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Riparian proper functioning condition assessment to improve watershed management for water quality

S. Swanson, D. Kozlowski, R. Hall, D. Heggem, and J. Lin

Abstract: Pollutants can be reduced, ameliorated, or assimilated when riparian ecosystems have the vegetation, water, and soil/landform needed for riparian functions. Loss of physical form and ecological function unravels assimilation processes, increasing supply and transport of pollutants. Water quality and aquatic organisms are response measures of accumulated upstream discharges, and ultimately of changes in riparian functions. Thus, water quality monitoring often fails to identify or lags behind many causes of pollution or remediation from riparian degradation. This paper reviews the interagency riparian proper functioning condition (PFC) assessment for lotic (running water) riparian ecosystems and outlines connections between PFC and water quality attributes (sediment, nutrients, temperature, and dissolved oxygen [DO]). The PFC interaction of hydrology, vegetation, and soils/landforms influences water quality by dissipating energy associated with high waterflow, thereby reducing vertical instability and lateral erosion while developing floodplains with captured sediment and nutrients. Slowing flood water enables aquifer recharge, deposition, and plant nutrient uptake. Water-loving, densely rooted streambank stabilizing vegetation and/or wood helps integrate riparian functions to maintain channel pattern, profile, and dimension with characteristics for a diversity of habitats. A complex food web helps slow the nutrient spiral with uptake and storage. Temperature fluctuations are dampened by delayed discharges, narrower and deeper active channels, coarser substrates that enhance hyporheic interchange, and shade from riparian vegetation. After assessment and implementation, monitoring recovery of impaired riparian function attributes (e.g., streambank plant species) naturally focuses on persistent drivers of water quality and aquatic habitat. This provides timely environmental indicators of stream ecological health and water quality remediation projects or land management.

Key words: environmental indicators—function—nutrients—rivers and streams—sediment—temperature

Water quality standards are based on needs for beneficial uses, whereas opportunities for remediation are often based on need(s) for riparian functions. Water quality or biological community assessments (USEPA 2009a, 2009b) cannot predict if an ecosystem is crossing geomorphic or ecological thresholds causing devastating changes to the riparian and aquatic ecosystems (Hall et al. 2014; Kozlowski et al. 2013). For nonpoint source issues, water quality data are lagging indicators (response indicators) and do not inform riparian resource managers or riparian restoration monitors in a timeframe relevant for adaptive management. Water quality and many other terrestrial and aquatic ecosystem goods and services depend on riparian functions. One of the goals of many federal, state, and tribal environmental and natural resource programs is to maintain and restore functionality of stream and wetland riparian areas. This impacts sediment and nutrient loads, dissolved oxygen (DO), and water temperature, and it sustains beneficial uses and values (fisheries, recreation, etc.) and ecosystem services. Regulating water pollution is a key Clean Water Act (CWA) tool. Success of the water programs (e.g., total maximum daily loads [TMDL] and the CWA Section 319 restoration program) in controlling point sources (PS) and nonpoint sources (NPS) is based on identifying actions to attain water quality standards (FWPCA 1972).

The US Environmental Protection Agency (USEPA) is revamping its impaired water body (CWA Section 303d) program to augment the TMDL focus with measures to better address restoration of impaired and protection of unimpaired waters. In 2012, the USEPA published its draft "Long-Term Vision for Assessment, Restoration, and Protection under the Clean Water Act Section 303(d) Program." The nonbinding document calls on states to identify protection planning priorities and coordinate implementation of key PS and NPS control actions to achieve water quality goals. The document emphasizes states' flexibility to adopt alternatives to developing TMDLs, especially in situations where a "straight to implementation" program can be enacted. The Nevada Nonpoint Source Management Plan (NDEP 2015) references riparian concepts 34 times and explicitly recognizes the role of riparian proper functioning condition (PFC) assessment in riparian and water quality management.

To help focus on opportunities for better riparian management, the National Riparian Service Team of the Bureau of Land Management (BLM) and US Forest Service (US FS) developed and continue to teach riparian PFC assessment (Pritchard et al. 1993, 1998; Dickard et al. 2015) along with teams of trainers in many states. The BLM and their Resource Advisory Councils adopted PFC as a local and national standard for riparian management in the 1990s. According to Dickard et al. (2015), "A lotic riparian area is considered to be in PFC, or 'functioning properly,' when adequate vegetation, landform, or woody material is present to:

- Dissipate stream energy associated with high waterflow, thereby reducing erosion and improving water quality.

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- Capture sediment and aid floodplain development.
- Improve floodwater retention and ground-water recharge.
- Develop root masses that stabilize streambanks against erosion.
- Maintain channel characteristics."

A focus on PFC is helping the BLM and many national forests (US FS 2012) and other agencies, landowners, and watershed collaborators to focus on riparian functions that improve water quality. Hudson (2015) recommended a similar approach for private grazed watersheds where regulation is socially challenging. The objective of this paper is to encourage all watershed managers to use the PFC tool and concepts to address and report water quality problems caused by impaired riparian functions.

Streams transport water, nutrients, minerals, sediments, and organic matter within a watershed. The natural or appropriate rate of transport and deposition can differ broadly within a watershed and among stream reaches (Dickard et al. 2015). Properly functioning stream and wetland riparian areas often sequester pollutants through physical and biological processes associated with form needed for flood energy dissipation. For example, a low-gradient and wide valley channel develops meanders that reduce slope and floodplains that spread flood waters across a wide vegetation-roughened surface. In a higher gradient setting, channel form needed for flood energy dissipation may involve woody vegetation and woody material providing roughness and structure for steps and pools. Deposition of bedload sediment and suspended material followed by plant succession creates new floodplain areas and thereby enhances aquatic and riparian habitat complexity. These physical processes support functions, such as aquifer recharge, and improve water quality. Impairment of riparian functions changes hydrologic, vegetative, and geomorphic interrelationships, which may trigger cascading environmental effects and long-term consequences, such as channel incision (Schumm 1979, 1984; Schumm et al. 1984; Simon and Rinaldi 2006; Corenblit et al. 2007; Hall et al. 2014). Maintaining healthy aquatic and riparian habitats depends on integrated riparian management (Dickard et al. 2015) that maintains or facilitates natural recovery of riparian functions after natural or anthropogenic disturbances. Maintaining physical functions sustains a diversity of land uses and water quality at levels better than required by state and tribal water quality standards (Kozlowski et al. 2013).

PFC is an interdisciplinary (botany, biology, hydrology, geomorphology/pedology, etc.) assessment protocol focusing on physical structure and functioning in relation to on-site potential. Although qualitative, it is based upon quantitative science and could be quantitatively measured (Dickard et al. 2015; Leonard et al. 1992). These qualitative on-site assessments provide context about the potential and needed attributes for ecosystem functions. PFC incorporates the important attributes that numerically based surveys commonly address. The PFC assessment adds context and value to quantitative inventory or monitoring data about water quality, physical habitat, and aquatic organisms. Analysis of quantitative data is often based on standard expectations or classifications that only partially capture inherent spatial variability or fail to distinguish it from differences related to management (USEPA 2013, 2009a, 2009b). The difficulty of correctly interpreting and defining spatial differences stems from the inability of some protocols (Hall et al. 2009; Hare et al. 2012, 2013) to adjust expectations for varying ecosystem function potential. For example, water temperature varies across elevation zones and differences in hydrology. Yet, USEPA/state water quality standards are based on beneficial uses, not the potential of local settings. The failure of not basing data analysis on local potential (Hall et al. 2014) makes it difficult or impossible to determine condition or measure effectiveness of best management practices (USEPA 2009a, 2009b).

