Linking Theory and Practice for Restoration of Step-Pool Streams

Anne Chin · Shannah Anderson · Andrew Collison · Barbara J. Ellis-Sugai · Jeffrey P. Haltiner · Johan B. Hogervorst · G. Mathias Kondolf · Linda S. O’Hirok · Alison H. Purcell · Ann L. Riley · Ellen Wohl

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Abstract Step-pools sequences are increasingly used to restore stream channels. This increase corresponds to significant advances in theory for step-pools in recent years. The need for step-pools in stream restoration arises as urban development encroaches into steep terrain in response to population pressures, as stream channels in lower-gradient areas require stabilization due to hydrological alterations associated with land-use changes, and as step-pools are recognized for their potential to enhance stream habitats. Despite an increasingly voluminous literature and great demand for restoration using step-pool sequences, however, the link between theory and practice is limited. In this article, we present four unique cases of stream restoration using step-pools, including the evolution of the approaches, the project designs, and adjustments in the system following restoration. Baxter Creek in El Cerri to, California demonstrates an early application of artificial step-pools in which natural adjustments occurred toward geomorphic stability and ecological improvement. Restoration of East Alamo Creek in a large residential development near San Ramon, California illustrates an example of step-pools increasingly used in locations where such a channel form would not naturally occur. Construction of a step-pool channel in Karnowsky Creek within the Siuslaw National Forest, Oregon overcame constraints posed by access and the type and availability of materials; the placement of logs allowed natural scouring below steps. Dry Canyon Creek on the property of the Mountains Restoration Trust in Calabasas, California afforded a somewhat experimental approach to designing step-pools, allowing observation and learning in the future. These cases demonstrate how theories and relationships developed for step-pool sequences over the past two decades have been applied in real-world settings. The lessons from...
these examples enable us to develop considerations useful for deriving an appropriate course of design, approval, and construction of artificial step-pool systems. They also raise additional fundamental questions concerning appropriate strategies for restoration of step-pool streams. Outstanding challenges are highlighted as opportunities for continuing theoretical work.

**Keywords**  Step-pools · River restoration · Environmental management · Human impacts · Channel design

River restoration has accelerated in recent years as the range of human impacts on river form and function is increasingly recognized (e.g., James and Marcus 2006), as maturation of theories in fluvial geomorphology and related disciplines have provided a scientific basis for application (Graf 1996; Kondolf and others 2003), and as synthesis efforts have sharpened our focus toward advancing the science (e.g., Bernhardt and others 2005; Palmer and others 2007; Wohl and others 2005). River restoration has also increased because practitioners have gained experience in translating academic research into applied designs (e.g., Haltiner and Beeman 2003), and lessons have been learned from postproject appraisals of implemented projects.

River restoration is multifaceted because of its interdisciplinary nature. It also involves academic scientists and applied practitioners, funding and regulatory agencies, and a wide variety of stakeholders. The potential dichotomies between disciplines, between researchers and practitioners, and between decision makers and the public pose particular challenges toward a unified science. As communication improves among scientists from the engineering, ecological, and geomorphic disciplines (Palmer and others 2003), the linkage between science and implementation (Wohl and others 2005) becomes critical for the success of restoration projects.

This article addresses the linkage between theory and practice for restoration of step-pool streams. Step-pools are characteristic bedforms found in high-gradient channels typically exceeding ~3–5%. Steps composed of cobbles and boulders alternate with finer materials in pools to form a rhythmic, staircaselike longitudinal profile. Until recently, little was known about the forms and processes of step-pool channels compared to pools and riffles associated with the meandering river in lower-gradient environments (Chin 1989). Significant advances in theory for step-pool sequences over the past two decades have made possible the restoration of steep channels using step-pools (Chin and Wohl 2005), so that restored step-pool channels are increasingly common (e.g., Purcell and others 2002). Urbanization impacts to step-pools are also more frequent now that development increasingly encroaches into steeper terrain in response to population pressures (e.g., Chin and Gregory 2001). Because step-pools are effective energy dissipators (e.g., Chin 2003), they are also increasingly used in restoring lower-gradient channels to stabilize incising stream channels affected by hydrologic alterations resulting from urbanization and other land-use changes. These include increased magnitude and frequency of peak discharges, increased duration and volume of flow, and reduced sediment supplies. The potential habitat enhancement benefits provided by step-pools (Scheuerlein 1999; Ward 1992), particularly their potential use to eliminate artificial drops in the channel longitudinal profile that are barriers to fish passage (Maxwell and others 2001), further make them valuable in stream restoration.

Despite the effectiveness of, and increasing demand for, step-pools in river restoration, little guidance is available for such applications. The increasingly voluminous literature also requires considerable time for practitioners to assemble, study, and understand. Although learning from specific case studies would be valuable, such cases are rarely documented in the published literature (but see Lenzi 2002; Morris and Moses 1998), and monitoring is almost nonexistent (see Clearwater Hydrology 2006; Lenzi and Comiti 2003). Thus, the use of step-pools remains a relatively new and important strategy that environmental managers and consultants are increasingly interested in, but, so far, the link between theory and practice is limited.

Herein, we profile four cases of stream restoration using step-pool sequences. We demonstrate how theories and relationships developed over the past two decades have been applied in real-world settings. We describe the evolution of the approaches, the project designs, construction process, and adjustments in the system following restoration. Using our collective experiences as academics, applied practitioners, and resource managers, we assess the successes, challenges, and constraints of those applications. We identify outstanding needs in terms of additional research. Our goals are to use these examples to assist others interested in similar applications, to synthesize lessons learned from these cases to improve future restoration efforts, and to provide feedback to researchers regarding the applicability of, and continuing need for, their work.

**The Scientific Context**

The development of the available science to guide stream restoration using step-pool sequences has been summarized in Chin and Wohl (2005). A recent review by Church and Zimmermann (2007), accompanied by at least a dozen...
relevant published journal articles in the past 2 years (e.g., Comiti and Lenzi 2006; Curran and Wilcock 2005, 2006; Milzow and others 2006; Wilcox and Wohl 2007; Wilcox and others 2006), give sense of the continuing strides in understanding the forms and processes of step-pool channels in particular (Chin and Wohl 2007) and of mountain streams in general (Wohl and Chin 2006). These publications, together with those referenced therein, provide the theories, detailed data, and technical information to formulate general guiding principles for the restoration of step-pool channels.

