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Title: Geomorphologist's Guide to Participating in River Rehabilitation

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Abstract

There is a strong scientific consensus that river corridors are badly damaged by societal impacts, costing the United States alone more than \$76 billion per year and harming many species beyond assignment of any dollar value. In response to this problem, society has called upon governments, scientists, and private consultants to “rehabilitate” rivers. A scientific consensus has emerged that “process-based” rehabilitation within a watershed-scale context is highly important for a successful outcome. Unfortunately, the science underlying linked abiotic-biotic processes in rivers is still rudimentary relative to the complexity of the ecosystem to design and build process-based solutions with the same success evident in the practice of medicine or the manufacture of buildings and other civil structures. Many existing practices have been vetted and found by scientific experts to be largely ineffective. Multiple paradigms for rehabilitation based on different combinations of scientific complexity, universality, and comprehensivity are diverging and splintering the technical community. Lacking a consensus among academic scientists and private practitioners, it is too soon to establish professional standards or regulatory requirements. Within this context, geomorphologists have a key role to get involved in all phases of river rehabilitation and bring their perspective and capabilities to bear on the grand challenge of preventing environmental collapse.

Keywords: river restoration, river rehabilitation, river assessment

1. Introduction

During World War I, medical doctors were tasked with diagnosing and treating a wide array of problems- gunshot wounds, gangrene, typhus fever, trench fever, trench foot, venereal diseases, mustard gas poisoning, boils, Spanish Influenza, gastroenteritis, and shell shock as well as the common array of illnesses facing all people in all generations. Yet at that time there were few of the highly effective treatments available today. They had syringes, aspirin, antiseptics, anesthesia, and limited X-ray equipment, but none of the key potent drugs (e.g. antibiotics, sulfonamides, or cortisone), life-sustaining chemicals (e.g. insulin, numerous vaccines, or vitamins/nutrition), life-sustaining technologies (e.g. respirator, heart-lung bypass machine, pacemaker, or artificial heart), imaging technologies (e.g. ultrasound, magnetic resonance imaging, or computed tomography scanning), surgical techniques (e.g. dialysis, open heart surgery, or nerve transplant), organizational approaches (e.g. remote automated monitoring stations for nurses or Mobile Army Surgical Hospitals), or even some basic first-aids (e.g. band-aids or cardiopulmonary resuscitation). Blood transfusions were introduced only toward the end of the war. Meanwhile, life expectancy around the world at that time was less than half of what it is today. On the other hand, birth rates in developed nations were roughly double what they are now, so these deficiencies did not abate interdecadal human population growth.

Like medicine of the early 20th century, ecological engineering (defined as the science and practice of diagnosis, treatment, and prevention of degradations to linked abiotic-biotic environmental processes that benefit both humans and nature) of the early 21st century faces an array of complex problems. It has some rational theories and useful technologies, and is well-positioned to improve over time, but is far from achieving its purpose right now. However,

58 compared to the practice of medicine on individual humans, the stakes are higher in ecological
59 engineering, because species extinction is irreversible. Some aspects of ecosystem health that
60 are in alarming disarray, such as complex, natural physical and chemical processes, likely could
61 be brought back into good working order if only we knew how. Other simpler ecosystem
62 problems are technically solvable right now, but our dynamic human society has not figured out
63 how to sustainably coexist alongside a naturally dynamic ecosystem. Based on strong cultural
64 values on behalf of the ecosystem and the modern understanding of the utility of science and
65 technology, societies have gradually and firmly established the expectation that governments and
66 practitioners do ecological engineering to obtain a sustainable ecosystem. In the absence of any
67 effort, environmental collapse is a strong possibility (Lovejoy, 1988; Diamond, 2005).

68 Within this context, geomorphologists- scientists responsible for describing and explaining
69 earth surface landforms and processes- have a central role in the future of ecological engineering.
70 Geomorphologists have already helped document the scope and specific mechanisms of
71 degradation of the environment. They have also served as outspoken, effective skeptics of
72 institutional policies and actions regarding land and water management. Now they are being
73 asked to go beyond criticism to bring their knowledge and skills to bear on finding creative
74 solutions to the complex problems that exist. Despite the lack of needed tools that will continue
75 to improve over time, this is not a call that should be ignored. Over the last 20 years, the number
76 of students earning advanced degrees in geomorphology appears to have increased, with many
77 becoming practitioners. Academic, governmental, and private-practice geomorphologists all
78 need to play an active role in advancing the application of the discipline and integrate it with
79 other aspects of ecological engineering.

80 This chapter aims to present the current motivation for and status of ecological engineering

intended to “rehabilitate” (as defined in section three) a key part of the landscape relevant to this treatise on fluvial geomorphology- river corridors. There is a strong scientific consensus that river corridors are badly damaged, costing society tens of billions of dollars per year and harming many species. Key facts underlying this consensus are presented in section two. Democratic and technocratic institutions to perform ecological engineering have arisen in response to social concern, and these are described in section three. Sadly, the outcome of many river rehabilitation efforts thus far have been highly problematic, leading to many dilemmas that are discussed in section four. Ideally, the chapter would culminate in the presentation of recommended standards and practices for moving forward, but specific guidance on practices analogous to that provided by the Physician’s Desk Reference (PDR, 2009) or the American Society for Testing and Materials is not possible at this time. Instead, section five returns to what it means to be a geomorphologist and calls for rigorous practicing of this discipline through direct engagement.

2. Background

A central precept in geomorphology holds that the same physical processes transforming landscapes today have operated throughout geologic time, though at varying intensities in space and time (Thornbury, 1954). In the ancient past when this concept may have been first posited, the population of humanity was only a few hundred thousand individuals, where it stayed until ~1500 A.D. Given Earth’s habitable land area of ~135 million km², population density was just one person per ~400 km². By the time the precept was formalized by western naturalists in the 18th and 19th centuries, human population had risen to over one billion (seven people per km²),

and by the time of modern quantitative geomorphology it was over ~2.5 billion (United Nations, 1999). Today, human population and density are estimated to be ~6.775 billion and 50 per km², respectively (U.S. Census Bureau, World Population Clock Project). Some regions have significantly higher densities, with the tiny country of Monaco having >16,200 people per km² and 74 nations having > 100 per km². The onset of human activity and its rapid rise to a global impact question whether humanity is just another normal geomorphic agent along with wind, ice, and ants that may be viewed as acting over modestly different intensities and patterns.

With so many people coming to live in close proximity over such a short period of time, it appears that humans have in fact transformed the landscape by means and to a degree never before evident on Earth (NRC, 1992; Hooke, 1999), yielding the necessary infrastructure for nations to prosper and compete in a global economy. Civilization's development of the agricultural revolution enabled growth of vast stationary populations that cleared land, built roads, and utilized local resources intensively (Diamond, 1997). Later, the industrial revolution brought with it diverse chemicals now ubiquitous in the environment as well as modern formulations of concrete and steel, all of which impose sustained impacts fundamentally unlike the punctuated frequency and short duration of most natural disturbances. Hooke (1999) estimated that in the United States alone, humans move $\sim 7.6 \times 10^9$ tons of land material annually, whereas rivers transport only $\sim 1.0 \times 10^9$ tons per year. The largest earthmover in the world can now extract $> 76,000 \text{ m}^3$ of material each day, every day, turning mountains and valleys into uniform piles of dirt. Apart from extremely rare natural disasters (e.g., megavolcanic eruptions and glacial outburst floods), there is no comparable natural process for that and many other actions humans perform. Thus, it appears necessary to conceive of human-induced land and ecosystem transformation as fundamentally different in its scope and

mechanisms for as long as humanity dominates Earth's surface.

One facet of the human-altered landscape that is of special importance to civilization is the river corridor, defined as the channel, associated floodplain, and a narrow buffer of surrounding uplands. Humans living in river corridors have always had a distinct advantage in abundant aquatic food and water supply, land irrigation potential, improved hygiene and waste disposal, and effective transportation corridors. In the modern era, the river corridor and the water it holds serves mechanized versions of these classic uses as well as large-scale renewable energy supply, gold and gravel mining, industrial waste disposal, waterfront development, recreation, aesthetics, and management of ecosystem services (Wyant et al., 1995). For example, in the U.S. alone, there are >19,300 km of regulated navigable waterways transporting ~630 million tons of cargo valued at more than \$73 billion annually (Jackson, 2007; ASCE, 2009). As another example, £2 billion (~\$3.3 billion) per year of economic value are generated by anglers in the UK doing non-salmonid fishing (Robinson et al., 2003). The total value of river corridors to humanity may be incalculable, but an informal cost/benefit consideration provides a context for their economic value.

Many of the direct uses of river corridors and defensive measures to combat undesirable river hazards, such as flooding and bank erosion, require dramatic alteration to rivers. Common changes include straightening, damming, diverting flow, constricting width using levees, simplifying channel shape, reducing channel roughness, paving with concrete, vegetation removal, introduction of exotic species, watering livestock in channels, and burying underground in pipes or culverts. Total flood control expenditures in the U.S. 1928-2000 amounted to \$122 billion adjusted for inflation using 2001 dollars (Cartwright, 2005). Further, changes in the runoff basin upland from the river corridor affect water, sedimentary, biological, and chemical

fluxes down the river, necessitating a basin-wide management approach that can be extensive costly, and highly uncertain.