Riparian PFC assessment begins with an interdisciplinary consideration of potential, the highest ecological status a riparian area can attain in the present climate (Dickard et al. 2015). Potential, or potential natural condition, is based upon the concept of dynamic equilibrium of the vegetation and of the channel at grade (Leopold et al. 1964; Schumm 1979, 1984) within an ecosystem that corresponds to the physical setting (Rosgen 1994, 1996, 2006; Brierley and Fryirs 2000; Kondolf 2003; Brierley et al. 2011). The linkage between the channel, soil/landform, and vegetation allows the assessment to focus on stream reaches. Reaches are homogenous lengths differing from other reaches in their potential landform, hydrology, and vegetation to produce a repeating sequence of plant communities, habitats, biota, and water quality for beneficial uses. The rationale for the PFC assessment has been summarized in technical references (Prichard et al. 1993, 1998; Dickard et al. 2015). Water quality managers gain perspective by using PFC assessment by reach across the many reaches throughout a watershed or land holding. Clemmer (1994) describes methods for speeding PFC assessment by using aerial photography.

Each of the 17 items of the PFC assessment addresses one or more specific and important attribute, process, or function necessary to maintain a functioning riparian ecosystem. These attributes individually and/or collectively control capture, uptake, or assimilation rates of biogeochemical reactions, as well as storage and release. Because expectations for riparian form and function vary according to potential (Dickard et al. 2015), this paper will illustrate concepts by focusing on low-gradient streams. These settings are noted for their dependence on a combination of hydrophilic riparian vegetation, and floodplain access for maintaining channel form, bank stability, and many attributes and processes related to water quality.

Widespread impairment of riparian functions has been observed by the authors and is reflected in agency data where available (USDI BLM 2013). Riparian impairment often results from intentional (e.g., channelization, meander straightening, and leveeing) and unintentional human actions (e.g., riparian vegetation-impairing land use management, channel incision, and altered hydrology or sediment supply). Understanding the relationship between water quality and riparian PFC provides resource managers a tool to more effectively manage (Swanson 1996; Wyman et al. 2006; Aron et al. 2013; Hall et al. 2014; Dickard et al. 2015; Swanson et al. 2015) and monitor (Winward 2000; Burton et al. 2011) for water quality. A refocus on PFC for water quality management emphasizes leading indicators of the drivers of ecological processes. Current water quality monitoring approaches, though very effective for addressing PS or off-site pollution, use lagging indicators of the effectiveness of most land management impacts or riparian remediation projects (Hall et al. 2014; Aron et al. 2013). Furthermore, water quality varies greatly temporally. For example, temperature, nutrients, and other

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environmental variables fluctuate through time and space in relation to diurnal (daily) and annual cycles, and in response to storm hydrographs. Aquatic organisms alter their individual physiology and community structure to adapt to the respective ecosystems' normal range of variation (e.g., floods and droughts). Properly functioning streams and wetland riparian ecosystems provide a steadying influence on water quality and aquatic habitat attributes. Their attributes can be consistently measured most any time (when not snow-covered) without the need for average conditions based on repeated measures. However, repeated measures spaced to detect trend can quantitatively monitor progress of riparian attributes or from remediation projects, programs, or management (Burton et al. 2011; Brierley et al. 2010). This monitoring with adaptive management fits well as a "direct to implementation" (or category 4b) alternative to a TMDL in the CWA.

PFC assessment focuses on 17 items (indicators) in three categories—hydrology, vegetation, and geomorphology. Each item or statement receives a "yes" (the statement is true or meets criteria), "no," or "NA" (not applicable) by the interdisciplinary team after they observe reach conditions and consider functions relevant to local potential. NA is an acceptable response for all but 5 (3, 5, 13, 16, and 17) of the 17 items. For each item, space is provided on the PFC assessment form for notes. These groups and items are explained below to provide a framework for discussing water quality influences or riparian functions and ramifications of losing properly functioning conditions. The assessment process thus describes the observed conditions and their severity. Estimates or numerical measurements such as bankfull channel dimensions or bank height ratio (bank height divided by bankfull depth) add welcome clarity. Reach by reach assessments can then be combined to highlight the processes and locations driving risk and need or opportunity for remediation.

Hydrology

Hydrology is integral to riparian functions and water quality because channels form in relation to the distribution of water discharges through time as influenced by climate, geomorphic position, and stabilizing riparian vegetation (Rosgen 2006), much of which depends on abundant water or saturated soils (Winward 2000). Altering water flows or the equilibrium between the channel, vegetation, and floodplain can lead to subtle adjustments or major state changes (Dickard et al. 2015). In addition to influences on vegetation, erosion, and deposition, and therefore on channel pattern, profile, and dimension, hydrology affects water quality by influencing concentration of chemicals, thermal mass, and structure of aquatic habitats (Bilotta and Brazier 2008; Van Vliet and Zwolsman 2008).

1—Floodplain Is Inundated in "Relatively Frequent" Events. The active floodplain is the level depositional area adjacent to the river channel, constructed by the river in the present climate. It is at least partially inundated during moderate flood events (Wolman and Leopold 1957; Schmudde 1968; Alexander and Marriott 1999) occurring, on average, about two out of three years (Leopold 1994; Moody et al. 2003). Natural floodplains vary in character depending on their climatic setting, catchment size, valley width and slope, and sediment supply (Prichard et al. 1998; Rosgen 1996; Marti and Sabater 1996). The purpose of this item is to determine if frequent flood flows (1.5 to 2 year return interval and larger) are able to spread out on a low-lying area adjacent to the stream where such a floodplain is expected (figure 1).

A stream having frequent access to its floodplain dissipates flow energy across a wide surface. Energy dissipation during floods allows streambank vegetation to withstand peak flow forces (Item 13). Frequent flooding and saturated, possibly anaerobic, soil conditions sustain riparian vegetation (Girel and Pautou 1997; Kozlowski 1984), especially the stabilizing wetland plants needed for channel stability (Items 6, 8, 9, 10, and 11) (Girel and Pautou 1997; Bush and Van Auken 1984; Hupp and Osterkamp 1985; Baattrup-Pedersen et al. 2013).

Increased floodplain residence time provides more water recharge to groundwater aquifers, allowing water to seep back into streams during dry seasons or years (Freeze and Cherry 1979; Blackport et al. 1995). This helps stabilize flow and moderate water temperature (Caissie 1991; Blackport et al. 1995). Cooler groundwater discharge in summer allows higher DO (Caissie 1991; Power et al. 1999) particularly important to cold water fish. Additionally, warmer groundwater discharge in winter may keep water from freezing into the bed (anchor ice) and occupying refugia habitats (Cunjak and Power 1986; Power et al. 1999).

If the answer to Item 1 is "yes," water is spreading and infiltrating across a broad surface allowing excess sediment, nutrients, and pollutants to deposit (Marti and Sabater 1996), rather than move downstream where they could damage aquatic habitats and impair water quality (Bilotta and Brazier 2008). Denitrification (Schipper et al. 1993), accumulation of fine textured organic rich sediment, and phosphorous (P) adsorption are strongly influenced by water residence time from flooding (waterlogging) (Pinay et al. 1993; Girel and Pautou 1997; Kaushal et al. 2008).

When the response to Item 1 is "no," frequent floods are restricted from reaching a floodplain. This may result from an incised, smoothened, or oversized channel or an upstream reservoir. The effects of drought on base flow are magnified without adequate aquifer recharge. Van Vliet and Zwolsman (2008) found that decreases in discharge due to drought caused increased water temperatures, nutrient loads, and algal blooms. Where or when a stream incises (Item 16), it loses the important function of floodplain energy dissipation, inundation, and associated water quality benefits. The loss of floodplain function results in streambank erosion, which can increase pollutants in water (Shields et al. 2010). Where the response to Item 1 is "NA," a floodplain is not consistent with the geomorphic potential for the setting (e.g., steep step-pool channel type in a narrow valley).

