CHAPTER 2

Valley Segments, Stream Reaches, and Channel Units

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I. INTRODUCTION

Valley segments, stream reaches, and channel geomorphic units are three hierarchically nested subdivisions of the drainage network (Frissel *et al.* 1986), falling in size between landscapes and watersheds and the parameters usually measured at individual points along the stream network (see Chapters 3 and 4). Within this hierarchy of spatial scales (Fig. 2.1), valley segments, stream reaches, and channel geomorphic units represent the largest physical subdivisions that can be directly altered by human activities. As such it is useful to understand how they respond to anthropogenic disturbance, but to do so requires classification systems and quantitative assessment procedures that permit accurate, repeatable description and convey information about biophysical processes responsible for the development of current geomorphic conditions.

The location of different types of valley segments, stream reaches, and channel geomorphic units within a watershed exerts a powerful influence

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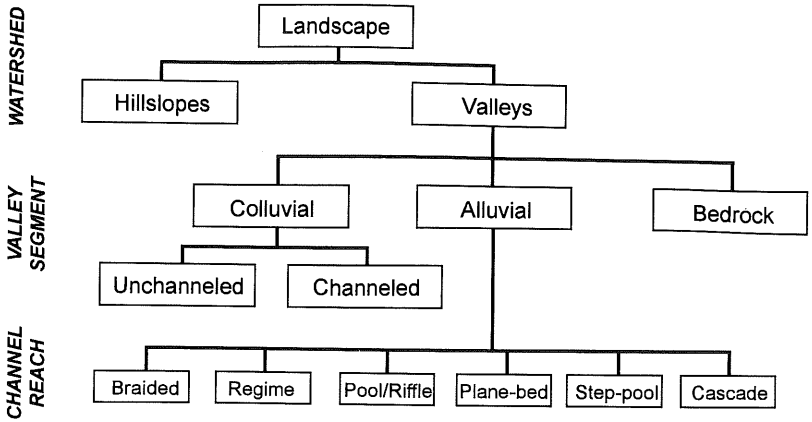

FIGURE 2.1 Hierarchical subdivision of watersheds into valley segments and stream reaches. Redrawn from Montgomery and Buffington (1993).

on the distribution and abundance of aquatic plants and animals by governing the characteristics of water flow and the capacity of streams to store sediment and transform organic material (Hynes 1970, Pennak 1979, Vannote *et al.* 1980, O'Neill *et al.* 1986, Statzner *et al.* 1988). The first biologically based classification systems were proposed for European streams. They were based on zones marked by shifts in dominant aquatic species, such as fishes, from a stream's headwaters to its mouth (Huet 1959, Illies 1961, Hawkes 1975). Recent characterizations of biologically based zones have considered the effects of physical processes and disturbance regimes on changes in faunal assemblages (Zalewski and Naiman 1985, Statzner and Higler 1986). Hydrologists and fluvial geomorphologists, whose objectives for classifying streams often differ from those of stream ecologists, have based classification of stream channels on topographic features of the landscape, substrata characteristics, and changes in patterns of water flow and sediment transport (Leopold *et al.* 1964, Shumm 1977, Richards 1982, Rosgen 1985, Montgomery and Buffington 1993). Other approaches to classifying stream types and channel units have combined hydraulic or geomorphic properties with explicit assessment of the suitability of a channel for certain types of aquatic organisms (Pennak 1971, Bovee and Cochnauer 1977, Binns and Eiserman 1979, Bisson *et al.* 1982, Beschta and Platts 1986, Sullivan *et al.* 1987, Hawkins *et al.* 1993).

There are several reasons why stream ecologists classify and measure valley segments, stream reaches, and channel geomorphic units. The first may simply be to describe physical changes in stream channels over time,

whether in response to human impacts or to natural disturbances (Gordon *et al.* 1992). A second reason for stream classification may be to group sampling sites into like physical units for purposes of comparison. This is often desirable when conducting surveys of streams in different drainages. Classification of reach types and channel geomorphic units enables investigators to extrapolate results to other areas with similar features (Hankin and Reeves 1988, Dolloff *et al.* 1993). A third objective for classification may be to determine the suitability of a stream for some type of deliberate channel alteration. Habitat restoration in streams and rivers with histories of environmental degradation is currently being undertaken in many locations, and some restoration procedures may be inappropriate for certain types of stream channels (National Research Council 1992). Successful rehabilitation requires that approaches be consistent with the natural hydraulic and geomorphic conditions of different reach types (Gordon *et al.* 1992) and do not impede disturbance and recovery cycles (Reice 1994). Finally, accurate description of stream reaches and channel geomorphic units often is an important first step in describing the microhabitat requirements of aquatic organisms during their life histories or in studying the ecological processes that influence their distribution and abundance (Hynes 1970, Schlosser 1987).

Geomorphically based stream reach and channel unit classification schemes are relatively new and still undergoing refinement. Stream ecologists will do well to heed the advice of Balon (1982), who cautioned that nomenclature itself is less important than detailed descriptions of the meanings given to terms. Thus it is important for investigators to be as precise as possible when describing what is meant by the terms of the classification scheme they have chosen. Although a number of stream reach and channel unit classification systems have been put forward, none has yet been universally accepted. In this chapter we will focus on two recently proposed classification schemes that can provide stream ecologists with useful tools for characterizing aquatic habitat at intermediate landscape scales: Montgomery and Buffington (1993) for valley segments and stream reaches, and Hawkins *et al.* (1993) for channel geomorphic units. Both systems are based on hierarchies of topographic and fluvial characteristics, and both employ descriptors that are measurable and ecologically relevant. The Montgomery and Buffington (1993) classification provides a geomorphic, process-oriented method of identifying valley segments and stream reaches, while the Hawkins *et al.* (1993) classification deals with identification and measurement of different types of channel units within a given reach. The chapter begins with a laboratory examination of maps and photographs for preliminary identification of valley segments and stream reaches, and concludes with a field survey of channel geomorphic units in one or more reach types.

A. Valley Segment Classification

Hillslopes and valleys are the principal topographic subdivisions of watersheds. Valleys are areas of the landscape where water converges and where the products of erosion, sediment, and organic debris are concentrated. Valley segments are distinctive sections of the valley network that possess geomorphic properties and hydrological transport characteristics that distinguish them from adjacent segments. Montgomery and Buffington (1993) identified three terrestrial valley segment types: *colluvial, alluvial,* and *bedrock* (Fig. 2.1), although they acknowledged that a fourth type, estuarine valleys, were important transition zones between terrestrial and marine environments. Colluvial valleys were subdivided into those with and without recognizable stream channels.

