

Channel Morphology

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Introduction

Channel morphology has become an increasingly important subject for analyzing the health of rivers and associated fish populations, particularly since the popularization of channel classification and assessment methods. Morphological data can help to evaluate the flows of sediment and water that influence aquatic and riparian habitat. Channel classification systems, such as the one developed by Rosgen (1994) provide a useful shorthand for summarizing key morphological attributes of a river system. Accordingly, researchers have hypothesized that channel classifications could explain variation in native fish populations in rivers of the Southwest (Rinne and Neary 1997; Rinne 2005). Rosgen's (1996) full methodology encompasses several levels of analysis arranged hierarchically from a general characterization of a stream basin to detailed measurements of channel change in specific reaches. The second and most popular level (Level II) of the Rosgen (1996) methodology provides a framework for categorizing stream reaches based on channel form and dominant substrate. While this classification is useful for describing variations in channel morphology, critics argue that it is less useful and perhaps even misleading for making inferences about channel condition and processes of development (Miller and Ritter 1996).

The objective of this chapter is to evaluate the results of using the Rosgen's (1996) Level II methodology to analyze morphological data collected from the Upper Verde River (UVR) of the Prescott National Forest between 1997 and 2000 (Medina and others 1997). Level II methods utilize channel materials, channel slope, entrenchment ratio, width/depth ratio, and sinuosity to classify streams as types A, B, C, D, E, F, and G (fig 5.1).

- A-type streams are incised headwater creeks and rivers with narrow and deep channels and steep slopes. They have single channels, entrenchment ratios <1.4 , width/depth ratios of <12 , and slopes $>4\%$.
- B-type streams are moderately incised, wide, and shallow with moderate slopes and are found in colluvial valleys. They are single channel streams with entrenchment ratios of 1.4 to 2.2, width/depth ratios >12 , and slopes between 2 and 4%.
- C-type streams are wide and shallow but are not incised as they are typical of low slope alluvial valleys on the lower portions of landscapes. These streams have higher entrenchment ratios (>2.2), width/depth ratios >12 , and slopes $<2\%$.
- D-channels are indicative of high sedimentation environments in that they are wide and shallow with multiple channels and low slopes. Entrenchment ratios are >2.2 and width/depth ratios are >40 . Slopes are generally $<2\%$ but can range up to 4%.

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Figure 5.1 — Rosgen (1996) classification system for natural rivers (from Endreny 2003).

- E-type channels represent one end point of channel evolution in that they are not incised and are narrow and deep in nature. They are representative of low slope (<2%) alluvial valleys. Entrenchment ratios are usually >2.2 and width/depth ratios are <12.
- F-type channels are single thread channels that are deeply incised. However, they are wide and shallow with slopes <2%. Entrenchment ratios are <1.4 and width/depth ratios are >12.
- G-type streams are single channels that are incised, narrow and deep in nature, and moderately sloped. Entrenchment ratios are <1.4 and width/depth ratios are <12. Slopes can be 2 to 4% in contrast to the lower gradient F-type channels.

Distinctive attributes of the river identified through the classification methodology helps to identify the prominent physical characteristics of the river that are important for its management. Such attributes can be considered when relating morphology and habitat suitability for native fishes. This analysis also examines problems in collecting and interpreting the data using the Level II framework. These findings are important for providing recommendations to land managers and other researchers to improve evaluations of the associations between morphology and native fish populations in the river.

Methods

Study Area

The Verde River and its tributaries flow through diverse geologic formations as they descend from the Colorado Plateau into a basin that had been closed as recently as a few million years ago (Pearthree 1993). Much of the UVR corridor (fig. 5.2) is lined with Paleozoic limestones and siltstones (fig. 5.3), but some reaches course through more erodible Holocene sediments (fig. 5.4).

These river terrace sediments were described by Cook and others (2010a, 2010b, 2010c) and consist of historical river terrace deposits that were deposited by paleofloods between A.D. 440 and 1650 according to radiocarbon dating. Other reaches are narrowly confined by relatively young basalt flows (fig. 5.5). Some reaches are relatively linear due to the bedrock confinement of the river (fig. 1.10A), but others contain meanders that have formed within recent river alluvium (fig. 1.10B). Due to confinement by basalt and sedimentary bedrock, the valley of the UVR can be characterized as moderately to highly confined, low gradient, and low relief. The physiography of the river changes dramatically below Sycamore Creek and into the Middle Verde River where extensive deposits of the Verde Formation along with younger alluvial deposits (fig. 5.2) permit the stream to follow a more broadly meandering pattern.

Data Collection

Channel morphology data were collected by hydrologic technicians on the Prescott National Forest at 138 locations sampled in the months of June and July between 1997 and 2000 (Medina and others 1997; fig. 5.6). Sampling locations were concentrated within segments of the UVR, in large part because those segments included more variable reaches and reaches with unusual channel form. However, some distinctive areas, such as the Perkinsville Basin, appear

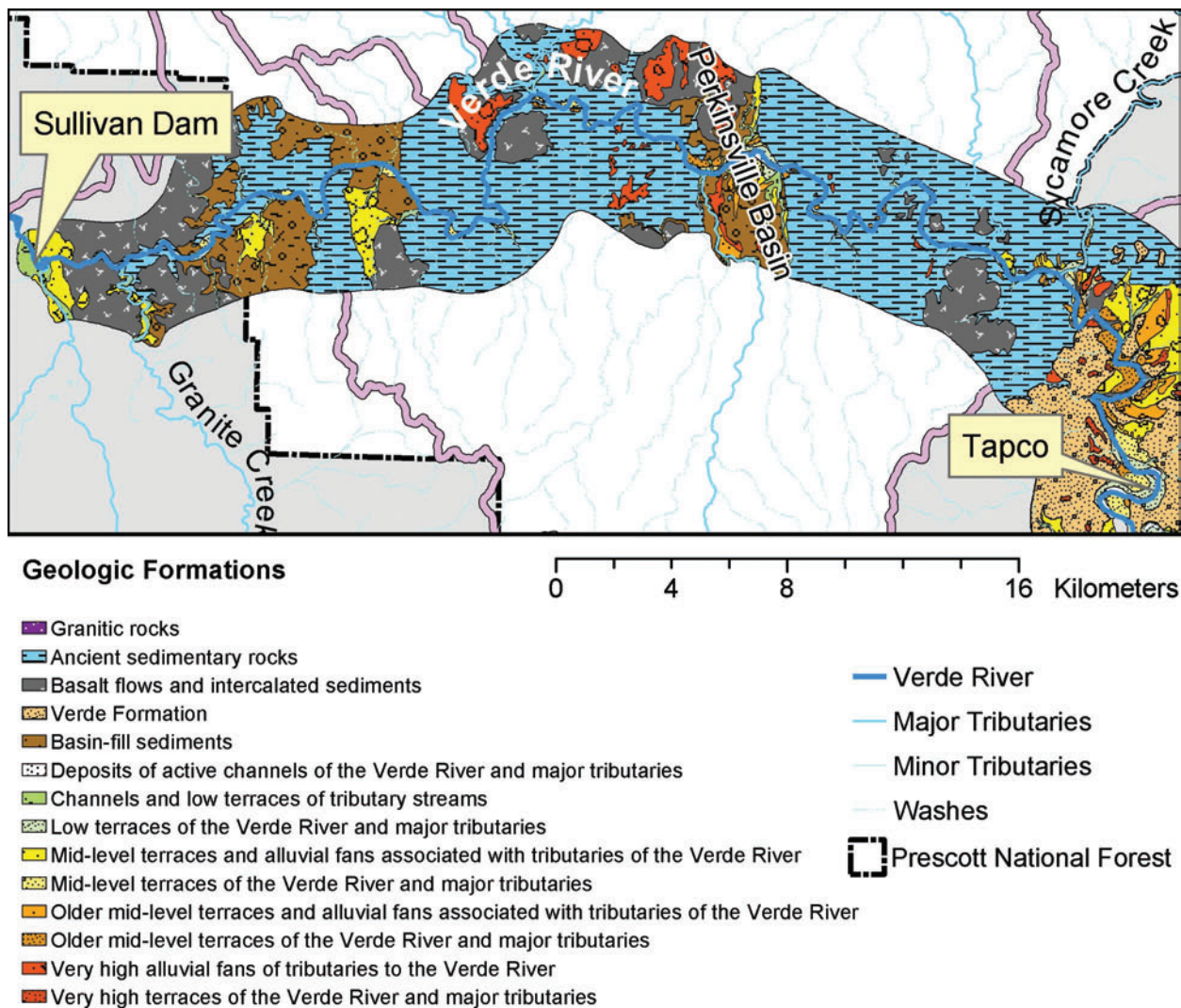


Figure 5.2—Geologic formations along the UVR, Prescott National Forest, Arizona. The major colors indicate: ancient sedimentary rocks (blue), basalt flows and inter-layered sediments (gray), older mid-level terraces of the UVR and its tributaries (brown), very high alluvial fans of tributaries of the UVR (orange), mid-level terraces and fans associated with tributaries of the UVR (yellow), and channels and low terraces of tributary streams (green).

underrepresented due to access limitations on some private lands. The technicians were trained and supervised by a Prescott National Forest hydrologist to survey channel cross-sections, to identify bankfull levels, and to measure slope and sinuosity following procedures detailed by Harrelson and others (1994) and Rosgen (1996). The field crews measured slope and sinuosity along longitudinal profiles at 115 of the locations (these data were not collected in 2000). The crews also conducted pebble counts at 110 of the sampling locations using the pebble count methodology developed by Bevenger and King (1995). In 1997, 75% of the pebble count samples included 100 particles each. The remaining samples and those in subsequent years included 315 particles each. The total length of surveyed reaches was 26 km (16 mi), which represents approximately 44% of the total 60 km (37 mi) from Sullivan Dam to the confluence with Sycamore Creek. The habitat at each cross-section was subjectively categorized as riffle, run, glide, or pool, depending on feature gradient and velocity.



