

Hydroecology and river restoration: Ripe for research and synthesis

Margaret A. Palmer¹ and Emily S. Bernhardt²

Received 13 June 2005; revised 18 October 2005; accepted 21 October 2005; published XX Month 2006.

[1] Research at the intersection of hydrology and ecology is central to a future in which human and ecological needs for water are met. We briefly identify several compelling research questions at this intersection, then focus on a critical research area central to hydroecology: river and stream restoration. Challenges in this area include the development of science to evaluate the effectiveness of restoration, particularly the cumulative effects of many small projects, to restore ecosystem processes under highly constrained conditions such as below dams or in urban settings, to push some aquatic ecosystems beyond “restoration” to boost their ability to perform functions of value to society, and to identify feedbacks associated with critical thresholds beyond which restoration is not possible. Meeting these research challenges requires research at the interface of social science and the disciplines of hydrology, geomorphology, ecology, and engineering, but hydroecology will be the central science.

Citation: Palmer, M. A., and E. S. Bernhardt (2006), Hydroecology and river restoration: Ripe for research and synthesis, *Water Resour. Res.*, 42, XXXXXX, doi:10.1029/2005WR004354.

1. Introduction

[2] Water is essential to life on earth. It is a determinant of biodiversity, ecological patterns and ecological processes. Meeting human water needs and sustaining the services that aquatic ecosystems provide remain one of the greatest challenges of the 21st century. The natural hydrologic variability that is pivotal to the ability of rivers and wetlands to absorb disturbances and be resilient has been greatly reduced through the construction of dams, the diversion of surface water, and the extraction of groundwater [Poff *et al.*, 2003]. Urbanization has caused dramatic changes in hydrologic regimes that have led to lower water tables and lake levels, loss of wetlands, and more intense flooding in streams [Booth, 1990; Paul and Meyer, 2001; Gleick, 2003]. All of these impacts have had dramatic ecological consequences ranging from changes in the rate of biogeochemical processes to the extinction of species [Brunke and Gonser, 1997; Postel and Richter, 2003]. Indeed, freshwater species are 6 times more likely to be at risk than their terrestrial or avian cousins [Ricciardi and Rasmussen, 1999].

[3] The science of hydroecology is center stage in both understanding and solving these problems. The term hydroecology refers to the intricate link between ecological systems and water and is broadly applied to research integrating the physical processes of hydrology with the biological processes of ecology. As such, it encompasses critical research questions that cannot be addressed without integration of the disciplines. It includes diverse research

foci spanning multiple scales. At global and regional scales, hydrological processes interact with climate and terrestrial vegetation to determine water availability for humans and their ecosystems. At regional and local scales, flora and fauna have coevolved with hydrological regimes such that changes in the frequency or magnitude of floods may lead to extirpation of species or shifts in distribution. Flow regimes and their interaction with the soils and aquatic sediments influence nutrient cycling, reproductive success of plants and biota and food web dynamics. Just as flow influences ecological processes and patterns, the latter exert a strong influence on water availability and quality. The ecological effects of water extractions and transfers may result in ecological feedbacks that in turn lead to new patterns of flow and water mixing.

[4] A great deal of new research and synthesis is needed in the emerging field of hydroecology to help provide answers to many critical questions: Will the intensity and spread of biotic outbreaks, disease, and invasive species increase as interbasin transfers of water and groundwater extractions increase? How will changes in the amount and flow paths of water affect vegetation and rates of nutrient transformation, and what level of feedback effects will there be on water availability and quality? How will urban and exurban expansion affect interception of rainfall, evapotranspiration, albedo, erosion, runoff and nutrient fluxes? Collectively, will these changes alter local humidity and temperature regimes, as well as fluxes of nutrients, within the system and into marine systems? The list of questions is endless because hydroecology is truly a frontier discipline.

[5] We focus specifically on the science needed to advance river and stream restoration because of the central role hydroecological research must play in advancing this field and, because restoration is emerging as an essential component of effective surface water management. We argue that hydrologists and ecologists must not only forge new research partnerships but must bring

¹Chesapeake Biological Laboratory, University of Maryland Center for Environmental Sciences, Solomons, Maryland, USA.