For restoration involving reconstruction of channel reaches with step-pool sequences, several groups of concepts or topical statements are relevant. First, the known relationships governing the step-pool geometry are central to guiding the design of step-pool channels. Second, the processes associated with step-pool sequences, particularly the ability of such sequences to adjust and re-form and the range of flows that step-pool structures can withstand and remain in place, provide important background to how artificially manipulated step-pool systems might perform after construction. Third, because of the dynamic and interconnected nature of watershed processes, an understanding of the occurrence and function of step-pool systems in the larger context of the drainage basin enhances the likelihood of success (Wohl and others 2005). These concepts, together with consideration of practical (e.g., economic) and political issues, as well as additional stated requirements (e.g., fish passage), guide the development and selection of specific design and process interactions for restoration projects.

Geometric Relationships

For a given channel reach with a specified slope, the spacing [or length ($L$)] and height ($H$) of steps comprise the main properties of the step-pool geometry. Spacing is scaled to the size of the channel and ranges from less than one to four channel widths (e.g., Billi and others 1998; Chartrand and Whiting 2000; Chin 1999; Curran and Wohl 2003; Grant and others 1990; Montgomery and others 1995; Wooldridge and Hickin 2002). Although the variability in step-pool spacing can be high (Zimmermann and Church 2001), a mode centering around less than one to two channel widths (Billi and others 1998; Chin 1989, 1999; Curran and Wohl 2003; Wooldridge and Hickin 2002) suggests a tendency toward systematically repetitive spacing, similar in this regard to pools and riffles (Keller and Melhorn 1978).

The length and height of individual steps are strongly related to channel slope ($S$). The inverse relationship between average step length and slope has been well established and supported by field data from a variety of locations (e.g., Chartrand and Whiting 2000; Chin 1999; Grant and others 1990; Hayward 1980; Judd 1964; Wohl and Grodek 1994; Wooldridge and Hickin 2002). This relationship is borne out in both log and clast steps (Wohl and others 1997), suggesting a fundamental mutual adjustment between step-pools and the hydraulic geometry of mountain streams (Chin 1989; Heede 1981). Step height similarly correlates with channel slope, whereby the steeper the slope, the higher the step (Billi and others 1998; Chin 1999; Duckson and Duckson 2001; Gomi and others 2003; Wohl and Grodek 1994). Thus, taken together, step frequency and size increase with increasing slope.

The height of steps is further dependent on the particle sizes available to form steps. The average ratio of step height to the median diameter of step particle sizes consistently ranges from 1.0 to 1.5 (Chartrand and Whiting 2000). Values for this ratio center around 1.2 for streams in the Santa Monica Mountains of southern California, where step particle size is defined as the average ($b$-axis) of the five largest particles comprising steps (Chin 1999). For the Eastern Alps of Italy, the relationship was twice the 90th percentile particle size ($D_{90}$) (Billi and others 1998). The constancy of the relation between step height and particle size was also demonstrated in laboratory experiments (Ashida and others 1984, 1985; Egashira and Ashida 1991; Tatsuzawa and others 1999). The fact that step height also correlates positively with the size of step-forming logs (Curran and Wohl 2003; MacFarlane and Wohl 2003; Wohl and others 1997) provides ample evidence of the direct control of the size of the step-forming materials on step height.

Within a given reach, idealized step-pool geometry is characterized by steps that are regularly spaced and the mean steepness ($HIL$) is slightly greater than the channel slope (Fig. 1). This step-pool geometry has been suggested in laboratory flume studies to offer maximum flow resistance (Abrahams and others 1995). A morphology that imparts greatest flow resistance also implies maximum stability for the step-pool channel reach. This morphology, thus, represents an equilibrium form adjusted to the flow regime, particle size, and slope. The ratio of ($HIL$)/$S$ typically ranges between 1 and 2 (Abrahams and others 1995; Duckson and Duckson 2001; Lenzi 2001; MacFarlane and Wohl 2003; Wohl and Wilcox 2005; Wohl and others 1997). Abrahams and others (1995) suggested an ideal value of 1.5, although the range of 1.0–1.5 characterizes many natural step-pool channels (Lenzi 2001, 2002), and values exceeding 2 are also commonly reported (Chartrand and Whiting 2000; Zimmermann and Church 2001). Higher values of the ($HIL$)/$S$ parameter correspond to exaggerated reverse gradients for step treads due to scouring in pools, whereas values below 1.0 indicate
incompetent flows to scour pools (Jackson and Sturm 2002). The step-pool geometry approximating maximum flow resistance \( \frac{H}{L} \) can be achieved over a period of channel adjustments (Chin and Phillips 2007), such as after floods, when step-pools reorganize and evolve gradually over time (Lenzi 2001).

**Process Considerations**

Step-pool sequences adjusted to the prevailing flow regime exert dominant influences on in-channel processes. High spatial and temporal variability characterize the tumbling flow of step-pool channels (e.g., Ashida and others 1986) as well as sediment movement (e.g., Schmidt and Ergenzinger 1992). Average velocity is higher approaching a step than elsewhere along the channel (Wilcox and Wohl 2007). The intensities of turbulence are greatest in pools below steps because of the concentration of energy dissipation (Wilcox and Wohl 2007; Wohl and Thompson 2000). Sediment is preferentially stored in, and later mobilized from, pools (Ashida and others 1976; Ergenzinger and Schmidt 1990; Marion and Weirich 1999) and near large woody debris (Ketcheson and Megahan 1991). The bed remains mostly stable during lower discharges, with only sand and fine gravel typically transported over a coarser surface layer (Marion and Weirich 1999). Flow resistance exhibits high variability and is influenced by discharge (Egashira and Ashida 1991; Lee and Ferguson 2002; Wilcox and others 2006). Energy loss and roughness between steps and pools grow more uniform as discharge increases (Chin 2003; Stuve 1990).

Step-pool sequences are capable of being mobilized over a range of flows. Although some are relics of former glacial processes and are thus relatively immobile under present climate conditions (Miller 1958; Newson and Harrison 1978; Trayler and Wohl 2000), most are products of present hydrologic regimes (Chin 1998; Gintz and others 1996; Lenzi 2001; Lenzi and D’Agostino 2000; Lenzi and others 1997). Instrumented watersheds in the Bavarian Alps (Ergenzinger 1992; Schmidt 1994) and Italian Alps (Billi and others 1998; D’Agostino and others 1994; Lenzi and others 1999) have captured processes during and immediately following discharges capable of destroying and subsequently reorganizing step-pool sequences. Following such events, the channel bed is typically characterized by poorly defined bedforms and low flow resistance. Flow resistance increases over days to months, as lower discharges create bed armoring and increasingly defined steps and pools (Ergenzinger 1992; Lenzi 2001; Madej 2001; Sawada and others 1983). The estimated recurrence interval for major floods that mobilize bed sediments in step-pool channels range from annual events (Ashida and others 1976; Sawada and others 1983) to 30–50 years (Lenzi 2001) to greater than 50 years (Chin 1998; Grant and others 1990). Such events can be accompanied by high rates of bedload transport over periods of hours to weeks (Sawada and others 1983).