The transformation of river corridors to serve humanity has induced widespread, chronic change to the environment. The scope of human-induced impacts spans hydrologic, hydraulic, geomorphic, water quality, and ecologic attributes that interface in the river system. It is not possible to catalog all such problems in this section, so for brevity, consider the example of the highly urbanized, ~450-km² Anacostia River basin in Maryland and Washington, D.C., with its land area 76% developed, 20% (mostly second-growth) forest, 3% pasture, and 1% cropland. During 1995-1997, the typical sediment load of this iconic river was ~47,000 tons/yr (~100 tons/km²/yr), whereas the established regulatory maximum is ~7,000 tons /yr (MDE and DCDE-NRA, 2007). The river is full of trash, as indicated by clean-ups held by the Anacostia Watershed Society since 1989 that have removed 790 tons of trash from the river, including 12,800 tires, while the city government has removed another ~500 tons of floating debris since 1992. Recently, the Environmental Protection Agency approved the first multi-jurisdictional trash limit for the river under the Clean Water Act, including stiff financial penalties for localities. The city is now skimming off 400 tons of trash per year and the federal government wants an extra 600 tons of trash removed annually. Fecal coliform counts in the river are quadruple the swimming standard (Goodman, 2010). Dissolved oxygen levels are half of normal, driven by excessive nutrient loads. Concentrations of toxic compounds, such as polychlorinated biphenols (PCBs), polycyclic aromatic hydrocarbons (PAHs), chlordane, dichlorodiphenyltrichloroethane (DDT), dieldrin, arsenic, copper, lead, and zinc are far above U.S. Environmental Protection Agency standards, in some cases orders of magnitudes higher (D.C., 2003a). On a daily basis, there are ~470 kg of oil and grease moving down the river

(D.C., 2003b). According to a Washington Post newspaper article, fish in the Anacostia have cancerous tumor rates as high as ever documented in the U.S. (Reel, 2004). These degradations are typical of those existing in urbanizing areas around the world. Rivers in rural areas are also highly altered for flood control, water regulation, and navigation as well as degraded by widespread non-point source pollution.

In turn, degraded river corridors cause significant economic and societal damage. The highest visibility damages are those associated with floods, which caused the most deaths and property damage of all types of natural disasters during the 20th century (Perry, 2000). All monetary values reported in this paragraph have been adjusted to 2001 dollars to enable comparison. Average annual flood damages in the U.S. 1929-2003 were \$2.74 billion (Pielke, 2002) plus the \$1.69 billion per year spent attempting to control floods (Cartwright, 2005), yielding a combined cost of \$4.43 billion per year. Flood damages have risen on average 3.45 % per year 1934-2001 (Cartwright, 2005), even in the face of the huge amount spent on flood control and given that the natural occurrence of rainfall and runoff in the U.S. has not risen over that period. This evidence strongly suggests that increasing societal use of river corridors is the cause of the rise in flood damages. Although not as widely known, a U.S. nationwide study published in the journal *Science* found that the economic cost of soil erosion and sedimentation in waterways is ~\$49.83 billion, after excluding the costs of sediments associated with flood damages (Pimentel et al., 1995). In addition to flood and sediment impacts, water quality degradation has similar economic repercussions. A study of the economic cost of eutrophication in U.S. freshwaters found an annual cost of ~\$1.8 billion (Dodds et al., 2009). Another study related to water quality found that the economic value of the decline in inland US water quality from 1994 to 2000 was >\$20 billion per year (Viscusi, 2008). Summing all these costs together

one arrives at an annual economic cost of \$76.06 billion per year for just these few measures.

While costs associated with a few water quality and physical parameters is high, dollars spent in the remediation of these impacts is disproportionate to other contemporary societal costs. An analysis of annual FBI uniform crime reports (also in 2001 dollars) indicates that the average annual cost of the monetary crimes of robbery, burglary, larceny-theft, and motor vehicle theft 1995-2005 was \$15.48 billion, while the U.S. Bureau of Justice Statistics reports that the average annual federal, state, and local budgetary expenditure on criminal justice over the same period was \$156.03 billion. Crime also causes a large number of deaths that cannot be figured into this calculation. Nevertheless, this information suggests that by a very conservative estimate, the monetary cost of environmental water problems is on par with that due to crime, yet less than 1/10 of the money is spent combating it.

In summary, human population is so large today that societal use of the Earth's surface is breaking many of the necessary functions of the world's ecosystems, causing significant and unsustainable economic and environmental harm (Lovejoy, 1988). Action is needed to alleviate the ecological crisis and there are several roles for geomorphologists to play in such activity. Calling out the scope and severity of the problems related to landform use and management is one of the important professional roles geomorphologists have, just as the American Society of Civil Engineers takes responsibility for announcing the heavily degraded state of civil infrastructure each year (e.g., ASCE, 2009). There is also a role for geomorphologists to envision creative solutions and blend ideas with others in broadly represented societal teams responsible for river management. Through professional organizations geomorphologists may be able to influence social policy affecting the use of riverine resources and the amount of dollars allocated to their preservation and rehabilitation, and individually they can be active voices in

how the rehabilitation of these resources occurs within localities and regions.

3. Context of River Rehabilitation

River degradation and its consequences are a common theme in popular culture today. Between oral histories passed down from parent to child to grandchild, multimedia broadcasts and recordings, and historical data of biological indicators, there exists a common perception that past “baseline” ecological conditions in rivers included populous and diverse aquatic and riparian communities interconnected by a food web and closely tied to natural physical and chemical conditions (Humphries and Winemiller, 2009). This modern perception has led to the notion that managing rivers to hold the line on current degraded conditions is inadequate. It is broadly expected that conditions be returned as much as possible to the perceived baseline “healthy” state (Norris and Thoms, 1999; Boulton, 1999). Some ecologists perceived little interest or financial willingness of society to do anything about the accelerating rate of environmental degradation (Lovejoy, 1988; Cairns, 1993), but in the same era, a survey to assess the public’s willingness to pay for boatable, fishable and swimmable quality water found that respondents were willing to pay an average of \$332 (in 2001 dollars) to achieve it (Carson and Mitchell, 1993). When multiplied by the U.S. population, that would yield ~\$100 billion (in 2001 dollars), which is comparable to all that has been spent fighting floods over 72 years. This demonstrated cultural will is matched by a scientific consensus that a systemic improvement is needed (e.g. Stanford et al., 1996; Poff et al., 1997; Moyle et al., 1998).

Many different terms have been put forward to define and describe efforts to manage and adjust rivers, with three of the more common and relevant ones being restoration, rehabilitation,

and enhancement (Sear, 1994; Wyant et al., 1995; FISRWG, 1998; Jungwirth et al., 2002; Shields et al., 2003). The concept of a return to the pre-existing natural state, as free from human interference as possible, is termed “river restoration” (Sear, 1994; Roni et al., 2008). Ideally, it means to take a river that has been disturbed or degraded by a specific human action (or set of actions), undo that, and alter the river back to a pre-action natural state. The natural state would not be defined simply in terms of structural descriptive characteristics or visually perceived “stability”, but in terms of the degree of functionality of essential, linked abiotic and biotic processes (Muhar et al., 1995; Wohl et al., 2005; Escobar and Pasternack, 2009). For example, at the local scale, there exist road crossings that are paved right over small streams, leaving the water to back up and flow over them (Fig. 1). These structures block fish migration and alter habitat due to sedimentation upstream and erosion downstream. In this case, river restoration to reinstate the ecological function of fish passage would involve removing the crossing, putting a bridge in its place with no piers in the river, removing the sediment plug from upstream, re-grading the impacted length of river, and installing substrates and instream channel features suitable for the channel type (e.g. boulder and wood clusters, point bars, and riffles) (Flosi et al., 2010). These actions undo the root causes and consequences of the degradation (Roni et al. 2005) and essentially involve getting out of the way so the natural system can recover and resume its normal activity (Kauffman et al., 1997). The effort would be strongly guided by historical photos and maps to achieve the pre-road condition and then monitored to insure that natural hydraulic and geomorphic processes were reinstated. In the case of chemical contamination, river restoration would involve removal or complete blockage of the source of the pollution along with a cleaning operation to decontaminate sediment and organisms stored in the downstream reach.

