance offered by the host materials. While channel hydraulics and stream hydrology provide a wealth of insight into river behavior, an understanding of sediment dynamics completes any geomorphic assessment. In gravel bed streams, much of the channel morphology relies on the dynamics of larger particles, such as gravels and cobbles, in relation to stream flow. For channel change to take place, be it shifting within the geologic flood channel or migration of the flood channel itself, the force generated by a discharge must be sufficient to entrain and transport those large particles. Complex sediment transport models provide detailed assessments of overall channel stability, but require large amounts of initial data for calibration. In addition, these models fail to capture the influence of local factors on sediment transport (Pickup, 1988).

This paper investigates the spatial variability in channel stability, or the probability from place to place that a channel will change position or shape by the entrainment of sediment. Spatial variability is important at two scales: between various geomorphic surfaces within a cross-section, and between different cross-sections within the river system. Studies of sediment transportation on the macroscale (reach scale) and megascale (segment scale) have long acknowledged the spatial variability of sediment accumulation and removal along rivers, noting the importance of local factors, such as tributaries, channel pattern, and human activities, in creating these variations (Hoey, 1992; Macklin and Lewin, 1989; Pickup, 1988). The present study documents the pattern of spatial variability of channel stability, as represented by stability thresholds, and distributions of force along a mid-sized dryland stream, the Verde River. It addresses the nature of variations in sediment transport by examining variations in stream competence through the creation of stability thresholds for different geomorphic surfaces within the river channel.

This paper addresses four research questions:

(1) Do all features, or geomorphic surfaces, within a cross-section have a similar probability of movement, or similar stability thresholds?

(2) Do similarly classified geomorphic surfaces along the river have similar stability thresholds?

(3) What do these variabilities suggest about the frequency of channel change in the Verde River system?

(4) What do these variabilities suggest about the nature of fragmentation and integration in the Verde River system?

Channel morphology and sediment data, combined with calculations of discharge and shear stress, facilitate the creation of stability thresholds for 14 cross-sections representing reaches of the Verde River. Comparison of these stability thresholds with the recurrence intervals of discharge along the Verde River allows statements to be made about the probability, or temporal scale, of channel change.

BACKGROUND

The analyses in this study draw from two areas of thought in fluvial geomorphology: the concepts of competence and capacity, and sediment transport and storage. This section briefly discusses these areas with an emphasis on discerning variability and understanding system fragmentation.

Competence and capacity, two concepts key to understanding the relationship between discharge and sediment transport, incorporate sediment caliber and sediment quantity. Competence refers to the largest particle size that can be moved by a particular flow, while capacity refers to the total amount of sediment that can be moved by a particular flow (Gordon et al., 1992). Competence usually addresses the entrainment of particles, such as sand and gravel-sized particles, while capacity usually addresses the transport of particles. In dryland rivers, the concept of competence offers the greater utility for two reasons. First, coarser particles, which require greater amount of force for entrainment, comprise most of the sediment of dryland streams (Graf, 1988). Second, through the combination of efficient slope processes and slow weathering rates, arid and semi-arid landscapes generate less fine sediment than streams are generally capable of transporting. This observation suggests that the amount of fine sediment that a stream actually transports is much less than it is capable of moving: stream capacity is often greater than measured suspended sediment transport. In such supply-limited streams, the amount of sediment transported relies heavily on the amount of sediment available to transport. The capacity of the flow limits sediment transport in humid and tropical streams: more rapid weathering and wasting processes produce a surplus of sediment available to transport. The term "transport-limited" refers to such streams where the water discharge determines the amount of sediment moved. Given that the river under study, the Verde River, is a dryland river, the present analysis focuses on stream competence.

Shear stress often serves as a measure of stream competence, as defined by:

$$\tau = \rho \, g \, R \, S \qquad (1)$$

where τ is shear stress, ρ is the density of water (91g/cm^3 at 4° C), g is the acceleration due to gravity (9.807 m/s^2), R is hydraulic radius (m), and S is the slope of the energy line, which under uniform flow conditions is equal to the channel bed slope (Gordon et al., 1992). In rivers with a high width-to-depth ratio, depth and hydraulic radius are roughly equal and thus those terms may be used interchangeably (Gordon et al., 1992). In discussing variability in competence and capacity, then, depth (related to discharge) and gradient become the sources of variation.