**The Watershed Context**

Step-pools are part of a series of channel morphological types that change systematically downstream within drainage basins. Channel types in mountain watersheds typically progress downstream from disorganized cascade reaches to fluviually organized step-pools, plane beds, pool-riffles, and dune ripple channels (Buffington and others 2003; Montgomery and Buffington 1997). Variations of this progression could reflect regional and watershed characteristics (Thompson and others 2006), such as the delivery of “nucleus” boulders from nearby landslides. Steps are also parts of channel units (Grant and others 1990) that typically vary with drainage area and particle size (Chin 2002), along with slope (Chartrand and Whiting 2000; Chin 2002; Grant and others 1990; Halwas and Church 2002). Step-pool channels have significantly steeper gradients (Wohl and Merritt 2005), coarser substrate, and higher values of shear stress and stream power for a given discharge than pool-riffle and plane-bed channels (Wohl and Merritt 2008). Step-pools represent an adjustment in boundary roughness to energy expenditure and are analogous to meandering in the vertical dimension (Chin 2002). The characteristic sequence of bedforms, channel units, and channel types develops in the drainage basin as flow, sediment, and gradient change systematically from headwater to outlet (Church 1992, 2002).

Within a watershed, step-pool channels are considered transport reaches that are less responsive to changes in
water and sediment discharge than channel segments with pool-riffle sequences or dunes and ripples farther downstream (Montgomery and Buffington 1997). The comparatively stable character of step-pools corresponds to the larger flows required to mobilize the coarse step particles. With changing land uses in mountain areas, however, including timber harvest, agriculture, grazing, and urbanization (Harden 2006; Wohl 2006), step-pool channels are increasingly subjected to greater pressures resulting from altered flow regimes. Direct in-channel disruptions can also lead to degradation of steep channels to the extent that they require restoration; these include channelization and the construction of dams. Understanding the responses of step-pool channels within changing environments is (e.g., Wohl and others 2007), therefore, critical for successful stream restoration.

**Approaches to Restoration Design**

From an engineering perspective, the use of step-pools in restoration can be viewed as a contemporary version of the traditional grade-control structures used to stabilize eroding channels. Whereas check dams and weirs (made of concrete, sheet piles gabions, etc.) have been used for many years in stream restoration, these rigid drop structures have increasingly been replaced by boulders (Haltiner and Vick, 1997; Lenzi 2002), large woody debris, and other more natural material (Scheuerlein 1999). Step-pools are also analogous to devices such as flow deflectors, low dams, and large woody debris/root wad structures used to improve habitat for fish (Burgess 1985; Downs and Thorne 1998, 2000; Morris 1995) and to allow fish passage (Haltiner and others 1996; Maxwell and others 2001). The potential ecological value of step-pools, coupled with the trend to replace rigid and environmentally damaging structures with softer methods (that are more geomorphically stable and provide improved aquatic and riparian habitat) to restore river channels (e.g., Chin and Gregory 2005), have prompted wider acceptance of the use of step-pools in stream restoration in the United States (Chin and Wohl 2005; Thomas and others 2000) and in Europe (Lenzi 2001; Scheuerlein 1999). Thus, the use of step-pools has become “promising” (Scheuerlein 1999) and “encouraging” (Lenzi 2001), as well as a “new area of interest” (Maxwell and others 2001) for river engineering.

Several methods have been described to design rock weirs and boulder check dams that mimic step-pool sequences. Most are concerned with determining the location or spacing of the features and the sizing and arrangement of the step material. Using field data from eight mountain streams in Colorado, Thomas and others (2000) developed regression equations to determine the pool length, scour depth, maximum pool width, and the amount of contraction required to provide downstream tailwater control. Step height is the independent variable determined by the elevation loss needed for the reach or by the habitat requirement in the downstream pool. The size of boulders is calculated with the design method of the US Army Corps of Engineers for riprap in steep slopes (USACOE 1991). Application of this procedure to four artificial steps in Colorado already in place since 1989 yielded good correlations for pool length. Measured depths were larger than predicted, however, because of scouring in the fine-grained pools of the artificial steps.

For designing high-gradient countersunk culverts that would enable fish passage, Maxwell and others (2001) and Maxwell and Papanicolaou (2001) developed formulas, based on laboratory experiments, to predict geometric and frictional characteristics of step-pool bedforms. For example, step height is correlated with the gravel-bed size distribution, relative submergence of the particles, and the Froude number:

\[
\frac{d_{\text{step}}}{H} = 2.0 \left[ \frac{Q}{gH^3} \left( D_{50}/H \right)^{1.5} \right]^{0.31}
\]

where \(d_{\text{step}}\) is step height, \(H\) is flow depth, \(\sigma = \sqrt{D_{84}/D_{16}}\) and denotes the standard deviation of the sediment size distribution, \(Q\) is the volumetric flow rate, \(g\) is gravitational acceleration, and \(D_{50}\) is the 50th percentile median particle size. Particle size relations for bed stability are given by

\[
t_{\text{cr}}^{*} = 0.03 F^{1.29} \gamma S \left( \gamma_s - \gamma \right) D_{84}
\]

where \(F\) is the Froude number, \(t_{\text{cr}}^{*}\) is the Shields parameter or critical stress, \(S\) is slope, \(\gamma_s\) is the sediment specific weight, and \(\gamma\) is the specific weight of water. Step spacing is related to step height and the streambed longitudinal slope:

\[
L = 7.39 \ln \left( \frac{d_{\text{step}}}{S} \right) - 5.52
\]

where \(L\) is the step spacing (in meters) and \(d_{\text{step}}\) is step height (in meters). Application of these equations to the Big Quilcene River in Washington compared well with measured values. Wider testing is needed, however, to determine the utility of these relations in stream restoration.