2—Beaver Dams Are Stable. Beaver (*Castor Canadensis*) dams are instrumental in hydrologically modifying valley bottoms and facilitating riparian recovery (Demmer and Beschta 2008) (figure 2). Presence of beaver dams increases hydrologic complexity and riparian width (Item 4) by influencing the formation of new meanders, pools, and riffles, and improved soil moisture conditions (Burchsted et al. 2010), which facilitates riparian plant growth (Items 6 through 12). Increased complexity of streambed morphologic functions affects aquatic biodiversity (Briggs et al. 2013; Smith and Mather 2013), including increased habitat heterogeneity, rearing and overwintering habitat, flow refuge, and water quality (Kemp et al. 2012; Bledzki et al. 2010). Where beaver dams are present, many implications for water quality depend on whether they are stable and

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Figure 1
Riparian area at risk of channel incision in background and incised in foreground. Sediment deposition on floodplain with infiltration and nutrient capture is converting to concentrated hydraulic forces with rapid bed and bank erosion.

actively being maintained. The purpose of this item is to determine if beaver dams are present and are being maintained or have been stabilized by vegetation.

Beaver dams/ponds alter channels and accumulate sediment (Burchsted et al. 2010). Much of the nutrient load is retained in floodplains and bottom sediment with a portion going downstream (Naiman et al. 1994). Beaver ponds reduce discharge due to evaporation and transpiration. They were found to lower concentrations of total nitrogen (TN), total P (TP), and total suspended solids (TSS) (Correll et al. 2000; Burchsted et al. 2010), and increase acid neutralizing capacity and pH (Margolis et al. 2001). Correll et al. (2000) found that prior to pond building, these constituents were highly significantly correlated with discharge. During high flows (spring runoff), TSS, TP, sodium hydroxide extractable P (NaOH-P), and total Kjeldahl N (TKN) were reduced when water flowed through a series of beaver ponds (Maret et al. 1987). Reduction was greater during warmer periods, suggesting biological processes were responsible (Maret et al. 1987). However, in low flows TN, dissolved organic carbon (C), TP, particulate P, ammonium (NH_4^+) and both total and methyl mercury ($[CH_3Hg]^+$) were elevated (Roy et al. 2009). Nitrates (NO_3^-) may have been transformed with microbial denitrification enhanced by anoxic substrates, ample organic matter, and increased residence times. Ortho-phosphate (OP) did not appear to be affected by the ponds (Maret et al. 1987). Klotz (2010), summarizing literature and using empirical data, found a 35.5% reduction of NO_3^- levels in water passing through beaver ponds.

If the response to Item 2 is "yes," beaver dams generally increase base flows and decrease high flow intensity, but not duration. During drought, ponds can provide complimentary habitat and increased water quality that enables successful fish reproduction (White and Rahel 2008). However, increased evapotranspiration may be important enough in some systems to reduce base flows.

When the response to Item 2 is "no," an unvegetated dam is not being maintained or cannot be maintained long-term due to limitations of the location, beaver forage, or woody building material. Loss of a dam means potential degradation and adjustment that can include stream incision with loss of floodplain access, riparian dehydration, channel widening, and lateral migration into accumulated sediment, organic matter, and nutrients. Implications to water quality are then similar to those addressed in Item 3. Sudden large dam failure can release stored water and sediment, potentially overwhelming downstream dams and reaches.

3—Sinuosity, Gradient, and Width/Depth Ratio Are in Balance with the Landscape Setting (i.e., Landform, Geology, and Bioclimatic Region). Streams differ in their gradient, pattern, and form depending on their landscape setting (Rosgen 1994, 2006; Kondolf et al. 2003; Brierley and Fryirs 2000). Steep headwater reaches tend to be sources of water and sediment. Middle or medium gradient reaches with sloping margins transport sediment to low gradient response reaches where the valley widens, allowing meanders (sinuosity) and floodplains. Floodplains (Item 1) act in concert with channel form and pattern and vegetation to keep hydraulic stresses within an acceptable range (Item 13), allowing for gradual channel migration. The purpose of Item 3 is to determine if the stream is in balance (i.e., shape, pattern, slope, and size) with its setting. Within a balanced system, a more natural pattern, profile, and dimension tend to maintain dynamic equilibrium and better process pollutants (Sweeney et al. 2004).

Accelerated erosion can result from management that impairs vegetation (Items 6 through 12) or floodplain access (Item 1), removes woody debris (Item 12), and from direct modification of floodplains or channels (Item 13). Leopold et al. (1964) discussed eight interacting variables (channel width, depth, slope [Item 3], hydraulic roughness and water velocity [Item 13], sediment load and size, and discharge [Item 17]) that adjust in relation to changes/alterations in any of these variables. Stream channelization varies from simple removal of rocks or snags, which can lead to faster water and channel incision, to channel reconfiguration (straightening) or reconstruction (Brookes 1985; Simon and Rinaldi 2006). These alterations can significantly increase erosion and sediment discharge (figures 1, 2, and 3) (Simon 1989; Simon and Rinaldi 2006; Hupp et al. 2009; Florsheim et al. 2011). Stream incision generally causes accelerated bank erosion and decreased riparian amelioration of water quality. Increased channel depth through incision (Item 16) abandons the floodplain (Item 1), lowers water table elevation, and decreases riparian plant growth (Item 8).

When the response to Item 3 is "no," altered sinuosity, gradient, or width/depth ratio often increases bank erosion (Item 15). Sediment and water quality problems are associated with nutrients from freshly eroded sediment, or the physical effects of excess sed-

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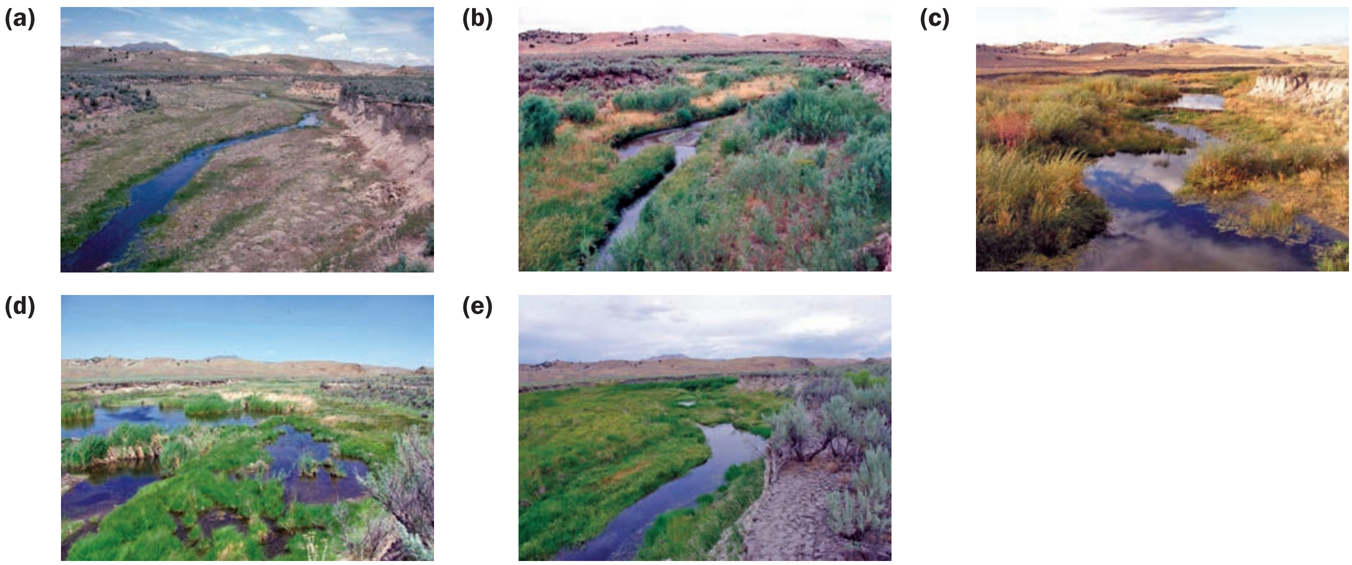
Figure 2