Figure 5.3—Limestone and siltstone bedrock near Duff Springs in the UVR. (Photo by Alvin L. Medina.)



Figure 5.4—Unconsolidated Holocene river-deposited sediments along the UVR channel near Burnt Ranch. (Photo by Daniel G. Neary.)



Figure 5.5—Basalt cliffs along the UVR downstream of Sullivan Lake. (Photo by Daniel G. Neary.)

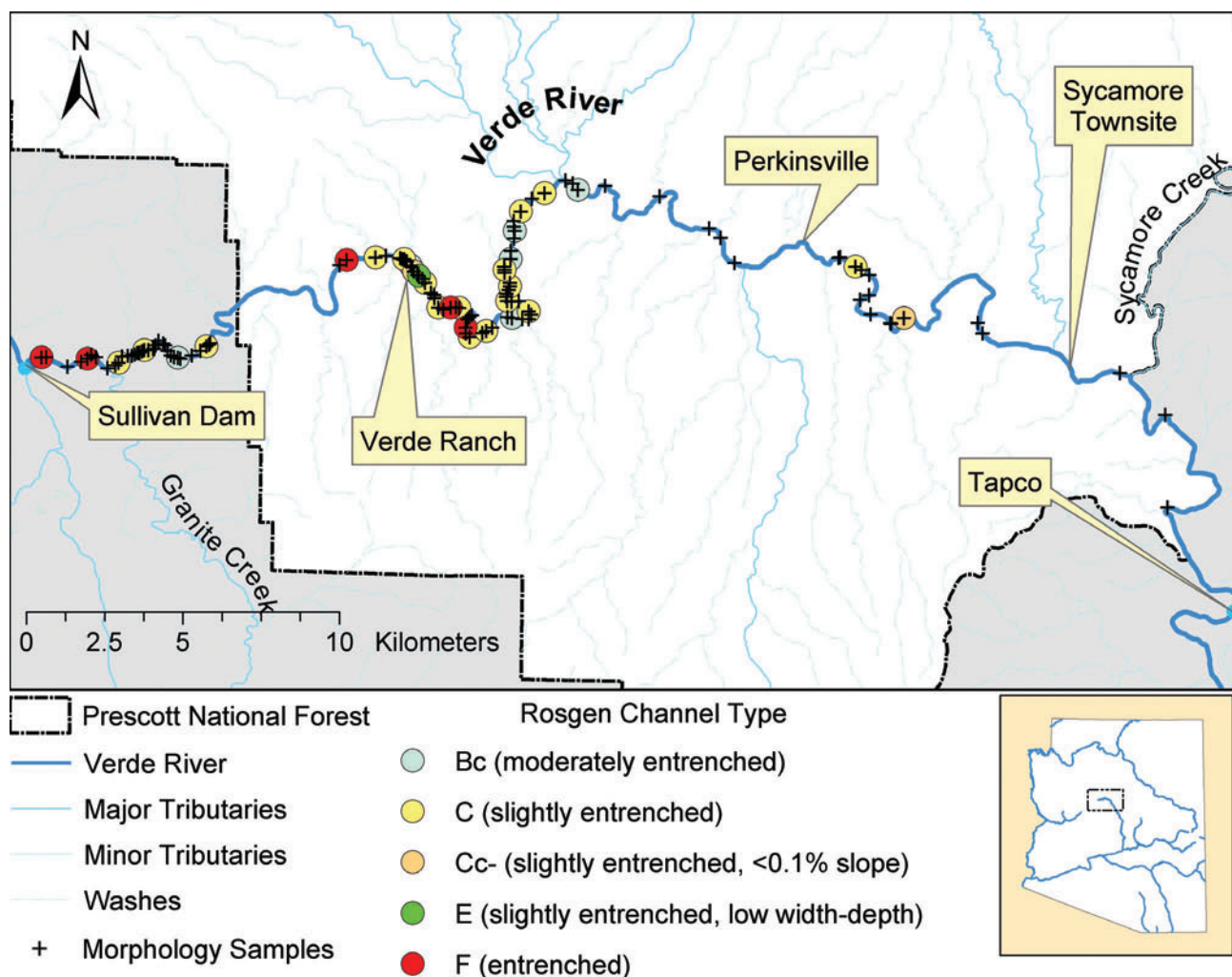


Figure 5.6—Location of channel morphology sampling sites, with differently colored dots representing reaches that were classified into different Rosgen Level I channel types.

Data Reduction and Analysis

Dataset—The large dataset developed by the field work was filtered and aggregated to render it useful for channel classification in accordance with Rosgen's (1994, 1996) methodology. The filtering involved elimination of data used in the classification analysis where data were incomplete or measurement stations were missing. In some years, sufficient funds were not available to re-measure every station. Aggradation of data was based on similarity within one year. The objective was to produce a dataset with common stations across all the years of the analysis. To yield more consistent estimates of bankfull dimensions, cross-sections were excluded that were established in glides, pools, or where low flows were split into two channels. Bankfull markers were found to be too inconsistent or confusing to be used reliably. Where suitable cross-sections were located within 20 channel widths of each other in reaches that appeared to have similar dimensions, average bankfull dimensions, slopes, and sinuosity were calculated for the entire reach encompassing those cross-sections. Figure 5.7 displays the channel types for 31 reaches that were classified in this manner, along with all 136 locations where morphological data were collected. Seven additional reaches were long enough to classify, but they were not because their associated cross-sections had been located

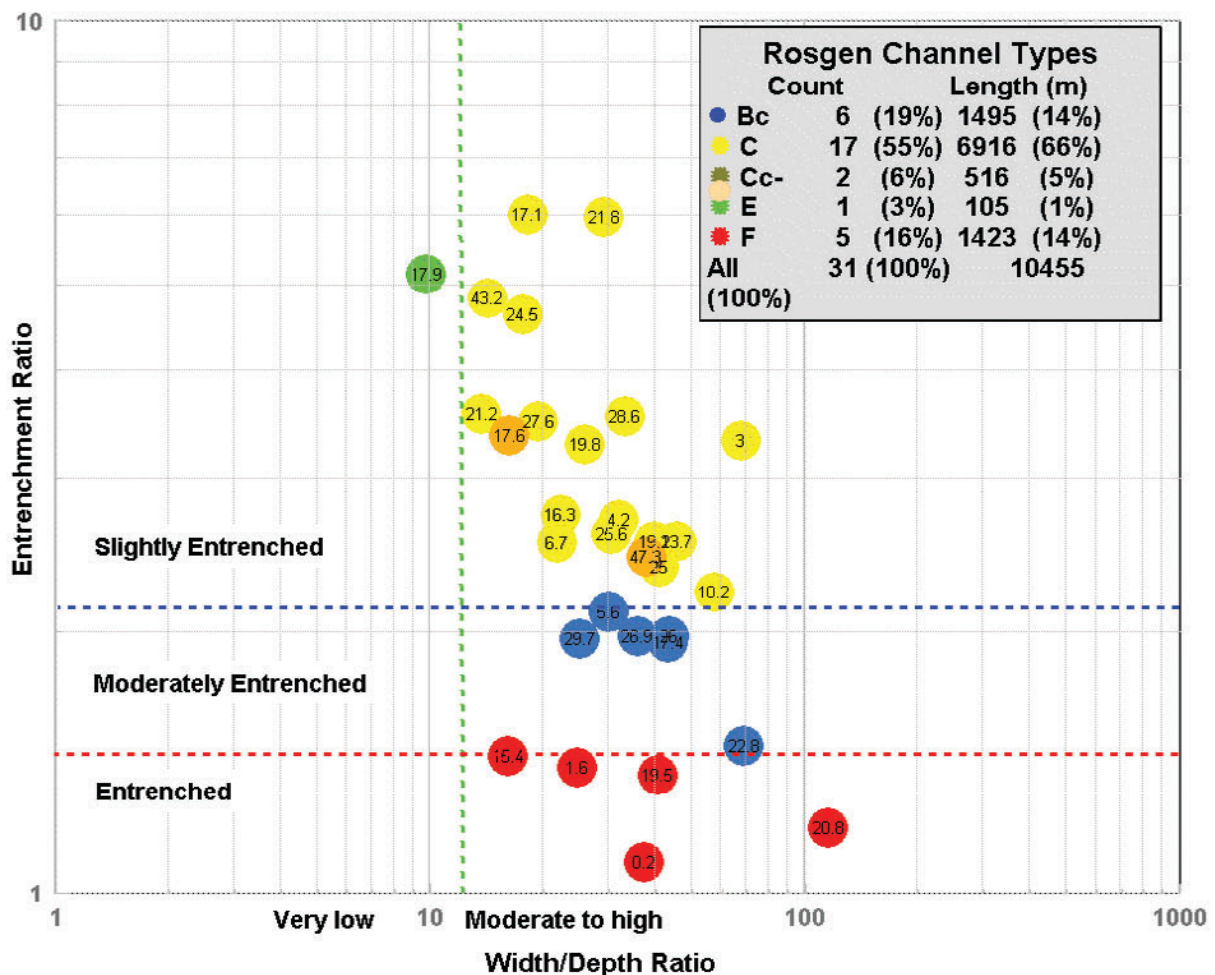


Figure 5.7—Width-depth ratios, entrenchment ratios, and Rosgen (1996) Level I channel types for classified reaches. Numbers within data point circles are width-depth ratios.

in pools or glides. Differences in cross-sections and pebble count distributions were examined at two reaches near the Paulden stream gauge (approximately 16.3 and 16.6 km or 10.2 and 10.4 mi downstream from Sullivan Dam) that had first been surveyed in 1997 and were re-surveyed in 2000. Differences in the percentage of fine sediments were calculated at those two reaches using a Chi-square contingency table (Bevenger and King 1995).