Unfortunately, this definition runs into numerous problems in practice. The conditions, processes, and ecological community of the original state are difficult to describe and quantify (Cairns, 1988), with the very concept of an “original state” highly questionable, since many rivers are perpetually dynamic in response to changing physical drivers, such as climatic and landscape variability (Kauffman et al., 1997; Brookes et al., 1998). Root causes of degraded present-day conditions in a river are uncertain and involve multiple, cumulative physical and chemical impacts within a larger milieu of basin-scale impacts and extended regional human activities (Sear, 1994; MacDonald, 2000; Pasternack et al., 2001; Wohl, 2005). Identifying the mechanisms by which the root causes yielded degradation can be challenging and expensive, if possible at all (e.g. Kondolf and Larson, 1995). For example, in the eastern United States, historical geomorphic analysis has revealed that the assumed natural reference state of streams in that region is faulty due to the role of tens of thousands of 17th- to 19th-century milldams in causing systemic change to river corridor processes and landforms (Walter and Merritts, 2008). Even worse, the trajectory of desired restoration can rarely follow in reverse the path of the degradation (a phenomenon known as hysteresis), so there is little to guide how recovery will occur through time (Amoros et al., 1987; Brooks et al., 2006; Brown and Pasternack, 2008). That is assuming that it is even practical to halt or change the root causes of degradation (Cairns, 1988).

Another issue with the term is that its political and marketing value now lead those who would like to undertake further river degradation for continued human uses to usurp its usage so that any project involving changing a river constitutes “restoration”, regardless of its proposed actions. For example, bank instability is often marketed as a sign of unnatural degradation, so bank stabilization to protect landowner property value is consequently advertised as river

restoration (Gillilan et al., 2005). Often bank instability is a natural and appropriate condition in alluvial rivers (Kondolf, 1998). In fact, rivers in semiarid and arid climates are subjected to storms that adjust channel dimensions periodically without ever returning to a long-term average state (Wolman and Gerson, 1978). Inadequate research is available to know whether streams in subalpine, alpine, periglacial, and glacial climates have a stable state given their sensitivity to climate variation and change. Thus, channel instability in and of itself is not necessarily a sign of degradation and it is not a sufficient justification for rehabilitation, though it is commonly used that way (Simon et al., 2007, 2008). Yet in private practice, the emphasis on optimism in marketing and need to spin projects to facilitate implementation promotes use and misuse of jargon.

To avoid these pitfalls, the term “river rehabilitation” has been advocated strongly in academia (Cairns et al., 1988; Wheaton et al., 2004a; Roni et al., 2008), by which is meant changing a river from a degraded state to an improved state with more functional abiotic-biotic processes reminiscent of what existed prior to degradation (Roni et al., 2005). In the absence of a simple anthropogenic disturbance, such as livestock grazing, the prior state usually refers to pre-agricultural or pre-industrial conditions, but it could also refer to the condition before any event or historical sequence of events perceived to cause degradation. Alternately, in the absence of a reasonable or desirable historical reference, such as when a river is relocated, one might consider “river enhancement”, defined as changing a river from a degraded state to an improved state on the basis of identified ecological potential, regardless of site history. Some consider this a form of rehabilitation and do not make a distinction (Sear, 1994; Shields et al., 2003). In river rehabilitation or enhancement there may be a limited opportunity to eliminate underlying human perturbations no matter how important they are (Hendry et al., 2003; Wohl,

2005; Brown and Pasternack, 2008), so the longevity of project benefits may be uncertain and limited (Brooks et al., 2006; Wheaton et al., 2010) or require active maintenance in perpetuity (Merz et al., 2006). For the rest of this chapter, the term “rehabilitation” will be used generally to apply to the full range of projects that aim to improve hydrogeomorphic and/or ecologic functionality in rivers, typically involving restoration, rehabilitation, enhancement, or other related activities. Though important, details about chemical rehabilitation to improve water quality is beyond the scope of this chapter. However one defines the action, what matters to society is that ecological conditions are improved (Kauffman et al., 1997; Wheaton et al., 2006).

People in many nations expect their governments to protect public riverine areas and hold private landowners and industries accountable for their environmental stewardship of rivers. This expectation drives some common motivations for river rehabilitations to be undertaken to address the problem (Bernhardt et al., 2005; Kondolf et al., 2007). Such expectations have been codified into governmental regulations over private lands, creating a concentrated financial burden for local landowners and land developers, who then have to respond to unfunded mandates by paying to address problems. Also, governments allocate tax dollars to agency technocrats to identify and prioritize relatively small rehabilitation projects that meet societal goals, such as increasing linear miles of riparian forest cover or abundance of certain species of fish. In a growing number of instances, community organizers and activists identify problems and raise money directly from the public to address them. Implementation of this vast array of small, localized projects generally occurs in the absence of a systematic, catchment-based framework (Sear et al., 1995; Hillman and Brierley, 2005). The European Union Water Framework Directive is an example of a new governmental approach to catchment management that may help organize efforts toward common objectives (European Commission, 2000).

No matter who aims to sponsor a river rehabilitation project and how diverse the stakeholders are, it is often up to the industry of environmental consulting (aka practitioners) to design and implement projects on private land. For small projects involving debris/trash removal and/or hydraulic structure placement on public lands, government agencies often use their own staff and volunteers, but consultants drive planning/vision and implementation for larger projects. Also, agencies that traditionally specialized in river engineering, such as the U.S. Army Corps of Engineers, now do river rehabilitation projects too in collaboration with private-practice consultants. In rare cases, academic scientists design projects (e.g. Loftin, 1991; Elkins et al., 2007).

After observing and reviewing many real projects, academics have produced diverse sets of guidelines for private practitioners on how rehabilitation *ought* to be done (e.g., Kondolf, 1995a, 1998, 2000; Downs and Kondolf, 2002; Wheaton et al., 2004a; Shields, 2007), but the recommendations can be cost prohibitive, difficult to remain true to over years of planning and implementation, or impossible to translate from theory into practice (Gillilan et al., 2005; Sawyer et al., 2009). Even broadly agreed upon concepts, such as the political consensus of the European Union Water Framework Directive, are difficult to implement. For example, 95% of England's rivers are at risk of failing legislated environmental objectives (Green and Fernández-Bilbao, 2006).

The dominance of consultants in rehabilitation design means that the outcome hinges on the breadth and depth of their disciplinary training and their ability to put their expertise into the larger context of the problem the rehabilitation aims to address. In contrast with large civil engineering companies, rehabilitation design firms are generally small and focus on a particular aspect of the problem, so subcontractors are often necessary to fill in missing expertise unique to

each project. Strong financial pressures exist to produce answers quickly with limited investigation into underlying system dynamics. Proffered solutions often promote the consultant's own skills and personnel (Gillilan et al., 2005). Private consultants have limited access to cutting-edge research published in expensive and diverse academic journals. They have a strong profit incentive to stick with well-established, standardized (if outdated) procedures. However, there is a scientific consensus that rehabilitation requires a team of experts coming from different disciplines and bringing diverse ideas and approaches for consideration (FISRWG, 1998; Jungwirth et al., 2002; Shields et al., 2003; Surridge and Harris, 2007; Brierly and Fryirs, 2008). This approach is well established in wetland rehabilitation (Montgomery et al., 2001), which is facilitated by a strong certification program hosted by the Society of Wetland Scientists, an organization blending practitioners, governmental regulators, and academics. It has been slower to take hold for river rehabilitation (Castro, 2008), because the river science community is extremely diverse, academic discipline-oriented (England et al., 2008), strongly divided between practitioners and theoreticians (e.g. Gillilan et al., 2005; Rosgen, 2008a; Simon et al., 2008), and poorly organized. It is common for multidisciplinary teams to spend the first few meetings arguing over terminology and the merits of different sets of pre-conceived notions and expectations, before everyone starts to open their minds and allow the data from baseline studies from the new project site to grow a mutual appreciation for the relevant considerations for that project (e.g. Hilden, 2000). Strong leadership, team cohesion and group longevity are thus critical.

Most developed nations have governments that blend democratic and technocratic decision-making approaches. The European Union Water Framework Directive requires public participation in the basin management (European Commission, 2000; Green and Fernández-

Bilbao, 2006). Yet numerous controversies over scientific research and science-based management (e.g., nuclear and hydro power) have reduced public confidence in what science can achieve on its own (Ludwig, 2001). Public funding sources beholden to political pressures particularly loathe paying for “science”, including project monitoring and analysis (Castro, 2008; England, 2008). Rehabilitation activities that require community organizing, such as trash clean-ups, fundraising, and volunteer-based monitoring work well within a strongly democratic framework. Unfortunately, many important rehabilitation needs require highly technical activities and focused planning meetings that can confound the patience and understanding of the public. Stakeholders often perceive that they have inadequate outlets to have their concerns and ideas heard. When that happens they try to re-direct meetings away from established agendas, frustrating the technical process. On the other hand, local knowledge and/or skepticism brought in by stakeholders can be highly beneficial when it relates to specific aspects of a project design and is not off-subject. An approach that works well is to designate a lead non-professional, committed stakeholder to represent the interests of many stakeholder groups on the technical team. That liaison can listen to those with concerns and filter input to retain the important items, while also developing a collaborative rapport with the technical team and ensuring transparency and accountability throughout the project.