(a) Incised stream had exported over a million cubic meters of sediment and nutrients after incision. (b) With altered management after 1991 and recovery of willows by 1999, (c) beaver had materials to build dams that slowed runoff by 2007. (d) Riparian functions increased base flows, capturing sediment and nutrients in a very wet year of 2011 so that water remained even in the very dry year of 2012. (e) Riparian functions allowed the stream in places to convert successfully from beaver ponds to an unponded stream with an accessible and well-vegetated floodplain. Riparian functions provided clean water for base flows in a series of drought years through 2014. Photos used by permission of Carol Evans, fisheries biologist, Elko US Department of the Interior Bureau of Land Management, and *Journal of Rangeland Applications*.



iment (Schumm 1979; Zaimes et al. 2009; Chapman et al. 2014). Higher width/depth ratios can increase insolation and radiation leading to greater fluctuation in water temperatures and DO. Increased sunlight and temperatures often facilitate algal blooms and a different mix of diatom and cyanobacteria species (Pan et al. 2006). Greater width and/or increased sediment may allow deposition of fine sediments in stream substrate creating benthic habitat conducive to only sediment tolerant organisms. Embeddedness can limit spawning-gravel DO and hyporheic groundwater/surface water interactions with limitations for riparian plant nutrient uptake and temperature moderation by groundwater.

4—Riparian Area Is Expanding or Has Achieved Potential Extent. A riparian zone achieves its potential aerial extent in two ways: (1) riparian vegetation can spread and survive to outer limits determined by topography, hydrology, and water table elevation; and (2) riparian vegetation can establish on soils deposited along the streambanks, narrowing the stream and helping it achieve an equilibrium width to depth ratio (Item 3) (figure 3). Riparian widening is generally associated with recruiting vegetation (Item 7), increased water elevation (Items 1 and 8), or with building a floodplain through channel narrowing (Items 3 and 14). The purpose of this item is to determine if the riparian area is recovering (figures 2 and 3), or has recovered, or is at potential (figure 4).

Riparian vegetation provides roughness that slows water velocity, allowing for sediment (Parsons et al. 1994; Osborne and Kovacic 1993) and organic matter deposition (Welsch 1991; Groffman et al. 1991; Correll 1997). The riparian zone is determined to be at its maximum potential width when the stream channel has narrowed (Item 3) and riparian expansion, with a high water table, is fully achieved (Zimmerman et al. 1967; Davies-Colley 1997; Sweeney et al. 2004). In surface runoff, most N is in the form of organic N associated with suspended solids, and P moves more efficiently on soil particles. Herbaceous and woody vegetation can be very effective at removing NO_3^- through deposition and absorption (Haycock and Burt 1993; Gilliam et al. 1997; Osborne and Kovacic 1993; Correll et al. 1996; Mayer et al. 2006), and biological (microbe and plant) uptake (Peterjohn and Correll 1984). In the recovery phase after degradation, riparian areas improve functionality and water quality as riparian width increases (Castelle et al. 1994; Gilliam 1994; Lowrance et al. 1997) through induced deposition and/or stabilized stream margins (DeSteven and Lowrance 2011). Riparian expansion is often one of the first indicators of, or steps toward, recovery (Schumm 1984; Schumm et al. 1984; Dickard et al. 2015). When the response to Item 4 is "no," riparian amelioration of water quality is diminished. In a degraded system the riparian zone can become dehydrated from incision (Item 16) or diminished by accelerated bank erosion (Item 15). Both have significant water quality ramifications.

5—Riparian Impairment from Upstream or Upland Watershed Is Absent. Each watershed delivers a predictable range of flows and sediment loads based on geology, geomorphology, land uses, and bioclimatic region. A properly functioning watershed, or catchment (European term), captures, stores, and slowly releases water from precipitation events. Changes in the watershed may contribute to impairment of the riparian reach being assessed. For example, excessive sediment delivery to the stream channel, a lack of sediment, too much or too little water, or a change in timing of water can lead to incision, aggradation, or changes in floodplain access, sinuosity, width/depth ratio, and gradient (Item 3). A variety of watershed management issues could cause changes such as inappropriate management of grazing, logging, fire,

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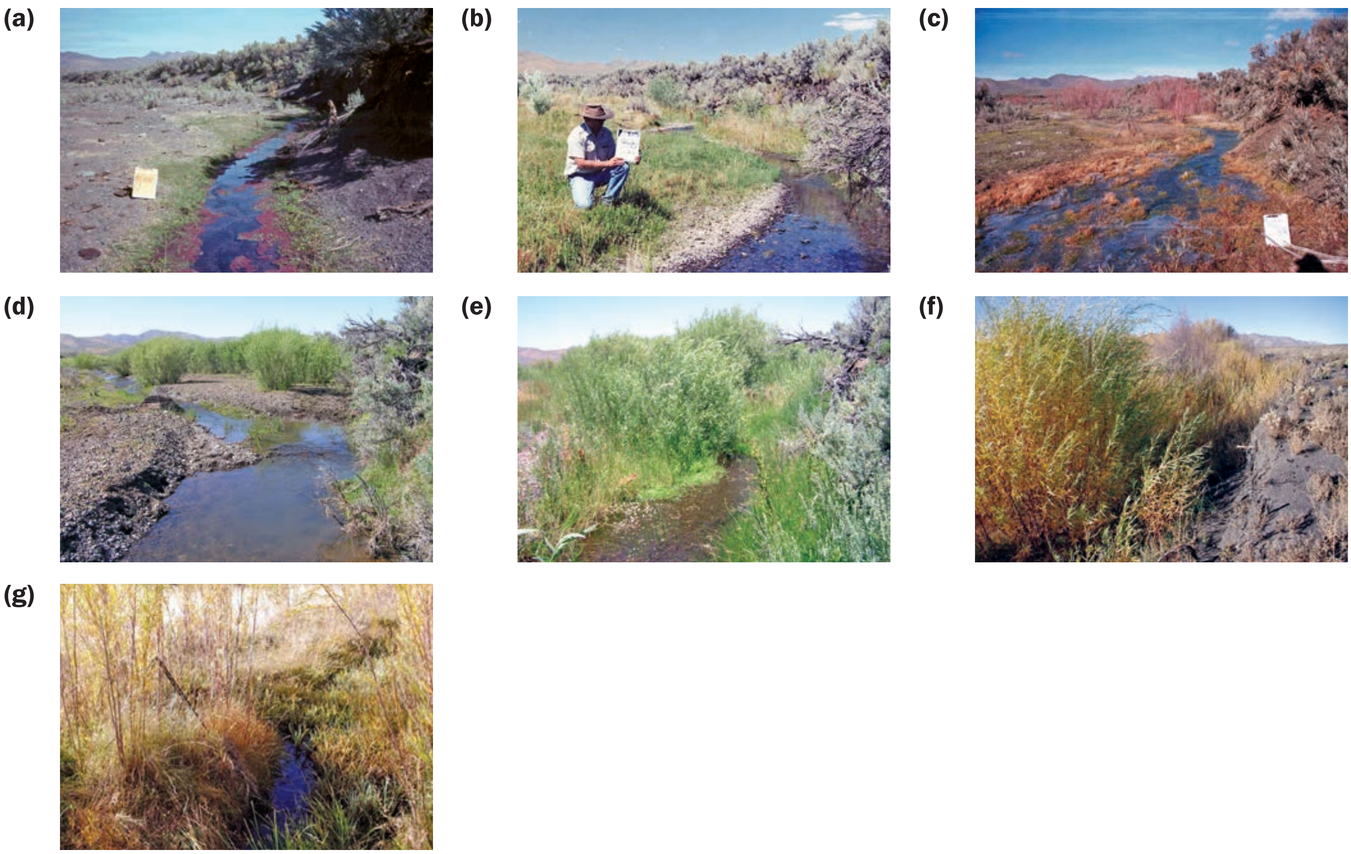
Figure 3

Stream incised decades ago and (a) season-long grazing continued until 1993. A change in management provided rest alternating with spring-only grazing. This allowed (b and c) growing-season recovery of plants after grazing. (d) Increased and stronger vegetation enabled the stream to capture substantial amounts of sediment in a flood year. (e and f) Riparian sedges and willows then grew up through the sediment and (f) the green vegetation resisted wildfire in 2012. Riparian vegetation and functions continued to filter sediments; aid in floodplain development that enhances aquifer recharge; and provide roughness and bank stability for a narrower, deeper, and shaded active channel (g) with improved water quality. Photos used by permission of Carol Evans, fisheries biologist, Elko US Department of the Interior Bureau of Land Management and *Journal of Rangeland Applications*.