Studies of sediment transport and storage have increasingly noted the variability of these processes in river systems. In a review of sediment transport studies, Hoey (1992) observed that this variability takes the form of bars in gravel-bed streams, and thus related bars of different sizes to different scales of channel processes. In process terms, these bars may represent slugs or waves of sediment moving through the system. The location and movement of segment scale bar forms (covering more than several channel widths) and reach scale bar forms (channel-width sized bars) are governed by geomorphic regime, as opposed to bedforms, which are controlled by hydraulic regime. Hoey (1992) noted that even though mega- and macroforms are subject to the same scale of processes, different processes may be operating in different places and different processes can create similar patterns of sediment movement and storage. At this scale, such processes or influences include: movement of bedload as sheets, bar and channel formation, drainage network interlinkages, and exogenous sediment inputs (e.g. tributary inputs or mining sediment). By extension, these observations imply that the Verde River transports and stores sediment by a variety of processes, largely related to sediment inputs from tributaries and human activity, such as gravel mining.

The irregular spatial and temporal variability in sediment movement and storage and the variety of processes that influence sediment transport become a resounding theme in studies of river systems. Macklin and Lewin (1989) emphasized the irregular location of sites of potential sediment accumulation along the river South Tyne in the United Kingdom. This variability makes modeling of sediment movement through river systems difficult, and renders models inadequate unless used as "black box" approaches to total system sediment output. Knighton (1989) noted this dilemma in the context of a river impacted by mining, but it appears applicable to unimpacted natural rivers as well. Similar to Hoey's (1992) conclusions, Pickup (1988) suggested that segment scale sediment waves are often associated with local sediment supply limitations, exogenous sediment supply, and channel pattern changes. In general, local factors appear to influence sediment transport and storage more than any segment-scale or systematic variations. The questions remain, however, as to the role of individual local factors and the variability of sediment transport over a range of discharges, or recurrence intervals. Land-use planning and prediction of river behavior require understanding of such river channel dynamics. This study attempts to answer some of these questions by the use of stability thresholds.

STUDY AREA

The Verde River drainage basin covers 17,213 km^2 in central Arizona, including sections of Coconino, Yavapai, Gila and Maricopa Counties (Figure 1). This study focuses on the 216 km of the river from Sullivan Lake, 3 km south of Paulden, to the upstream end of Horseshoe Reservoir, approximately 20 km northeast of Carefree. Elevations in the basin range from 1700-2300m along the Mogollon Rim and the Black Hills, to 618m along the river above Horseshoe Reservoir. The river descends 637 m in elevation, from 1255 m near Paulden to 618 m upstream of Horseshoe Reservoir, with an overall gradient of 0.0029 m/m.

The Verde River flows through a variety of geological settings, representative of the complex geology of the Transition Zone, the physiographic region separating the Colorado Plateau in northeast Arizona from the Basin and Range Province in the southwest part of the state (Arizona Bureau of Mines, 1958; Peirce, 1985; Reynolds, 1988). Three main regions comprise the geology of the basin, corresponding roughly to its upper, middle, and lower parts. The upper basin is largely underlain by Paleozoic sedimentary rocks covered with basalt flows from the Pliocene to late Miocene, into which the Verde River has incised a canyon up to 100 m deep (Lehner, 1958; Reynolds, 1988). The middle basin corresponds with the Verde Valley, a large structural valley containing the late Tertiary limestones, lake and stream deposits, and volcanic units of the Verde Formation (Jenkins, 1923; Elston et al., 1974; Reynolds, 1988). The lower part of the Verde basin consists of a variety of Tertiary basalts and Precambrian granites, once again placing the river in a canyon setting (Reynolds, 1988).

In general, the geomorphology of the Verde River reflects a geologic setting of narrow valleys and broader basins (Pearthree, 1996). Despite variations in flood plain size and sediment storage, the Verde River exhibits a consistent compound channel configuration with a distinct low-flow channel within a wider flood channel. This wider flood channel consists of the relatively narrow low-flow channel and a large side bar comprised of coarse material. The compound channel, comprised of both the low-flow channel and the flood channel, is the active channel for the Verde River because of the lack of vegetation on side bars, the lack of a distinct morphological boundary between the low-flow channel and bars, and the coarse nature of the material comprising the bars.

The Verde River drainage basin, occurring in a semiarid climate, exhibits a range of temperature and precipitation conditions. These conditions give rise to spatial variation in precipitation inputs to and evapotranspiration losses from the drainage basin. Resulting surface moisture conditions impact the type of vegetation and infiltration characteristics of the surface, both important influences on runoff generation. Precipitation is seasonal, induced in the winter by frontal storms and in the summer by monsoon convectional events and the monsoon (Owen-Joyce and Bell, 1983; Owen-Joyce, 1984). Spatial variations in precipitation amounts within the basin result from orographic effects.