Valley segment classification describes valley form based on dominant types of sediment input and transport processes. The term sediment here includes both large and small inorganic particles eroded from hillslopes. Valleys can be filled primarily with *colluvium* (sediment and organic matter delivered to the valley floor by mass wasting (landslides) from adjacent hillslopes), which is usually immobile except during rare hydrologic events, or *alluvium* (sediment transported along the valley floor by streamflow) which may be frequently moved by the stream system. A third condition includes valleys that have little soil but instead are dominated by bedrock. Valley segments distinguish portions of the valley system in which sediment inputs and outputs are transport- or supply-limited (Fig. 2.2). In transport-limited valley segments, the amount of sediment in the valley floor and its movements are controlled primarily by the frequency of high streamflows and debris flows capable of mobilizing material in the streambed. In supply-limited valley segments, sediment movements are controlled primarily by the amount of sediment delivered to the segment by inflowing water. Valley segment classification does not allow forecasting of how

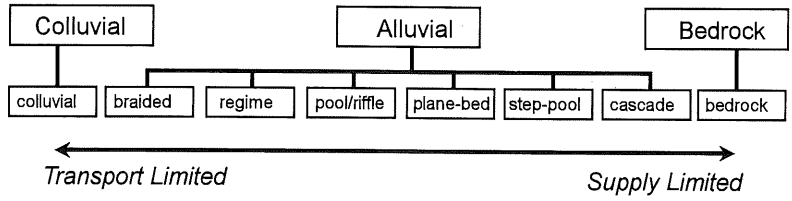

FIGURE 2.2 Arrangement of valley segment and stream reach types according to whether their substrates are limited by the supply of sediment from adjacent hillslopes or by the fluvial transport of sediment from upstream sources. Redrawn from Montgomery and Buffington (1993).

the characteristics of the valley will change in response to altered discharge or sediment supply. Reach classification, according to Montgomery and Buffington (1993), is more useful for characterizing responses to such changes.

Colluvial Valleys Colluvial valleys serve as temporary repositories for sediment and organic matter eroded from surrounding hillslopes. In colluvial valleys, fluvial (waterborne) transport is relatively ineffective at removing materials deposited on the valley floor. These materials gradually accumulate in steep headwater valleys until they are periodically flushed by debris flows (rapidly moving slurries of water, sediment, and organic debris) or in low-gradient landscapes by periodic expansion of the alluvial channel network during episodes of very high discharge. After removal of sediment by large hydrologic disturbances, refilling processes in colluvial valleys begin again (Dietrich *et al.* 1986).

Unchanneled colluvial valleys are headwater valley segments lacking recognizable stream channels. They possess soils derived by erosional processes from adjacent hillslopes, a property which distinguishes them from steep headwater valleys of exposed bedrock (Montgomery and Buffington 1993). The depth of colluvial deposits in unchanneled colluvial valleys is related to the rate at which material is eroded from hillslopes and the time since the last major disturbances that emptied them. The cyclic process of emptying and refilling occurs at different rates in different geoclimatic regions and depends on patterns of precipitation, geological conditions, and the nature of hillslope vegetation (Dietrich *et al.* 1986). Although unchanneled colluvial valleys do not possess defined streams, they are areas where water is concentrated and have sometimes been called "zero-order" stream basins (Montgomery and Dietrich 1988). Seasonally flowing seeps and small springs serving as temporary habitat for some aquatic organisms that may be present in these areas.

Channeled colluvial valleys contain low-order streams immediately downslope from unchanneled colluvial valleys. Channeled colluvial valleys may form the uppermost segments of the valley network in landscapes of low relief or they may occur where small tributaries cross floodplains of larger streams. Flow in colluvial channels tends to be shallow and ephemeral or intermittent. Because shear stresses (see Chapter 4) generated by streamflows are incapable of substantially moving and sorting deposited colluvium, channels in these valley segments tend to be characterized by a wide variety of substrata and organic matter particle sizes. Episodic scour of channeled colluvial valleys by debris flows often governs the degree of channel incision in steep terrain, and like unchanneled colluvial valleys there are cyclic patterns of sediment emptying that periodically reset the depth of collu-

vium. The frequency of sediment-mobilizing discharge or debris flows determines the amount of sediment stored in colluvial valleys.

Alluvial Valleys Alluvial valleys are supplied with sediment from upstream sources, and the streams within them are capable of moving and sorting the sediments at erratic intervals. The sediment transport capacity of an alluvial valley is insufficient to scour the valley floor to bedrock, resulting in an accumulation of valley fill primarily of fluvial origin. Alluvial valleys are the most common type of valley segment in many landscapes and usually contian streams of greatest interest to aquatic ecologists. They may be *confined,* a condition in which the hillslopes narrowly constrain the valley floor with little or no floodplain development, or *unconfined,* with a developed floodplain. A variety of stream reach types (Fig. 2.1) may be associated with alluvial valleys, depending on the degree of confinement, gradient, local geology and erosional processes, and discharge regime.

Bedrock Valleys Bedrock valleys have little valley fill material and usually possess confined channels lacking an alluvial bed. Montgomery and Buffington (1993) distinguish two types of bedrock valleys: those sufficiently steep to remain permanently bedrock floored and those associated with low order streams recently excavated to bedrock by debris flows. Bedrock channels in shallow gradient valley segments indicate that streams have enough power to maintain a high sediment transport capacity.

B. Channel Reach Classification

Channel reaches consist of relatively homogeneous associations of topographic features and channel geomorphic units, which distinguish them in certain aspects from adjoining reaches (Table 2.1). Transition zones between adjacent reaches may be gradual or sudden, and exact upstream and downstream reach boundaries may be a matter of some judgment. Colluvial and bedrock valley segments possess only colluvial and bedrock reach types (Table 2.1; Fig. 2.2), respectively, but alluvial valleys can exhibit a variety of reach types. Montgomery and Buffington (1993) hypothesized that reach differentiation in alluvial valleys was related to the supply and characteristics of sediment and to the power of the stream to mobilize its bed. Six alluvial reach types were recognized.