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farming, roads, etc. A well-functioning riparian zone tends to be resilient, handling some increases and decreases of water or sediment without exceeding a threshold of stability. The purpose of this item is to determine if changes in the water and/or sediment being supplied to a riparian reach contribute to its impairment, altered form, or loss of functions. Additional watershed management issues could cause water pollution, but not riparian impairment (altered form and function). Examples of these issues include suspended sediment from accelerated erosion, eutrophication from over fertilization, and toxic chemicals or altered stream temperatures that do not diminish stabilizing plants. These water quality issues would not be assessed with PFC.

When the response to Item 5 is "no," (watershed is contributing to riparian impairment), the direct implication for water quality is usually an increase in sediment load and the associated pollutants that come with it. Loss of key riparian plants from dehydration could do the same, and thus trigger the water quality implications of other items (e.g., Items 11 and 13). Erosion brings pollutants that can include nearly anything, depending on what is occurring within the watershed. Secondary implications may exceed direct effects. Once a change in bedload sediment or bed elevation exceeds a threshold, adjustments to channel form often release fine sediment with stored nutrients through bank erosion (Items 3, 15, 16, and 17). Water quality and quantity are closely linked, especially in low flow conditions.

Vegetation

Vegetation is a major influence on riparian form and function. Roots bind soil for streambank stability. Exposed plants and woody material provide roughness that slows water flow. Shade reflects radiation, steadying temperatures. Plant production plays a major role in riparian communities, habitats, and food webs. Vegetation influences water chemistry with nutrient uptake and input of leaf litter and other organic materials.

6—There Is Adequate Diversity of Stabilizing Riparian Vegetation for Recovery/Maintenance. Plants thrive in different microsites, uptake/process nutrients, mitigate pollutants, and trap sediment (figures 2, 3, and 4). Many riparian plant species have evolved to withstand the tremendous forces of flood discharge (figures 2, 3, and 4) (Swanson 1996; Corenblit et al. 2011) with their extensive root systems (Manning et al. 1989; Winward 2000; Corenblit et al. 2007). For riparian recovery, at least some stabilizing species must be present. Stabilizers include most tall clumped willows (*Salix* sp.

L.), rhizomatous sedges (*Carex* sp. L.), rushes (*Juncus arcticus* Willd.), and bulrushes (*Scirpus* or *Schoenoplectus* sp. Rchb.), but few grasses and few forbs (herbaceous dicots) (Burton et al. 2011). Bluejoint reedgrass (*Calamagrostis canadensis* Michx.), switchgrass (*Panicum virgatum* L.), and American mannagrass (*Glyceria grandis* S. Watson) are stabilizers (Winward 2000). A diverse composition of stabilizing vegetation reduces the risk that an environmental stressor for one species (e.g., plant disease) will diminish stability from vegetation that is needed when possibly catastrophic events occur. Presence is the foundation for recovery and the water quality implications discussed in Items 7 through 12. The purpose of the item is to document the presence of two or more species of stabilizing plants for each needed life form (herbaceous and woody) depending on reach potential.

When the response to Item 6 is "no," present conditions are likely to be highly unstable. Colonizing early successional plants with weaker root systems may provide some remediation but may not persist during high flows when vegetation roughness and bank stability are most important. Stabilizing plants may eventually come in from upstream or elsewhere, but their absence delays the processes for channel (Dickard et al. 2015) and riparian vegetation recovery (Items 7 through 12). Riparian composition is affected by prolonged excessive grazing (figures 2a and 3a), mechanical injury, fine sediment deposition, inundation during flood events (Girel and Pautou 1997; Broadfoot and Williston 1973), fire, plant diseases and parasites, shading, nutrient availability, and plant succession. However, the presence of riparian stabilizers allows their considerable abilities for expansion and riparian self-healing, with water quality remediation, when management improves or with recovery after damaging events (figures 2 and 3).

7—There Are Adequate Age Classes of Stabilizing Riparian Vegetation for Recovery/Maintenance. Recruitment in and near the stream increases or perpetuates shade and water contact, which can decrease water temperature, DO fluctuation, and algal growth (Ghermandi et al. 2009). Growing plants assimilate nutrients, increase roughness (Manning coefficient), and increase bank stability. Collectively, plants of various ages perpetuate riparian functions (Items 6 through 12). Established older mature plants represent considerable C and nutrient storage. In some cases, they provide dead wood that adds structure and roughness to channels and floodplains (Items 12 and 13). Middle-aged plants are capable of reaching water tables during drought and provide resiliency to communities with less susceptibility to disease and fire. Young plants are more susceptible to die-off in drought if their root systems have not grown to reach a persistent capillary fringe over a water table (Item 8). Conditions for successful recruitment may not occur in the same locations within different ecosystems (Scott et al. 1996), or occur every year. However, they must happen often enough to maintain the population (Mahony and Rood 1998). Recruitment is an effective indicator of whether present management allows maintenance or recovery of riparian vegetation for functions that eventually and collectively enhance water quality (Items 8 through 12). The interrelationships of age structure can be complex, but generally expanding, stable, or diminishing populations (Kormondy 1969) can be recognized (figures 3e to 3g and 4). The purpose of this item is to determine if age classes are present, indicating recruitment to maintain an area, or to allow an area to recover. When the response to Item 7 is "no," conditions are not right for recruitment (Mahoney and Rood 1998) or were not right for some important age class.

8—Species Present Indicate Maintenance of Riparian Soil-Moisture Characteristics. Obligate, facultative wetland, or facultative species (Reed 1988; Lichvar and Kartesz 2012) usually indicates the hydrology is suitable to maintain a riparian-wetland community (figures 2, 3, and 4). By definition, hydrophytes grow in wet places where upland plants usually cannot. Riparian vegetation improves aquatic habitat conditions by reducing solar heating through shading, maintaining a narrow and deep channel in low order streams (Brown and Krygier 1970), and cooling via evapotranspiration (Beschta 1984; Theurer et al. 1984; Sinokrot and Stefan 1993), especially in forested ecosystems (Peterjohn and Correll 1986). The purpose of this item is to determine, from observations of plant species and their location, if soil moisture or level of the water table is being maintained or is moving toward its potential extent.

If the response to this item is "yes," hydrophilic (i.e., water-loving) plant communities are present where expected during maintenance or recovery, including streambanks, point bars, midchannel bars, or sometimes stream channel bottoms (Winward 2000). Many hydrophilic species have root masses that effectively bind soil (Items 6 and 9), and drive riparian functions that improve floodplain access (Items 1 and 3). Hydrophytes are directly connected to stream water through hyporheic interchange, and nutrient uptake adds to pollution assimilation. When the response to Item 8 is "no," less hydric riparian plants, or plant communities, indicate channel incision (Items 1 and 16) has lowered the water table, or decreased flows make less water available at critical times. This impacts current functions (Items 1, 3, 7, and 9 through 12), and may lead to cascading effects of channel adjustment (Items 13, 16, and 17) with release of sequestered sediment, nutrients, and pollutants.