Morphological criteria were employed in designing boulder check dams that resemble step-pool sequences for a mountain stream in northern Italy (Lenzi 2002). This application utilizes the theory suggested by Abrahams and others (1995) that a step-pool geometry within the range \(1 \leq (H/L)/S \leq 2\) provides maximum flow resistance and, therefore, imparts greatest stability. For the general study region, field surveys suggested that the equation \(0.5 \leq (H/L)/S \leq 2.1\) is more appropriate, with a mean value of 1.4
for the \((H/L)/S\) parameter. For the specific channel reach, \((H/L)/S\) was chosen to range between 1.1 and 1.3 following detailed field surveys; these values generated weak reverse bed slopes upstream of the check dams. Similarly, the height of the structures above the ground was calculated from a field-derived relation based on particle size. For the study area, \(H/D_{90} = 2\) (Billi and others 1998) with a range of 1–4. The artificial structures designed with these relations withstood flood events with return periods of 7–10 years and 20–25 years during the final stages of construction. Channel adjustments documented 4 years later showed little change in some of the artificial steps, whereas significant scour holes developed in others (Lenzi and Comiti 2003). An advantage of this morphological approach is that predicting the equilibrium slope is not necessary, as in traditional engineering design, because the calculated step-pool configuration yields reverse slopes in between steps (Lenzi 2002; Lenzi and Comiti 2003).

The Case Studies

The scientific principles outlined earlier, together with consideration of the approaches available for designing artificial step-pool sequences, provide the basis for discussing the four case studies. These cases are chosen to represent a range of designs that reflect the state of knowledge of step-pool sequences at the time of construction. They also represent a range of environments that pose specific requirements and constraints for building artificial step-pool channels. They are examples for which some data are available before and after restoration. The varying time periods of construction (1996–2006) also allow some observation of the rate of adjustment in the systems following restoration.

Baxter Creek

A 70-m underground reach of Baxter Creek in El Cerrito, California (Contra Costa County) was “daylighted” and restored in 1996 as part of a citywide storm drain renovation program (Owens-Viani 1997). Many urban creeks in the San Francisco Bay Area were culverted in the 1940s in response to drainage concerns. Rather than repairing and maintaining aging culverts, the city of El Cerrito decided that it would be more cost-effective to re-create a surface channel in the residential area of Poinsett Park.

The Waterways Restoration Institute designed and oversaw the restoration, which involved bed reconstruction and bank stabilization. Regional hydraulic geometry relationships provided guidelines for designing channel dimensions based on drainage areas. These relations yielded a design width of \(\sim 2\) m (6 ft) and a depth of \(\sim 0.3\) m (1 ft). The channel sinuosity and slope were also selected according to characteristics for the region, including a steep 10% valley slope. Bank stabilization involved placement of bundles of willows (fascines) placed parallel to the stream on top of the bankfull channel. Trees planted along the banks included alders (\(Alnus\) sp.), big leaf maple (\(Acer macrophyllum\)), California dogwood (\(Cornus californica\)), ninebark (\(Physocarpus opulifolius\)), currant bushes (\(Ribes\) sp.), and native willow (\(Salix\) sp.). The creek was designed to accommodate a 10-year flood (Owens-Viani 1997). Purcell and others (2002) and Chin and Phillips (2007) provided additional details for the characteristics of the study site, including references to maps of the area.

The steep channel slope of 10% suggested a step-pool morphology for the stream bed, although embryonic theories for step-pools at that time provided little guidance for design. Using some of the rocks salvaged from the excavation, five step-pool structures were built to span the 70-m-long channel reach (Fig. 2a). This resulted in an average length of 14 m between steps, corresponding to approximately seven channel widths.

Channel surveys conducted in 1996, 1999, 2005, and 2006 documented postconstruction redistribution of large...
rocks into more closely spaced steps. These morphologic adjustments are consistent with the closer spacing between steps of equilibrium step-pool geometry, as shown by more recent research. Redistribution of the rock material initially occurred during the winter flows of 1997 (Fig. 2b). Step frequency increased in subsequent years as the slope was broken up into smaller drops (Fig. 2c), with a total of 20 well-developed step-pool sequences evident by 2005. During this period, Baxter Creek had experienced storm events with recurrence intervals exceeding 14 years (Boucher 2006).

Examination of the longitudinal profile of 2005 (compared to that of 1999) indicates that stability and maximum flow resistance had been achieved in the step-pool system (Fig. 3). Whereas the step-pool spacing was too far apart initially, the step-pool sequences exhibited an average length of 2.9 m in 2005, which corresponds to 1.6 channel widths. Analysis of length and height relations relative to slope yielded a value of 1.1 for the \( \frac{H}{L}/S \) parameter. This value is close to the ideal for step-pools (Abrahams and others 1995) and is consistent with those of many natural streams (e.g., Lenzi 2001). The ratio of step height to step particle size (Chin 1999) of 1.1 for the 2005 channel is also consistent with natural step-pool sequences (Chartrand and Whiting 2000; Chin 1999). Thus, the geometry of the present step-pool sequences represents an end product of a self-organization process toward a morphology that imparts maximum flow resistance and stability in the system (Chin and Phillips 2007).

Resurveys at one cross section over a 10-year period indicated only minor changes (Fig. 4). Most notable was the deepening of a pool. The apparent changes on the right bank slope are probably artifacts of differences in the cross-section survey line resulting from the lack of monuments on the right bank end of the cross section. The reconstructed channel had maintained its integrity in the decade since restoration.

An assessment of ecological conditions conducted in 1999 additionally showed that the restored section of Baxter Creek had better biological and habitat quality than an unrestored reach upstream without step-pool bedforms (Purcell and others 2002). The restored site scored higher in habitat parameters that included bank stability, vegetative protection, velocity/depth regime, and epifaunal substrate/available cover. Benthic macroinvertebrates also scored higher in the restored site in several metrics, including taxa and family richness, and the richness and percent of EPT individuals. EPT refers to individuals within the orders Ephemoroptera, Plecoptera, and Trichoptera, which are generally considered sensitive to perturbations in stream quality. The improvements in ecological conditions were noted within the first few years following restoration (Purcell 2004).

**East Alamo Creek**

In conjunction with a large (\( \sim 26 \text{ km}^2 \)) residential development on former ranch lands, Philip Williams and Associates Ltd. (PWA) designed and implemented a stream restoration plan for the severely degraded channel system of Alamo Creek (Contra Costa County) and its tributary, East Alamo Creek. Intensive grazing over the past 150 years has resulted in channel incision of \( \sim 3-8 \text{ m} \) and extensive widening and bank collapse in this channel system in Dougherty Valley near San Ramon, California. The regional restoration involved the re-creation of stable low-flow channels and accessible floodplains for 8 km of incised channels, including \( \sim 1 \text{ km} \) of East Alamo Creek.
(Fig. 5a) along a greenbelt area adjacent to the edge of the new development (PWA 1999). The design objectives specified creation of a geomorphically stable channel and riparian habitat linked to the adjacent open space, as well as provision of 100-year flood hazard protection and an aesthetic corridor to include a multiuse pathway. Haltiner and Beeman (2003) described PWA’s conceptual design approach. The restoration included installation of a 180-m reach of step-pools, grading of an adjacent floodplain terrace, biotechnical stabilization techniques for the bank and floodplain, and extensive revegetation with native vegetation from the area. The project was completed in 2001 (Fig. 5b).