Although emerging groundwater gives the Verde River a low baseflow throughout the year, tributary streams contribute most of the total water yield and high flows to the main stem. The characteristics of the tributaries --location within the basin, subbasin area, and relief-- influence the magnitude and timing of flows on the tributaries, which in turn influence the magnitude and timing of flows on the Verde main stem. The tributaries contribute sediment as well, increasing the importance of understanding the patterns of flows on the tributaries and the nature of the relationship between the tributaries and the main stem.

Perennial flow in the Verde River begins at Del Rio Springs about 2 km downstream of Sullivan Lake. Eight perennial tributaries feed the Verde River, all of which except one (Tangle Creek) enter the river from the north or east (Figure 1). Tributaries entering the Verde River from the north or east contribute more water to the system because they drain a larger land area and receive the snowmelt from Mogollon Rim. Streams in the upper part of the basin and streams the southwestern edge of the middle basin flow intermittently, only in response to rainfall or small amounts of snowfall (Owen-Joyce and Bell, 1983). The basin hosts ten U.S. Geological Survey (U.S.G.S.) gauging stations, four on the main stem of the Verde and six on tributary streams. Table 1 provides summary data, including the discharges for floods of various recurrence intervals, for these stations.

METHODOLOGY

Surveys of 14 cross-sections along the Verde River provide the primary data for the stability analysis. A software package created by Bureau of Land Management, XSPRO, provided simulation of various discharges at each cross-section (Grant et al., 1992). Using equations derived from the basic continuity, momentum, and energy relationships of fluid mechanics, XSPRO calculates width, hydraulic radius, discharge, velocity, and shear stress for various stages of flow through the specified cross-section. In rivers with a high width-to-depth ratio, such as the Verde River, depth and hydraulic radius are roughly equal and thus those terms are used interchangeably throughout this investigation (Gordon et al., 1992). Three of the cross-sections (11 Abandoned Ranch, 13 Bear Siding, and 23 SOB Canyon) have lower width-to-depth ratios, making the depth for hydraulic radius substitution less accurate.

Input variables for the analysis include the surveyed cross-section, channel gradient, and an estimate of channel roughness. For this study, channel gradients were obtained from 7.5 minute series topographic maps over a distance of 216 km and a vertical drop of 637 m. Analyses of fourteen cross-sections of the Verde River using XSPRO yielded computations of discharge and shear stress for different stages for each cross-section.

Field observations generated estimations of Manning's *n* as a parameter for hydraulic roughness. Acrement and Schneider (1989), Barnes (1967), and Thomsen and Hjalmarson (1991) provided written and visual guidelines for estimation of Manning's *n*. The Manning's *n* values used in this study ranged from 0.02 for a smooth, sandy channel to 0.12 for flows outside of channel banks over cobbles and through trees and brush. Manning's *n* is related to discharge through cross-section measurements and a technique referred to as the slope-area method:

$$Q = (A R^{2/3} S^{1/2}) / n \qquad (2)$$

where A equals cross-sectional area of the channel, R equals hydraulic radius, S is the slope of the energy line, which under uniform flow conditions is equal to the channel bed slope, and n equals Manning's *n*.