4. Dilemmas in Rehabilitation

Normally, a review of current practice in any profession would first describe standard procedures and then address advanced complications, but here the two topics will be reversed. Practitioners, government regulators, and regulated enterprises are generally eager to embrace a

403 universal rehabilitation approach that will standardize methods, stabilize costs, and simplify
404 impact assessment. Academic scientists are highly skeptical about existing rehabilitation
405 methods, yet based on decades of research there is a strong scientific consensus about the breadth
406 and depth of problems facing river corridors, so inaction may not be socio-politically acceptable.

407 Presently, there is no scientific consensus about what the scientific foundations for river
408 rehabilitation are, what the practice should entail, and who should do it (or be allowed to do it).
409 Instead, the community is faced with a set of challenging dilemmas that need to be resolved prior
410 to standardization. Uncertainty in river rehabilitation is so severe that it is now a vibrant
411 subdiscipline until itself (Darby and Sear, 2008).

412 Some people deride this “pessimistic” perspective, because it is perceived that cultural
413 and political support behind river rehabilitation is jeopardized when the public is exposed to
414 skepticism and dissent. Confidence, energy, and optimism are essential traits for practitioners
415 marketing rehabilitation services. What the public actually opposes is the difference between
416 what scientists or governments promise is going to happen versus what people actually
417 experience (Ludwig, 2001), irrespective of whether the promise is optimistic or pessimistic.
418 Some times river rehabilitation projects are done to prop up local, regional, or national
419 economies with inadequate accountability or project merit. In the case of nuclear power,
420 scientists optimistically told people to expect cheap, limitless energy and instead the world got
421 Chernobyl, Three Mile Island and an unsolvable nuclear waste problem (Ludwig, 2001). As
422 another example, consider the status of public sentiment about global climate change. In 2007
423 Intergovernmental Panel on Climate Change issued its most thorough, rational, and certain
424 conclusions about the existence, causes, and impacts of climate change (IPCC, 2007). Since then,
425 Gallup polls show that the percent of Americans who view the seriousness of global warming as

exaggerated has increased from 33% to 48% and the percent perceiving global warming as caused by human activities has declined from 61% to 50% (Newport, 2010). Was the public simply turned off by pessimistic scientific findings? What is most likely is that the climate-change dialogue shifted from a scientific debate to a pop-culture showdown. Celebrity icons (e.g. Al Gore, Leonard DiCaprio, and Martin Sheen), United Kingdom scientist e-mails, and news stories of polar bears drowning in the Arctic Ocean (Iredale, 2005) were very easy for skeptics and detractors to tear down in popular culture. In the postmodern era of the cult of celebrity, pop media will socially construct the demise of any message based on the perception of how celebrity icons behave and whether the points meet a common-sense test, regardless of scientific evidence. Geomorphologists should be mindful of the public's awareness of uncertainty and skepticism of authority (Brookes et al., 1998), regardless of whether their message is hopeful or skeptical.

4.1 Complexity, Universality, Comprehensivity

One set of technical issues that is in dispute addresses the degree of complexity, universality, and comprehensivity of a rehabilitation project. Complexity has to do with the level of sophistication and detail applied to the development and analysis of a rehabilitation design. It has less to do with the set of questions and goals posed and more to do with the rigor of analysis applied and the range of creative freedom enabled in design. Universality is about the choice to prefer empirical local knowledge or analytical universal equations. Either way there are important assumptions and deficiencies that need to be accounted for (Pasternack, 2008; Brown and Pasternack, 2009). Comprehensivity relates to the breadth of specific hydrogeomorphic

processes and ecological functions incorporated. Often projects assume that there are essential “indicator” metrics that are representative of system conditions, such as indices of biotic integrity (Norris, 1999). For the sake of discussion, assuming the most-extreme form of each of these axes of decision-making yields eight endmember approaches to river rehabilitation (Table 1). Some of these endmembers utilize aspects of the categorization of analog, empirical, and analytical rehabilitation approaches proposed by Skidmore et al. (2001). They also draw on the different types of “realism” (detailed, apparent, statistical, and essential) described by Dietrich et al. (2003). In practice, an individual approach fitting one endmember may grow and change over time, so this classification is not intended to pigeonhole specific schemes. A key dilemma of this diversity of approaches is that independent communities of rehabilitation specialists are splintering and developing independent, hardened identities that may delay acceptance of new science stemming from the other approaches and generally confuse sponsors and the public as to which approach to follow.

As a theoretical ideal, using the approach that is the most comprehensive, universal, and complex ought to yield the most beneficial outcome with the least uncertainty. For now, it is uncertain whether there is enough science in place to support it- practitioners are more confident in technical prowess and academics are less confident in it. Few independent assessments have been done for this type of project. One of the challenges with complexity is that the mechanisms of transferring new knowledge to practitioners are inadequate. There is presently no certification or licensure requirement for practitioners. Some practitioners lack the education necessary to understand new research findings (Schmidt, 2008). Similarly, professional licensure often requires continuing education, which helps transfer new research into common usage.

Another way advances in complex rehabilitation might transition into the private sector

would be through the hiring of new professionals with advanced degrees that incorporate new geomorphic research. However, in my experience employers are slow and unwilling to take the risk of trying the ideas of their new hires, and they face impediments to doing so from the institutional barrier imposed by pre-maturely accepted standardized practices in their region. In discussions with specialists in fluvial geomorphology that have joined environmental consulting and rehabilitation design firms, I have been told that they have been viewed as less-competent outsiders by the culture of licensed civil engineers, even when they have identical physics, math, engineering, and AutoCAD education and training. Lacking a Professional Engineer license, the geomorphologists cannot formally approve complex designs for dynamic systems. In reviewing such designs, civil engineers lacking the same specialized education and experience tend to replace design features with more conservation, static design elements. Also, clients may not understand why extra measures associated with supporting natural river dynamics are necessary and veto costly project features.

Another challenge with complexity and comprehensivity is that simplicity and essentiality have the benefit of significantly lower cost. Attempting a comprehensive approach requires identifying a very large matrix of ecological functions to address and then hiring a specialist to work on each function. Even if one could figure out all the functions and their links to physical processes, it is highly uncertain how society would develop a prioritization among the full set (for new insights on multicriteria decision making see Corsair et al., 2009), recognizing that anthropogenic impacts on the environment cannot be extirpated. A comprehensive approach is perhaps unavoidable for the largest systems (e.g. Chesapeake Bay, Great Lakes, Everglades), but for a small project it should not be overly burdensome and may be necessary to obtain a resilient outcome. Given the relatively small amount of money presently

495 available for river rehabilitation and the large scope of degradation, it may be argued that only a
496 low-cost simple, essential approach is possible, regardless of the uncertainty and risk as to
497 whether they yield the assumed benefits. Unfortunately, there are vast numbers of small
498 projects, and when considered as a whole their potentially oversimplified designs could yield
499 regional, cumulative, negative impacts. Perhaps a century from now scientists will be reporting
500 on how to rehabilitate after the era of tens of thousands of harmful interventions that followed
501 the era of tens of thousands of milldams. Some people subscribe to the philosophy that simple is
502 elegant, though how simple one defines a project is a function of their level of education and
503 capability as well as that of civilization as a whole. Will society be more tolerant and supportive
504 of a smaller number of expensive yet likely beneficial projects or many cheap yet risky projects?
505 It is clear from the example of health care that individuals choose the most advanced care with
506 the least risk that they can receive for themselves, regardless of cost, when the cost is covered by
507 insurance or a socialized system. However, at the societal level, it is common to choose a
508 balance of risk/benefit and cost (e.g. subsidized insurance for those in the 100-year floodplain
509 and establishment of non-zero levels of toxic chemicals in drinking water). It appears premature
510 to answer these questions at this time.

511 In terms of universality, there are strong disciplinary differences that affect rehabilitation
512 design, design testing, and post-project evaluation. Some scientists conceive of the world as
513 stochastic and thus use statistics and probability theory heavily. Others view the world as
514 deterministic and governed by universal, natural law; they use a mechanistic approach based on
515 physical and/or chemical theories that should apply equally everywhere. Another group of
516 deterministic disciplinarians focus on observation and empiricism that is specific to each locality.
517 These different paradigms can be cultural barriers to teamwork and it is uncertain what balance

of the three concepts should be used in rehabilitation. For example, should a rehabilitation program emphasizing scientific evaluation and adaptive management be designed with randomly placed replicate features with a sound statistical foundation or a stratified sampling scheme mindful of the well-known patterns of landform structure and dynamics of water and sediment?