The design included a four-step process: (1) determine the overall channel reach slopes; (2) use geomorphic criteria to determine the initial step-pool dimensions; (3) conduct hydraulic analysis to verify the design and estimate rock sizes; (4) refine the design to improve constructability. Key channel characteristics included a channel bed consisting of dense clay, with almost no occurrence of sand-size or larger sediment supply. The local topography and constraints associated with the new development resulted in two step-pool channel reaches (one 80-m reach at 3% and one 100-m reach at 5% slope).

The geomorphic design tools for the step-pool sequences included reference reach data from field surveys and empirical equations from the literature. First, the conceptual design objective specified a limit for the net elevation difference between grade control structures (including step-pools); values of 0.5 m and 0.3 m were chosen for the 5% and 3% reaches, respectively, to meet this objective. These specified elevation losses, together with the reach slope, enabled the length or spacing between steps to be calculated \( L = H/S \). Next, because empirical relationships were not available from the literature for this region, surveys of two nearby step-pool streams provided reference guidelines for determining the pool depths and the local gradient of the step treads. These data indicated \( (H/L)/S \) ratios of 2.0 and 2.3 for the local streams, higher than the theoretical 1.5 value suggested by Abrahams and others (1995). Third, using an initial value of 2.0 for \( (H/L)/S \), the length and height dimensions for the initial step-pool design were calculated and compared to those estimated with the empirical equations of Thomas and others (2000) for Colorado streams. Finally, the empirically derived pool depths were compared with scour analysis methods to ensure that the pool depth exceeded the expected depth of scour at the base of each step.

For hydraulic analysis, PWA used HEC-RAS (a one-dimensional step backwater program) to select materials, optimize the design dimensions, and quantify energy dissipation. The method of Robinson and others (1997) for sizing rock chute structures provided the guidelines for selecting rock sizes that would not move during the 100-year event to construct the steps. Boulders with a diameter of 1.7 m were specified. HEC-RAS also provided the algorithm to model flows over steps, to ensure that the location of the hydraulic jumps was stable (Froude number greater than 4.5) in each of the plunge pools over the range of design flows. This is important to ensure that energy dissipation occurs as a continuous process over the length of the step-pool reaches. PWA (2001) provided additional details of the design calculations.

The design refinements relied on engineering judgment and experience to improve the constructability of the step-pools. Refinements included the addition of deeper rock foundations on every third or fourth structure. This ensured that if rocks did move and the rock structures experienced reshaping, the entire sequence of structures would not be at risk. Methods to construct the steps by placing extremely large rock were also developed.

The resulting step-pool dimensions were generally larger than the theoretical, reference, and empirical information would predict (Table 1). Given the urban setting and

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**Fig. 5** East Alamo Creek: (a) before restoration, July 1998; (b) postconstruction, during first notable flow event, December 2001 (Photographs by PWA; J. Haltiner)
expected increases in design flows from the development, the stability of the step-pool structures was an especially important consideration. In addition, construction of step-pools using large boulders in a watershed with minimal supply of sediment greater than sand or gravel meant that if the structures failed, they would not be supplied with new boulders to enable steps to reform. Thus, not allowing the structures to deform or mobilize during high flow was important.

A postproject assessment of the restoration of East Alamo Creek conducted in Fall 2006 indicates overall channel stability and vegetation establishment for the project reaches (Adair and Perasso 2006, Unpublished report). The step-pools have remained in place since installation in 2001; the sizing of the sequences corresponds to their stability. Analysis of peak flow data available for nearby San Ramon Creek indicates that a flood with recurrence interval of 9 years had occurred in 2003. As the step-pool channels in East Alamo Creek were designed for 100-year events, future large events would continue to test the performance of the artificial structures.

Channel surveys and qualitative inspections at East Alamo Creek revealed several issues common to artificial step-pool structures, from which valuable lessons can be learned. The primary issue for the structures is that water flows through the steps in lower flows, rather than over the top. Because the step boulders are much larger than the soil matrix, a filter fabric “pillow,” filled with sand and gravel, was placed in the steps to prevent piping around the boulders. Although intended to trap fine-grained sediment in the flows and seal the steps, this technique was not effective. An alternative of using sheet piles (steel or vinyl) buried upstream of the step face as an impermeable barrier might be more effective in future designs. Greater attention to the mix of rock sizes, as well as the median particle size, might also help to create a matrix that packs together well. Second, although the sides (wings) of the rock steps extended into both banks up to the expected level of the 100-year design flood and the steps were backfilled with soil to allow vegetation establishment, much of the soil was scoured during floods. The steps became more visible as rock structures than intended, compared with those in the restored reaches that were less steep where extensive vegetation has been reestablished. Thus, a maintenance program is suggested for future projects to replace the soil. These issues were not entirely anticipated in the design phase of the restoration, but they highlight common concerns (e.g., Morris and Moses 1998) and provide opportunities for improvement in future projects. The installation of step-pool sequences in East Alamo Creek illustrates an example of step-pools increasingly used in locations associated with urban developments, where such a channel form would not naturally occur.