Hierarchical Analysis—A hierarchical assessment provides the physical, hydrologic, and geomorphic context for linking the driving forces and response variables at all scales of inquiry (Rosgen 1996). There are four levels to the Rosgen hierarchy (fig. 5.8). Level I describes the geomorphic characteristics that result from the integration of basin relief, landform, and valley morphology. Level II provides a more detailed morphological description of stream types based on channel dominant substrates and extrapolated from field-determined reach information. Level III describes the existing condition or “state” of the stream as it relates to its channel stability, sediment supply, erosion response potential, flow regime, and overall geomorphic function. Additional field parameters are evaluated that influence the stream state (e.g., riparian vegetation, sediment supply, flow regime, debris occurrence, depositional features, channel stability, bank erodibility, and direct channel disturbances). These analyses are both reach- and feature-specific and are especially useful as a basis for integrating companion studies (e.g., fish habitat indices and surveys of riparian communities). Measurements are taken to

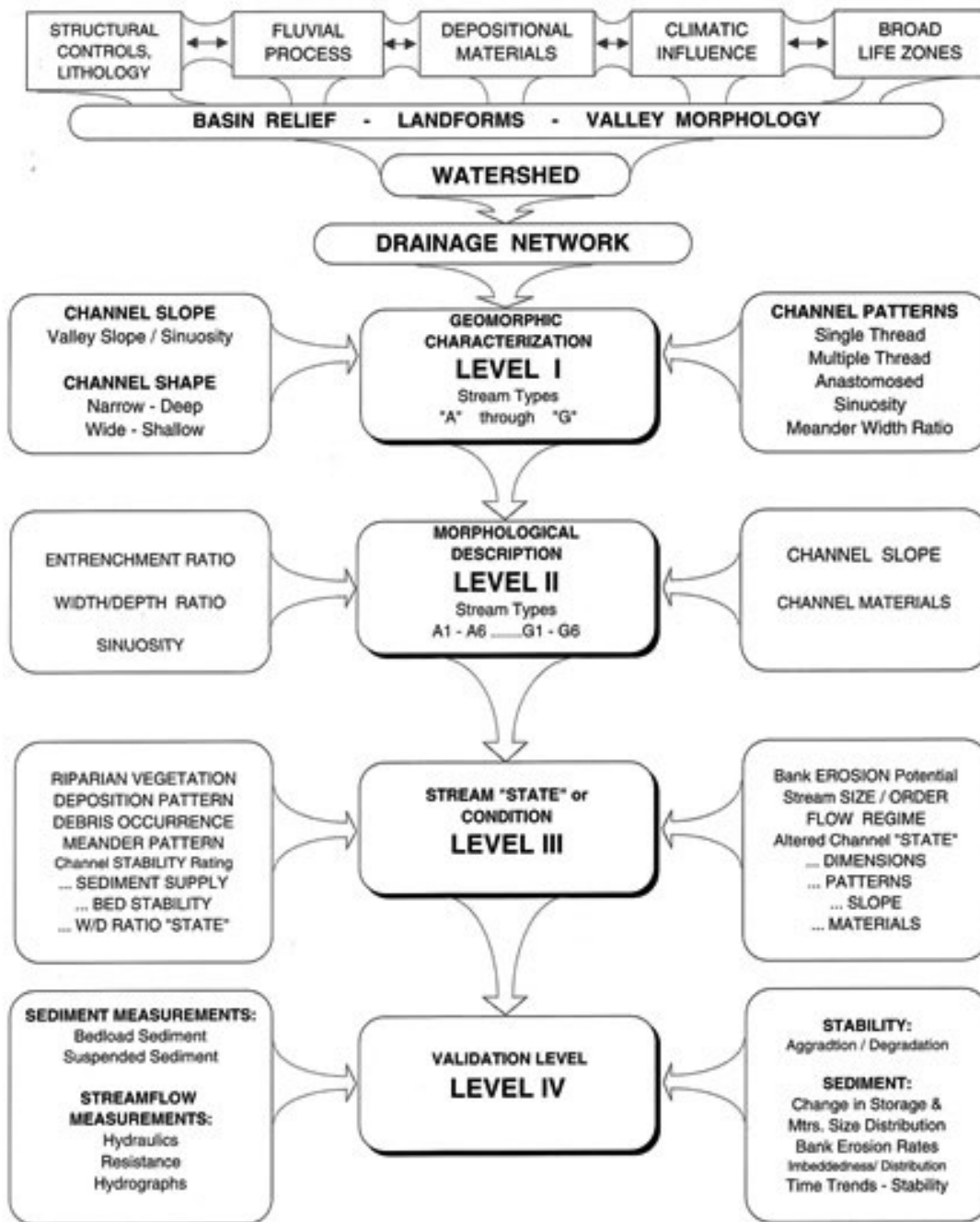


Figure 5.8—Rosgen's (1996) stream classification hierarchy used in the UVR channel classification (from Endreny 2003).

Level IV to verify process relationships inferred from preceding analyses. The objective is to establish empirical relationships for use in prediction (e.g., to develop Manning's "n" values from measured velocity; correlating bedload versus discharge by stream type to determine sediment transport relationships; or calculating hydraulic geometry from gaging station data). Empirical relationships are specific to individual stream types for a given statistic and enable extrapolation to other similar reaches for which Level IV data are not available.

Stream classification data used in the Level I through IV analyses of the UVR include a number of geomorphic and fluvial parameters. An example of typical data is shown in table 5.1. The distinctions between the basic types use uppercase letters (e.g., A, B, C, F, and E). Distinctions between the gradient subclasses within the basic classification types utilize the lowercase letters (e.g., Bc and Cc).

Table 5.1—Examples of Level II stream classification data for UVR cross-sections (Rosgen 1996). Data are: year (Yr), station number (STN), bankfull width (BFW), bankfull maximum depth (BFMD), flood prone area (FPA), valley distance (VD), stream distance (SD), channel slope (CSLP) and valley slope (VSLP), width/depth ratio (W/D), entrenchment (ENT), sinuosity (SIN), channel type (CHT), and median sediment diameter (D50).

Stream geomorphic parameters used in classification													
Yr	STN	BFW	BFMD	FPA	VD	SD	CSLP	VLSP	W/D	ENT	SIN	CHT	D50
		<i>m</i>					%	%					<i>mm</i>
97	15b	9.71	0.48	21.02	840	843	0.223	0.224	35.96	2.16	1.000	B4c	6.8
97	111	9.28	0.52	32.63	545	619	0.115	0.130	33.14	3.52	1.135	C4	1.5
97	5	9.15	0.67	12.76	76.4	97	1.330	1.688	24.73	1.39	1.270	F3	154.0
97	33	6.03	0.75	16.09	771	1104	0.272	0.389	11.17	2.67	1.430	E4	9.6

Results

Valley Type

The UVR valley is a type IV valley (fig. 5.9). Rosgen (1994, 1996) described it as the classic meandering, entrenched or deeply incised, and confined landform. This valley is the typical canyon and gorge type often with gentle elevation relief and valley-floor gradients of generally less than 2%. Steeper reaches are well interspersed with low-gradient reaches, thereby diversifying habitats. These valleys are generally structurally controlled and incised in highly weathered materials. However, F-type streams are often found in this valley type where the width of the valley floor accommodates both the channel and a floodplain (fig. 5.10). C-type channels are also often found in this type of valley. This is the case on the UVR where 61% of the channels are C-type, 19% are B-type channels, 16% are F-type channels, and 3% are E-type channels (figs. 5.1, 5.7 and 5.10; table 5.2). Depending on streamside materials, the sediment supply is generally moderate to high.