²Department of Biology, Duke University, Durham, North Carolina, USA.

88 engineers, geomorphologists, and social scientists firmly
89 into the partnerships.

90 2. River Restoration as a Hydroecology 91 Research Frontier

92 [6] Ecological restoration of rivers should result in a
93 watershed's improved capacity to provide clean water,
94 consumable fish, wildlife habitat, and healthier coastal
95 waters. Throughout the U.S., management agencies are
96 already investing heavily in this approach. Our work with
97 the National River Restoration Science Synthesis (NRRSS)
98 project documented an exponential increase in the number
99 and costs of river restoration projects in the U.S. over the
100 last decade. However, we also found that little is known
101 about the relative effectiveness of most restoration practices
102 in meeting ecological goals [Palmer et al., 2003; Bernhardt
103 et al., 2005; Hassett et al., 2005]. As ecological restoration
104 of rivers becomes more prevalent, it is essential to examine
105 the history of restoration and to suggest a future that moves
106 the diverse disciplines involved in river restoration forward
107 toward an integrated approach for improving the health and
108 function of freshwater and coastal ecosystems.

109 [7] Developing sound science to maximize the ecological
110 and societal benefits of river restoration is now critical. Here
111 we identify several research priorities that should be central
112 to this process.

113 [8] We begin with our perspective on the paths that the
114 practice and science of river restoration have taken, why we
115 believe those paths should converge, and what directions
116 those paths must take in the future. We argue that a broad-
117 scale increase in the number of projects that are ecologically
118 effective [Palmer et al., 2005] will not happen unless
119 several, currently divergent paths meet: engineering, hydro-
120 ecology, geomorphology, ecology, landscape design, and
121 cultural anthropology. Expertise from different disciplines
122 toward a common goal is essential for hydrological synthesis
123 and is also essential for dealing with complex problems such
124 as declining biodiversity and altered ecosystem processes,
125 both of which are related the flux of water and sediments.

126 3. Toward a Convergence of Restoration Paths

127 [9] River and stream restoration have historically been
128 the purview of hydrologists, particularly hydraulic engi-
129 neers. A brief glance at many restoration manuals will
130 reveal engineering-based instructions on "restoring mean-
131 ders to straight channels," "revetting river banks," and
132 "controlling river beds" [e.g., Tuttle and Wenberg, 1996;
133 Richardson et al., 2001; River Restoration Centre, 2002].
134 The historical roots of this first restoration path, the engi-
135 neering path, grew out of an emphasis on flood control.
136 Engineering methods were developed to increase the flow
137 capacity of channels by, for example, deepening and
138 straightening channels. Thus the historical engineering
139 focus was on designing river channels to efficiently route
140 water away from infrastructure and/or toward agricultural
141 fields or city water supplies often without much regard for
142 these conduits as functioning ecosystems.

143 [10] The second path of river restoration was one that
144 focused on rivers as natural, living systems. This path
145 developed in response to infrastructure failures in engi-
146 neered rivers and a growing appreciation of the key role

147 that intact river ecosystems play in providing vital ecosys-
148 tem services [Gilvear, 1999; Wohl et al., 2005]. Recogniz-
149 ing that purely technological approaches to managing rivers
150 were insufficient led to the hydrogeomorphic engineering
151 path which modified the historical, strict engineering ap-
152 proach to a merger of design and geomorphological princi-
153 ples. The aim was now to imitate natural alluvial systems
154 using softer engineering approaches that focus on the
155 dynamics of sediment and water movement [Soar and
156 Thorne, 2001]. Hydrogeomorphic restoration attempts to
157 restore natural channel forms and hydrographs to degraded
158 rivers [Shields et al., 2003].