Karnowsky Creek

Karnowsky Creek in the Siuslaw River Basin in Siuslaw National Forest (Lane County), Oregon has been the focus of an 85-acre (0.34-km²) meadow restoration project. In past ownership, the relatively steep (2.7%) Tributary 3 of Karnowsky Creek had been channelized into a straight ditch along the side of its valley to accommodate

### Table 1  Final step-pool design compared to empirical and reference values, East Alamo Creek, CA

<table>
<thead>
<tr>
<th>Design criteria</th>
<th>Avg. channel slope ($)(m/m)$</th>
<th>Drop height (m)</th>
<th>Pool depth (m)</th>
<th>Total step Height (m)</th>
<th>Pool length (m)</th>
<th>Avg ($H/L)/S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical value (Abrahams and others 1995)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>1.5</td>
</tr>
<tr>
<td>Surveyed reference reaches (Marin County, CA)</td>
<td>0.041–0.046</td>
<td>NA</td>
<td>NA</td>
<td>0.43–0.47</td>
<td>NA</td>
<td>2.0–2.3</td>
</tr>
<tr>
<td>Empirical relationships (Thomas and others 2000; Colorado streams)</td>
<td>0.03</td>
<td>NA</td>
<td>0.1</td>
<td>0.4</td>
<td>4.2</td>
<td>NA</td>
</tr>
<tr>
<td>Final step-pool design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3% reach (standard pools)</td>
<td>0.03</td>
<td>0.3</td>
<td>0.6</td>
<td>0.9</td>
<td>6.8</td>
<td>3.0</td>
</tr>
<tr>
<td>3% reach (deep pools)</td>
<td>0.03</td>
<td>0.3</td>
<td>1.0</td>
<td>1.3</td>
<td>6.0</td>
<td>4.3</td>
</tr>
<tr>
<td>5% reach (standard pools)</td>
<td>0.05</td>
<td>0.5</td>
<td>0.6</td>
<td>1.1</td>
<td>6.4</td>
<td>2.2</td>
</tr>
<tr>
<td>5% reach (deep pools)</td>
<td>0.05</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
<td>5.6</td>
<td>3.0</td>
</tr>
</tbody>
</table>

* Drop height is the elevation change from step crest to the next step crest
* Pool depth is the elevation difference between the bottom of pool to the next step crest
* Total step height is elevation change from step crest to pool bottom (equals sum of drop height and pool depth)
* Pool length is the distance from the base of one step to the next step crest
* $H$ and $L$ are step height and step length, respectively. In this computation, $H$ is total step height and $L = 10$ m
agriculture. It had downcut severely to an extent that it drained groundwater from one side of the valley. The tributary is intermittent, but it can experience large flows during winter storms. In Fall 2003 through 2004, the US Forest Service implemented a restoration project to re-create a functional channel, fill in the ditch that was ~3 m deep in places, and increase groundwater storage in the valley. Step-pools were added to the design for grade control, because the gradient of the channel was steep enough to occur at the transition between a pool-riffle morphology and step-pool channel type. Because one of the goals of this restoration was to create habitat downstream for coho salmon, reconstructing this degraded ditch with step-pool sequences would also enable natural gravels to move through the steps and supply the spawning habitat reach in the mainstem below the tributary.

The restoration began with the creation of a topographic map of the valley floor with 1-ft contours that revealed low spots and remnant channels. To re-create a more natural channel, the plan view of the new channel was located by "connecting the dots" of the low spots to take advantage of the remnant channels in the middle of the valley floor. This plan view also mimicked the historic conditions, as shown on old aerial photographs. Some of the alluvial fan material comprising the valley floor, removed from the lower portion of the valley, provided the fill for the deeply eroded ditch. The lower portion of the valley floor was regraded to match the overall valley gradient.

The geomorphic criteria described by Lenzi (2002), based on the principle of maximum flow resistance (Abrahams and others 1995), provided guidance for the step-pool design. Field surveys conducted in the Oregon Coast Ranges revealed a similar range of natural variability for step height and length relations as that found in the Eastern Alps in Italy, such that the following applied: 0.5 ≤ (H/L)/S ≤ 2.1. To keep the design simple, (H/L)/S was set to 1, so that the slope between steps would match the stream gradient without exaggerated reverse slopes. A step height of 0.15 m (0.5 ft) was also chosen based on previous work with constructing steps through culverts. A channel slope of 2.7% and H/L = S yielded a step length of 5.6 m, with a range of 11.3 m [for a (H/L)/S ratio of 0.5] to 2.7 m (for a ratio of 2.1). These design criteria generated an eventual spacing of ~6.0 m (20 ft.) for the constructed steps.

Steps in Oregon’s Coast Range streams are commonly made of fallen logs and debris jams (e.g., Marston 1982); inclusion of boulders is less common given that the local bedrock, the Tyee Formation, consists of weakly consolidated sandstone and siltstones. Importing competent material by truck was cost-prohibitive due to the distance from local quarries. As a result, a temporary access road across an existing stream and wetland was constructed. Step construction utilized sandstone boulders (2–4 ft in diameter) from a nearby borrow area and logs cut from felled trees (20–30 in diameter) and hauled to the site. Some round river rock saved from the original ditch was also used to seed the new channel in places. An exposed bedrock hillslope in the Tributary 3 valley that contained competent sandstone provided a borrow source for angular material, which was then mixed with fines and was compacted behind steps to prevent the logs from under cutting.

Construction began by creating a channel with a width and depth that approximated natural stream channel dimensions upstream. At the step locations, a trench dug across and perpendicular to the stream channel allowed initial placement of a footer log. The excavator placed a second log on top of it, slightly offset so that flow would hit the footer log. The ends of both logs were buried in the stream bank. They extended ~3 m beyond the stream banks to prevent erosion around the ends of the logs (Fig. 6a). Boulders were also dug into banks just below each step to minimize bank erosion and failure of the step during high flow. The logs were placed so that the top of the step was at grade with the streambed; the streambed appeared smooth at completion of the project (Fig. 6b). This design allowed the stream to scour its own pools. In additional, conifers planted in the valley floor would provide future shade and large woody debris to the stream. Willow staking in banks provided additional bank stability. Subsequent observations indicated that pools had scoured sufficiently downstream the logs by the second winter (January 2006) to develop sequences of steps and pools (Fig. 6c). Until the step-pools developed and provided energy dissipation, however, the high-energy flows tended to erode the unstable banks. The bank erosion that occurred during this early phase suggested that an initial smooth gradient might not be optimal, although the stream had not cut around any of the steps. Once the steps formed and dissipated stream energy, bank erosion occurred only in localized areas where flow energy was concentrated. These observations suggest that pools might be created in the initial construction, at least partially, although these considerations have to be weighed against the added costs involved. Planting banks with willow cuttings as soon as possible after construction might also have helped to mitigate the bank erosion.

Longitudinal profiles surveyed in 2005, 2006, and 2007 showed the development of the log step sequences from a smooth grade (Fig. 7). During this period, the restored channel had experienced a 5-year flow event in November 2006. The primary changes in the profiles are the scouring and deepening of some of the pools below steps. Aggradation upstream of some of the steps in the upper profile also occurred. Because the newly constructed channel is
still likely adjusting, more time might be needed to test the system over a greater range of flows to reveal completely the performance and functioning of the log steps.