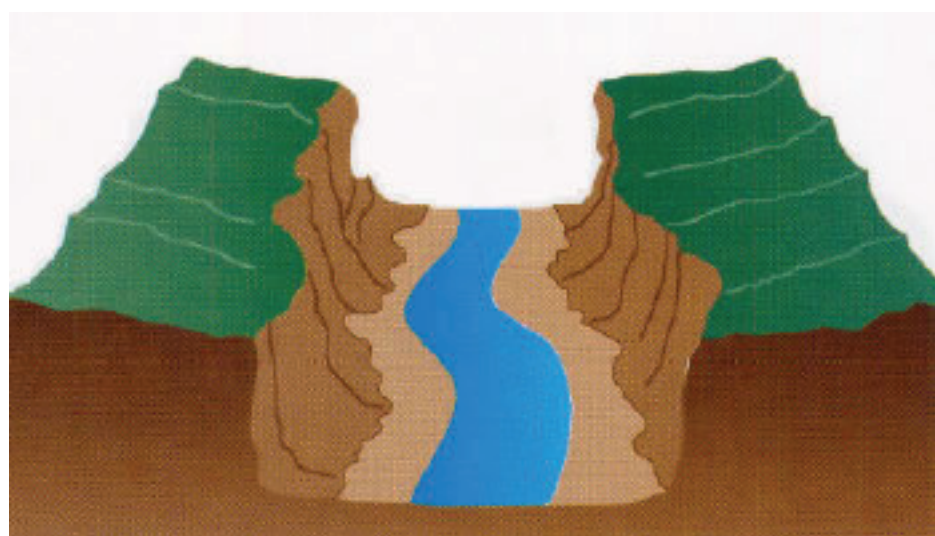


Figure 5.9—Rosgen (1996)
Type IV valley form that
comprises much of the UVR
(from Endreny 2003).

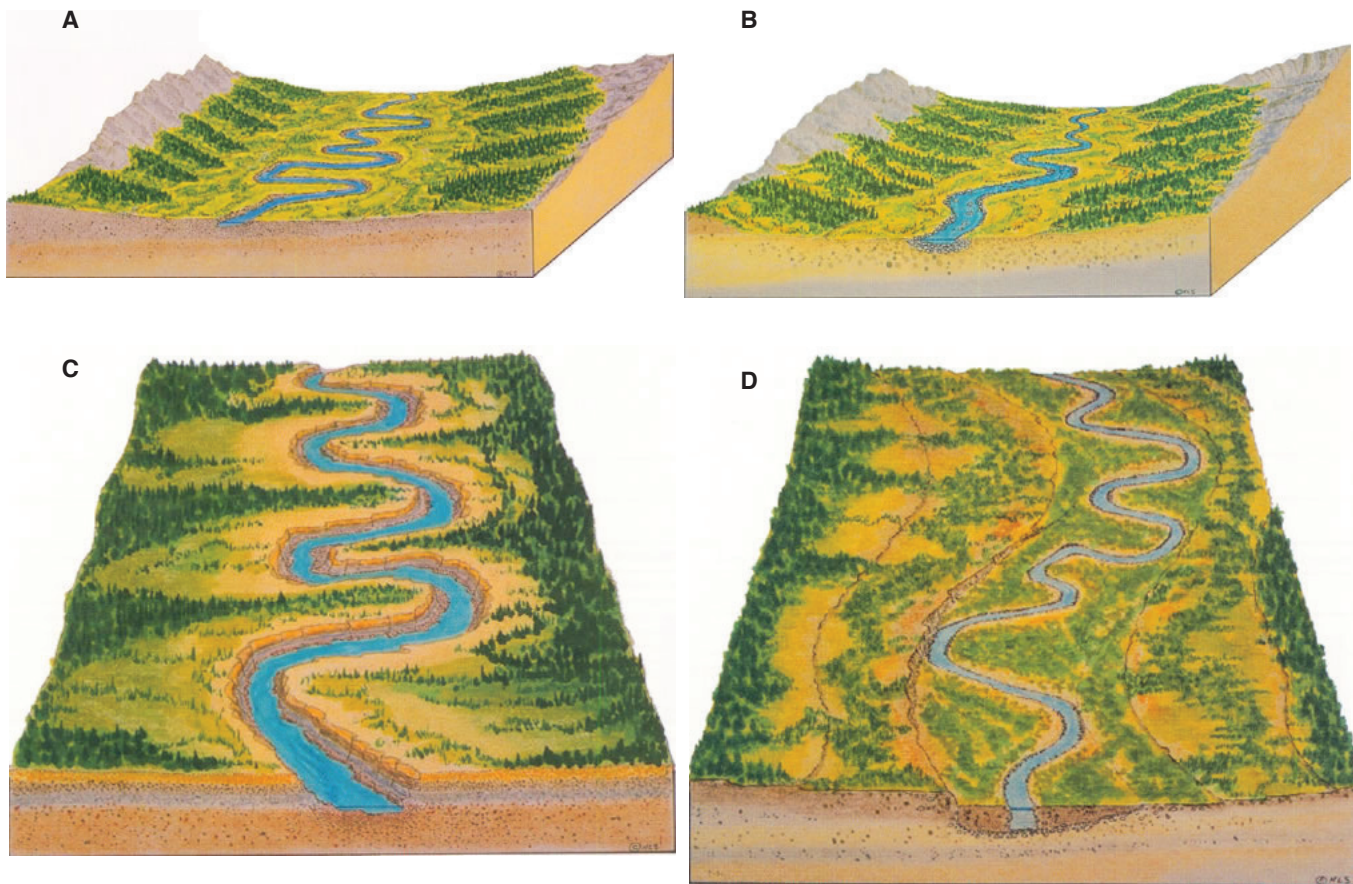


Figure 5.10—Channel types of the UVR according to Rosgen (1996) (from Endreny 2003): A = C-type channel and valley, B = B-type channel and valley, C = F-type channel and valley, D = E-type channel and valley.

Table 5.2—Characteristics typical of C-, B-, F-, and E-type stream channels found in the UVR.

Stream type	Portion of UVR	Entrenchment ratio	Width/depth ratio	Sinuosity	Slope range
	%				%
C	61	>2.2	>12	>1.2	<0.1-3.9
B	19	1.4-2.2	>12	>1.2	<2.0-9.9
F	16	<1.4	>12	>1.2	<2.0-3.9
E	3	>2.2	<12	>1.5	<2.0-3.9

Cross-Sectional Dimensions and Channel Types

Figure 5.7 shows the breakdown of channel type classifications relative to width-depth ratio and entrenchment ratio. This arrangement shows that channel types can be seen as falling along a continuum rather than lying into discrete categories since some reaches lie close to the boundaries between channel type classes. The majority of reaches in the study area were slightly entrenched alluvial channels characterized by riffle-pool sequences (Rosgen C-types and Cc-subtypes).

About one-third of the reaches were moderately entrenched (Bc-type) or highly entrenched (F-types). The moderately entrenched reaches commonly featured long pools separated by short rapids, and they often occurred downstream of tributary confluences where alluvial deposits impinged on the main channel. Highly entrenched channels occurred in canyon reaches, including two reaches in the basalt-walled canyon that extends several kilometers below Sullivan Dam (figs. 5.2 and 5.5). One reach that met the criteria for the very narrow, vegetation-dominated (E-type) channel is a contiguous but relatively short (105 m or 345 ft) section of the UVR at the Verde Ranch. Other E-type channels are widely dispersed in the UVR, even shorter in length, and not considered in the general channel-type distribution.

The Verde River did not exhibit consistent channel dimensions downstream, but rather showed substantial variation from one reach to the next. Figure 5.11 depicts estimated width of the flood-prone area at the reaches used for channel classification, arranged longitudinally downstream. The chart suggests high variability in the width of the floodplain, which, in part, reflects the patchy distribution of canyon-bound and broad valleys. However, estimates of flood-prone area widths are very sensitive to the identification of bankfull level. Figure 5.12 indicates that there was roughly a one-half order of magnitude in variation of field-determined bankfull width, mean depth, and cross-sectional area. That variation may have been due to differences in identification of the bankfull level between survey crews, complex channel morphology, differences in substrates (e.g., finer sands and silts versus cobbles and boulders), and/or indistinct indicators of bankfull levels.

One of the most important observations about the channel classes of the UVR is the lack of D channels. These channels are multiple channel systems described as “braided streams” within broad alluvial valleys or on alluvial fans (Rosgen 1996). Braided channels are characterized by high bank erosion rates, excessive deposition, and annual bed location changes. The conditions that result in channel braiding are: high sediment supply, high bank erodibility, moderately steep gradients, and very flashy storm runoff conditions. Although flashy runoff can occur in the UVR, as indicated by the flow duration curves, most of the other conditions do not hold (see Chapter 4). This lack of D-type channels is an important piece of evidence indicating that the watershed condition of the surrounding uplands at present is definitely satisfactory. The UVR is simply not experiencing high levels of sediment input. The channel classes, entrenchment ratio, and continued narrowing and deepening are not indicative of a river system with high sediment loading. The Verde River is processing all of its sediment and then some because it still shows evidence of downcutting. The major fine sediment river deposits adjacent to the UVR channel that were mapped by Cook and others (2010) date from A.D. 440 to 1650 so they have nothing to do with modern management of the UVR (see Chapter 4).