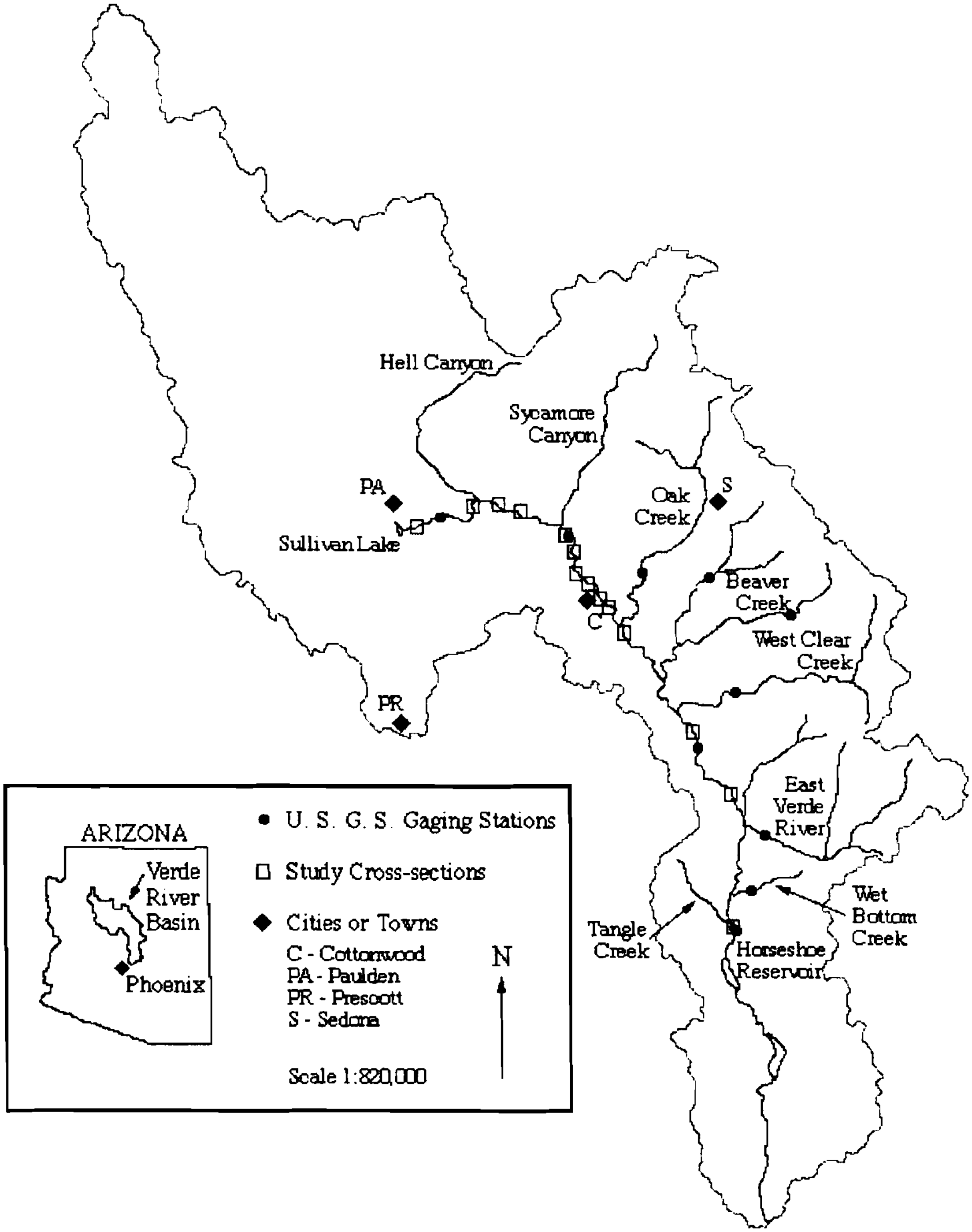

Figure 1. Map of the Verde River drainage basin, including study segments, cross-sections, and U. S. Geological Survey gauging stations.

Table 1. Descriptive Statistics and Discharges for Selected Recurrence Intervals for Ten Gauging Stations in the Verde River Basin (Source: U.S.Geological Survey Gage Records)

	Main Stem Verde River					**Tributaries**				
Discharge (cms)	**Paulden**	**Clarkdale**	**Camp Verde**	**Tangle Creek**	**Oak Creek**	**Dry Beaver**	**Wet Beaver**	**West Clear**	**East Verde**	**Wet Bottom**
Length of Record	33	35	20	51	54	36	35	32	34	29
Record peak	657.2	1507	3371	4108	747.9	753.5	453.3	702.5	665.7	209.1
Mean annual maximum	6.1	18.3	39.7	63.2	7.3	4.1	2.9	5.6	8.2	1.3
Mean annual minimum	0.7	2.3	4.5	5.4	0.8	<0.1	0.2	0.5	0.3	<0.1
Annual mean	1.3	5.6	13.3	16.7	2.5	1.3	1.0	2.0	2.0	0.5
2-year flow	14.2	89.5	174.5	233.1	47.3	37.1	27.6	42.2	38.5	15.7
5-year flow	57.5	279.9	492.9	688.4	135.7	104.0	72.8	130.9	113.6	46.5
10-year flow	123.2	490.1	847.0	1195.5	229.2	172.2	113.9	219.5	192.9	73.4
25-year flow	286.1	864.0	1504	2127.5	393.8	289.0	176.5	359.8	331.4	111.0
50-year flow	498.6	1229	2179	3087.8	549.6	396.6	229.2	481.6	464.6	139.7
100-year flow	830.0	1671	3031	4249.3	739.4	521.2	286.1	614.7	623.2	167.7