Cascade Reaches This reach type is characteristic of the steepest alluvial channels. A few small pools may be present in cascade reaches, but the majority of flowing water tumbles over and around boulders and large woody debris. Waterfalls ("hydraulic jumps") of various sizes are abundant in cascade reaches. The large size of particles relative to water depth effec-

TABLE 2.1
Characteristics of Different Types of Stream Reaches (modified from Montgomery and Buffington 1993)

	Colluvial	Bedrock	Cascade	Step-pool	Plane-bed	Pool-riffle	Regime	Braided
Predominant bed material	Variable	Bedrock	Boulder	Cobble/boulder	Gravel/cobble	Gravel	Sand	Variable
Bedform pattern	Variable	Variable	None	Vertically oscillatory	None	Laterally oscillatory	Multilayered	Laterally oscillatory
Dominant roughness elements	Boulders, large woody debris	Streambed, banks	Boulders, banks	Bedforms (steps, pools) boulders, large woody debris, banks	Boulders and cobbles, banks	Bedforms (bars, pools) boulders and cobbles, large woody debris, sinuosity, banks	Sinuosity, bedforms (dunes, ripples, bars), banks	Bedforms (bars, pools)
Dominant sediment sources	Hillslope, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Fluvial, hillslope, debris flows	Fluvial, bank erosion, debris flows	Fluvial, bank erosion, inactive channels, debris flows	Fluvial, bank erosion, inactive channels	Fluvial, bank erosion, debris flows
Typical slope (%)	>20	Variable	8–30	4–8	1–4	0.1–2	<0.1	<3
Typical confinement	Strongly confined	Strongly confined	Strongly confined	Moderately confined	Variable	Unconfined	Unconfined	Unconfined
Pool spacing (channel widths)	Variable	Variable	<1	1–4	None	5–7	5–7	Variable

tively prevents substrata mobilization during typical flows. Although cascade reaches may experience debris flows, sediment movement is predominantly fluvial. The cascading nature of water movement in this reach type is usually sufficient to remove all but the largest particles of sediment (cobbles and boulders) and organic matter. What little fine sediment and organic matter occurs in cascade reaches remains trapped behind boulders and logs, or is stored in a few pockets where reduced velocity and turbulence permit deposition. The rapid flushing of fine sediment from cascade reaches during moderate to high flows suggests that transport from this reach type is limited by the supply of sediment recruited from upstream sources (Fig. 2.2).

Step-Pool Reaches Step-pool reaches possess discrete channel-spanning accumulations of boulders and logs that form a series of steps alternating with pools containing finer substrata. The diameter of the structures anchoring each step usually equals or exceeds bankfull flow depths (Montgomery and Buffington 1993). Step-pool reaches tend to be straight and have high gradients, coarse substrata, and small width to depth ratios. Pools and alternating bands of channel-spanning flow obstructions typically occur at a spacing of every one to four channel widths in step-pool reaches, although step spacing increases with decreasing channel slope (Grant *et al.* 1990). A low supply of sediment, steep gradient, infrequent flows capable of mobilizing coarse streambed material, and a heterogeneous substrata composition appear to promote the development of this reach type.

The capacity of step-pool reaches to temporarily store fine sediment and organic matter generally exceeds the sediment storage capacity of cascade reaches. Flow thresholds necessary to transport sediment and mobilize channel substrata are complex in step-pool reaches (Montgomery and Buffington 1993). Large bed-forming structures (boulders and large woody debris) are relatively stable and move only during extreme flows. In very high streamflows the channel may lose its stepped profile, but step-pool morphology becomes reestablished during the falling limb of the hydrograph (see Chapter 3, Whittaker 1987). During more frequent bankfull flow periods, fine sediment and organic matter in pools is transported over the large, stable bed-forming steps.

Plane-Bed Reaches Plane-bed stream reaches lack a stepped longitudinal profile and instead are characterized by long, relatively straight channels of uniform depth. They are usually intermediate in gradient and bed roughness (the degree to which substrata particles protrude from the streambed and impede water movement) between steep, boulder-dominated cascade and step-pool reaches and the more shallow gradient pool-riffle reaches. At low to moderate flows, plane-bed stream reaches may

possess large boulders extending above the water surface, forming mid-channel eddies. However, the absence of channel-spanning structures or significant constrictions by streambanks inhibits the development of pools. Particles in the surface layer of plane-bed reaches are larger than those in subsurface layers and form an armor layer over underlying finer materials (Montgomery and Buffington 1993). This armor layer prevents transport of fine sediments except during periods when flow is sufficient to mobilize armoring particles.

Pool-Riffle Reaches This reach type is most commonly associated with small to mid-sized streams and is a very prevalent type of reach in alluvial valleys of low to moderate gradient. Pool-riffle reaches tend to possess lower gradients than the three previous reach types and are characterized by an undulating streambed that forms riffles and pools associated with gravel bars. Also, unlike most cascade, step-pool, and plane-bed reaches, the channel shape of pool-riffle reaches is often sinuous and contains a predictable sequence of pools, riffles, and bars in the channel. Pools are topographic depressions in the stream bottom and bars form the high points of the channel. Riffles are located at cross-over areas from pools to bars. At low streamflow, riffles often travel from one side of the exposed channel to the other, although streams with sufficiently large width-to-depth ratios may have braided rather than single channels (Leopold *et al.* 1964). Pool-riffle reaches form naturally in alluvial channels of fine to moderate substrata coarseness (Leopold *et al.* 1964, Yang 1971) with single pool–riffle–bar sequences occurring every five to seven channel widths (Keller and Melhorn 1978). Large woody debris (LWD) anchors the location of pools and creates upstream sediment terraces that form riffles and bars (Lisle 1986, Bisson *et al.* 1987). Streams rich in LWD tend to have erratic and complex channel morphologies (Bryant 1980).

Channel substrata in pool-riffle reaches is mobilized annually during freshets. At bankfull flows, pools and riffles are inundated to such an extent that the channel appears to have a uniform gradient, but local pool–riffle–bar features emerge as flows recede. Movement of bed materials at bankfull flow is sporadic and discontinuous (Montgomery and Buffington 1993). As portions of the surface armor layer are mobilized, finer sediment underneath is flushed, creating pulses of scour and deposition. This process contributes to the patchy nature of pool-riffle reaches, whose streambeds are among the most spatially heterogeneous of all reach types.

Regime Reaches Regime stream reaches consist of low gradient, meandering channels with predominantly sand substrata, although regime characteristics can occur in streams with gravel or boulder–cobble stream-

beds. Regime reaches occur in higher order channels within unconstrained valley segments and exhibit less turbulence than reach types with high gradients. Shallow and deep water areas are present and point bars may be present at meander bends. As current velocity increases over the fine-grained substrata of regime reaches, the streambed is molded into a predictable succession of bedforms, from small ripples to a series of large dune-like elevations and depressions (Gordon *et al.* 1992). Sediment movement occurs at all flows and is strongly correlated with discharge. The low gradient, continuous transport of sediment, and presence of ripples and dunes distinguish regime reaches from pool-riffle reaches (Montgomery and Buffington 1993).

Braided Reaches Braided reaches usually occur in high-order streams and are characterized by numerous gravel and sand bars scattered throughout the channel (Gordon *et al.* 1992). Aside from the wide span of the active channel relative to adjacent unbraided sections of the channel network, braided reaches share many properties of regime reaches: predominantly sand and gravel substrata, easily erodible streambanks, and continuous sediment transport. In braided reaches the locations of bars change frequently and the channel containing the main flow can often move laterally.