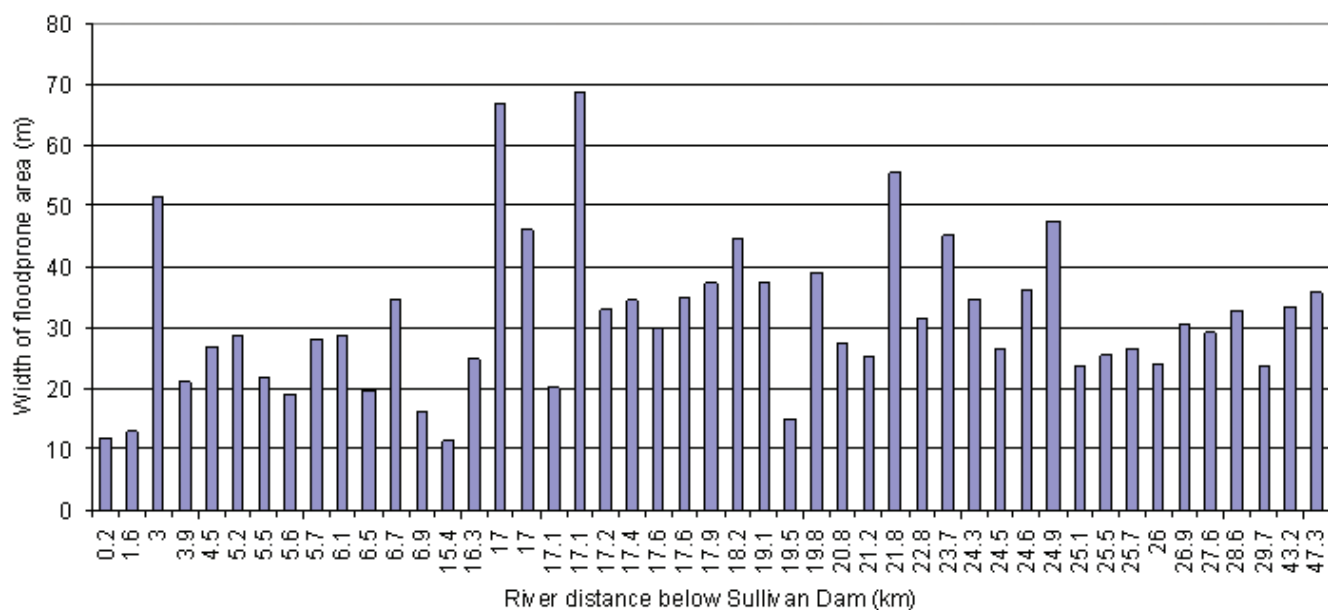


Figure 5.11—Floodprone area width at the reaches used for channel classification, arranged longitudinally downstream.

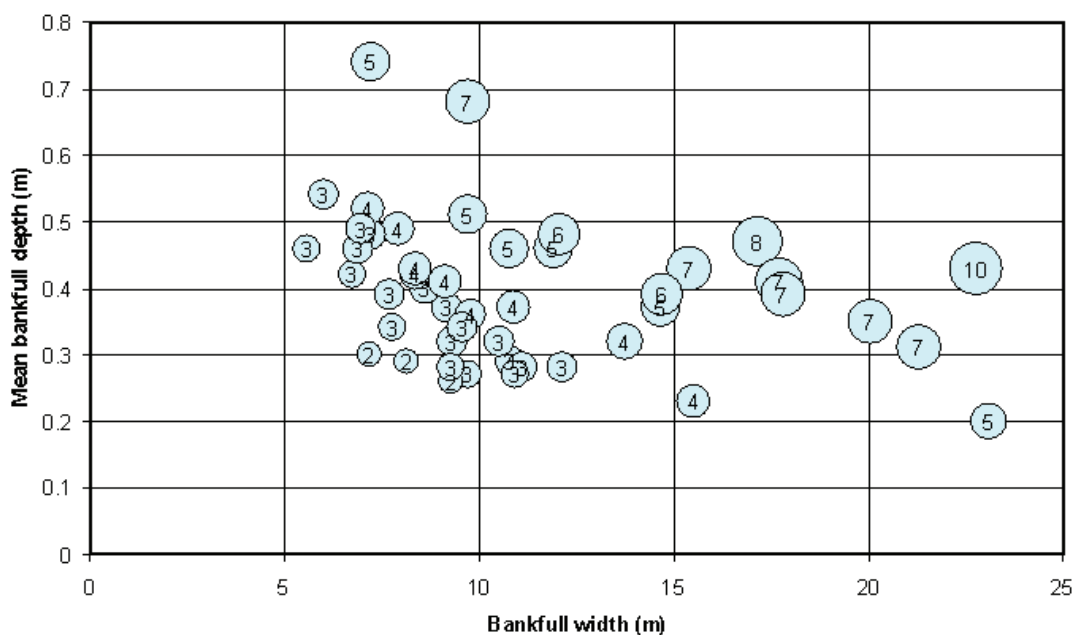


Figure 5.12—Bankfull width (X-axis), bankfull mean depth (Y-axis), and approximate bankfull cross-sectional area (size of bubbles) for classified reaches.

Channel Sinuosity and Gradient

A combination of low-gradient and relatively straight reaches characterized much of the UVR. Variation in slope was analyzed at two scales. First, slopes for the 38 reaches that were long enough for classification were summarized. Gradient of these reaches was consistently below 2%, with two reaches (Cc-types) being extremely low gradient (<0.001 slope). However, field crews surveyed three reaches with slopes $>2\%$. Those reaches were too short to meet the requirements for channel classification, since Rosgen (1996) recommended measuring a reach that is a minimum of 20 channel widths in length or two meander wavelengths. The data for those reaches serve to characterize variation in sinuosity and slope at a finer scale. Sinuosity of individual reaches ranged from 1 to 1.6, with a mean of 1.15 (fig. 5.13a). Slopes of individual reaches ranged from 0.0% to 2.4%, with a mean of 0.5% (fig. 5.13b). The median slope across all sampled reaches (0.4%) was equal to the total slope across all sampled reaches (the total elevation drop divided by the total length of all sampled reaches). Both of those values were equal to the overall 0.4% estimated river slope from Sullivan Dam to the town site of Sycamore above the confluence with Sycamore Creek. This suggests that the sampled reaches were representative of the UVR.

Dominant Particle Sizes

Analysis of pebble count data reveals that the median (D50) particle size was predominantly gravel or very coarse sand in riffle reaches, while the dominant particle in pool reaches tended to be fine gravel or sand (fig. 5.14). Boulder-dominated reaches were restricted to the uppermost reach in a basalt-bound canyon. Many of these boulder deposits were moved about and deposited during the 1993 flood on the UVR (fig. 5.16). Reaches with large amounts of silts or clays were not commonly found, and then only in reaches where the channel gradient was diminished due to bedrock controls, coarse sediment deposits, woody debris, or beaver dams.

Temporal Consistency

The two cross-sections at the Paulden gauge that were resurveyed in June 2000 had equivalent lateral determinations of bankfull (fig. 5.15). The cross-section in a riffle reach filled (estimated bankfull cross-sectional area decreased by 11%, from 3.7 to 3.3 m²), while the cross-section in a pool reach scoured (estimated bankfull cross-sectional area increased by 27% from 8.3 to 10.5 m²). The wetted widths of the channel decreased 16% at the riffle cross-section and 36% at the pool cross-section. Part of this change is attributable to a 13% smaller flow on the day when the cross-section was surveyed in 2000 (0.65 m³ s⁻¹ on 7/16/1997 versus 0.57 m³ s⁻¹ on 6/5/2000, according to U.S. Geological Survey gauge data). Mean water depth decreased by 25% in the riffle reach (from 0.28 to 0.21 m), while it increased by 22% in the pool reach (from 0.16 to 0.19 m). Particle size distributions differed between pebble count samples on July 16, 1997 and July 12, 2000, as fines in a riffle reach decreased from 40% to 28% (P-value = 0.016, chi-square test), while fines in a pool reach decreased from 62% to 49% (P-value = 0.015, chi-square test)."