Dry Canyon Creek

A recent restoration project in Calabasas in southern California (Los Angeles County) utilized step-pools to restore a steep (8.3%) ephemeral tributary of Dry Canyon Creek. Dry Canyon Creek drains into the Los Angeles River, which empties into the Pacific Ocean. The stream had been severely undercut and overrun by non-native plants that were choking the indigenous species. The channel had narrowed in places and reduced valuable habitat. The stream had also accumulated debris from the surrounding urban area (Fig. 8a), including rubble and concrete slabs from attempts to build retaining walls along the creek to extend usable land. This reach of the creek occupies the property recently acquired by the Mountains Restoration Trust (MRT) to serve as the headquarters of the Trust. Restoration of Dry Canyon Creek began in Fall 2006 with a three-pronged plan to meet objectives for habitat restoration, bank stabilization, and human needs (Gilbard 2007). The stream bank and adjacent floodplain were graded and planted with native vegetation, which utilized biotechnical stabilization techniques.

Restoration of the steep tributary of Dry Canyon Creek with step-pools had the advantage of abundant reference information nearby. Situated within the Santa Monica Mountains, characteristics of the Dry Canyon watershed are similar to those of nearby Cold Creek and Big Sycamore Creek in terms of slope, elevation, and drainage area. Theoretical insights developed for the step-pool morphology in Cold Creek and Big Sycamore Creek (e.g., Chin 1998; 1999; 2002) are applicable for restoration design. For empirical relationships, 464 step-pool sequences in 13 channel reaches of Cold Creek and Big Sycamore Creek exhibit average step lengths of 1.6 times the active channel width; step length is related to channel slope as 

\[ L = \frac{2.67}{S^{0.206}} \]

where step particle size is the average of the \( b \)-axis of the five largest rocks comprising each step.

To guide the specific design of the Dry Canyon tributary, however, relationships developed for reaches of Cold Creek and Big Sycamore Creek with the most similar characteristics in terms of slope, particle size, and channel width were used. The step length and height relations of these reaches relative to slope exhibit a range such that the following equation applied: 

\[ 1.1 \leq \frac{H}{L}/S \leq 2.5 \]

The average \((H/L)/S\) ratio is 1.8. Given this, a \((H/L)/S\) value of 1.3 was selected for the initial calculations for determining length and height relations for step-pools. This value gives more modest reverse slopes in the step treads for the new channel to enable natural scouring to occur over time. The exaggerated reverse slopes caused by deep pools in Cold Creek and Big Sycamore Creek had likely developed over the 15–80 years that those steps had been in place (Chin 1998). Thus, with step height calculated as 1.2 times the...
size of coarse particles present in the channel (Chin 1999), as measured, step length could be determined. The design calculations yielded a step length of ~4.9 m and step height of 0.5 m for rock sizes of 0.41 m.

Construction of the artificially manipulated step-pools proceeded with a philosophy of producing as natural a channel as possible in appearance and function. Using rock material from within the channel, the particles were expected to be mobilized by natural flows. The design also allowed pools to scour naturally over time, so they were not dug initially. Thus, the design guidelines provided approximate locations and dimensions for step-pools, serving as “training wheels” for natural processes to fine-tune the step-pool morphology to an equilibrium form.

Upon completion (Fig. 7b), the restored channel of Dry Canyon Creek exhibited 10 step-pools spaced ~2.1 widths apart. The steps ranged in length from 3.3 to 4.9 m (average: 4.0 m) and in height from 0.23 to 0.37 m (average: 0.3 m). Step particles averaged 0.31 m. Calculations of competence (Chin 1998) suggested that steps of similar sizes under comparable conditions in the Santa Monica Mountains are capable of mobilization by flows with recurrence intervals ranging from 8 to 20 years. As-built surveys (Fig. 9) further indicate a step-pool geometry characterized by \((H/L)/S\) ratios ranging from 0.7 to 1.2. These relatively low values reflect the lack of pool development in the newly constructed channel and are expected to increase with flows. The process of scouring in pools is evident in measurements conducted after one storm event on 26–27 January 2008; pools deepened by as much as 0.18 m. These initial adjustments resulted in an average \((H/L)/S\) ratio of 1.1 in the reconstructed step-pool reach. Based on data from gauges in nearby creeks, the estimated recurrence interval of the flow is 2–3 years (Bandurraga,
personal communication). Continued monitoring of the restored channel will reveal the adjustments and functioning of the system over time.

Synthesis, Lessons Learned, and Outstanding Needs

The set of examples presented in this article illustrates a range of design approaches for step-pool sequences that has been utilized in stream restoration over the past decade. These approaches developed in conjunction with advances in theory for step-pool sequences, as described in the first parts of this article. The approaches emphasize geomorphic and hydraulic processes, rather than simply channel form, as in many methods widely used (Wohl and others 2005). The principle of maximum flow resistance suggested by Abrahams and others (1995), in particular, has provided a key basis for restoration design. The reliance on this theory results in part from the ease of its applicability, in that it translates into measurable geometric relationships [as expressed by $1 \leq (H/L)/S \leq 2$]. The designs presented in this article were selected also for the specific settings based on information available at that time and under requirements and constraints of the particular environments.

Many lessons derive from the case studies. Baxter Creek illustrated an early application of artificial step-pools; although the initial design envisioned a spacing that was too far apart, the mixture of rocks was sufficiently sized relative to slope and the flow regime to allow the system to “self-organize” through natural adjustments (Chin and Phillips 2007) toward geomorphic stability and ecological improvement. Restoration of East Alamo Creek within a large residential development required a comprehensive approach utilizing geomorphic, hydrologic, hydraulic, and sediment transport analysis, together with reference empirical relationships; the larger-than-predicted dimensions of the step-pool sequences reflect stability considerations that have primacy over fully natural function under such settings. Construction of the step-pool channel in Karnowsky Creek within the Siuslaw National Forest overcame constraints posed by access and the type and availability of materials; these issues led to the placement of logs intended to allow natural scouring to occur below steps. For Dry Canyon Creek, proximity to nearby reference sites allowed creation of step-pool geometries likely to be successful. Ownership of the site by the Mountains Restoration Trust (a public-benefit land trust with environmental education as one goal) also gave an advantage of utilizing a somewhat experimental approach, with the intention of observing and learning from the responses of the artificial step-pool systems in future years.