C. Channel Geomorphic Unit Classification

Channel geomorphic units, also called channel units or habitat types, are relatively homogeneous areas of the channel that differ in depth, velocity, and substrata characteristics from adjoining areas. The most generally used channel unit terms for small to mid-sized streams are riffles and pools. Individual channel units are created by interactions between flow and roughness elements of the streambed. Definitions of channel units usually apply to conditions at low discharge. At high discharge, channel units are often indistinguishable from one another and their hydraulic properties differ greatly from those at low flows.

Different types of channel units in close proximity to one another provide organisms with a choice of habitat, particularly in small streams possessing considerable physical heterogeneity (Hawkins *et al.* 1993). Channel unit classification is therefore quite useful for developing an understanding of the distribution and abundance of aquatic plants and animals in patchy stream environments. Channel units are known to influence nutrient exchanges (Aumen *et al.* 1990), algal abundance (Tett *et al.* 1978), production of benthic invertebrates (Huryn and Wallace 1987), invertebrate diversity (Hawkins 1984), and the distribution of fishes (Bisson *et al.* 1988, Schlosser 1991). The frequency and location of different types of channel

units within a reach can be affected by a variety of disturbances, including anthropogenic disturbances that remove structural roughness elements such as large woody debris (Lisle 1986, Sullivan *et al.* 1987) or impede the ability of a stream to interact naturally with its adjacent riparian zone (Beschta and Platts 1986, Pinay *et al.* 1990). Channel unit classification is therefore useful for understanding the relationships between anthropogenically induced habitat alterations and aquatic organisms.

Hawkins *et al.* (1993) modified an earlier channel unit classification system (Bisson *et al.* 1982) that had proven to have certain deficiencies, including the application of similar terms to dissimilar types of stream habitat. Hawkins *et al.* (1993) proposed a three-tiered system of classification (Fig. 2.3) in which investigators could select the level of habitat resolution appropriate to the question being addressed. The first level distinguished fast water (*riffle*) from slow water (*pool*) units. The second level distinguished turbulent from nonturbulent fast water units and slow water units formed by scour from slow water units formed by dams. The third level of classification further subdivided each type of fast and slow water unit based on unique hydraulic characteristics and the principal kind of habitat-forming structure or process.

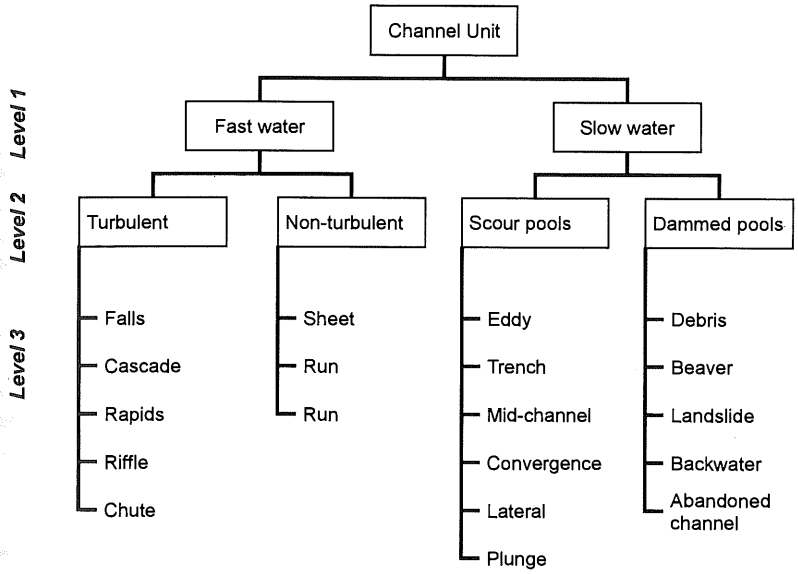

FIGURE 2.3 Hierarchical subdivision of channel units in streams. Redrawn from Hawkins *et al.* (1993).

Turbulent Fast Water Units The term "fast water" is a relative term that describes current velocities observed at low to moderate flows and is meant only to distinguish this class of channel unit from other units in the same stream with "slow water." Most of the time, but not always, slow water units will be deeper than fast water units at a given discharge. The generic terms riffle and pool are frequently applied to fast and slow water channel units, respectively, although these terms convey limited information about geomorphic or hydraulic characteristics of a stream. Current velocity and depth are the main criteria for separating riffles from pools in low to mid-order stream channels. There are, however, no absolute values of either velocity or depth that can be used to identify riffles and pools, and in some cases the depth and velocity of certain riffles and pools may be the opposite of what is expected.

Hawkins *et al.* (1993) recognized five types of turbulent fast water channel units (Table 2.2). Channel units are classified as turbulent if they possess supercritical flow, i.e., hydraulic jumps sufficient to entrain air bubbles and create localized patches of white water (see Chapter 4). Some turbulence is present in nonturbulent channel units but it is not sufficiently strong to entrain air bubbles, and the appearance of the flow is much more uniform. Turbulent fast water channel units are listed in Table 2.2 in approximate descending order of gradient, bed roughness, current velocity, and abundance of hydraulic steps.

TABLE 2.2
Types of Turbulent and Nonturbulent Fast Water Channel Geomorphic Units and the Relative Rankings of Variables Used to Distinguish Them

	Gradient	Supercritical flow	Bed roughness	Mean velocity	Step development
Turbulent					
Falls	1	n/a	n/a	1	1
Cascade	2	1	1	2	2
Chute	3	2	4	3	5
Rapids	4	3	2	4	3
Riffle	5	4	3	5	4
Nonturbulent					
Sheet	Variable	6	6	6	5
Run	6	5	5	7	5

Note. Rankings are in descending order of magnitude where a rank of 1 denotes the highest value of a particular parameter. Step development is ranked by the abundance and size of hydraulic jumps within a channel unit. From Hawkins *et al.* (1993).

Falls are essentially vertical drops of water over a full spanning flow obstruction and are commonly found in bedrock, cascade, and step-pool stream reaches. *Cascade* channel units consist of a highly turbulent series of short falls and small scour basins, frequently characterized by very large substrata sizes and a stepped longitudinal profile; they are prominent features of bedrock and cascade reach types. *Chute* channel units are typically narrow, steep slots in bedrock. They are common in bedrock reaches and also occur in cascade and step-pool reaches. *Rapids* are moderately steep channel units with coarse substrata, but unlike cascades possess a somewhat planar (vs stepped) longitudinal profile. Rapids are the dominant fast water channel unit of plane-bed stream reaches. *Riffles* are the most common type of turbulent fast water in low gradient (<3%) alluvial channels and are found in plane-bed, pool-riffle, regime, and braided reaches. The substrata of riffles tends to be somewhat finer than that of the other turbulent fast water units and the relative abundance of white water is also reduced.