As part of the analysis, I divided each cross-section into geomorphic surfaces based on relative position of the feature and field observations of changes in topography, sediment size, and vegetation. Generally, cross-sections consist of the following geomorphic surfaces: low-flow channel, side-channel bar (referred to as the side bar), overflow channel, active channel (the low-flow channel, side bar, and overflow channel), flood plain, side slopes, and terraces. Not all features are present in every cross-section. Figures 2 and 3 present sample cross-sections with labeled geomorphic surfaces, or subsections. These subsections of each cross-section were assigned Manning's *n* values as an estimate of roughness. The cross-section analyses also provided calculations of discharge and shear stress for each subsection within a cross-section. The following discussion focuses on variations in discharge and shear stress on the features most often present in the cross-sections: the low-flow channel, side bar, and flood plain. The side bar determines the position of the low-flow channel, making determination of the stability of the side bar key to understanding and predicting shifts within the active channel. Migration of the active channel, or flood channel, depends in part on the stability of the flood plain material.

Sediment data collected for the 14 study cross-sections provided a measure of resistance to flow for a variety of geomorphic surfaces within the cross-sections. I collected samples of fine sediment deposits, comprised largely of particles less than 2 mm in diameter, for laboratory analysis. Sieving of air and oven-dried samples generated particle size distributions I used the Wolman pebble count method, modified to reduce sampler-related bias, to assess coarse sediment deposits, most often those on the bed of the channel or side bars (Wolman, 1954; Marcus et al., 1995).

Critical shear stress is the amount of tractive force, or shear stress, required to entrain a particle (Gordon et al., 1992). Symbolized by τ_c, critical shear stress can be estimated using a simplified Shields equation:

$$\tau_c = 0.97 \text{ d} \tag{3}$$

where d is a representative particle size (Gordon et al., 1992). The empirically derived coefficient takes bed roughness into account. In this study, both d_{50} (median particle size) and d_{84} have been considered as the representative particle sizes. Shields initially developed the equation to describe movement of sand grains. Others have subsequently modified the equation for the entrainment of larger particle sizes found in gravel-bed streams (Baker and Ritter, 1975; Church, 1978; Carling, 1983; Wiberg and Smith, 1987). Several factors not taken into account in this study that may influence entrainment include the degree exposure of the particles to shear, the role of suspended load in viscosity, and the effects of solid transmitted stress. The range of sediment sizes warrants the use of the unmodified equation, which will underestimate the critical shear stress for pebbles, cobbles, and boulders; consideration of critical shear stress using d_{84} compensates for this underestimation. Using median particle size yields the assumption that where shear stress in a subsection exceeds the critical shear stress for the sediment comprising that subsection, at least half of the sediment will be mobile. Using d_{84} yields the assumption that where shear stress exceeds critical shear stress for that subsection, at least 84% of the sediment will be mobile.

Instability, for the purposes of this research, is technically defined as the flow condition (*i.e.* a discharge related to a particular recurrence interval) under which the shear stress exceeds critical shear stress, setting particles in motion, and possibly leading to changes in channel morphology. Graf (1983) referred to that flow condition as a threshold condition of instability, here referred to as a stability threshold. Exceeding the threshold condition of instability does not necessarily result in channel change. This approach does not take into account the duration of flow which exceeds the threshold nor does it account for the rate or distance of movement of the sediment once it is entrained. Hydraulic conditions (such as turbulence), channel morphology, and sediment fabric (such as degree of packing) all influence entrainment (Knighton, 1987). At best, the Shields equation and the calculated stability threshold conditions reflect a mean assessment of particle motion.

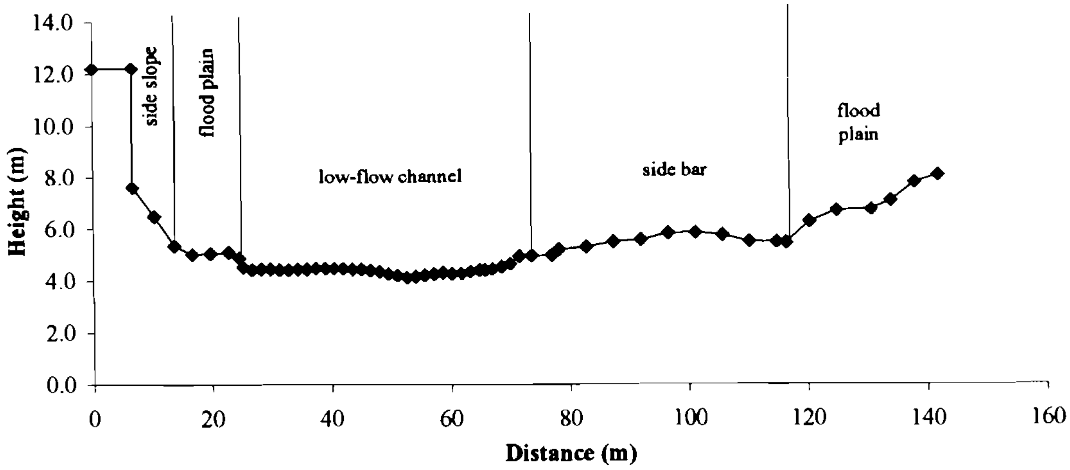

Figure 2. Surveyed cross-section for 33 Dead Horse Ranch State Park.