An important outcome of considering the options in Table 1 is that the entire language of river rehabilitation practitioners and the goals they aim to achieve either are already or will soon become incommensurate across approaches as each one matures. Sociological study of science shows that as a paradigm matures, its culture diverges from other paradigms and it becomes difficult to cross-communicate (Kuhn, 1962). This is highly visible in the on-going debate between a segment of rehabilitation practitioners versus geomorphology and engineering professors over a widely used approach, commonly referred to as “natural channel design” (Hey, 2006; Rosgen, 2006), which blossomed out of a valley and river classification scheme (Rosgen, 1994; 1996). Numerous critiques of the approach exist and are based on theory and actual post-project appraisal (Kondolf, 1995b; Miller and Ritter, 1996; Doyle and Harbor, 2000; Juracek and Fitzpatrick, 2003; Simon et al., 2007; Pasternack, 2008; Roper et al., 2008; Simon et al., 2008; Buchanan et al., 2010), but they have not dented its popularity as a low-cost, qualitatively understandable framework. Notably, Rosgen (2008a) cites a lack of training and experience in “natural channel design” by top academic geomorphologists with years of formal education, scientific research experience, and project implementation experience as a primary basis for what he sees as the fatal flaws in the critiques against the method, which is exactly what Kuhn (1962) and subsequent studies show as characteristic of clashes between incommensurate paradigms. Rosgen (2008a) reports that 540 hours of training are provided for the natural channel design approach if a student chooses to take all available training sessions. Such graduates commonly

541 design and build projects even after completing only a subset of the total courses offered. Can
542 you imagine if a structural engineer was allowed to fully design and construct a bridge with that
543 limited amount of training? In comparison a university graduate student in a traditional
544 geomorphology, ecology, or engineering discipline might take 4 courses in an 18 week semester
545 (with 3 hours of formal instruction per week and an additional 3 hours of homework per each
546 hour of instruction), obtaining 1,296 hours per academic year, plus all the hours they put into
547 their individual research projects. A Masters' degree is commonly two years, so that would be
548 2,592 hours plus independent research. However, even with all that extra training, newly minted
549 graduates subsequently undergo a long period of further mentoring by their employers (as well as
550 licensure examinations for engineers) before being given the responsibility of overseeing
551 projects. Rosgen (2008b) points out many training gaps associated with a traditional education,
552 especially with regard to practical field-based techniques. Not to pick on any one rehabilitation
553 method, because some involve even less training than the natural channel design approach, but
554 society's acquiescence to a very low standard of education and experience for bulldozing rivers
555 is appalling.

556 Although the goals of a river rehabilitation project must be clearly stated and prioritized
557 (FISRWG, 1998; Beechie et al., 2008), the types of goals that are stated end up aligning with the
558 paradigm used to achieve them. Morphological goals are relatively simple to state and achieve,
559 while process-based goals require more data and thorough analysis, though user-friendly tools
560 for this are rapidly growing and their cost decreasing. The more complex and comprehensive
561 design hypotheses are, the more the goals focus on specific mechanisms that are still being
562 worked out, necessitating further scientific development (Wheaton et al., 2004a,b). Similarly,
563 the frontiers of science of interest to each paradigm are significantly different. For example, the

simple, essential, local paradigm would prioritize more research into quantifying attributes of regional reference reaches and in-channel structures, while the comprehensive, complex, universal paradigm requires more research in the mechanisms of abiotic-biotic interactions for diverse terrestrial, riparian, and aquatic species. Notably, an approach that begins as simple often becomes more complex, and different practitioners of that approach may settle on different levels of its complexity. For example, the natural channel design paradigm had four phases in 1996 (Rosgen, 1996) and grew to eight phases by 2006 (Rosgen, 2008a,b); it will probably grow further as its usage brings new challenges and insights into its paradigmatic view. As a result, simply defining broad scientific challenges for the whole community is problematic. Care should be used in performing meta-analyses of rehabilitation outcomes to be mindful of the different paradigms and their different metrics of assessment of their performance.

4.2 Process-based Rehabilitation

For over one hundred years, geomorphologists have recognized that the landforms on the Earth's surface are the expression of a dynamic interaction among forces and materials (Gilbert, 1877; Davis, 1909). It is understood that the interactions, or processes, leave their distinctive imprint on landforms, with each process (or suite of concurrent processes) developing its own characteristic assemblage of landforms (Thornbury, 1954). Yet caution is warranted in inferring process from form or force alone. Equifinality can occur; different sets of processes may yield similar landforms. A *force* is not a process, but rather the *interaction* is the process, so the attributes of both forces and materials matter to the signature of a landform and its associated ecosystem functioning. Many processes are socially constructed abstractions of reality and thus their presence can only be inferred. The use of adjustments to forces and materials to influence

processes is what the practice of river rehabilitation entails, but there is a lot of uncertainty over the what, where, when, and how of any adjustments.

A river is a landform, but it is also an open system participating in dynamic fluxes of mass (water, sediment, chemical constituents, and biological materials), momentum, and energy passing through the watershed via longitudinal, lateral, and vertical pathways of connectivity (Vannote et al., 1980; Sear, 1994; Kondolf et al., 2006). By reference to the mathematics of differential equations that is used to represent such systematics, there exist inputs, boundary conditions, and equations (often with simplifying parameters). The physical expression of such a system is governed by the combination of all of those, not just a single component. The sensitivity of system behavior to adjustments in any one component depends on the status of the other components (Escobar and Pasternack, 2010). This poses a dilemma for the practice of river rehabilitation in that it is unclear the extent to which normative system behavior may be recovered by the manipulation of any subset of adjustments to forces and materials (Wohl et al., 2005).

In practice, many poor-performing rehabilitation projects focus on adjustment of landform morphology with no awareness of the role of processes or in light of overly simplistic, local conceptions of form-process relations. Common rehabilitation practices susceptible to this problem include addition of hydraulic structures (Brookes, 1990; Thompson and Stull, 2002; Buchanan et al., 2010), placement of flat, wide gravel salmon spawning beds below dams (Kondolf et al., 1996), and pure morphological classification-based rehabilitation (Smith and Prestegard, 2005; Simon et al., 2007; Buchanan et al., 2010). Similarly, denudation of floodplains during construction of re-introduction of meanders may be necessary, but it institutes undesirable effects and processes atypical of most natural streams in subalpine, temperate, and

semi-arid regions (Buchanan et al., 2010), such as loss of floodplain roughness (Smith and Prestegard, 2005), bank erosion/failure (Beeson and Doyle, 1995), channel instability (Smith and Prestegard, 2005), and excessive rill erosion on the floodplain and banks filling in the channel. Post-project appraisals of failed projects commonly find that rivers exhibit a suite of processes after construction that were not accounted for in project designs (Sear, 1994; Kondolf, 1995b; Thompson and Stull, 2002; Simon et al., 2007; Roni et al., 2008; Buchanan et al., 2010). Often there is a desire to have a particular channel form aesthetically indicative of a properly functioning ecosystem, but then to have it physically constrained to avoid any risk to surrounding real estate and civil infrastructure (Fig. 2). Gillilan et al. (2005) point out that many projects begin with strong ecological and geomorphic principles, but devolve in the face of safety concerns, bureaucratic barriers, and practitioners' need to avoid financial risk if problems arise. These problems are linked to society's unease with unexpected, dynamic outcomes.

As a reaction to these failures, the idea of unleashing force to "let the river do the work" and rehabilitate itself has been promoted (Stanford et al., 1996; Poff et al., 1997). The idea of a natural flow regime with discharge as a "master variable" dictating river functioning and the trajectory of channel change is a useful aid in conceiving of how flow alterations affect rivers (Poff et al., 1997; Parker et al., 2003). However, most dammed rivers are not only degraded by the natural response to that impact, but they are also heavily impacted by engineered channel controls (Jacobson and Galat, 2006; Brown and Pasternack, 2008) and/or invasive vegetation too widespread and strong for adjusted flow releases to overcome (Pasternack, 2008). There is mounting evidence that in light of multiple and cumulative anthropogenic impacts on rivers, adjustments to flow regime alone are equally as ineffective at achieving recovery of processes. For example, reinstatement of the natural flow regime in Mesopotamian marshlands increased

the area of open water, but the landscape pattern is controlled by drainage engineering (Mertes, 2004). Also, a comparison of the habitat value of pre- versus post-engineered channel forms of the lower Missouri River with either a natural or regulated flow regime found that adjusting channel form is far more beneficial than adjustment the flow regime, if only one of the two could be achieved (Jacobson and Galat 2006). On a large river rehabilitation effort on the Trinity River in Northern California, an artificially designed “natural flow regime” has been implemented, but a century of anthropogenic impacts have altered channel geometry such that anthropogenic physical constraints limit the utility of added water in rehabilitation (Brown and Pasternack, 2008). In the absence of thorough, quantitative analysis of the suite of mechanisms linking a particular flow regime on a particular river to specific dynamic fluvial processes and ecological functions (Richter and Thomas, 2007; Beechie et al., 2010), simply tinkering with flows is no different than tinkering with morphology, and a similar likelihood of success or failure may be expected.