Nonturbulent Fast Water Units Two types of units were termed nonturbulent by Hawkins *et al.* (1993). *Sheet* channel units are rare in many watersheds but may be common in valley segments dominated by bedrock. Sheets occur where shallow water flows uniformly over smooth bedrock of variable gradient; they may be found in bedrock, cascade, or step-pool reaches. *Run* channel units are fast water units of shallow gradient, typically with substrata ranging in size from sand to cobbles. They are characteristically deeper than riffles and because of their smaller substrata have little if any supercritical flow, giving them a nonturbulent apperance. Runs are common in pool-riffle, regime, and braided stream reaches, i.e., mid- and higher order channels. Their average velocity tends to be lowest of the fast water units (Table 2.2).

Scour Pools There are two general classes of slow water (pool) channel units: pools created by scour that forms a depression in the streambed and pools created by the impoundment of water upstream from an obstruction to flow (Table 2.3). Scour pools can be created when discharge is sufficient to mobilize the substrata at a particular site, while dammed pools can be formed under any flow condition. Hawkins *et al.* (1993) recognized six types of scour pools.

Eddy pools are caused by the scouring action of eddies behind large flow obstructions along the edge of the stream. Eddy pools are located on the downstream side of the structure that caused the eddy and are usually proportional to the size of the obstruction. Eddy pools are often associated with large woody debris along streambanks and can be found in virtually all alluvial reach types.

TABLE 2.3
Characteristics of Slow Water Channel Geomorphic Units

	Location	Longitudinal profile	Cross-sectional profile	Substrate features	Forming constraint
Scour pools					
Eddy	Bank	Middle	Middle	Surface fines, not resistant to scour	Flow obstruction causing lateral deflection
Trench	Thalweg	Uniform	Uniform	Bedrock or sorted, resistant to scour	Bilateral resistance
Mid-channel	Thalweg	Middle	Middle	Sorted, variable resistance to scour	Constriction at upstream end
Convergence	Thalweg	Middle	Middle	Sorted, variable resistance to scour	Convergence of two streams
Lateral	Thalweg	Head or middle	Side	Sorted, variable resistance to scour	Flow obstruction causing lateral deflection
Plunge	Thalweg	Head	Upstream or middle	Sorted, variable resistance to scour	Full-spanning obstruction causing waterfall
Dammed pools					
Debris dam	Thalweg	Tail	Highly variable	Usually sorted, not resistant to scour	Large woody debris dam of fluvial origin
Beaver dam	Thalweg	Tail	Highly variable	Surface fines, not resistant to scour	Beaver dam
Landslide dam	Thalweg	Tail	Highly variable	Often unsorted, variable resistance to scour	Organic and inorganic matter delivered by mass wasting from adjacent hillslope
Backwater	Bank	Tail	Highly variable	Unsorted with surface fines, not resistant to scour	Obstruction at tail impounding water along margin of main channel
Abandoned channel	Floodplain	Highly variable	Highly variable	Unsorted with surface fines, not resistant to scour	Lateral meander bars that isolate an overflow channel from the main channel

Note. Location denotes whether the unit is likely to be associated with the thalweg of the channel (the main part of the flow) or adjacent to a bank. Longitudinal and cross sectional profiles refer to the deepest point in the unit relative to the head, middle, or tail region of the unit. Substrate characteristics refer to the extent of particle sorting (i.e., particle uniformity) and resistance to scour. The channel unit forming constraint describes the feature most likely to cause pooling. Modified from Hawkins *et al.* (1993).

Trench pools, like chutes, are usually located in tightly constrained, bedrock-dominated reaches. They are characteristically U-shaped in cross-sectional profile and possess highly resistant, nearly vertical banks. Trench pools can be among the deepest of the slow water channel units created by scour and their depth tends to be rather uniform throughout much of their length, unlike other scour pool types. Although often deep, trench pools may possess relatively high current velocities.

Mid-channel pools are formed by flow constrictions that focus scour along the main axis of flow in the middle of the stream. Unlike trench pools, mid-channel pools are deepest near the head. This type of slow water channel unit is very common in cascade, step-pool, and pool-riffle reaches. Flow constriction may be caused by laterally confined, hardened banks (bridge abutments are good examples), or by large flow obstructions such as boulders or woody debris, but an essential feature of mid-channel pools is that the direction of water movement around an obstruction is not diverted toward an opposite bank.

Convergence pools result from the confluence of two streams of somewhat similar size. In many respects convergence pools resemble mid-channel pools except that there are two main water entry points, which may result in a pattern of substrata particle sorting in which fines are deposited near the head of the pool in the space between the two inflowing channels. Convergence pools can occur in any type of alluvial stream reach.

Lateral scour pools occur where the channel encounters a resistant streambank or other flow obstruction near the edge of the stream. Typical obstructions include bedrock outcrops, boulders, large woody debris, or gravel bars. Many lateral scour pools form next to or under large, relatively immovable structures such as accumulations of large woody debris or along a streambank that has been armored with rip-rap or other material that resists lateral channel migration. Water is deepest adjacent to the streambank containing the flow obstruction and shallowest next to the opposite bank. Lateral scour pools are very common in step-pool, pool-riffle, regime, and braided reaches. In pool-riffle and regime reaches, lateral scour pools form naturally at meander bends in gravel-bedded streams even without large roughness elements (Leopold *et al.* 1964, Yang 1971).

Plunge pools result from the vertical fall of water over a full spanning obstruction onto the streambed. The full spanning obstruction creating the plunge pool is located at the head of the pool and the waterfall can range in height from less than a meter to hundreds of meters, as long as the force of the fall is sufficient to scour the bed. A second, far less common type of plunge pool occurs in higher order channels where the stream passes over a sharp geological discontinuity such as the edge of a plateau, forming a large falls with a deep pool at the base. Depending on the height of the

waterfall and the composition of the substrata, plunge pools can be quite deep. Overall, plunge pools are most abundant in small, steep headwater streams, especially those with bedrock, cascade, and step-pool reaches.

Dammed Pools Dammed pools are created by the impoundment of water upstream from a flow obstruction, rather than by scour downstream from the obstruction. They are distinguished by the type of material causing the water impoundment and by their location in relation to the thalweg (Table 2.3). The rate at which sediment fills dammed pools depends on sediment generation from source areas and fluvial transport from upstream reaches. Due to their characteristically low current velocities, dammed pools often have more surface fines than scour pools and fill with sediment at a much more rapid rate. However, some types of dammed pools tend to possess more structure and cover for aquatic organisms than scour pools because of the complex arrangement of material forming the dam. Additionally, dammed pools can be very large, varying with the height of the dam and the extent to which it blocks the flow. Highly porous dams result in little impoundment. Well-sealed dams usually fill to the crest of the dam, creating a spill.