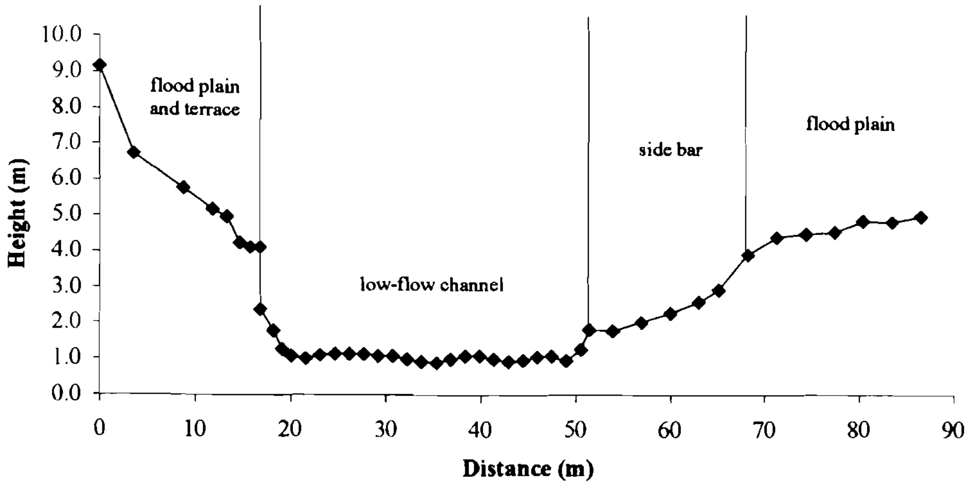

Figure 3. Surveyed cross-section for 34 White Horse Inn (89A Bridge).

RESULTS AND DISCUSSION

Consideration of channel stability involves comparison of the energy available for sediment transport in a river reach and the size of available sedimentary particles. In this case, the concept of competence --as measured by shear stress as a function of discharge-- assesses the available energy, and is used as a point of comparison within and between the study cross-sections. This study presents stability thresholds as a means of highlighting variabilities in the distribution of shear stress and discharge within cross-sections, and variabilities in sediment caliber within the Verde River system which lead to fragmentation --variations in channel stability-- in river behavior.

Sediment Variability

Median particle sizes along the Verde River do not vary in a systematic fashion in the downstream direction, but do show some consistency in their distributions within the cross-sections. Median particle sizes for the bed of the low-flow channel range from 1.4 mm to 32 mm (medium sand to large pebbles) with an average size of 12.5 mm (medium pebbles). Side bar sediments exhibit a similar spread, ranging from 1 mm to 45 mm (medium sand to cobbles) for median particle size, with an average size of 20.4 mm (large pebbles). In general, the two upper-most cross-sections, 11 Abandoned Ranch and 12 Hell Point-- contain the finest bed and bar sediments (mostly sands), as does 34 White Horse Inn. The sediment data presented in this research remain incomplete due to hazardous sampling conditions at some of the cross-sections. Gaps in the data reflect the predominant nature of sediment data availability and collection for many rivers.

Stability Thresholds

This stability assessment aims to identify at which recurrence intervals of flow certain geomorphic features within a cross-section will be mobilized. Two cross-sections, only three river miles apart in segment 3 of the Verde River, serve as examples for stability assessment. Figures 2 and 3 show the subdivided cross-sections for 33 Dead Horse Ranch State Park and 34 White Horse Inn. These two reaches are instructive because they represent two different scenarios along the Verde River within a short distance.

Features or cross-sections are unstable for a given flow condition when the shear stress generated by that flow exceeds the critical shear stress required to move particles comprising the channel (i.e. $\tau > \tau_c$). Table 2 displays the critical shear stresses (using both d_{50} and d_{84}) for three geomorphic features within the example reaches and the shear stress generated by the flow over those features for four flow conditions: the two year flow, the five year flow, the ten year flow, and the 25 year flow (34 White Horse Inn only). These two examples display the conditions characteristic of the rest of the study reaches: a flow with a five year recurrence interval mobilizes at least half the sediment comprising all geomorphic features within the cross-section. In other words, channel change potentially occurs on average every five to ten years. Graf (1983) reported a similar threshold discharge of instability for the Salt River in central Arizona, suggesting that dryland, gravel-bed streams are more dynamic than humid region rivers. This result emphasizes the importance of moderately high flows in shaping some of the Verde River, counter to the hypotheses that extreme high events (25 year flows or greater magnitude) or consistent low flow events (as is the case for humid region rivers) accomplish the most geomorphic work (Wolman and Miller, 1960; Wolman and Gerson, 1978).