9—Stabilizing Plant Communities Capable of Withstanding Moderately High Streamflow Events Are Present along the Streambank. The streambank is where high velocity flows contact material easily eroded if not stabilized (figures 1, 2, and 4). Most later-successional hydrophilic plants have root masses capable of withstanding high streamflow events (Winward 2000; Burton et al. 2011). Where these plants minimize bank erosion, they reduce sediment and nutrient delivery. The purpose of this item is to determine if the streambanks have the right plant community types for recovery and maintenance of the riparian wetland area. Item 6 evaluated whether stabilizing species for recovery/maintenance (Weixelman et al. 1996; Manning and Padget 1995; US FS 1992) are present. This item evaluates whether stabilizing plants are in communities that are on the streambanks where the need is greatest and in patches large enough to stabilize at least some banks (Winward 2000). This is necessary for Item 11 that assesses their adequacy.

When the response to Item 9 is "no," stabilizing plants are not dominant, and streambanks often are undercut and collapse during high flows. This can change the geometry of the stream (e.g., becoming broad and shallow), leading to water quality and other problems associated with Items 3 and 15. Where weakly rooted streambank vegetation or bare banks allow erosion, most or all sediment is delivered directly into the stream, resulting in a sediment-delivery ratio much greater than from upland erosion (Phillips 1991).

10—Riparian Plants Exhibit High Vigor. Plants exhibiting high vigor indicate strong

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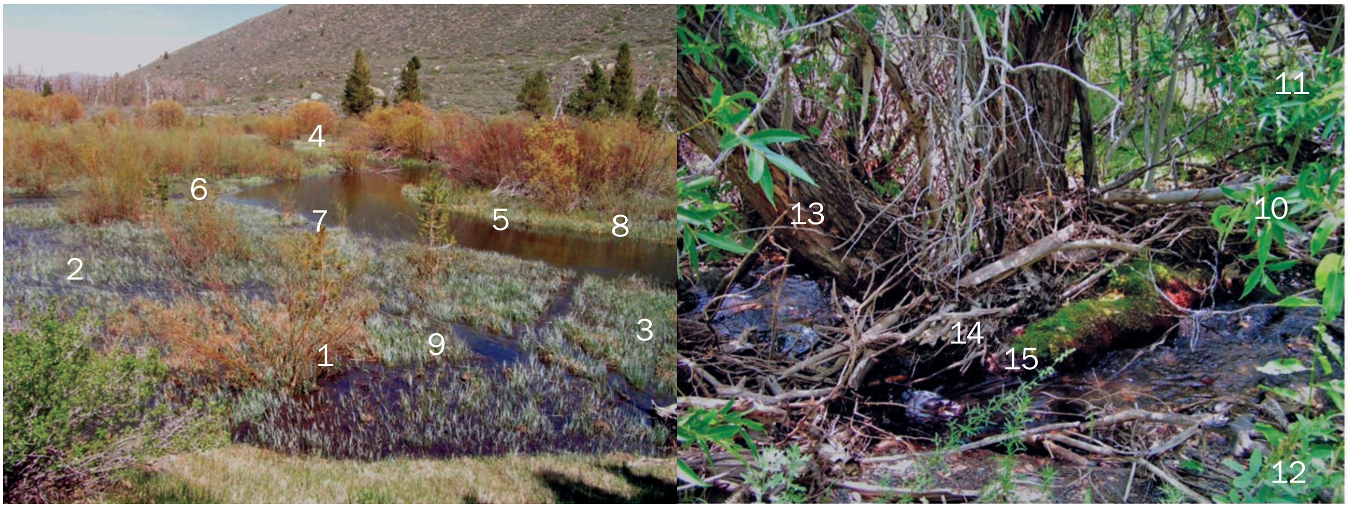
Figure 4

Photos showing physical effects of riparian vegetation on water movement and cycling (expanded from Tebacchi et al. [2000]). Some numbers representing effects could occur in multiple additional microsites. Both locations are functioning properly.



1. Slowing and modifying over-bank flow and watershed runoff with roughness and turbulence from stems, branches, leaves, and detritus.
2. Increasing overbank flow or floodplain access, which increase the wetted surface area and residence time for infiltration and aquifer recharge.
3. Increasing infiltration rate with organic chemistry for soil structures and absorbancy.
4. Increasing the capillary fringe and soil water storage capacity with fine roots and soil organic matter.
5. Slow water at the margins of wide channels, thus inducing deposition and floodplain/bank formation with vegetation growth into the channel.
6. Stabilizing banks to enable meanders to persist and sinuosity to become high, which decreases gradient and velocity.
7. Enable hyporheic interchange and spawning survival by narrowing channels so they become and stay coarser with less embeddedness.
8. Decreasing temperature extremes and summer evaporation by narrowing the channel, which decreases insolation and radiation, increases aquifer discharge, and increases hyporheic interchange with more constant-temperature groundwater, and by providing shade.
9. Increasing floodplain substrate macroporosity with roots and partitioning by particle size in deposition.
10. Transpiration.
11. Interception and condensation of atmospheric water.
12. Evaporation from leaves, etc., of intercepted water from rain, snow, and dew.
13. Increasing stem flow (the concentration of rainfall by leaves, branches, and stems).
14. Back pressure from logs and logjams slows high flows, lessens streambank erosion, and facilitates sediment deposition and storage. Sediment deposition creates areas for water storage and riparian plant colonization.
15. Increasing turbulence, oxygenation, and habitat complexity in channel from root exposure and complex channel form.

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reproduction and rooting systems. Rapidly growing plants process, store, and sequester more nutrients (Bruggemann et al. 2011; Hill 1996; Gilliam et al. 1997) (Item 4). Vigorous riparian plants provide bank stability, shade, and ameliorated water temperatures (Items 2, 3, and 4). Healthy graminoids have larger and stronger leaves and stems, and are more effective at sustaining shear stress and providing roughness (Item 13) for the deposition of particulates. The purpose of this item is to determine if the riparian plants are healthy and robust, or are in a weakened or stressed state or possibly dying out.

When the response to Item 10 is "no," as riparian plants weaken or die out, the reach becomes vulnerable to alteration of the riparian functions important to water quality. Plant succession and colonization of bare areas is slowed. Plants become weaker from improper land use management (e.g., grazing for long periods, especially when uplands are dry without providing periods for riparian plant recovery during the growing seasons) (Wyman et al. 2006; Swanson et al. 2015). Dehydration from channel incision (Items 1 and 16) weakens wetland and riparian plant roots (Toledo and Kauffman 2001).

11—Adequate Amount of Stabilizing Riparian Vegetative Is Present to Protect Banks and Dissipate Energy during Moderately High Flows. Depending on stream type, at least 70% to 90% of streambanks should be covered with stabilizing vegetation or anchored rocks or logs to function properly (figures 3 and 4). Streambank stabilizers may increase nutrient uptake, promote shade and DO, and filter sediment coming from overland flows. Also, they provide bank stability and floodplain access (Item 1) needed to maintain channel width/depth ratio, sinuosity, and gradient (Item 3). The water quality benefits realized by Items 6 to 10 are magnified as more stabilizing species/communities grow and/or expand on streambanks (Tabacchi et al. 2000). The purpose of this item is to determine if there is an adequate amount of vegetation present to protect banks and dissipate stream energies from high-flow events.

When the response to Item 11 is "no," other items in the vegetation part of the list may or may not be yes. In some ways floods are the ultimate test of streambank vegetation. While water quality during the flood may not be the biggest concern, alterations to channel form and riparian functions during floods can have lasting water quality consequences—for example, converting the area from sequestering to releasing sediment and nutrients. Inadequate stabilizing riparian cover puts banks at risk of excessive erosion during high flows. When this allows alteration of channel form or pattern (Item 3), floodplain access (Item 1), or vertical stability (Item 16), dramatic adjustments can have lasting consequences.