Hawkins *et al.* (1993) identified five types of dammed pools, three of which occur in the main channel of streams. *Debris* dam pools are typically formed at the terminus of a debris flow or where large pieces of woody debris floated downstream at high discharge lodge against a channel constriction. The characteristic structure of debris dams consists of one or a few large key pieces that hold the dam in place and that trap smaller pieces of debris and sediment that comprise the matrix.

Beaver dam pools are unlike debris dam pools in that they usually lack large key pieces but instead consist of a tightly woven smaller pieces sealed on the upstream surface with fine sediment. Some beaver dams may exceed 2 m in height, but most dams in stream systems are about $\leq$1 m high. In watersheds with high seasonal runoff, beaver dams may breach and be rebuilt annually. In such instances, fine sediments stored above the dam are flushed when the dam breaks.

Landslide dam pools form when a landslide from an adjacent hillslope blocks a stream, causing an impoundment. Dam material consists of a mixture of coarse and fine sediment and woody debris. When landslides take place during severe storms with high discharge, some or most of the fine sediment in the landslide deposit may be rapidly transported downstream leaving behind structures too large to be moved by the flow. Main channel landslide pools are located primarily in laterally constrained reaches of relatively small streams. They are most abundant in step-pool reaches, although some are found in pool-riffle reaches of larger order streams.

Dammed pools are nearly always less abundant than scour pools in alluvial channels, due to the rapidity with which they fill with sediment and the temporary nature of most dams.

Two types of dammed pools located away from the main channel are found only during low flows. *Backwater* pools occur along the bank of the main stream at an entrance to a blocked floodplain channel. They can be found in areas where a gravel bar or other topographic feature prevents water from the main channel from entering the secondary channel. Backwater pools often appear as a diverticulum from the main stream and possess water flowing slowly in a circular pattern. Pool-riffle, regime, and braided reaches are most likely to possess this type of channel unit.

Abandoned channel pools have no surface water connections to the main channel and are formed by bars deposited along the margin of the main stream that isolate secondary channels at low flow. Abandoned channel pools are floodplain features of pool-riffle, regime, and braided reaches that may be ephemeral or maintained by subsurface flow (see Chapter 6).

II. GENERAL DESIGN

A. Site Selection

It is generally impossible to locate examples of every type of valley segment, stream reach, and channel geomorphic unit in one watershed due to regional differences in geology and hydrologic regimes. Selection of study sites will emphasize a comparison of commonly occurring local reach types. In the laboratory, maps and photographs will be used to determine approximate reach boundaries based on stream gradients, degree of valley confinement, channel meander patterns, or significant changes in predominant rock type. The main goal of the laboratory portion of this chapter is to practice map skills and to locate two or more distinctive stream reach types.

B. General Procedures

While it is possible to infer valley segment and reach types from maps and photographs, preliminary classification should be verified by a visit to the sites. Identification of channel geomorphic units from aerial photographs, especially for small streams enclosed within a forest canopy, is virtually impossible and always requires a field survey. In the laboratory, the stream of interest can be divided into sections based on average gradient and apparent degree of valley confinement. Topographic changes in slope can provide important clues with regard to where reach boundaries might exist, but the scale of many topographic maps (including USGS 7.5-min

series maps) may be too coarse to reveal key changes in stream gradient and valley confinement that mark reach transitions in very small streams. Maps may also not provide particularly accurate information on the sinuosity of the stream or the extent of channel braiding, except perhaps for maps of large rivers. However, topographic maps are essential for plotting changes in the elevational profile of a stream, as well as changes in valley confinement.

Aerial photographs are usually available from natural resource management agencies and should be used to supplement information extracted from maps. Aerial photographs can be used to accurately locate changes in channel shape in streams not obscured by forest canopies. Orthographic photographs provide a three-dimensional, if somewhat exaggerated, perspective of landscape relief but require stereoscopic map reading equipment that optically superimposes offset photos. This equipment can range from pocket stereoscopes costing $20 to mirror reflecting stereoscopes costing $2000. Low-altitude aerial photographs (1 : 12,000 scale or larger) are most useful and should be examined whenever available. Geological and soils maps of the area will help identify boundaries between geological formations, another important clue to the location of different reach types. Vegetative maps or climatological maps (e.g., rainfall or runoff), if available, provide additional information about the setting of the stream. Landsat imagery can be helpful at large landscape scales but does not usually provide the resolution needed for designation of reach boundaries in small streams.

Once the stream has been subdivided into provisional reach boundaries in the laboratory, contrasting sites are visited and all or part of the reach(es) of interest is surveyed on foot using the criteria in Tables 2.2 and 2.3 to identify channel units. This is often a time-consuming process, depending on the accessibility of the reach, its length and riparian characteristics, and the time required to conduct an inventory of channel units within the reach. Surveys of channel units in small to mid-sized streams typically involve teams of two to three people covering 1–5 km day^{-1}, and it may not be feasible for purposes of this exercise to survey an entire reach if it is a long one. Rather, representative sections of a reach can be studied, provided that the sections include examples of each type of channel unit present in the reach as a whole (Dolloff *et al.* 1993). A useful rule of thumb is that reach subsamples should be at least 30–50 channel widths long, for example, a survey of channel units in a reach with an average exposed channel width of 10 m should be at least 300–500 m long. During the survey the team should verify that the preliminary classification of valley segment and reach type in the laboratory was correct. Any significant changes in reach character should be noted, particularly if the stream changes from one reach type to another. The valley segment type most often surveyed by stream

ecologists will be alluvial (bedrock and channeled colluvial reaches are easily recognized). Diagnostic reach characteristics are given in Table 2.1.

Surveys of channel unit composition can be used simply to determine the presence and number of each type of unit in the reach. More often, however, investigators wish to establish the percentage of total wetted area or volume in each channel unit type on the date the stream was surveyed. Simple counts of the number and type of channel unit can be completed almost as fast as it takes to walk the reach but estimates of surface area or volume can require considerable time, depending on the complexity of the channel and size of the units. Highly accurate estimates of area and volume involve many length, width, and depth measurements of each unit. Visual estimation of the surface area of individual channel units has proven to be a reasonably accurate and much less time-consuming technique (Hankin and Reeves 1988, Dolloff *et al.* 1993). However, visual estimates must be periodically calibrated by comparing them with careful measurements of the same channel units. Part of this exercise will involve performing such a comparison.