Under this shear stress approach to stability, a threshold exists, dividing conditions of stability and little sediment motion, from conditions of instability and sediment mobility. Geomorphic thresholds refer to conditions or values, of shear stress for instance, the exceedence of which results in abrupt or gradual change (Bull, 1979). In reality, since the geomorphic features in river channels are comprised of a range of particle sizes, particles are set in motion through a range of discharges and the range of shear stresses imparted by those flows. However, the concept of a threshold for cross-section or feature stability holds promise as a tool for identifying patterns of stability. For example, Harvey et al. (1979) used field observations to identify thresholds for sediment movement, and therefore channel change. Bull (1980) advocated the use of ratios for identifying thresholds in a variety of geomorphic settings. A stability ratio of actual shear stress over critical shear stress facilitates the identification of a threshold for channel stability.

With this result in mind, stability ratios were created for geomorphic features within all study cross-sections for the two year flow (Table 3). These values indicate the ratio between the shear stress generated by the two year discharge on a particular geomorphic feature and the critical shear stress required to mobilize the sediment comprising the feature. The threshold for mobilization, or instability, equals one: values greater than one indicate feature mobilization. Overall, the two year flow mobilizes over half of the bed material in the low flow channel at all cross-sections and over half of the particles in distinct overflow channels. Sediment from side slopes, usually fine material, is also entrained under this flow condition. Variability exists in the stability ratios for the side bars: the two year flow mobilizes over half of the sediment in side bars in just over half the cross-sections, but not in the remaining reaches. Using d_{84} as the representative particle size yields even greater variability: some cross-sections have mobility of at least 84% of the sediment during a two year flow event, while other cross-sections have only between 50% and 84% of the sediment mobilized. Three of the unstable side bars contain finer sediments (d_{50} < 10 mm,), including two upper-most basin reaches and 34 White Horse Inn. The other four unstable bars occur in river segments with variations in shear stress rather than variations in resistance; these variations in shear stress likely reflect local differences in depth and slope related to some combination of factors related to sediment supply, channel morphology, channel pattern, and valley morphology.

The probability that a combination of factors controls channel stability makes discerning the exact nature of the influencing factor difficult. For example, one cross-section, 31 TAPCO, is notable for its location on a meander bend and its position at the upstream end of the relatively unconfining Verde Valley. Its relative instability during the two year flow event probably results from the combination of at least these two factors. Another reach located on a meander bend, 22 Sycamore Canyon I, and another reach located in the upper Verde Valley, 32 Tuzigoot, do not show instability on the order of that at 31 TAPCO.

Table 2. Shear Stress and Critical Shear Stress Values for 33 Dead Horse Ranch State Park and 34 White Horse Inn

		low-flow channel	**side bar**	**flood plain**
τ_c ***critical shear stress*** ***(N/m^2)***				
using d_{50}				
	33 Dead Horse Ranch	21	22	0.11
	34 White Horse Inn	1.4	2.4	0.23
using d_{84}				
	33 Dead Horse Ranch	70	53	0.21
	34 White Horse Inn	10.7	22	0.42
τ ***shear stress*** ***(N/m^2)***				
2 year flow				
	33 Dead Horse Ranch	29	7.3	4.5
	34 White Horse Inn	35	15	0.4
5 year flow				
	33 Dead Horse Ranch	46	25	13
	34 White Horse Inn	63	42	14
10 year flow				
	33 Dead Horse Ranch	60	38	19
	34 White Horse Inn	82	61	18
25 year flow				
	34 White Horse Inn	79	58	32

This observation suggests that sediment transport and storage are fragmented rather than integrated. Each reach of a river must be considered individually, as a case study, eliminating the possibility of creating general models of the influence of local factors on sediment transport. On the other hand, the apparent instability within all cross-sections at a flow magnitude greater than the ten year flow suggests that the system is integrated on this pseudo-temporal level. The greatest spatial variability in stability occurs with flows between the one and two year recurrence interval. However, it is probable that much of the Verde River experiences channel change on average every five years.