159 [11] The third path was opened when ecologists began to
160 get involved in restoration. While this path is not really even
161 cleared yet, it is one that focuses on supporting biodiversity
162 and ecosystem services by restoration of natural processes
163 [Clarke et al., 2003; Palmer et al., 2005; Wohl et al., 2005].
164 Ecological endpoints such as biodiversity, or more often
165 restoration of a single species, have also been identified as
166 desired endpoints for some engineering or hydrogeomor-
167 phic engineering restoration projects but these projects do
168 not typically focus on restoration of the underlying ecolog-
169 ical processes that support these endpoints. The historic
170 assumption behind hydrogeomorphic restoration is that "if
171 we build it, they will come," "they" being loosely defined
172 as the suite of species and the ecosystem functions found in
173 reference streams. Determining under what conditions this
174 assumption is true by explicitly linking hydrogeomorphic
175 and ecological research in river ecosystems should be the
176 driving force behind ecological river restoration research.
177 For example, channels can be regraded to reduce erosion
178 but physical stability requires vegetation. If the ecological
179 process of seed dispersal is not restored (e.g., by ensuring
180 floodplain inundation or removing dams that isolate river
181 reaches), native vegetation is unlikely to recruit and even if
182 planted may not survive. Often what happens is that
183 invasive species take hold and may cause unanticipated
184 problems.

185 [12] Where are we now with respect to these paths? The
186 scientific and engineering community is struggling to be at
187 the point of intersection of these paths. Each discipline
188 (hydrology, geomorphology, ecology, and engineering) has
189 something to offer yet this is an awkward intersection, each
190 discipline is characterized by different knowledge struc-
191 tures, different cultures, and very different approaches to
192 problem solving [Benda et al., 2002]. Our observation has
193 been that each group is a little suspicious of the others and
194 while there is discussion of bridging these disciplines to
195 develop restoration principles for rivers, this is certainly not
196 a path well worn. However, biological diversity and eco-
197 logical processes are inextricably linked to the flux of water
198 and sediments. If we hope to return running water ecosys-
199 tems to "healthier" states, we must evaluate the interplay
200 between restoration of ecological processes (e.g., productiv-
201 ity, biogeochemical transformations, habitat suitability,
202 etc.) and the hydrologic and geomorphic context in which
203 these processes are grounded. We next explore research
204 frontiers at these disciplinary intersections.

205 4. Research at the Convergence Point

[13] The successful intersection of the engineering, hydrogeomorphic and ecological sciences to inform river

208 restoration not only requires a cultural shift among the
 209 scientific community but also requires new research. Right
 210 now some of the research needs could be easily met if more
 211 data on the outcome of restoration projects were available.
 212 The fraction of written project records that indicate moni-
 213 toring was planned or implemented is shockingly low
 214 (<4000 of ~37,000 projects [Bernhardt *et al.*, 2005]).
 215 While conversations with project managers suggest that
 216 much more information on outcomes is known, this infor-
 217 mation is extremely difficult to obtain (Bernhardt, unpub-
 218 lished data). It has certainly not been synthesized. A
 219 synthesis of this would allow us to identify what types of
 220 restoration approaches and in what contexts (watershed
 221 position, land use, climatic and flow regime, etc.), are most
 222 successful in meeting the desired goals. If we can identify
 223 common elements of success or failure, this would allow us
 224 to adapt our restoration methods and/or adaptively manage
 225 projects post implementation. Thus a top research priority
 226 should be data synthesis efforts to evaluate the ecological
 227 effectiveness of past restoration projects, particularly those
 228 types of projects that are extremely expensive (e.g., flood-
 229 plain reconnection) or are highly interventionist (e.g., chan-
 230 nel reconfiguration).