In conducting channel unit surveys the question inevitably arises "What is the relative size of the smallest possible unit to be counted?" For channels with complex topographic features and considerable hydraulic complexity, this is a very difficult question. Fast water units possess some areas of low current velocity and slow water units usually have swiftly flowing water in them at some point. Location of channel unit boundaries for survey purposes is almost always subjective. Except for waterfalls, transitions from one unit to the next are gradual. In general, an area should be counted as a separate unit if (1) its overall physical characteristics are clearly different from those of adjacent units and (2) its size is significant relative to the size of the wetted channel. A guideline for what constitutes "significant" is that the greatest dimension of the channel unit should equal or exceed the average wetted width of the reach for units in the stream's thalweg, and one-half the average wetted width of the reach for units along the stream's margin. It is quite possible (and should be expected) that channel units will not all be arranged in linear fashion along the reach but that some units will be located next to each other, depending on the presence of flow obstructions and channel braiding.

Channel unit surveys challenge investigators to balance the accuracy of characterizing stream conditions over an entire reach against the precision obtained by carefully mapping a limited subsection of the reach. The greater the desired precision, the more time will be required for the survey and the less the area that can be covered within a given time. Rapid techniques for visually estimating channel unit composition in stream reaches exist (Hankin and Reeves 1988, Dolloff *et al.* 1993) as well as precise survey

methods for mapping the fine details of channel structure at a scale of one to several units (Gordon *et al.* 1992). Which technique is appropriate will be governed by the nature of the research topic. In all cases, investigators must keep in mind that discharge will strongly influence the relative abundance of different channel unit types; therefore, it is often desirable to repeat the survey at a variety of flows.

Although inventories of channel units in reaches of small streams can be conducted by one person, it is much easier and safer for surveys to be carried out by teams of at least two to three people. Because it is necessary to measure lengths and widths repeatedly, one person can be assigned to each side of the channel, while the third can record data and take additional notes. Although practiced survey crews become proficient at identifying channel unit boundaries and maximizing data gathering efficiency, it is important to work slowly and deliberately. It is far better to take the time to collect accurate data than to be in a hurry to complete the reach survey; further, the risk of accidents declines with careful planning and time management and cautious attention to detail. Work safely.

III. SPECIFIC EXERCISES

A. Exercise 1: Stream Reach Classification

Laboratory Protocols

1. Select a watershed. Assemble topographic maps, aerial photographs, and other information pertinent to the area. Within the watershed, select a stream or streams of interest.

2. Using the topographic map, construct a longitudinal profile of the channel beginning at the mouth of the stream and working toward the headwaters. Use a map wheel (also called a curvimeter or map measure) or a planimeter to measure distance along the blue line that marks the stream. If a map wheel or planimeter is not available, a finely graduated ruler may be substituted. In either case, be sure to calibrate the graduations on the map wheel, planimeter or ruler against the map scale. Record the elevation and distance from the mouth each time a contour line intersects the channel. Plot the longitudinal profile of the stream with the stream source nearest the vertical axis (Fig. 2.4).

3. Visually locate inflection points on the stream profile (Fig. 2.4). These points often mark important reach transitions. Compute the average channel slope in each segment according to the formula

$$S = \frac{E_u - E_d}{L}, \tag{2.1}$$

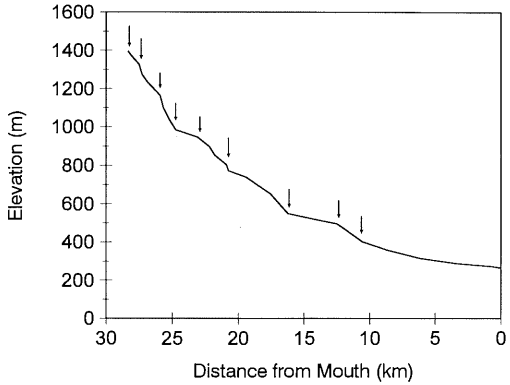

FIGURE 2.4 Hypothetical example of a stream profile constructed from a topographic map. Arrows denote changes in gradient that may mark reach boundaries.

where S represents average slope; E_u, elevation at upstream end of stream reach; E_d, elevation at downstream end of stream reach, and L, reach length. Remember to use common distance units for both numerator and denominator.

4. Examine the shape of the contour lines intersecting the stream to determine the approximate level of valley confinement in each segment. The width of the channel will not be shown on most topographic maps, but the general shape and width of the valley floor will indicate valley confinement (Fig. 2.5).

5. With the aid of a stereoscopic map reader, magnifying lens, or dissecting microscope, examine photographs of the stream segments identified on the topographic map. If it is possible to see the exposed (unvegetated)

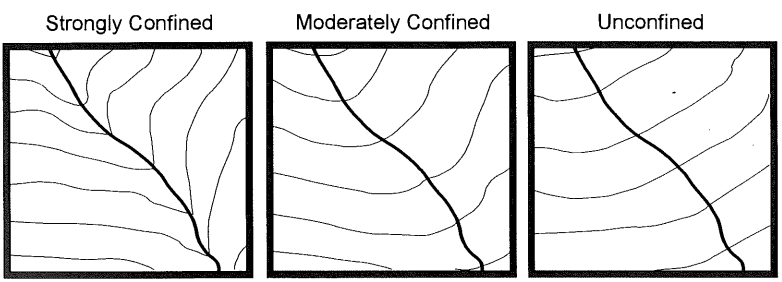

FIGURE 2.5 Appearance of strongly confined, moderately confined, and unconfined channels on topographic maps.

channel in the photographs, estimate the width of the exposed channel and compare it to the estimated width of the flat valley floor. Use the following to determine the approximate degree of confinement for the reach:

Valley Floor Width < 2 Channel Widths	Strongly Confined
Valley Floor Width = 2–4 Channel Widths	Moderately Confined
Valley Floor Width > 4 Channel Widths	Unconfined.

6. Compare average gradients and valley floor widths of each segment on the longitudinal stream profile with geological, soils, vegetation, and climatological maps of the watershed. Changes in the boundaries shown on these maps may help in more precisely locating reach boundaries and in forming hypotheses about reach conditions that can be evaluated during visits to the sites. From all available evidence, determine the most likely valley segment and reach type (or range of types) for each segment based on the features summarized in Table 2.1. Select one or more reaches for site surveys.

Field Protocols It may be possible to combine certain aspects of the field survey in this exercise with field methods discussed in Chapters 3 and 4. One reach may be surveyed on one field trip and a second reach surveyed on a different field trip.

1. Upon arrival at the site, inspect the stream channel, adjacent valley floor, and hillslopes to verify the accuracy of preliminary valley segment and reach classification. If it is possible to do so (for example, from a vantage point that permits a panoramic view of the valley floor), locate landmarks that mark reach boundaries and that are easily visible from the stream itself.

2. If the reach is too long to complete the exercise within 2–4 h, select a representative section of the reach for the channel unit survey. Location of representative sections may be based on ease of access, but the section should typify the reach as a whole and be long enough to likely contain all types of channel units in the reach (30–50 channel widths). Use the descriptions of channel unit types in Tables 2.2 and 2.3 to identify the units.