Inevitably, adjustments to both forces and materials are important tools in river rehabilitation, and the key is to center the entire practice on processes. Many articles promote the virtues of process-based river rehabilitation as a concept (Sear, 1994; Kauffman et al., 1997; Beechie and Bolton, 1999; Trush et al., 2000; Wheaton et al., 2004a,b; Wohl et al., 2005). Diverse physical mechanisms and ecological functions affect a project site over different time scales that tend to be linked to specific spatial scales (Rosgen, 1996; Montgomery, 1999; Thomson et al., 2001; Simon et al., 2008). It is easy to point out the problems with rehabilitation projects (including process-based ones) built at the site-scale (Muhar et al., 1995; Wheaton et al., 2006; Roni et al., 2008) without considering the impacts of other processes occurring in the catchment (Gardiner, 1990; Simon, 1992; Sear, 1994; Sear et al., 1995). Ideally, the solution is

to do watershed rehabilitation (Frissell et al., 1993; Kondolf and Downs, 1996; Wissmar and Beschta, 1998) to fix root causes (Sear, 1994; Beechie and Boulton, 1999; Kondolf et al., 2006; Roni et al., 2008; Beechie et al., 2010).

Unfortunately, however uncertain the practice of site-scale rehabilitation may be, comprehensive, catchment-level rehabilitation methods are significantly more uncertain and untested (Hillman and Brierley, 2005). Watershed rehabilitation is as much a socio-political and legal activity as it is a technical one (Wohl et al., 2005). Kibel (2007) presents five case studies on the difficult challenges of rehabilitating large urban rivers in the United States and geomorphology is hardly mentioned, because there are so many other overwhelming societal considerations. Numerous institutional barriers (e.g. overlapping and conflicting regulatory jurisdictions, private land ownership, competing infrastructural management needs, limitations to what science can achieve, environmental justice, etc.) are endemic (Dovers, 2001; Kibel, 2007; Surridge and Harris, 2007). Collaborative approaches are being attempted (Gerlak, 2006), but are also being highly criticized (Winegrad and Ernst, 2009).

A significant complication with watershed rehabilitation is that excess sediment from the long history of logging, intensive agriculture, milldams, mining, and urbanization has been stored throughout many impacted basins (Jacobson and Coleman, 1986; Water and Merritts, 2008), so a reduction in input from one area could be offset by the release of material from a storage area (Pasternack et al., 2001). Presently, modeling tools cannot accurately predict coupled hydrologic-sediment flux dynamics under different watershed rehabilitation scenarios, though many such models purport to and are improving (e.g. MIKE-SHE, LISEM, SWAT, CAESER, and CHILD- ordered from hydrological to geomorphological in orientation). Shields (in press) recently evaluated a large-scale, long-term stream erosion control effort over more than

a decade in six Mississippi watersheds that used conventional methods based on sound science. He found that five of six watersheds showed no decrease in flow-adjusted suspended sediment concentration. The one that did show a decrease had eight reservoirs built in it, which may have abated sediment, but may not be viewed as rehabilitating the watershed in the sense of instilling natural mechanisms. At a larger scale, Winegrad and Ernst (2009) eviscerated the catchment-based rehabilitation of Chesapeake Bay, which is one of the longer-standing and more thorough efforts that exist in the United States. It is possible that the large scope, open-ended costs, institutional complexity, and negative publicity of watershed-wide actions relative to their uncertain benefits will pose socio-political and economic challenges in many cases.

In a survey of people interested in river rehabilitation, Wheaton et al. (2006) found that a growing number of site-scale projects and rehabilitation methods are incorporating watershed assessments to help nest rehabilitation within a catchment context (e.g. Wheaton et al., 2004a). Beechie and Bolton (1999) argue that the sequencing of actions throughout a watershed to address causative processes impacting the ecosystem may be adjusted based on local management objectives. This approach is mindful of longer term landscape-scale drivers of downstream conditions, while also appropriately prioritizing actions that help sustain populations in the short term. Different sequencing may be appropriate for urban versus rural settings. Pasternack (2008) and Beechie et al. (2010) also presented hierarchically nested approaches for performing river rehabilitation that recognize that different ecological functions require intervention at different spatial scales. Ideally, small-scale elements might emerge from distal, large-scale adjustments, but they also might not (or not for a very long time). The extent to which watershed-wide efforts are necessary to enable downstream, site-scale rehabilitation as opposed to accounting for watershed fluxes and in-basin disturbances in local river rehabilitation

design is presently uncertain and likely dependent on local and regional conditions. This is a topic of rapid scientific advancement right now, facilitated by the emergence of environmental informatics, detailed computer models, and affordable methods for collection of large scale, detailed aerial imagery and topographic data (Pasternack, 2008).

Because all alluvial rivers naturally experience landform changes through time (Simon et al., 2007; 2008), it is possible that instead of restoring a river or a watershed to a fixed endpoint intended to have “stable” process and/or landforms, it may be more viable to nudge river dynamics into a systemic trajectory that can dynamically yield a restored condition over time. Many assessments of direct manipulation of channel form and installation of artificial instream features and riparian plantings to “actively” rehabilitate system structure have found either no benefits or short-lived benefits (Kauffman et al., 1997; Thompson and Stull, 2002; Brooks et al., 2006). As an alternative, “passive rehabilitation” involves adjusting boundary conditions or riverine inputs with the expectation that much larger self-sustainable changes will emerge on their own. Hughes et al. (2005) and Gillilan et al. (2005) argue that there needs to be a relaxation of expectations of certainty in river rehabilitation outcomes associated with such passive actions to account for greater variability and dynamism in rehabilitated rivers. Sometimes rehabilitation is as simple as injecting gravel into a river (Fig. 3) or halting a harmful land use, such as livestock grazing, and allowing the system to recover over time (Kauffman et al., 1997). As a little more complex example, a laser-leveled agricultural field next to a leveed river can be turned into a river floodplain with a patchwork of seasonally inundated herbaceous marsh and forested swamp simply by removing a ~50-100 m strip of levee and allowing energetic floods to re-shape the field (Florsheim and Mount, 2002) (Fig. 4). It would be much more expensive to do that with construction machinery and imported materials.

As with the other dilemmas described above, this one invokes long-standing philosophical conundrums and is as highly uncertain as the method it aims to replace. What constitutes a “stable” river, what is the time scale at which stability is achieved, what connections exist between channel stability and community structure in different settings, and what should be done for river types that are never stable? What are the essential connections between adjustable metrics of topographic form, adjustable river flow, and derivative riverine functions? What are the mechanistic feedbacks at play along a proposed trajectory of rehabilitation? Is there hubris in thinking humanity can do river rehabilitation right actively or passively, or should people just somehow go away? Culturally, this concept is appealing, because the idea of “letting the river do the work” seems more natural and less invasive, and thus is highly valued in a post-modern Western society concerned with the environmental consequences of decades of modern industrial “can-do” culture (Ludwig, 2001). However, population growth remains an underlying driver of degradation; is the risk associated with assuming passive rehabilitation will work in the absence of thorough mechanistic evaluation worth taking? Further scientific advances supporting both active and passive river rehabilitation (e.g. Wohl et al., 2005) can improve the likelihood of success. Great advances have been achieved in medicine and engineering, so it is premature to assume that civilization will not ever get river rehabilitation figured out.

At the moment, the central technical issue in applying passive rehabilitation is determining the extent to which it is enough to figure out the types of nudges to make (e.g. flood pulses, structure removal, and land use stoppage) and then mimicking natural versions of those or whether complex and comprehensive analyses need to be done to ensure that the resulting trajectory of change is actually beneficial (Hughes et al., 2005; Simon et al., 2007; 2008). For

748 simple situations (e.g. stopping livestock grazing, knocking down levees, cleaning up pollution
749 spills, and removing fish passage barriers), both passive and active rehabilitation are likely to
750 work, whereas in complex systems both are equally highly uncertain and require thorough
751 analysis. There is no difference in likelihood of success for complex systems between crudely
752 mimicking natural structure or forces and assuming that either approach will yield natural
753 process. The value of carefully designing processes in a rehabilitation, whether implementation
754 is passive or active, lies in ensuring that the sought after ecological functionality is achieved, and
755 it appears unlikely that mimicry alone can yield that (Pasternack, 2008; Simon et al., 2007;
756 2008). However, what constitutes a simple project where mimicry can work versus a complex
757 one where it cannot remains highly uncertain.

758 When used together with inadequate versions of adaptive management (discussed below),
759 passive rehabilitation on large systems could institute repeated disturbances that further degrade
760 the system in the absence of reliable, objective predictions of system dynamics (Kauffman et al,
761 1997). For example, a large test of this approach is being carried out on the Grand Canyon
762 where pulses of flood water are being released from a large dam to achieve specific geomorphic
763 and ecological goals. However, the central ideas underlying the initial test and a subsequent one
764 in 2004 were refuted and little sustainable benefit was achieved (Rubin et al. 2002; Gloss et al.
765 2005; D. J. Topping et al., 2005; Draut and Rubin, 2005). After a decade of further study and
766 refined testing, most fundamental process questions remain unanswered (Melis et al., 2004).
767 While it is helpful that passive rehabilitation is trying to address system drivers, it will not be
768 possible to evaluate its effectiveness until adequate predictive tools are available to confidently
769 design and assess riverine physical and ecological dynamics. Nevertheless, passive
770 rehabilitation may be the only affordable way to approach large-river rehabilitation, and thus it is

771 important to keep striving to advance the underlying science.

