Hydrologic Connectivity

A Call for Greater Emphasis in the World's Wilderness

BY CATHERINE M. PRINGLE

Hydrologic connectivity refers to the movement of matter, energy, and/or organisms within water and between elements of the hydrologic cycle (Pringle 2001 a, b). Humans have altered this property on local, regional, and global scales. Because of the continual transport that characterizes hydrologic systems, an effect originating in any part of the landscape may be evident at a distant geographic location, sometimes within protected places such as wilderness. Therefore, dams, water diversions, groundwater extraction, and nutrient and toxic loading outside of wilderness pose significant threats that are difficult to forecast.

The subject of hydrologic connectivity has typically been ignored in theoretical and practical pursuits of wilderness protection. When allocation decisions and management traditions were established for most wilderness in the United States, the science of hydrologic connectivity was in its infancy. Also, many alterations of hydrologic connectivity are beyond the direct control of managers because they are outside wilderness boundaries, and there is commonly a lack of data on hydrologic connections between wilderness resources and surrounding areas. The role of water, both aboveground and below the surface, must become a more integral consideration of wilderness integrity.

Waterways in wilderness can be defined as having interactive pathways along three spatial dimensions: longitudinal (headwater-estuarine), lateral (riverine-riparian/floodplain), and vertical (riverine-groundwater) (Ward and Stanford 1989). Only when all of these dimensions are adequately considered, along with climatic factors, are we really talking about hydrologic connectivity at landscape levels (Pringle 2001 b). Hydrologic connectivity has not been part of the traditional scientific literature surrounding the management and conservation of wilderness landscapes. Only during the last decade have we accepted the premise generally that groundwater and surface waters are interconnected as a single resource (e.g., Winter et al. 1998). We still lack data on how the hydrology of wilderness areas and wild rivers fit into the greater landscape. There is little information in the U.S. about the contribution of wilderness or wild river classification to the protection of water quality, either within wilderness or for off-site benefits. Basic information on river discharge is often not available. There is a need to consider the size, shape, and configuration of wilderness areas with respect to watersheds, regional aquifers, and precipitation patterns in making allocation decisions and understanding the effects of natural or human-caused disturbance (Pringle 2001 b).

Article author Catherine M. Pringle with her 14-month-old daughter, Pamela-Julissa, tubing the Chattahoochee River in northern Georgia. Photo courtesy of Catherine Pringle.

How Is Wilderness Affected by Hydrologic Connectivity?

Four global patterns have emerged in human-dominated landscapes that have important implications for the location and

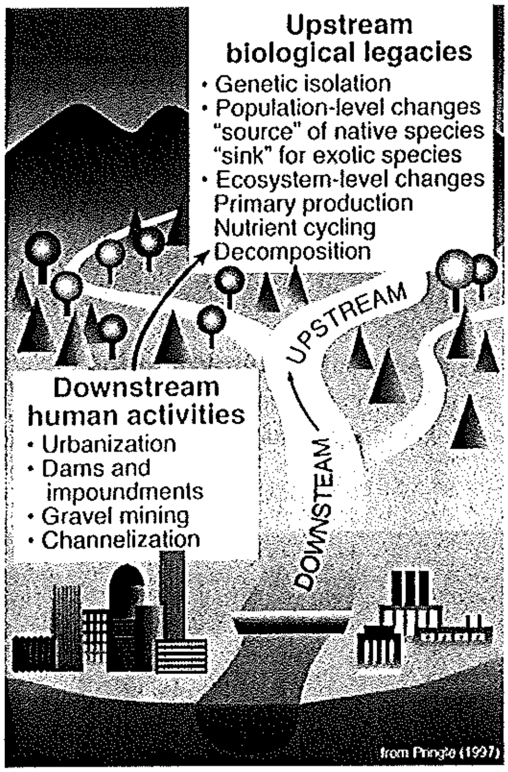

Figure 1—Potential downstream influences on upstream communities. Figure from Pringle (1997).

management of wilderness: (1) the extensive and rapid deterioration of lower watersheds, deltas, estuaries, and receiving coastal waters; (2) the deterioration and loss of riverine floodplains, connecting wetlands, and riparian ecosystems; (3) the deterioration of irrigated lands and connecting surface waters; and (4) the isolation of upper watersheds. The isolation of upper watersheds, many of which are protected within wilderness boundaries, merits close attention by the wilderness community.

Trends in human settlement and socioeconomic development have played a major role in determining where wilderness has been protected within watersheds. Human populations have exhibited a general pattern of settling in lowland coastal areas and fertile river valleys and then moving inland and upland. Consequently, many wilderness areas are located in upper watershed areas of highlands rock and ice.

Oftentimes governments set aside land as wilderness because of a combination of low potential for agricultural production, high scenic value, and/or protection for human water supplies—with ecological and wildlife values as a secondary benefit. Many of these areas now contain some of the last vestiges of intact habitat, wildlife, and other natural features in human-dominated landscapes across the globe, yet they are vulnerable because they have become progressively more and more isolated from their lower watersheds (Pringle 1997).