231 [14] To complete such a synthesis requires new research
 232 on how best to measure ecological effectiveness and more
 233 broadly how to quantify multiple ecosystem services in
 234 meaningful ways [Meyerson *et al.*, 2005]. Most river
 235 restoration projects are intended to achieve multiple goals
 236 with the most common being riparian and water quality
 237 management [Bernhardt *et al.*, 2005]. Yet even for those
 238 projects that are monitored, only one or two parameters are
 239 typically tracked; most often these are physical parameters
 240 such as cross-sectional area. When multimetric “indices of
 241 biological integrity” [e.g., Karr and Chu, 1999] are used,
 242 they assess ecological structure such as biodiversity and
 243 habitat but do not evaluate the processes that underlie this
 244 structure (e.g., primary production). Quantifying less tangi-
 245 ble ecosystem services such as water purification or climate
 246 control that are provided by riparian restoration are even
 247 more of a research challenge. Can we design restoration
 248 projects to not only meet immediate societal needs (e.g.,
 249 stabilize eroding banks) but to enhance ecosystem services
 250 (e.g., removal of excess nutrients or moderate temperature
 251 extremes), and, can we measure these less tangible benefits
 252 then include them in models to quantitatively explore
 253 benefits and trade-offs?

254 [15] A second research frontier that would help merge
 255 ecological and hydrogeomorphic approaches to restoration
 256 includes the development and testing of theory on how
 257 “much” restoration of a natural flow regime is
 258 “enough.” Considerable research has documented the
 259 extensive link between natural flow variability (particu-
 260 larly the timing of floods) and life history events such
 261 as fish spawning and aquatic insect emergence [Poff *et al.*,
 262 1997]. This has led to efforts to restore flow regimes,
 263 particularly on impounded rivers [Postel and Richter,
 264 2003]. Yet often it is not possible to return a system to
 265 its historic flow regime. The question then becomes how
 266 best to manage flows for particular ecological benefits,
 267 are there threshold levels of variability that should be
 268 restored, and how do these levels differ across species
 269 and ecological processes?

[16] A third research frontier is in the area of urban 270
 stream restoration. What approaches can be used to maxi- 271
 mize environmental benefits when restoring in a built 272
 environment? Restoration of urban streams requires a focus 273
 on multiple assaults: thermal stress, high peak flows and 274
 low base flows, chemical pollution, and eroding banks. 275
 Further, urban streams are routinely subjected to “acci- 276
 dents” such as failed storm water infrastructure and pulses 277
 of sediments following new construction projects. This 278
 leads directly to a fourth research frontier that extends even 279
 beyond the urban setting: Are there thresholds past which 280
 riverine systems cannot recover or are there threshold events 281
 in which a small assault to the system can result in a large 282
 change in ecosystem state? Restoration research may need 283
 to identify internal feedbacks in rivers that contribute to the 284
 resilience of the system. 285

[17] Increasingly, the scientific community is being asked 286
 to think beyond ecosystem resilience and develop restora- 287
 tion methods that will actually boost ecological perfor- 288
 mance. Thus a fifth research frontier includes restoration 289
 approaches to design ecosystems that provide maximum 290
 rates of ecosystem services such as denitrification and 291
 sediment removal. Here “restoration” projects might in- 292
 volve creating novel ecosystems (e.g., treatment wetlands or 293
 floodplains akin to water treatment facilities) that have little 294
 historic precedent, but allow downstream surface waters to 295
 recover from upstream insults. Thus this frontier requires 296
 that we conceive of restoration success more broadly than 297
 within individual projects, toward protecting/restoring con- 298
 ditions for the greatest extent of river. 299

[18] In a similar vein, the sixth frontier is finding new 300
 and creative ways to measure the cumulative contribution 301
 of individual projects to overall watershed improvement. 302
 Empirical data and landscape models are needed to 303
 prioritize the selection of future restoration sites and to 304
 develop basin-scale monitoring approaches that look not 305
 at on-site improvements, but catchment-scale changes in 306
 species diversity and abundances and water quality. 307
 Robust, coupled hydrogeomorphic-ecologic models have 308
 the potential to revolutionize all of these frontier areas of 309
 research and to link them together. Models also allow us 310
 to identify areas where we need more information and 311
 even experimentation. 312