772 There is one cautionary note associated with the eventual widespread use of process-
773 based rehabilitation. Just as the term “river restoration” has been usurped for the marketing of
774 any channel intervention regardless of its geomorphic or ecological merits, there are now cases
775 where project proponents are warping the concept of process-based rehabilitation to justify
776 questionable practices. Specifically, practitioners may advocate that the presence of geomorphic
777 change after construction proves that a dynamic, self-adjusting channel trending toward
778 ecological self-sustainability has been achieved. Is geomorphic process after construction
779 necessarily indicative of a successful outcome?

780 Imagine a scenario in which a person re-designs a reach on the Degraded River with the
781 following rehabilitation goal- to re-activate geomorphic processes and trend toward a self-
782 maintaining ecosystem. It is very possible that one effective way to achieve rapid and dynamic
783 processes would be to take every empirical equation, scientific principle, and model prediction
784 that exists about fluvial processes and then build a reach that *violates* them all. Just build
785 something that is totally unstable. Relative to the success criteria of a view of "process-based"
786 geomorphology in terms of creating dynamism that improves the system from the as-built
787 condition, the project designer is going to get high grades, because it is a guarantee that this
788 horrific channel is going to re-activate a strong and natural geomorphic response; it is possible
789 that anything that happens is going to change the Degraded River in the direction of improved
790 self-sustainability. In reality, the situation would not be so extreme, but increasingly cases of
791 failed design (evident after thorough analysis of processes) are being represented as successes
792 merely because the as-built site is changing on its own.

793 The difference between a genuine process-based rehabilitation and a false claim of

natural dynamism lies in understanding that there are geomorphic dynamics associated with normative, expectable processes versus geomorphic dynamics associated with recovery from a seriously harmful engineered disturbance to a system. A system built with wrong scientific underpinnings that exhibits dynamism is not a process-based rehabilitation (e.g. Smith and Prestegard, 2005; Buchanan et al., 2010), but rather just one more ecological disturbance to a system. Projects are supposed to weigh the potential benefits of the specific design against “environmental impacts”, including the potential calamity of sustained disturbance when a floodplain is denuded and/or a system is forced to geomorphically adjust itself to make up for poor design. The key point is that a project should not get credit merely for creating dynamism, and dynamism in and of itself not always ecologically appropriate or beneficial (or necessarily bad, either). It comes down to what mechanisms a design suggests will occur, what happens and why (Smith and Prestegard, 2005; Buchanan et al., 2010). Wheaton et al. (2004b) explains the idea of a design hypothesis (see definition in Table 1) and shows how one can transparently test whatever is incorporated into a design. That article presents a case study with examples of short-term tests, and then a follow up study evaluated some geomorphic design hypothesis after the maximum flow release possible by the dam in that case (Wheaton et al., 2010). This article illustrates how one can design things in line with expected processes and end up with normative geomorphic dynamism that renews habitat according to a rational set of linked design hypotheses. To be a genuine process-based rehabilitation, a project must therefore layout transparent design hypotheses and test the outcome to determine if the trajectory of change or stability is consistent with the expectations from the design hypotheses.

4.3 Learning Lessons, Choosing Winners

Adaptive management and adaptive monitoring (see definition in Table 1) have been popular topics in river rehabilitation. By designing a project to be transparent and have specific, testable design hypotheses, it ought to be possible to use adaptive management to figure out what geomorphic concepts work for a given system, thereby improving local management and advancing the applied science and practice of river rehabilitation. As laudable as this goal may be and however theoretically interesting this method is, the dilemma lies in the practicality of its application so far (Hillman and Brierley, 2005). Designing a project to meet the criteria of adaptive management requires greater rigor than commonly used (Walters, 2007). Many project sponsors detest and some even disallow investing in scientific inquiry and design to the extent possible (Walters, 2007). Monitoring programs often have flawed designs or are not carried out properly, leading to faulty engineering or the wrong future adaptation (Reid, 2001). This causes confusion when the outcome of a project is interpreted differently based on visual appearance and storytelling (Buchanan et al., 2010). Vast resources spent on environmental impact assessment and legal maneuvers take away from what might be done in support of design and adaptive management. Once set, the adaptive goals and methods must then be adhered to long enough for data analysis to evaluate project outcomes (Lee, 1999). However, it is very common for personnel involved in a project to change in just a few years, ruining the mutual, interdisciplinary understanding that has been painstakingly developed. Strong leadership is essential for adaptive management (Walters, 2007), but is difficult to maintain with such turnover, because leadership is built on respect and mutual experience. New people bring in different values, interests, goals, and methods. Institutional pressure exists to try new (and popular) actions and declare the onset of an action as a “success”, while there is fear over the consequences of past actions being deemed failures- though no meaningful consequences to

failure appear to exist at an institutional level (Winegrad and Ernst, 2009). Finally, budgetary decisions rarely prioritize monitoring, so when problems arise monitoring is cut out in favor of further action (Walters, 2007). The National Science Foundation often refuses to fund independent, science-based monitoring of rehabilitation projects, as they view the activity as the responsibility of those sponsoring projects and the science being investigated as not “bold” enough. Instead of a sequence of well thought out adaptive management experiments, rehabilitation efforts often at best provide trial-and-error learning and at worst a continual disturbance to the system that further degrades conditions (Winegrad and Ernst, 2009). Perhaps some individuals can do adaptive management “right”, but in light of how it is commonly turning out, adaptive management is another highly uncertain aspect of rehabilitation.

Finally, another societal conundrum in promoting river rehabilitation today is deciding whether to invest in saving the most degraded systems from their final collapse or taking the ones that are still relatively functional and making them even better. Systems that are heavily degraded might have a much greater number of ecological functions rehabilitated, if only to a poor to moderate level of functionality and at great cost, while those systems already at that level could likely have improvements to fewer functions yield dramatically more increases in select riparian and aquatic populations at a significantly lower cost. It is the difference between survival versus well-being. Some of largest systems are assumed to be too important to allow to collapse, though it is uncertain how to stop that from happening (Winegrad and Ernst, 2009). Environmental collapse driven by excessive human consumption and climatic change is a historical fact (Diamond, 2005). Modern human population size and density imposes limits on how far rehabilitation can go in many regions. In terms of water quality, many improvements have resulted from dramatic reductions in the per capita release of nutrient effluent 1970-2000.

However, continued population growth is now offsetting those per capita improvements with shear numbers of people and causing a return to net release again in some regions. Presently there is no systemic assessment of the relative benefits of saving systems from collapse versus optimizing already functional systems.

5. Standard Rehabilitation Practice?

There is presently no standard approach to river rehabilitation. Many different river rehabilitation approaches, frameworks, methods, principles, protocols and schemes have been put forward- too many to cite in a list- but few have been independently evaluated. Underlying scientific ideas and practicable engineering technologies are still inadequately tested to the levels of accuracy and resilience necessary to justify their codification in norms of practice, regulations, or laws (Wohl et al., 2005). Many academic ideals regarding rehabilitation practice turn out to be impracticable (e.g. Sawyer et al., 2009). Societal institutions for planning and implementing rehabilitation are not working well; they need more iteration and testing. Market-based schemes promoting river rehabilitation have not been tested. However much society and its governmental representatives want a reliable, standard solution right now, it is just not there.

Many academic scientists and some practitioners believe that standardization for river rehabilitation is not preferable or appropriate. Although rivers accord with natural laws, many geologic, ecologic, and societal aspects of a local or regional problem involve unique elements that would not be solvable with a standard operating procedure. Kondolf (1995b) told the story of an ecologically functional pool in a Sierra Nevada stream that was filled in as part of a restoration project dutifully following the standards of the precursor to the natural channel design

method. The reason the practitioner gave was that the unique pool did not belong in a type B channel. If applied as a standard, this practitioner's idea would preclude local diversity and complexity of channel form on the basis of a river classification scheme that does not account for sub-channel-width scale fluvial geomorphology, whose systematic scientific inquiry is only now emerging.

An important improvement in river management in recent decades has been a rapid growth in the appreciation that a geomorphologist is needed to help plan river rehabilitation. However, there is still a lack of understanding of what exactly geomorphology is and how it relates to ecological functions. River managers with little formal education in river processes are often ready to tinker with channel morphology without understanding how a river works as a system. Some rehabilitation designs are as simple as an artist's rendition of an assemblage of rocks and wood, which then becomes codified into an implementation plan. Therefore, the role of the geomorphologist is one-part educator and one-part doer. The goal is to bring the idea of a link between dynamic landform structures and river functions into meeting rooms. For example, a biologist may present data showing the spatial distribution of organisms in a river in relation to depth, velocity, and substrate type, but not realize that the pattern of unique assemblages of physical conditions present is in turn controlled by undulating valley walls or a subtle change in river slope. Geomorphology offers a more general explanation to ecological phenomena that others are often not used to looking for or worrying about.