12—Plant Communities Are an Adequate Source of Woody Material for Maintenance/Recovery. Streams differ in the degree to which wood from riparian vegetation becomes an integral part of their structure and energy dissipating mechanisms (Naiman et al. 2002; Elosegi et al. 2010). Wood provides roughness, dams for step pools, and armor for banks (figure 4). It reduces channel erosion and sediment transport, allowing particulate matter to be retained to further build the floodplain. Forested or woody dominated riparian communities often have over-story cover providing shade. The evapotranspiration effect keeps air and water temperatures more consistent (Malcolm et al. 2004). Woody debris creates diverse channel morphology and aquatic habitat (e.g., cover) important to various life stages and species with diverse needs (Lee et al. 2004). Water can be oxygenated by plunging over debris, dams, or steps. On smaller streams, the influence of even smaller wood, including branches and root crowns of woody shrubs (e.g., willows [*Salix* sp.]), can be important (Bilby and Ward 1989; Gurnell et al. 2002; Simon et al. 2006). While much of this paper has emphasized the functions of low-gradient streams, the importance of woody plants and debris has been studied most on steeper streams (Bilby and Ward 1989; Naiman et al. 2002; Malcolm et al. 2004). The lack of wood has allowed many streams to suffer significant mass wasting events that greatly diminished aquatic habitat and water quality (Gurnell et al. 2002). The purpose of this item is to determine if the woody material essential for the riparian ecosystem can be supplied by its riparian plant communities.

When the response to Item 12 is "no," riparian plant communities do not provide enough woody material. This weakens riparian functions and makes channels susceptible to erosive forces and incision. As existing wood decays, without replacement, a reduction in channel roughness accelerates flow velocities and shear stress (Item 13), reduces floodplain access (Item 1), and increases export of sediments (Item 17), organic matter, and nutrients (Elosegi and Sabater 2013). This changes channel geometry and aquatic habitat, and channel changes trigger an associated loss of water quality discussed in Item 3.

Geomorphology

Geomorphology processes integrate climate or hydrology with parent materials, sediment, and vegetation to create a landform. Landform adjustments involving erosion and deposition can release or sequester sediment, one of the largest water pollutants (USEPA 2009a, 2009b). Channel form resulting from altered channel erosion or deposition of bedload sediments governs many biological, hydrological, ecological, and geomorphic responses related to water quality.

13—Floodplain and Channel Characteristics (i.e., Rocks, Woody Material, Vegetation, Floodplain Size, and Overflow Channels) Are Adequate to Dissipate Energy. The type and amount of vegetation on the banks and floodplain influence hydraulic roughness and water velocity (Correnblit et al. 2007). Reduced velocity decreases erosion and sediment transport and encourages deposition. Water velocity also decreases with more floodplain surface area accessible, or with overflow channels and with more friction from roughness elements (e.g., vegetation, rocks, debris, and channel bends) (figures 2, 3, and 4). Reduced velocity increases stage or flood depth, increasing opportunities for hydrating floodplain soils, aquifers, and plant communities. Decreased flow velocity increases water residence time, allowing for plants to process/absorb nutrients/pollutants before detained water contributes to post-peak discharge. With energy dissipation, stable banks maintain pattern, profile, and dimension (Item 3), and thereby avoid excess erosion and later insolation (Leopold et al. 1964; Larsen et al. 2006). Floods have the highest potential for erosive forces and for sediment deposition. The purpose of this item is to determine if the flood plain size is adequate (especially important as channels build a new floodplain after incision), and if enough of the right features are present to create friction and dissipate energy during 5-, 10-, and 25-year flow events. The water quality benefits of these features have already been addressed in Items 1, 3, 4, 11, and 12 related to floodplain accessibility, channel form, riparian width, streambank stabilizing

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vegetation, and woody debris. When the response to Item 13 is "no," flood forces can substantially alter channel form and riparian functions needed to maintain or restore water quality.

14—Point Bars Are Revegetating with Stabilizing Riparian Plants. Meanders create a low velocity zone adjacent to point bars that form through deposition of bedload and later suspended sediment. Vegetation growing on deposited coarse bedload material increases stability and roughness, decreases flow velocities, increases deposition of finer suspended sediment (figures 2e and 3b to 3g) (Robertson and Augspurger 1999; Steiger and Gurnell 2003; Rood et al. 2003; Robertson 2006; Polzin and Rood 2006), and encourages meander development (Erskine et al. 2009, 2012; Rominger et al. 2010; Tal and Paola 2010), which decreases stream gradient and power (Bagnold 1966). Deposition of fine alluvial soil facilitates revegetation while it removes water pollution. Narrow channels with clean coarse substrates (Dickard et al. 2015) and meanders with a higher bed elevation on the upstream side encourage hyporheic interchange. This enables nutrient uptake by riparian plant roots and denitrification with fine organic soil at the capillary fringe (Triska et al. 1993). The purpose of this item is to establish whether riparian plant communities are establishing on point bars where needed.

When the response to Item 14 is "no," water or land management prevents point bar colonization by riparian plants. Sinuous channels become overly wide and straight or fail to mature. Channels may become braided or incised (Rosgen 1994, 1996, 2006). Without bank-stabilizing and energy dissipating vegetation, water quality implications related to Items 3, 13, 15, and 16 can arise as channel geometry adjusts during high flows.

15—Streambanks Are Laterally Stable. Lateral stream movement with bank erosion is a natural process for meandering streams. However, the rate and location are critical. The appropriate rate depends on sediment supply, channel materials (Schumm 1960, 1963), climate (Wolman and Gerson 1978), as well as the landscape setting, and therefore on stream pattern, profile, and dimension. This item is strongly tied to Item 3 and its water quality implications. The purpose of this item is to determine if the active channel is slowly progressing across its valley floor, or proceeding rapidly, without balance, in a manner that would change form and function away from potential. Increased channel width reduces unit stream power (Bagnold 1966) causing aggradation when the stream cannot carry its sediment load. However, accelerated channel migration, or avulsion, can cut-off meanders and steepen a stream. This increases bed shear stress, bed erosion, and incision (Item 16). Water quality implications associated with these outcomes include direct effects of erosion adding sediment and nutrients to the stream (Zaimes et al. 2009), and indirect effects from altered channel pattern, profile, and dimension (see Items 3 and 13).

When the response to Item 15 is "no," accelerated bank erosion or excessive avulsion, often with slumps, sloughs, and fractures, can lead to channel widening; stage lowering and floodplain dehydration; removal or weakening of riparian vegetation; rapid sediment deposition with midchannel bars; development of unstable, multithread channels; filling pools; and embedding stream bottoms with sediment. Lateral instability may be driven by the following: (1) excess sediment supply (Item 5) causing midchannel bars that add to bank shear and bank erosion in places other than the outside of bends; (2) altered flows causing excess bank shear stress (Larsen et al. 2006); (3) incision that increases bank stress; or (4) land or water uses that weaken banks through dehydration, poor grazing or recreation management, or removed riparian vegetation by farming, logging, etc.

16—Stream System Is Vertically Stable (Not Incising). A vertically stable system is not down-cutting beyond natural rates (generally detectable on the order of centuries or more). Vertical stability maintains floodplain access (Item 1) with energy dissipation (Item 13) allowing storage and processing of sediments, toxins, and nutrients. Incision initiates a long process of channel evolution. Bed erosion vastly increases the rate of bank erosion (Item 15) and channel widening (Simon and Thomas 2002) (figure 1). Sediments are then delivered downstream (Vannote et al. 1980) at high rates, especially in high flows that are contained in the channel (Item 1). Water quality degradation often persists for decades or longer until channel equilibrium geometry and riparian functions reestablish (figures 2, 3, and 4). The purpose of this item is to document if the bed of the channel is at risk of or actually eroding into the valley floor at an accelerated rate.