5. End of the Path: The Most Challenging 313 Research Frontier 314

[19] Is the convergence of engineering and hydroecoge- 315
 morphic principles sufficient to move restoration science 316
 into the 21st century? We believe not. The final research 317
 frontier is restoration science that is informed by social 318
 science scholarship. Rarely are restoration decisions based 319
 entirely on environmental issues and even if they are, city 320
 planners, managers, and citizens influence project designs 321
 and prioritization. Views on restoration goals and 322
 approaches differ among all these groups and, of course, 323
 from those of the scientists and engineers. Even if we had 324
 the scientific knowledge to guide stream restoration for 325
 multiple benefits, the likelihood of that knowledge playing 326
 a key role in the design of restoration projects is slim unless 327
 we develop mechanisms for ensuring that knowledge is 328
 used and viewed as valuable. This requires input from 329

330 cultural anthropology, environmental education, landscape
331 architecture and city planners.

332 [20] Restoration will be most effective when watershed
333 inhabitants, scientists, planners and designers understand
334 the views, values and cognitive models each has toward
335 rivers and the place of rivers in the lives of people [Gross,
336 2003]. As citizens are educated about river degradation,
337 when they support intervention to improve their rivers, and
338 when they feel ownership of and pride in the resulting
339 restoration project, the projects are far more likely to be
340 successfully implemented. Similarly, when scientists and
341 planners better understand stakeholder needs and values,
342 they may be able to develop scientifically informed designs
343 that balance environmental needs and human needs. How-
344 ever, scientists need the tools to accomplish this and
345 developing those requires research at the interface of social
346 science and the restoration disciplines of hydrology, geo-
347 morphology, ecology and engineering.

348 [21] Hydroecology will be the central science linking the
349 traditional restoration disciplines. Thus hydrologists and
350 ecologists must play leadership roles in initiating these
351 linkages and extending linkages to the social sciences.
352 Effective restoration project designs and site selection both
353 depend on a thorough understanding of hydrologic connec-
354 tivity, the interplay between land use change and water
355 export, and the interaction between ecology and the flux of
356 water.

357 [22] **Acknowledgment.** This is contribution 3900 of the University
358 of Maryland Center for Environmental Science, Chesapeake Biological
359 Laboratory.

360 References

361 Benda, L. E., L. Poff, C. Tague, M. A. Palmer, J. Pizzuto, S. Cooper,
362 E. Stanley, and G. Moglen (2002), How to avoid train wrecks when using
363 science in environmental problem solving, *BioScience*, 52, 1127–1136.
364 Bernhardt, E. S., et al. (2005), Restoration of U.S. rivers: A national
365 synthesis, *Science*, 308, 636–637.
366 Booth, D. B. (1990), Stream channel incision following drainage-basin
367 urbanization, *Water Res. Bull.*, 26, 407–417.
368 Brunke, M., and T. Gonser (1997), The ecological significance of exchange
369 processes between rivers and groundwater, *Freshwater Biol.*, 37, 1–33.
370 Clarke, S. J., L. Bruce-Burgess, and G. Wharton (2003), Linking form and
371 function: Towards an eco-hydromorphic approach to sustainable river
372 restoration, *Aquat. Conserv. Mar. Freshwater Ecosyst.*, 13, 439–450.
373 Gilvear, D. J. (1999), Fluvial geomorphology and river engineering: Future
374 roles utilizing a fluvial hydrosystems framework, *Geomorphology*, 31,
375 229–245.
376 Gleick, P. H. (2003), Global freshwater resources: Soft-path solutions for
377 the 21st century, *Science*, 302, 1524–1528.
378 Gross, M. (2003), *Inventing Nature: Ecological Restoration by Public*
379 *Experiments*, Lexington Books, Lanham, Md.