3. If optical, electronic, or sonic rangefinders will be used to measure distances, calibrate them at the beginning of each field trip by measuring the distance between two points with a tape and adjusting the readings on the rangefinders to match the known distance. Optical rangefinders, in particular, can become misaligned if dropped and should be recalibrated frequently.

4. If surface area will be estimated visually, it may be helpful to calibrate the "eye" of the observer by placing several rectangles or circles of plastic of known area on the ground before beginning the survey. The pieces of plastic (e.g., old tarps) should approximate the sizes of typical channel units at the site.

Calculations If channel units are measured, average width and depth are calculated according to the following formulas:

$$\text{Average width} = \frac{\text{Width measurements}}{\text{Number of measurements}} \tag{2.2}$$

$$\text{Average depth} = \frac{\text{Depth measurements}}{\text{Number of measurements}}. \tag{2.3}$$

Area and volume of each channel unit are calculated as follows (be sure to use common units):

$$\text{Area} = \text{Length} \times \text{Average width} \tag{2.4}$$

$$\text{Volume} = \text{Length} \times \text{Average width} \times \text{Average depth}. \tag{2.5}$$

The percentage of each type of channel unit in the reach, by area or volume, is

$$\%\ \text{of Area} = \frac{\text{Area of channel unit type}}{\text{Total area of reach}} \times 100 \tag{2.6}$$

$$\%\ \text{of Volume} = \frac{\text{Volume of channel unit type}}{\text{Total volume of reach}} \times 100. \tag{2.7}$$

B. Exercise 2: Visual Estimation of Channel Units

1. Most channel unit surveys progress in an upstream direction, but this is not required. It is necessary, however, to be able to recognize channel unit boundaries. These boundaries are often marked by abrupt gradient transitions, which tend to be more easily visible when looking upstream than when looking downstream. Begin at a clearly monumented starting point. This may consist of a man-made structure such as a bridge or some other permanent feature of the landscape. If semipermanent markers are used (e.g., a stake or flag tied to a tree), the location of the marker should be precisely referenced. Global positioning system (GPS) equipment has been used successfully for some reach surveys, but this technology may not work well under a heavy forest canopy in areas of high topographic relief.

2. Divide into teams of two or more individuals. Moving along the stream away from the starting point, the team should identify and record each channel unit as it is encountered (Table 2.4). Units located side-by-side relative to the thalweg (e.g., a pool in the main channel and an adjacent backwater) should be so noted.

3. Record the distance from the starting point of the reach survey to the beginning of each channel unit. This can be accomplished with a measuring tape (or hip chain), rangefinder, or GPS. Unless GPS is used, it will most likely be necessary to measure distances from intermediate reference points along the channel because bends in the channel or riparian vegetation will obscure the view of the starting point. For small streams, it may be helpful to locate intermediate distance reference points at short intervals (e.g., 50 m).

4. For each channel unit, visually estimate the wetted surface area and note it on the data form (Table 2.4). Periodically (e.g., every 10 channel units), use the techniques of Exercise 3 below to measure the length and width of a channel unit after its area has been visually estimated. Record these measurements on the data form, as they will be used to determine any systematic bias in the visual area estimates, and will make it possible to calculate a correction factor.

C. Exercise 3: Detailed Measurements of Channel Units

1. Perform steps 1–3 from Exercise 2.

2. For each channel unit, measure its greatest length in any direction and record this length on the data form (Table 2.4). Widths must be measured at right angles to the line defining the greatest length.

3. Measure the wetted width at regular intervals along the length of the channel unit. Although five width measurements are shown in Table 2.4, the number can vary at the discretion of the investigators. Geomorphically simple units require fewer width measurements than units with complex margins.

4. If the volume of each channel unit is to be estimated as well as the area, record the depth of the stream at regular intervals across the channel at each width transect. If the stream is wadeable, depths are usually measured with a telescoping fiberglass surveyor's rod, graduated wading staff, or meter stick (for very small streams). For very large streams, an electronic depthfinder operated from a boat may be appropriate. At a minimum, depth should be determined at one-third and two-thirds the distance from one side of the channel to the other at each width transect, yielding two depth measurements for each width measurement (Table 2.4). Once again, complex channel units require more depth measurements for accurate volume estimates than geomorphically simple units.

TABLE 2.4
An Example of a Field Data Form for Conducting Channel Unit Surveys

Location _____ Date _____ Surveyors _____

Stream _____ Discharge _____ _____

Quad map _____ Time _____ _____

Starting point _____ Water temp _____ _____

Channel unit	Distance from start	Area (estim.)	Greatest length	Widths					Depths									
				1	2	3	4	5	1	2	3	4	5	6	7	8	9	10

Note. Channel units can be identified by an acronym or alphanumeric designation. Modified from Dolloff *et al.* (1993).

IV. QUESTIONS

1. Were preliminary determinations of valley segment and reach types from maps and photographs correct when sites were visited in the field? What types of valley segments and stream reaches would be easy to identify from maps and aerial photographs? What types would be difficult to identify?

2. What would likely happen if each reach type were to experience a very large precipitation event, such as a flood with a 100- to 200-year recurrence interval? Would the effects be similar to other large disturbances such as inputs of massive volumes of fine sediment?

3. Give a few examples of situations where a stream reach might change from one type to another.

4. How does riparian vegetation influence the characteristics of different reach types? For one or two types, describe how alteration of the riparian plant community could affect channel features.

5. If the channel unit survey compared visual estimates of surface area with estimates derived from actual length and width measurements, was there a tendency for visual estimates to over- or underestimate area? Were errors more apparent for certain types of channel units than for others? Explain why, and suggest a way to correct for systematic bias in the visual estimates.

6. Describe several ways of displaying channel unit frequency data.

7. Describe how the properties of different types of channel units might change with increasing streamflow.

8. Based on your knowledge of the habitat preferences of a certain taxon of aquatic organism (e.g., an aquatic insect or fish species), suggest how that organism would likely be distributed among the channel units within that reach or reaches that were surveyed.

9. How would the frequency of different types of channel units in a reach likely change in response to removal of large woody debris? To extensive sediment inputs? To destruction of riparian vegetation? To a project involving channelization of the reach?

V. MATERIALS AND SUPPLIES

Field Materials

100-m fiberglass tape or hip chain
30-m fiberglass tape
Flagging

Global positioning system (GPS) instrument (optional)
Meter stick
Optical, electronic, or sonic rangefinder
Surveyor's rod or graduated wading staff

Laboratory

Aerial photographs
Geologic, soils, climate, and vegetation maps (optional)
Graph paper
Map wheel (map measure), planimeter, or digitizer
Stereoscope
Topographic maps

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