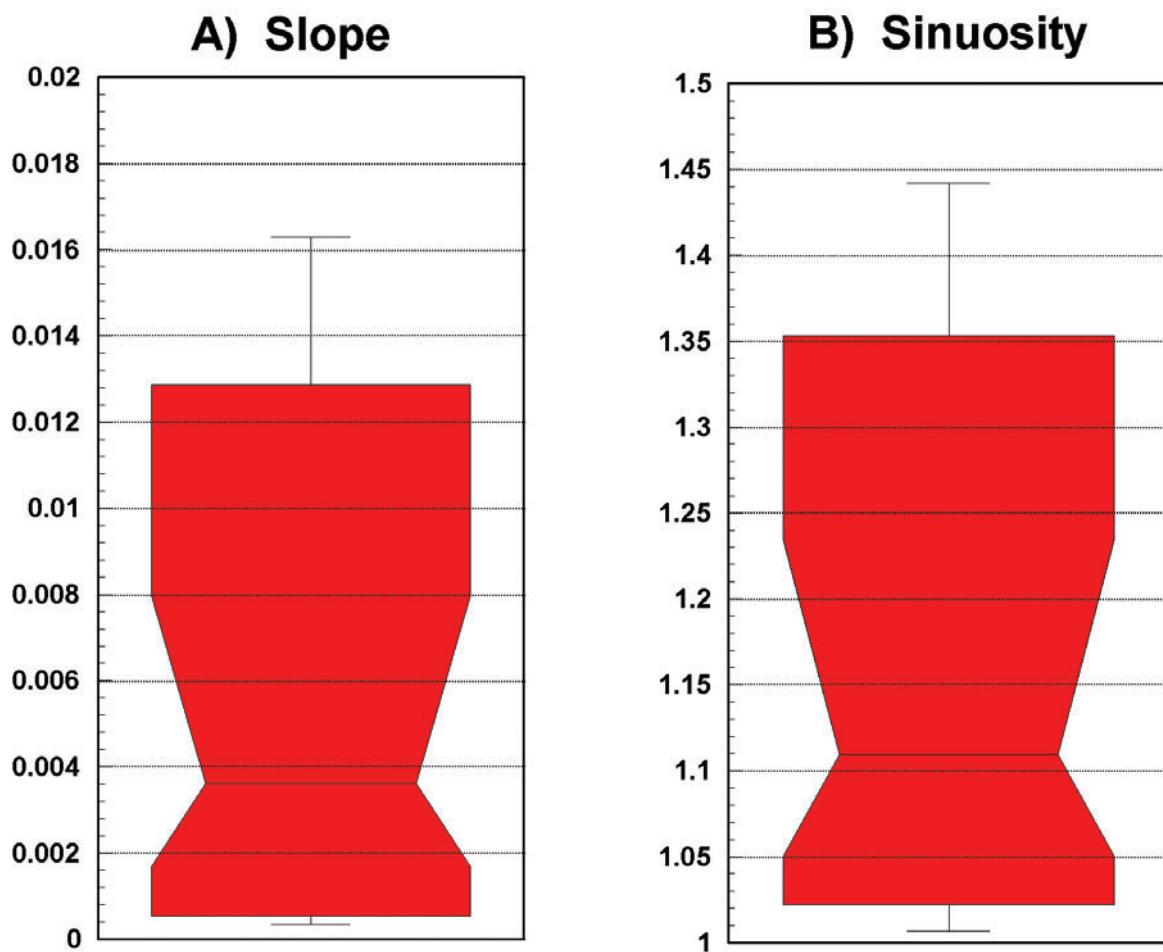
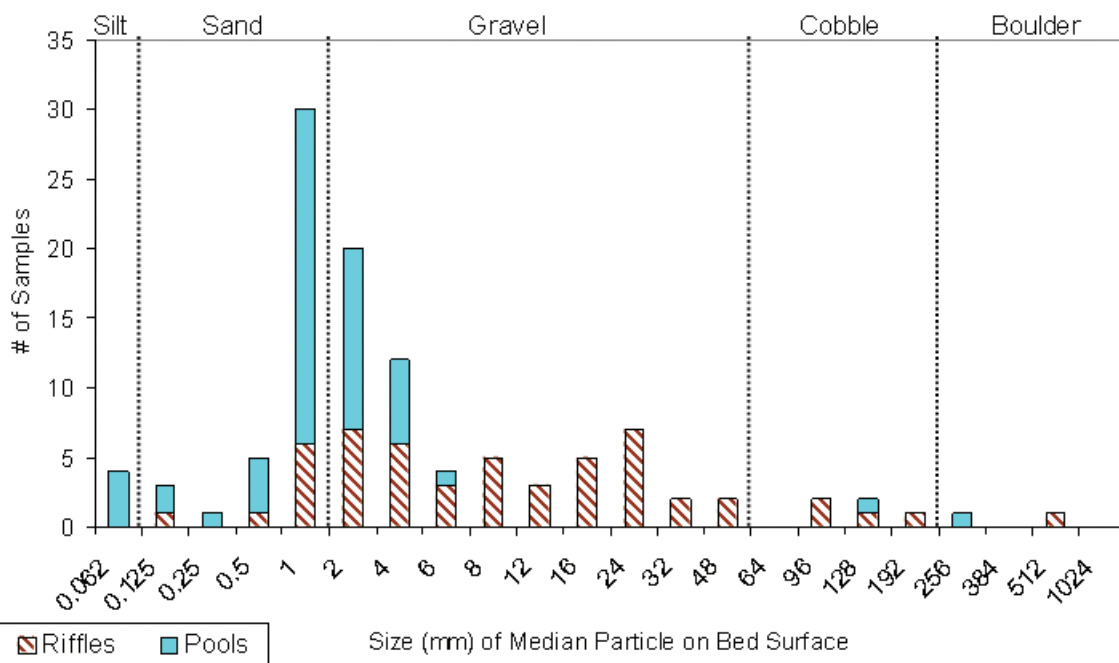


Figure 5.13—Box-and-whisker plots of sinuosity (a) and slope (b) across sampled reaches. Notches indicate the median values and the upper and lower edges of the box indicate the 25th and 75th percentiles (Frigge and others 1989).



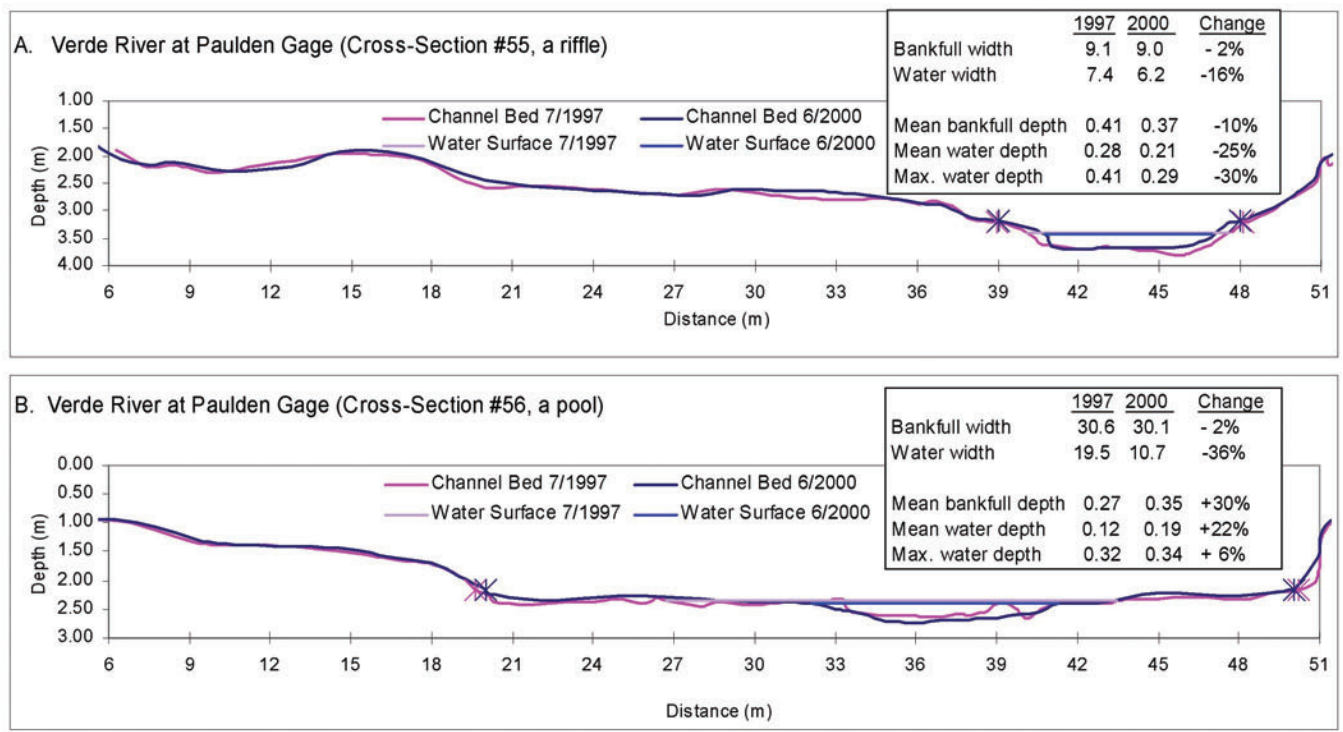


Figure 5.15—Overlay of repeated cross-sections that were measured in July, 1997, and June, 2000, across a riffle (A) and a pool (B) on the UVR near the Paulden gauge. The table within each figure summarize the dimensions of the bankfull and wetted channels.

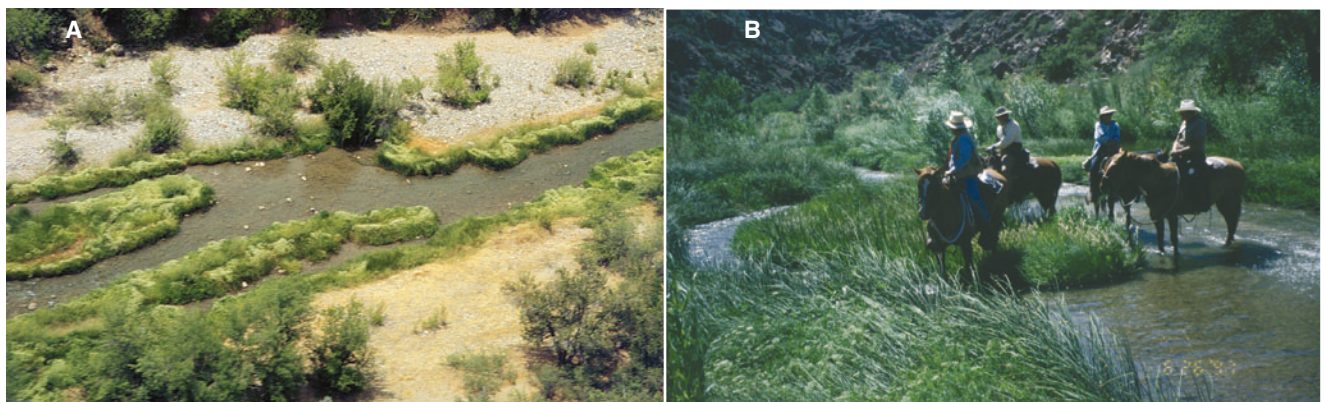


Figure 5.16—UVR channels (A) in a boulder-cominated sediment bar near Hells Canyon confluence and (B) downstream from the Verde Ranch and upstream of a canyon-confined river reach showing a C-type channel with elements of a E-type channel.