When the response to Item 16 is "no," erosion from focused hydraulic stress or an imbalance of sediment and water (Item 17) may create hydromorphological impacts (Elosegi and Sabater 2013) and exceed a geomorphic threshold (Schumm 1979; Simon and Rinaldi 2006). If bed erosion exceeds natural rates, increased bed shear stress accelerates degradation, lowering base level for upstream reaches. Headcuts (also known as nick points) and nick zones quickly cut headward (often on the order of meters per year or per storm), incising up through the riparian system (Downs and Simon 2001; Merritts et al. 2011) (figure 1). Reestablishing vertical stability occurs with widening of the incised channel allowing point bar and new floodplain deposition, which eventually increases width of floodable areas (Items 4 and 13) (figures 2 and 3). Recovery processes can bring back balance to the stream (Leopold et al. 1964; Schumm 1984; Schumm et al. 1984; Simon 1989; Rosgen 1996, 2006; Simon and Rinaldi 2006; Zeedyk and Clothier 2009; Dickard et al. 2015) by recovering riparian functions.

17—Stream Is in Balance with the Water and Sediment that Is Being Supplied by the Drainage Basin (i.e., No Excessive Erosion or Deposition). While discharge of water and sediment varies greatly due to geologic and bioclimatic reasons, equilibrium geometry forms in response to their balance. When the water or bedload sediment from upstream is out of balance (Item 5), net degradation (Item 16) or aggradation (figure 2d) (Lane 1955) occurs. Too much sediment is an obvious water quality problem, but so is too little. A lack of sediment (such as below impoundments) can degrade habitat for sediment or substrate size-dependent organisms and change channel form as a result of excess (unbalanced) bottom scour (Item 17), or insufficient sediment to repair streambanks (Item 4). Net degradation alters floodplain access (Item 1) and channel sinuosity, width/depth ratio, and gradient (Item 3). Lowered water table (Item 8) changes the soil environment and plant community composition. Degradation unleashes a chain of channel evolution and water quality consequences discussed in Items 1, 3, 5, and 16. Excess aggradation can lead to midchannel bars and lateral instability (Item 15). Excess sediment filling pools deteriorates fish habitat. The purpose of this item is to identify if the riparian wetland area is out of balance with

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the stream flow and material being supplied. When the response to Item 17 is "no," this balance is not being maintained.

The most common imbalances are caused by upstream functionality issues and improper land use and management (Item 5), or by reservoirs trapping sediment. Trapping sediment, especially bedload, in a reservoir often causes downstream incision and lateral instability, because eroded bed material (geomorphically more significant than suspended sediment) is not replaced by newly deposited bedload. This is called the hungry water problem (Kondolf 1997). Reduced sediment (Gordon and Meentemeyer 2006) or excess flow (Andrews 1986) accelerates bank, or bed erosion (Dunne and Leopold 1978; O'Driscoll et al. 2009) and severely alters riparian functions and riparian and aquatic habitats (Braatne et al. 2008).

Discussion

Water quality monitoring is often implemented to ascertain pollutant levels. Acceptable levels of pollutants are set and applied by establishing water quality standards for each beneficial use. Waters not meeting standards for their designated beneficial uses are listed by states or tribes as impaired water bodies (CWA Section 303[d]). This initiates the TMDL process. A TMDL may be set for each listing, usually based on modeling predictions that consider, among other things, sources, flows, estimates of pollutant concentrations, and waterbody assimilative capacity. The TMDL is then allocated among the lands and sources of pollution in the watershed. Education/implementation funding toward best management practices for keeping pollutants from entering the waterway have usually been the first efforts to protect the aquatic ecosystem.

Unfortunately, allocation of loads does not necessarily reflect opportunity to reduce pollution. Some streams have little natural potential to improve due to erosive settings, hot springs, or unique valley geology. Some have geographically marginal ability to support their designated beneficial uses, and water quality does not reflect a problem with watershed or pollution management. Other streams have water quality that meets standards, but is far below what it could be with better riparian functions and watershed management (Kozlowski et al. 2013, 2016; Swanson et al. 2015).

Properly functioning streams and wetland riparian ecosystems provide a steadying influence on water quality and aquatic habitat attributes. Many streams (and other types of water bodies) are themselves the source of sediment, or nutrients, due to their failure to function properly (Hall et al. 2014). Impaired waters often have extreme temperatures and sediment-nutrient loads, low DO at critical times, and poor habitat for aquatic organisms. All these can result from loss of riparian functions. In these cases, reducing an external load is not the solution or not the whole solution. Rather, riparian functions must be restored to reduce pollution-releasing processes like erosion, and engage assimilation-sequestration processes that slow the nutrient spiral with floodplain flooding, plant uptake, and creation of complex niches and food webs. This can be done with improved management of a variety of land uses, (e.g., grazing) as long as their management (Wyman et al. 2006; Swanson et al. 2015) embraces the attributes and processes needed for riparian functions. Riparian assessment and ambient monitoring programs should identify risk and opportunities for recovery, adaptively focusing resources toward effective land and water management strategies. Understanding riparian functions and fluvial processes for dynamic equilibrium can motivate "purchase of river corridor easements, or local channel and floodplain management rights" (Kline and Cahoon 2010) rather than active restoration and especially construction of pollution-transporting armored or trapezoidal channels that provide little or no habitat. Understanding functions in relation to potential and recovery processes can focus remediation efforts on locations ready to recover (e.g., because of channel widening after incision) and empower patience where not. While erosion of incised channel banks adds sediment, the process also creates space for floodplains, meanders, sediment capture, and other riparian functions (Schumm 1984; Schumm et al. 1984; Swanson 1996; Rosgen 2006; Zeedyk and Clothier 2009; Dickard et al. 2015).

Different riparian areas and stream or river reaches naturally have water and habitats with very different temperature, chemical, and physical characteristics when at potential or at least functioning properly. Therefore, one would expect only a weak statistical relationship between PFC and water quality across an ecoregion; watershed; or any large geographic area, such as a state. This does not diminish the power of PFC for improving our understanding of water quality management opportunities. Rather, it speaks to the need for any data driven approach to start with the foundation of diverse expectations. That is, to connect form and functions to water quality processes, and to evaluate opportunities for self-healing, remediation, and improvement. PFC assessment begins with an interdisciplinary team describing potential and then identifying reaches that are at PFC, functional-at-risk, or nonfunctional. Assessment is very useful for triage. PFC assessment focuses attention on areas where a change in management can prevent unraveling or effect recovery. Managers also learn about the need for specific objectives for remediation by identifying the site-specific problems ("no" items).

Dickard et al. (2015) describe an integrated seven-step process for managing riparian areas:

1. PFC assessment;
2. identify resource values (e.g., listed species habitats);
3. prioritize reaches for management, restoration, or monitoring;
4. identify issues and establish goals and objectives;
5. design and implement management and restoration actions;
6. monitor and analyze the effectiveness of actions; and
7. implement adaptive actions.

Where water quality issues are driven by riparian functionality issues, this could become quite compatible with measures the USEPA is considering. That is, to evaluate 303(d) success more directly and to focus on actions designed to attain water quality through acknowledging positive actions of others to restore impaired waters or protect unimpaired waters.

Summary and Conclusions

Information from items in hydrology, vegetation, and geomorphology groups are intended to aid an interdisciplinary team in observing indicators of opportunities for improved management to restore or maintain PFC. Individual items also suggest direct and indirect relationships to water quality. A "yes" in a relevant PFC item generally contributes to a decrease in sediment movement; an increase in nutrient sequestration; and a moderation of flow, temperature, and DO extremes.

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Furthermore, water quality embraces the physical and biological, not just the chemical aspects of habitat. Properly functioning riparian areas provide far more complex and biologically productive aquatic and riparian habitat. Restoring functionality benefits aquatic organisms both directly by improving habitat and indirectly by improving water quality. Only by including the functionality of the riparian system can the 303d (impaired water quality water body) listing process effectively address many water quality issues. When this approach is used, managers will be focusing on leading rather than lagging indicators because they will be focusing their management actions and quantitative monitoring on the driving attributes, processes, and ecological functions.

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