CONCLUSION

The stability assessment, through the identification of stability thresholds (ratios) provides answers to the research questions outlined at the beginning of this paper. Different geomorphic surfaces, or features, exhibit different stability thresholds, in part due to variation in mean particle size and in part due to variations in shear stress

Table 3. Stability Ratios for Two Year Flows Using d_{50} and d_{84}

Cross-section		**low flow channel**	**side bar**	**overflow channel**	**flood plain**	**side slope**
11 Abandoned Ranch						
	d_{50}	**14.6**	**4.2**	--	0	**48.8**
	d_{84}	**6.2**	**1.8**	--	0	**30.0**
12 Hell Point						
	d_{50}	**26.6**	**20.8**	--	**33.1**	--
	d_{84}	**11.3**	**1.4**	--	**23.8**	--
13 Bear Siding						
	d_{50}	**2.7**	0.5	**1.8**	**41.0**	--
	d_{84}	0.4	0.1	0.3	**24.8**	--
21 Perkinsville						
	d_{50}	**2.8**	**1.0**	--	**10.7**	--
	d_{84}	0.5	0.3	--	**3.3**	--
22 Sycamore Gage Site						
	d_{50}	**1.9**	0.4	--	0.9	--
	d_{84}	0.6	0.1	--	0.3	--
23 SOB Canyon						
	d_{50}	**8.0**	0.4	--	**22.1**	--
	d_{84}	**3.3**	0.2	--	**12.1**	--
31 TAPCO						
	d_{50}	**20.4**	**54.6**	--	0.5	--
	d_{84}	**2.8**	**15.8**	--	0.2	--
32 Tuzigoot						
	d_{50}	**1.9**	0.9	--	**3.0**	**118.3**
	d_{84}	0.4	0.1	--	**1.5**	**2.3**
33 Dead Horse Ranch State Park						
	d_{50}	**1.4**	0.3	--	**40.1**	**18.5**
	d_{84}	0.4	0.1	--	**21.4**	**4.1**
34 White Horse Inn						
	d_{50}	**25.3**	**6.1**	--	**1.7**	**114.4**
	d_{84}	**3.3**	0.7	--	**1.0**	**44.8**
41 Thousand Trails						
	d_{50}	**8.2**	0.5	**9.9**	--	**25.3**
	d_{84}	**1.6**	0.2	**4.5**	--	**16.5**
44 Beasley Flat						
	d_{50}	**3.1**	**4.2**	**5.0**	--	**91.8**
	d_{84}	**1.0**	**1.7**	**2.0**	--	**52.0**
51 Childs						
	d_{50}	--	--	--	**86.7**	--
	d_{84}	--	--	--	**47.1**	--
62 Sheep Bridge						
	d_{50}	**1.2**	**1.1**	--	**60.6/20.0***	--
	d_{84}	0.5	0.2	--	**57.1/11.0**	--

Bold values indicate exceedence of the stability threshold (stability ratio > 1).
Absent values due to absence of particular feature or sediment sample.
* First value for the left flood plain, second value for the right flood plain.

generated by a particular channel morphology. Low-flow channel and flood plains are partially mobile at the two year flow, while only some side bars are unstable. The variability in stability thresholds particularly in the middle Verde (segments 3 and 4) emphasizes the role of a combination of local factors and suggests a closer examination of sediment sources in the Verde basin, particularly the tributaries. At least half of the sediment comprising all surfaces in the study cross-sections are unstable for the 10 year recurrence interval discharge, implying that within channel shifting and channel change potentially occur on average every 10 years. Clearly, in terms of sediment mobility, the Verde River is integrated during moderate and high flows.

This work corroborates others' conclusions regarding the difficulty in understanding variations in sediment movement and storage. Combinations of reach-scale influences create much of the system fragmentation rather than segment-scale or systematic factors. On some levels, however, these variations disappear. For example, moderate to high flows on the Verde River correspond with unstable conditions (sediment entrainment) throughout the system. In order to better model and explain variations in stability, sediment transport, and sediment storage, these levels of fragmentation and integration need to be considered and identified.

ACKNOWLEDGEMENTS

This work was undertaken in conjunction with a project entitled "Channel Processes and Sediment Dynamics for the Verde River Watershed, Arizona," jointly sponsored by the Arizona Department of Environmental Quality and the Department of Geography, Arizona State University, funded by the Environmental Protection Agency (ADEQ Contract No. 95-0137). The author wholeheartedly thanks these agencies and the project managers, Kris Randall and Will Graf, for their assistance and guidance. The author also thanks two anonymous reviewers for their careful reading and insightful suggestions.

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