Discussion

Confined alluvial valleys with low gradients, like the UVR, are typically dominated by low-gradient entrenched channels (F-types), but less entrenched channels (C-types) often develop where the valley floor widens sufficiently to accommodate a floodplain (Rosgen 1996). Two areas in particular, the Verde Ranch and the Perkinsville Basin, feature broader valley settings where more sinuous channel types (C- and E-types) can develop (fig. 1.10). Narrow, deep, and highly sinuous channels (E-types) are often considered an end-point of channel development resulting from dense growth of herbaceous riparian vegetation (Rosgen 1996). One reach on the private lands of the Verde Ranch attained a very low width-depth ratio in association with dense growth of three-square bulrush (*Schoenoplectus americanus*) (fig. 5.16).

The frequent occurrence of moderately entrenched (Bc-type) and highly entrenched (F-type) channels reflects the control of bedrock and old alluvial deposits geologic controls on floodplain development. Entrenchment can result from recent channel degradation due to land uses or it may be a natural outcome of geologic confinement. The cause and timeframe of entrenchment is important for evaluating channel stability, since a channel in a bedrock-walled canyon will be more stable than a system that has experienced recent degradation. Entrenchment of the UVR appears to be a reflection of natural geologic confinement and long-term degradation rather than a recent response to other factors (Pearthree 1996).

Methodological Concerns in Channel Typing

Channel typing has many practical limitations for management of riverine ecosystems, which include technical challenges (Juracek and Fitzpatrick 2003) as well as the possibility that classification systems can distort views of natural systems (Kondolf 1995). A key element of evaluating river morphology using the Rosgen channel classification is the proper identification of bankfull level and the flood-prone area. Some scientists have questioned the geomorphic significance of both of these features, particularly in arid regions (Miller and Ritter 1996). Others have pointed out that the high potential for errors in identifying bankfull could lead to inappropriate inferences about river morphology (Juracek and Fitzpatrick 2003). Such errors are more likely when survey crews are inexperienced and change from year to year.

A lack of consistency between bankfull indicators from site to site may not simply be a measurement problem, but it may also reflect natural fragmentation in geologically complex areas (Fonstad 2003). Variation in bankfull is also common along confined rivers, because they can have floodplains that vertically accrete and erode episodically at different points along the river (Nanson 1986). Recently stripped floodplains will have greater frequency of bankfull flow, while more mature floodplains will have less frequent bankfull flows.

The re-surveys of two reaches near the Paulden gauge yielded consistent bankfull estimates, suggesting that crews were observing consistent morphological features. However, the UVR features a variety of flat surfaces, including floodplain terraces (Medina and others 1997), side channels, and sediment bars behind woody plants. Such complexity makes it difficult to determine bankfull level using field features. As a result, one would expect to see high variation in bankfull dimensions based on field measurements, as shown in fig. 5.12. Differences in slope and roughness could account for substantial variation in bankfull dimensions, but it also seems likely that the variation reflects inconsistencies in identifying bankfull. Such variation remained even after excluding more than half of the cross-sections that were measured in pools and glides. Because bankfull dimensions should be measured in riffle reaches where the channel reaches its narrowest point (Rosgen 1996), bankfull dimensions measured in pool reaches would tend to be overestimates.

Results from this analysis were compared with other studies of the Verde River to assess the accuracy of the bankfull identifications. The median cross-sectional area from the data examined in this study was 3.5 m² (38 ft²) and the median bankfull width was 9.7 m (32 ft). These results were very close to the median values that were obtained from the cross-section closest to the stream gauge on the UVR near Paulden. At that same location, Moody and Odem (1999) estimated bankfull area to be 15.9 m² (171 ft²), bankfull width to be 28.2 m (93 ft), mean depth to be 0.6 m (2 ft), and bankfull discharge to be 26.8 m³ s⁻¹ (946 ft³ s⁻¹), with a corresponding

return interval of 1.7 years. That result was considerably higher than the 1.3 year return interval for two gauges further downstream on the Verde River, and it was at the high end of the range for all of the streams that were surveyed.

Validating field bankfull measurements with measured flows would help to resolve discrepancies in field determinations. Phillips and Ingersoll (1998) reported historic stream gauge data indicating that the “low-flow” channel at the Paulden gauge had an area of 12.9 m² (139 ft²), with a top width of 20.8 m (68 ft), a mean depth of 0.6 m (2 ft), and a discharge of 8.9 m³ s⁻¹ (313 ft³ s⁻¹). That discharge, which was only one-third of that estimated by Moody and Odem (1999), corresponds to a 1.3-year return interval. An accompanying photograph of the river during that measurement (April 16, 1995) suggested that the flow was consistent with bankfull, i.e., the water was beginning to spread laterally across the floodplain. Rosgen (1996) suggested that bankfull levels are often overestimated, as observers mistake a low terrace for the active floodplain, which could explain the high values reported by Moody and Odem (1999). Such discrepancies in bankfull dimensions could have important implications for interpreting the energy level of the system, and therefore, its behavior. For example, Moody and Odem’s (1999) high estimates of bankfull flow (26.8 m³ s⁻¹) and channel slope (1.6%) would place the river among high-energy streams that are prone to braiding, as characterized by Leopold and Wolman (1957) and Kondolf and others (2001), or to episodic floodplain stripping (Nanson and Croke 1992). The results from Phillips and Ingersoll (1998), by comparison, fall within the range of lower-energy meandering streams. If bankfull is not consistent, then it becomes difficult to interpret the river’s dynamics using channel typing methodologies.

The bankfull dimensions at most of the cross-sections in this dataset (fig. 5.12) are smaller than those reported by Phillips and Ingersoll (1998). However, the authors’ measurements included a much lower value for water-surface slope (0.0008 or 0.08%) than the slope measurements in this dataset. Increasing slope by a factor of 10 would correspond to reducing channel area by half, to approximately 6.5 m² (70 ft²). Such a value would fall within the range of the data reported here (fig. 5.12), but it would still be higher than the median value. Raising estimates of bankfull dimensions would have altered the estimates for UVR entrenchment and width-depth ratios, which, in turn, could have changed the categorization of reaches at the margins between Rosgen channel types (figs. 5.7 and 5.10). Specifically, it would likely have shifted channel classifications toward the more entrenched types, but fig. 5.7 indicates that few reaches lay close to the boundary for F- types. Consequently, in this situation, the overall distribution of channel types likely would not have changed very much.

While channel typing is useful for inventory of large areas, users must recognize that existing classification systems impose arbitrary boundaries across a continuum of natural channel characteristics and processes (Kondolf 1995; Miller and Ritter 1996; Juracek and Fitzpatrick 2003). For the UVR sample, Rosgen’s (1994, 1996) classification denotes categories along a continuum from unentrenched reaches (C- and E-types) to entrenched reaches (F-types); with the Bc-type representing an intermediate zone (fig. 5.7). Although Rosgen (1994) acknowledged that reaches with borderline dimensions may be placed into one type or another, his “management interpretations” emphasize the discrete categories. As a consequence, a naïve interpreter might conclude that the Bc-type reaches of the UVR are qualitatively more stable, have less potential for bank erosion, and have higher recovery potential than either the C- or F-type reaches, which seems inconsistent with the idea that these reaches represent variations along a continuum.

Channel type classifications often do not clearly explain that divisions may be arbitrary and therefore of questionable ecological significance (Kondolf 1995; Miller and Ritter 1996). Moody and others (1998) categorized the Verde River at Paulden as a Bc-type, but Moody and Odem (1999) re-categorized it as an F-type in their report. They stated that the Bc-type was quite common in central and southern Arizona, and that the study sites that represented these channel types appeared “relatively stable, which is consistent with the classification system.” However, the authors classified other channels with similarly low gradient and moderate entrenchment as F-types because the channels “showed signs of instability (i.e., active cut banks).” Managers reviewing such evaluations should be mindful that the first two levels of the Rosgen methodology do not provide an objective basis for evaluating stream stability (Miller and Ritter 1996; Juracek and Fitzpatrick 2003).

Significance of Channel Types

A coarse analysis of channel morphology helps to describe qualities of the UVR that provide structure to its important aquatic habitats. The majority of reaches in the UVR were low-gradient, gravel-bedded, alluvial channels that fit within the parameters of the Rosgen C4-type. The uppermost segment between Sullivan Dam and Granite Creek departs from this general pattern, as boulder-dominated, entrenched channels (Rosgen F2-type) predominate. Basalt formations confine this segment, and the effects of the dam may limit deposition of the fine sediments required for extensive growth of riparian vegetation (Medina and others 1997). Both of these types are associated with low gradients, which is a distinctive feature of the UVR. Low-gradient channels are normally highly sinuous (Rosgen 1994), but sinuosity throughout the UVR is relatively low, owing to the confinement by canyon walls and resistant floodplain terraces (Pearthree 1996). Moody and Odem’s (1999) regional study of channel types also found that alluvial channels of the UVR and central Arizona, in general, were relatively less sinuous than is typical for low-gradient systems.