Although there are different tools geomorphologists bring to river rehabilitation depending on their paradigmatic orientation (Table 1), there are some common questions that they seek to answer. This is where geomorphologists should find commonality. Geomorphic analysis involves mapping the shape of landforms to describe their spatial patterns, observing

landforms over time to record their changes, exploring the drivers and mechanisms of landform change, and evaluating the responses of biological, chemical, and hydrological processes to geomorphic change. Beyond understanding natural conditions and dynamics, geomorphology is essential in planning societal use of the landscape and in figuring out the impacts of societal activity on the environment and through it the externalities that spring back to harm society. What are the essential physical processes at work in a system and what landforms are they associated with? What is the historical trajectory of landform change in a system? What are the relative roles of natural secular trends, variations, and disturbances as well as anthropogenic impacts driving landform change? How do ecological functions interact with landforms and physical processes? How does geological structure and lithology influence channel processes? What are the sources, fluxes, and sinks of sediment moving through a catchment? Shedding light on these questions as part of a thorough pre-project baseline characterization can initially add uncertainty to rehabilitation, because this knowledge highlights the dynamic and transient nature of a system, which has irreducible uncertainty in it. However, that can be coped with by shifting initial design goals away from imposing static, stable conditions to incorporating heterogeneity, resilience, and dynamism. These ideas are part of a shift in philosophy away from attempting to “eliminate” uncertainty to learning how to cope with it (Darby and Sear, 2008). For now, the best approach is for individual practitioners to continue to learn within their disciplines, listen to experts from other disciplines, remain open-minded to new ideas, and use a transparent, rigorous approach to testing design hypotheses (Wheaton et al., 2004b).

The rapid growth in availability of digital data and free geospatial visualization tools is an important advancement underway. To enable its broad usage, more baseline environmental data is needed, in contrast to the present policy of decommissioning streamflow gaging stations.

932 River corridor topography and bathymetry based on survey data with a resolution of 1 point per
933 m² and aerial imagery with a pixel resolution of 1 cm² should be sought, because the cross-
934 section and longitudinal profile have reached the limits of their utility as the basic units of
935 measurement in fluvial geomorphology. Governments should perform LIDAR mapping and
936 low-altitude color digital photography of all terrestrial regions for use in science, planning, and
937 rehabilitation. Highly detailed geospatial data will bring new spatially explicit computational
938 models unfettered by the oversimplified assumptions of current methods (Brown and Pasternack,
939 2009; Sawyer et al., 2010). These data and models will drive the next generation of improved
940 theories and possibly yield the necessary prediction capability for accurate river rehabilitation
941 design.

942 Creative approaches to making river rehabilitation practicable need more exploration.
943 For those who criticize oversimplified rehabilitation approaches and efforts, it is hypocritical to
944 continue to use oversimplified geomorphic assessment methods- one can no longer just show up
945 after the fact, demand some photos and data for back-of-the-envelope calculations, and write up
946 the standard critique. Whereas geomorphologists have historically played the outsider role of *ex*
947 *post facto* commentator and skeptical spoiler, it is now time to lead toward positive solutions.
948 This requires a willingness to step outside of comfortable disciplinary boundaries and ivory
949 tower “ought to” mentality to take scientific risks that will yield the hallmarks of the next
950 generation. Professional liability insurance is readily available to geomorphologists at a
951 reasonable price, for those who desire an extra measure of personal financial protection before
952 getting involved. Transparency and experimental design mindful of dynamic landscape
953 processes are the scientific methods geomorphologists can champion as vital participants inside
954 boardrooms. These will enable more detailed, process-based post-project appraisal than is

commonly occurring by geomorphologists right now. This is essential to get past the narrow mindset of declaring projects as successes or failures and get on with testing specific design hypotheses to figure out how to reinstate geomorphic mechanisms. An example of the level of detailed geomorphic and ecologic post-project appraisal that can be achieved by being an active participant in rehabilitation design is demonstrated by Wheaton et al. (2010). They used 2D hydrodynamic modeling and digital elevation model differencing based on repeated detailed topographic surveys to document that the rehabilitation project in question actually reinstated the hydrogeomorphic mechanism of flow convergence routing that not only rejuvenated riffles and pools, but also increased their ecological functionality. It is uncertain if what they observed will persist over decades with the aid of regular upstream gravel augmentation, but at least this was a thorough, transparent, and objective inquiry. That level of scientific inquiry is only possible by embedding into the rehabilitation endeavor itself to ensure that designs include specific, testable design hypothesis commensurate with the state-of-the-art in geomorphic theory.

6. Final Thoughts

The approach taken in this chapter has been to contrast the certainty over the need for river rehabilitation with the large uncertainty over how to actually go about it. Geomorphologists are used to coping with complex systems that are difficult to characterize, and so it is not surprising that they want to see more critical thinking with intercomparisons of multiple methods of calculating each rehabilitation metric and generally more caution in setting goals, creating designs, and tracking outcomes. Yet at some point geomorphologists have to commit and engage in this endeavor on behalf of society. History shows that a strong interplay

exists between scientific advancement and practical problem solving. Society could not get to successful open-heart surgery without figuring out how to build a heart-lung bypass machine. Performing open-heart surgery then reveals new insights into cardiopulmonary function that then drives new scientific insight. The grand challenge of staving off environmental collapse stands before the geomorphic community right now. Geomorphic ideas and technologies are presently inadequate to meet this challenge. Divergent paradigms are fracturing scientists and practitioners. Committed effort and engagement in river rehabilitation on behalf of society provide the best hope.

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1361 LIST OF FIGURES

1362

1363 Figure 1. Road crossing on Arroyo Mocho in California that was removed as part of a stream
1364 rehabilitation project to eliminate migration barriers in the channel network.

1365 Figure 2. Photo of an originally meandering White Marsh Run in Maryland on the Atlantic
1366 coastal plain that was historically straightened and then more recently returned to a
1367 meandering morphology, but not allowed to actually migrate. The as-built condition had root
1368 balls installed into the banks, but those failed to prevent bank erosion, so riprap was installed
1369 to guarantee no more natural dynamism.

1370 Figure 3. Gravel/cobble a) injection below Englebright Dam on November 29, 2007 followed by
1371 b) flood-induced redistribution, size fractionation, and deposition behind flow obstructions in
1372 2009 and 2010. Lower image was manipulated to differentiate deposited sediment (light
1373 areas of riverbed) versus ambient bedrock (dark areas of riverbed).

1374 Figure 4. Water flooding through an artificial levee breach (background) onto a former
1375 agricultural field (foreground) along the Cosumnes River in California. ATV at left for scale.

1376

Table 1. Idealized endmember approaches to designing river rehabilitation projects.

Comprehensivity	Universality	Complexity	
		Simple	Complex
Essential	local	regional reference design of landform based on channel typing; assume hydrogeomorphic and chemical processes as well as ecological functions derive from landform traits	develop testable design hypotheses* about key hydrogeomorphic or chemical process and its links to an indicator ecological function**; do detailed hydrogeomorphic or chemical assessment as well as assessment of the linkage with the indicator function using a scaled-down physical or chemical model of the design
	universal	use linear or low-order analytical equations of indicator hydrogeomorphic or chemical process and an indicator ecological function with many assumptions to set and test hydrogeomorphic design without critically evaluating their suitability	develop testable design hypotheses about key hydrogeomorphic or chemical process as well as its links to an indicator ecological function; use nonlinear and high-order analytical equations about hydrogeomorphic or chemical process as well as its links to an indicator ecological function with as few assumptions as possible in analytical methods.
Comprehensive	local	Diverse team spanning all potential hydrogeomorphic and chemical processes as well as ecological functions; all experts apply their pre-existing experience for the region to specify design and "test" against experience	Diverse team spanning all potential hydrogeomorphic and chemical processes as well as ecological functions develops testable design hypotheses that span and link abiotic-biotic nexus; use pilot-scale testing with mesocosm experiments and "adaptive monitoring and management"*** of full-scale projects to test design hypotheses to the extent possible
	universal	Diverse team spanning all potential hydrogeomorphic and chemical processes as well as ecological functions; all experts use their simplest analytical equations to specify and test design without regard to equation assumptions	Diverse team spanning all potential hydrogeomorphic and chemical processes as well as ecological functions develops testable design hypotheses that span and link abiotic-biotic nexus; apply detailed, multi-module computational models with as few assumptions as possible to assess design

*defined as a mechanistic inference, formulated on the basis of scientific literature review, and thus assumed to exist in nature and be true as a universal scientific principle (Wheaton et al., 2004b).

**defined as an attribute or activity associated with biota whose condition and needs are symptomatic of the state of the ecosystem and whose rehabilitation will be associated with improving the state of the ecosystem.

***defined as an iterative process of decision making in the face of significant uncertainty based on observation and assessment of project performance. Monitoring approach may also be iteratively updated (Holling, 1978; Florsheim et al., 2006).

a) injection

b) redistribution