Hassett, B., M. A. Palmer, E. S. Bernhardt, S. Smith, J. Carr, and D. Hart 380
(2005), Status and trends of river and stream restoration in the Chesape- 381
peake Bay Watershed, *Front. Ecol. Environ.*, 3, 259–267. 382
Karr, J. R., and E. W. Chu (1999), *Restoring Life in Running Waters: Better* 383
Biological Monitoring, Island, Washington, D. C. 384
Meyerson, L. A., J. Baron, J. Melillo, R. J. Naiman, R. I. O'Malley, 385
G. Orians, M. A. Palmer, A. S. P. Pfaff, and O. E. Sala (2005), Aggre- 386
gate measures of ecosystem services: Can we take the pulse of nature?, 387
Front. Ecol. Environ., 3, 56–59. 388
Palmer, M. A., D. D. Hart, J. D. Allan, E. Bernhardt, and the National 389
Riverine Restoration Science Synthesis Working Group (2003), Bridging 390
engineering, ecological, and geomorphic science to enhance riverine 391
restoration: Local and national efforts, in *Proceedings of a National* 392
Symposium on Urban and Rural Stream Protection and Restoration: 393
EWRI World Water and Environmental Congress, pp. 1–9, Am. Soc. of 394
Civ. Eng., Reston, Va. 395
Palmer, M. A., et al. (2005), Standards for ecologically successful river 396
restoration, *J. Appl. Ecol.*, 42, 208–217. 397
Paul, M. J., and J. L. Meyer (2001), Streams in the urban landscape, 398
Annu. Rev. Ecol. Syst., 32, 333–365. 399
Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegard, 400
B. Richter, R. Sparks, and J. Stromberg (1997), The natural flow 401
regime: A paradigm for river conservation and restoration, *BioScience*, 402
47, 769–784. 403
Poff, N. L., J. D. Allan, M. A. Palmer, D. D. Hart, B. D. Richters, A. H. 404
Arthington, K. H. Rogers, J. L. Meyers, and J. A. Stanford (2003), River 405
flows and water wars: Emerging science for environmental decision 406
making, *Front. Ecol. Environ.*, 1, 298–306. 407
Postel, S., and B. Richter (2003), *Rivers for Life: Managing Water for* 408
People and Nature, Island, Washington, D. C. 409
Ricciardi, A., and J. B. Rasmussen (1999), Extinction rates of North Amer- 410
ican freshwater fauna, *Conserv. Biol.*, 13, 1220–1222. 411
Richardson, E. V., D. B. Simons, and P. F. Lagasse (2001), River engineer- 412
ing for highway encroachments: Highways in the river environment, 413
Rep. FHWA NHI 01-004, Natl. Tech. Inf. Serv., Springfield, Va. 414
River Restoration Centre (2002), Manual of river restoration techniques, 415
Silsoe, U. K. (Available at <http://www.therrc.co.uk/manual.php>) 416
Shields, F. D., R. R. Copeland, P. C. Klingeman, M. W. Doyle, and 417
A. Simon (2003), Design for stream restoration, *J. Hydrol. Eng.*, 129(8), 418
575–584. 419
Soar, P. J., and C. R. Thorne (2001), *Channel Restoration Design for* 420
Meandering Rivers, Rep. ERDC/CHL CR-01-1, Flood Damage Reduct. 421
Res. Program, U.S. Army Eng. Res. and Dev. Cent., Vicksburg, Miss. 422
Tuttle, R. W., and R. D. Wenberg (1996), *Engineering Field Handbook*, 423
chap. 16, *Streambank and Shoreline Protection*, 143 pp., Nat. Resour. 424
Conserv. Serv., Washington, D. C. (Available at <http://www.info.usda.gov/CED/ftp/CED/EFH-Ch16.pdf>) 425
Wohl, E., P. L. Angermeier, B. Bledsoe, G. M. Kondolf, L. MacDonnell, 427
D. M. Merritt, M. A. Palmer, N. L. Poff, and D. Tarboton (2005), 428
River restoration, *Water Resour. Res.*, 41, W10301, doi:10.1029/ 429
2005WR003985. 430

E. S. Bernhardt, Department of Biology, Duke University, Durham, 432
NC 27708, USA. 433

M. A. Palmer, Chesapeake Biological Laboratory, University of 434
Maryland Center for Environmental Sciences, P.O. Box 38, Solomons, 435
MD 20688, USA. (mpalmer@umd.edu) 436