The UVR is distinctive in the Southwest because it is relatively stable in terms of hydrology (see Chapter 3) and geomorphology (Pearthree 1996; Beyer 1998;). Although secondary channels are common below confluences with tributaries, the upper segment of the Verde River lacks braided conditions (Rosgen D-types), which often indicates instability due to a high sediment supply and/or losses of riparian vegetation (Kondolf 1995; Rosgen 1996; Montgomery and Buffington 1998). Although Rosgen’s Level II classification does not provide a sufficient basis for interpreting stream stability and sediment loading, more detailed analyses of historical geomorphology, bank erosion, and hydraulic measurements can address those issues (Juracek and Fitzpatrick 2003). For the UVR, the conclusions of a historical geomorphology study (Pearthree 1996) and a channel stability study based on shear stress calculations (Beyer 1998) are both consistent with the lack of braided channels in suggesting that the river is able to efficiently process its sediment loads.

Although the UVR appears geomorphically stable, that stability is not necessarily favorable for native fishes because braided channels provide habitat for riffle-dwelling natives (Rinne 2003a, 2003b). Narrow, well-vegetated channels (typified by Rosgen E-types), on the other hand, may favor nonnative predators (Rinne and Neary 1997). Vegetative growth can induce channel narrowing and retention of sediments that can shift C-type channels toward E-type channels (Rosgen 1996). Indeed, Beard (2004) reported that several small stream channels

in central Arizona had narrowed and deepened in response to vegetative growth attributed to exclusion of livestock grazing. However, George and others (2002) found no changes in bankfull channel width in grazing intermittent streams in central California, which they attributed to presence of bedrock controls, coarse soil textures, a lack of undercut banks, and a natural lack of woody species conducive to trapping sediment. Kondolf (1993) suggested that many years of exclusion may be needed to induce significant changes in channel morphology.

A lack of floods, high base flows, and livestock exclusion facilitated dense growth of streamside aquatic vegetation along the UVR (see Chapters 6 and 7), and pebble counts at the site that was re-sampled showed a significant increase in fine sediment. Nevertheless, most reaches in this study did not qualify as E-types. The lack of extremely narrow channels may reflect the fact that major floods in the UVR during recent decades have primarily been winter scouring events, which did not result in the extensive deposition of fine sediments in the floodplain that would facilitate narrowing. As a general principle, channels of low-energy streams with modest sediment loads are expected to change slowly (Kondolf 1995). Consequently, the Verde River was unlikely to exhibit major changes in channel type between scouring floods, even in reaches where the amount of fine substrates and aquatic vegetation increased.

On the other hand, Rinne and Miller (2006) reported that the wetted channel substantially narrowed and deepened at two fish sampling sites along the upper Verde River between 1994 and 2000. Furthermore, streamside aquatic vegetation grew dramatically along the river during this period. Results from the two cross-sections (one riffle and one pool) that were resurveyed at the Paulden gauge support the possibility that the wetted channel narrowed without corresponding changes in the bankfull channel. The cross-sectional area of the wetted channel in the riffle shrank by 38%, substantially more than the approximately 13% decrease in flow between the two sampling periods. The combination of narrowing and filling of the low-flow channel implies that water velocity increased through the riffle cross-section. Water flowing through the pool cross-section, on the other hand, narrowed and deepened. Pebble counts at the two reaches showed significant decreases in fine sediment, which could have been the result of flushing as the water flow became faster and narrower. The results from these two reaches support more widespread observations that the wetted channel narrowed due to vegetative growth along the river. The two reaches also demonstrate the value of examining changes in both pools and riffles separately, since examining changes only in the riffle would have missed the deepening of the pool.

Limitations of Channel Typing

Despite its virtues as a communication tool, channel classification does not provide a deep understanding of fundamental geomorphic processes that regulate riverine development (Doyle and others 1999; Goodwin 2004). The Rosgen channel type classification was designed to describe variation across huge regions, so it is not surprising that its value for explaining variation in aquatic habitat for a particular river has considerable limitations. Moreover, the distinctive qualities of the Verde River may require methods that focus on finer scales. For example, due to its hydro-geomorphic stability, aquatic habitat in the river may experience important successional processes even as bankfull characteristics remain unchanged. In addition, the Rosgen classification focuses on variations in slope that are largely irrelevant to the UVR because it does not emphasize distinctions within the 0 and 2% slope range. Rosgen's (1994, 1996) system sorts unusually low-gradient B- and

C-type streams into Bc- and Cc-subtypes, but the management interpretations emphasize the distinctions between the basic types (the upper-cased letters) rather than distinctions between the gradient subclasses (the lower-cased letters). This limitation is not unique to the Rosgen classification, as an alternative reach classification system developed by Montgomery and Buffington (1998) also does not provide for discrimination within low-gradient, pool-riffle systems. Consequently, classifications applied at the reach scale suggest that variation in geomorphic response would be relatively limited along the UVR.

Analysis at finer scales, however, suggests that the proportions and gradients of particular channel units (riffles and pools) are biologically important. In particular, high-gradient riffles constitute important habitats for riffle-dwelling native fishes. Because they are relatively steep ($>2\%$), these features assume the appearance of Rosgen's (1994, 1996) B-types or Montgomery and Buffington's (1998) plane bed channel types. Indeed, one of the sampled reaches was initially classified as a B-type channel with a slope of 2.3%. However, it was only 24 m (79 ft) long, or two times the estimated bankfull width of that reach. Rosgen (1994) suggested that distinct categories can be applied to reaches that are only tens of meters long, but his field procedures suggest that two bankfull widths is far too short to constitute a full reach. Applying a methodology that does not recognize such features as ecologically significant could lead to misinterpretations. For example, after examining associations between native fishes and channel types in a segment of the UVR, Rinne and Neary (1997) argued that C-type channels appeared more favorable to native fishes than did E-type channels. However, the authors also recognized that a high-gradient riffle located within an E-type channel had disproportionately high numbers of the native desert sucker (*Catostomus clarki*). Reach-scale classifications often fail to explain variations in velocity, gradient, and substrate that are strongly tied to native fish abundance (Converse and others 1998). Although understanding relationships across scales is always critical when evaluating aquatic habitats (Frissell and others 1986), the low gradient of the Verde River may render fine-scale morphologic variation particularly important.

Management Implications

To obtain useful information for sustaining the upper Verde River ecosystem, managers need to consider both technical and conceptual issues concerning data collection. These issues are intertwined, because obtaining useful information at finer scales generally requires more precise techniques and explicit stratifications. Careful applications of the Rosgen level II classification can be informative, but managers should be cautious when interpreting results of channel typing. For example, the 1999 report by Moody and Odem conveyed the impression that the gaging sites that they examined had high energy and highly entrenched channels which they characterized as unstable. However, a lower bankfull estimate, as we and others have found, suggested that the stream has more moderate energy and is dominated by the C channel type that is typical for an alluvial river. Overall, the morphology and channel typing data that we examined reveals that the Verde River has a distinctively low gradient, moderate entrenchment, and low sinuosity.

Channel typing does provide useful guidance for managers, but time-trend monitoring requires more detailed procedures. For example, Rosgen's (1994, 1996) methodology for pebble counts, as well as the zigzag procedure used to obtain the data in this study, loses resolution by mixing geomorphically distinctive units

(Kondolf 1997). Because both of those methods sample the bankfull channel, they may not be as relevant for aquatic assessments as sampling only the wetted channel. Furthermore, designing cross-section measurements to satisfy the requirements of channel typing tends to ignore changes in pool dimensions that may provide valuable information on sediment dynamics and predator habitat. More detailed, repeated sampling, as suggested in the fourth level of Rosgen's methodology, is needed to examine trends in fish habitat at fine scales.

A sound scheme for stream monitoring needs to consider geo-fluvial and biological processes in three-dimensions, through time, and across spatial scales (Poole and others 1997). The morphology data in this study is not well-suited for examining fine-scale changes in habitat units that are most relevant to fish. Pool habitats tend to expand in the aftermath of floods and exclusion from grazing (Gunderson 1968, Magilligan and McDowell 1997, Madej 1999). Monitoring techniques need to be sensitive to changes in those key habitat units. Fisheries monitoring efforts commonly classify and measure pools, riffles, and other channel units using methods that are not particularly repeatable, precise, and reliably quantifiable (Poole and others 1997). To understand how the channel is evolving, repeated measurements of longitudinal profiles would provide useful data (Madej 1999); however, profiles are difficult to monument in systems that are prone to scouring floods. Integrated mapping and classification of morphology and substrate has been recommended for quantifying physical differences and changes in aquatic habitat (Buffington and Montgomery 1999). Such intensive, small-scale procedures are more time-consuming than reach-scale channel classifications, but they would serve to more reliably evaluate morphological influences on fish habitat.

Summary and Conclusions

Measurements of channel morphology and application of channel classification have become a common tool for describing variation in rivers. The Rosgen (1994, 1996) classification system was applied to geomorphic data collected at 138 locations on the UVR between 1997 and 2000. The results showed that this segment of the river is dominated by gravel-bedded alluvial channels (B-, C-, and E-types) across a continuum of entrenchment. While channel typing is not a sufficient basis for evaluating channel stability, the lack of braided channels (D-type) is consistent with more detailed studies that describe the UVR as hydrogeomorphically stable. Channel typing does reveal that the river has a distinctive combination of low slope and low sinuosity. Due to the river's distinctive qualities, changes in riparian vegetation and aquatic habitat will occur at scales that are finer than those used for channel classification. Managers and researchers should adapt their sampling methods to focus on understanding such fine-scale changes in the river.