The lessons from these case studies allow us to develop a set of considerations useful for restoration of step-pool channels. They include issues pertaining to the design of step-pool sequences, the regulatory environment for permitting, and construction and monitoring of artificial step-pool sequences (Table 2). The answers to these

<table>
<thead>
<tr>
<th>Table 2 Considerations for design, approval, and construction of artificial step-pool sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
</tr>
<tr>
<td>Are empirical relationships available and appropriate for the region and setting?</td>
</tr>
<tr>
<td>Are steps allowed to move and behave as dependent variables in the fluvial system?</td>
</tr>
<tr>
<td>Do the materials erode easily to enable flows to carve pools within a reasonable time?</td>
</tr>
<tr>
<td>Are there requirements for habitat or fish and wildlife passage?</td>
</tr>
<tr>
<td>Is sealing within step particles a likely problem?</td>
</tr>
<tr>
<td>Will erosion likely occur around steps?</td>
</tr>
<tr>
<td>What are the consequences if the project does not function as intended?</td>
</tr>
<tr>
<td><strong>Permitting and regulatory environment</strong></td>
</tr>
<tr>
<td>Are proposed designs consistent with regulatory agency criteria?</td>
</tr>
<tr>
<td>Are agencies willing to consider/accept alternative methods?</td>
</tr>
<tr>
<td>How much disturbance of existing channels is acceptable to environmental regulatory agencies?</td>
</tr>
<tr>
<td><strong>Construction and long-term monitoring/maintenance</strong></td>
</tr>
<tr>
<td>Are local/ existing rock materials available for constructing steps?</td>
</tr>
<tr>
<td>What size of rock can be handled on-site?</td>
</tr>
<tr>
<td>Are qualified construction crews available?</td>
</tr>
<tr>
<td>How much on-site construction observation/guidance is needed?</td>
</tr>
<tr>
<td>How much design-build vs. detailed plans and specifications is appropriate?</td>
</tr>
<tr>
<td>How much tolerance from the design specifications is acceptable?</td>
</tr>
<tr>
<td>Is there a program for post-construction monitoring and maintenance?</td>
</tr>
<tr>
<td>What is the appropriate frequency of post construction monitoring?</td>
</tr>
<tr>
<td>How should long-term maintenance be funded? What is the expected cost? Who will perform this maintenance?</td>
</tr>
</tbody>
</table>
questions dictate which of the available concepts, empirical relationships, or theoretical considerations might be emphasized in restoration design. The case studies outlined here also elicit fundamental (and sometimes philosophical) questions concerning the appropriate strategy for restoration using step-pools (Table 3). These include, for example, the extent to which steps should be “designed” and pools should be created during restoration. Additional observation, experimentation, and research are likely needed to yield insight into these questions. Consideration of whether the impacts that led to degradation are in-channel or watershedwide (e.g., Harden 2006; Wohl 2006) might also determine whether restoration of a step-pool reach is appropriate, as opposed to catchment-scale efforts (Downs and Gregory 2004). Constraints, requirements, and practical considerations of particular situations will also dictate what approaches are feasible. Although stream restoration using step-pool sequences has progressed along with developments in theory, many outstanding challenges still remain (Table 4). These challenges provide opportunity for continuing research.

As with all stream restoration projects (e.g., Downs and Kondolf 2002; Kondolf and Micheli 1995; Kondolf and others 2007; Palmer and others 2007), monitoring restored step-pool systems and making the monitoring results available to practitioners is important, so that the adaptive management loop is closed. The understanding gained from such observations will prove invaluable for improving future restoration designs. Artificial step-pool systems also provide unique field laboratories with which to test theoretical concepts concerning the genesis and evolution of step-pool systems. Theory and practice converge, therefore, with respect to restoration of step-pool systems. Because of the increasing significance of, and urgent need for, installation of steps and pools under changing land uses, we advocate a continuing focused effort toward bridging science and implementation for successful stream restoration using step-pool sequences (Wohl and others 2005). Echoing the sentiments reported in Bernhardt and others (2007), we also advocate the direct collaboration of researchers, applied practitioners, and resource managers toward improving future restoration design and advancing restoration science.

Acknowledgments We thank Rune Steoresund, Kate Huxster, and Drew Goetting as well as Samantha Sellers and Eric Williams for assistance with field surveys in Baxter Creek and Dry Canyon Creek, respectively. We also thank the numerous individuals who provided insightful discussions during the course of this project. PWA acknowledges the work of Michael Burke in the step-pool design of East Alamo Creek. Cristina Alejandre and David Laurenco assisted with manuscript preparation. W. Andrew Marcus and two anonymous reviewers provided helpful comments that improved the final manuscript. This article was developed with support in part from the National Science Foundation (BCS 0620543).

Table 3 Fundamental questions concerning appropriate strategy for restoration using step-pool sequences

<table>
<thead>
<tr>
<th>Question</th>
<th>Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are impacts that led to restoration in-channel or watershed wide?</td>
<td>Are efforts necessary to address processes at the watershed scale, in addition to the step-pool channel?</td>
</tr>
<tr>
<td>Is restoration of a step-pool reach appropriate if watershed-scale impairments exist?</td>
<td>Should we create pools during restoration, or just build steps and allow pools to scour naturally?</td>
</tr>
<tr>
<td>Should we create pools during restoration, or just build steps and allow pools to scour naturally?</td>
<td>How much should we “design” steps versus simply introducing clasts and allowing them to form steps naturally during high flows?</td>
</tr>
<tr>
<td>What grain-size range and mixture should be present between the relatively immobile step-forming clasts?</td>
<td>How stable should the banks be, given that step-pools channels tend to adjust and maximize roughness vertically rather than laterally?</td>
</tr>
<tr>
<td>What is the role of wood in different settings, and how do we determine the proportion of wood versus non-wood steps, the geometry of wood vs. non-wood steps, and the residence time and size of wood in forested systems?</td>
<td>How can we most effectively balance the sometimes conflicting requirements between different objectives? For example, in a project where fish passage and channel stability are both objectives, rock sizing would likely involve compromises. Larger rocks are more stable, but particle size strongly influences step height, which is a limitation to fish migration.</td>
</tr>
</tbody>
</table>

Table 4 Outstanding challenges for restoration using step-pool sequences

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our ability to translate idealized relationships and models to real-world settings;</td>
<td>Our capability to construct adjustable step-pool bedforms that respond to prevailing flow and channel hydraulics;</td>
</tr>
<tr>
<td>The increasing need to build step-pool bedforms where they are not found naturally (e.g., lower-gradient areas) because of altered hydrogeomorphologic conditions due to land-use changes;</td>
<td>Potential problems associated with the viability of organisms adapted to a different bedform regime;</td>
</tr>
<tr>
<td>Predicting the responses of artificial step-pool systems under changing environmental conditions.</td>
<td></td>
</tr>
</tbody>
</table>

References

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