Effects of isolation of upper watersheds on the biological integrity of wilderness are not well understood. We do know, however, that modifications of lower watersheds such as water abstraction, channel modification, land use changes, nutrient discharge, and toxic discharge can set off a cascade of events upstream that are often not immediately associated with these original downstream sources of disturbance (Pringle 1997). Human disturbances in lower watersheds can alter streams and rivers in their upstream reaches on levels from genes to ecosystems (see Figure 1): (1) genetic and species-level changes, such as reduced genetic flow and variation in isolated upstream populations; (2) population and community-level changes that occur when degraded downstream areas act as population "sinks" for source populations of native species upstream or, conversely, as "source" populations of exotic species that migrate upstream; and (3) ecosystem-and landscape-level changes in nutrient cycling, primary productivity, and/or regional patterns of biodiversity. There is a critical need for research at all of these levels.

The U.S. Caribbean National Forest (the largest [11,269 ha, 27,825 ac] natural forest left in the Caribbean Islands) provides a neotropical example of how downstream hydrological alterations and pollution outside of a biological reserve can potentially affect upstream ecosystem dynamics. In contrast to the anadromous salmonids of the Pacific Northwest of the United

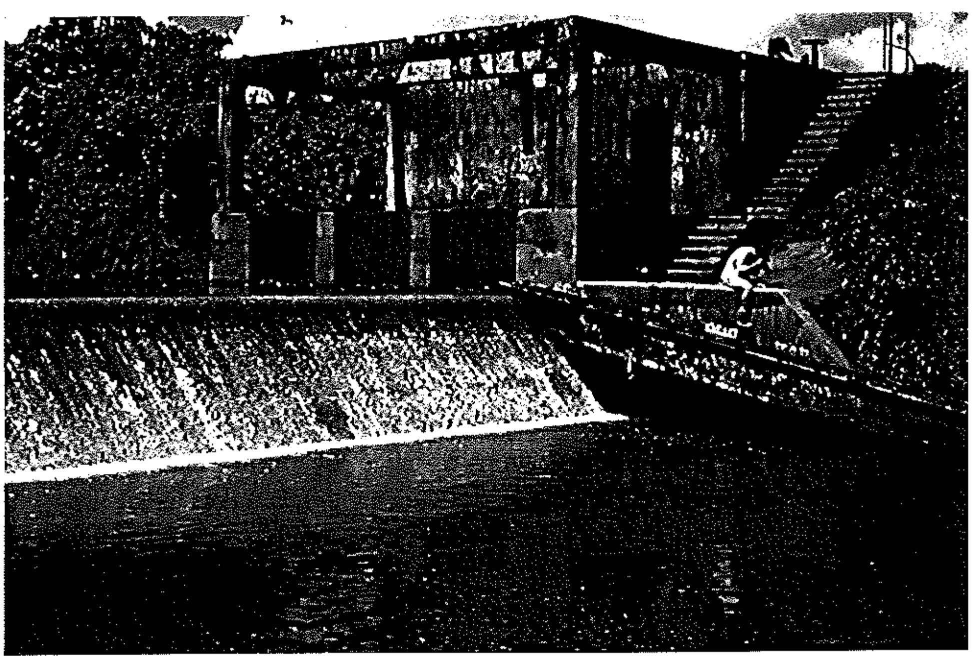

Figure 2—The Espiritu Santo dam and water intake downstream from the Caribbean National Forest in northeastern Puerto Rico. Note the defunct fish ladder (below the dam) and the triple-barred water intake (above the dam sill on the right). Photo by Catherine Pringle.

States, which are often blocked by dams, most of the fishes and shrimps that inhabit the streams of the Caribbean National Forest are amphidromous (drifting to the estuary and/or ocean as larvae, where they spend a relatively short period of time, and then returning upstream as juveniles to spend their adult lives).

Since all of the fishes and shrimps that inhabit the nine major streams draining the forest are migratory (e.g., March et al. 1998), water extraction associated with dams and pollution from sewage treatment plants (in rapidly developing coastal areas) can potentially affect recruitment of adults upstream and related ecosystem processes. For example, low versus high abundances of shrimps can cause interstream differences in algal and insect abundance, algal community composition, and total amounts of benthic organic matter (Pringle et al. 1999). If migratory shrimps and fishes were to be extirpated above dams and water intakes, as has been observed above high dams without water spillways in other regions of Puerto Rico (Holmquist et al. 1998), concomitant changes in ecosystem structure and function might occur. While dams associated with water intakes within and outside of the Caribbean National Forest are not large (usually less than 3 meters; see Figure 2) and they have spillways, the large number of these structures and the volume of water withdrawn from rivers is cause for major concern (Pringle and Scatena 1999; Figure 3). Water intakes result in massive mortality of larval shrimps migrating down to the estuary. During some times of the year, no water is released over many dams and all fish and shrimp larvae suffer direct mortality when they are sucked into the water intake during their migration to the estuary. Recommendations for improving hydrologic connections between the Caribbean National Forest and downstream adjacent areas include establishment of in-stream flow and habitat requirements of migratory biota and maintenance of minimum flows over dams, installation and upkeep of functional fish/shrimp ladders on dams, and implementation of more environmentally sensitive water withdrawal systems (Benstead et al. 1999).

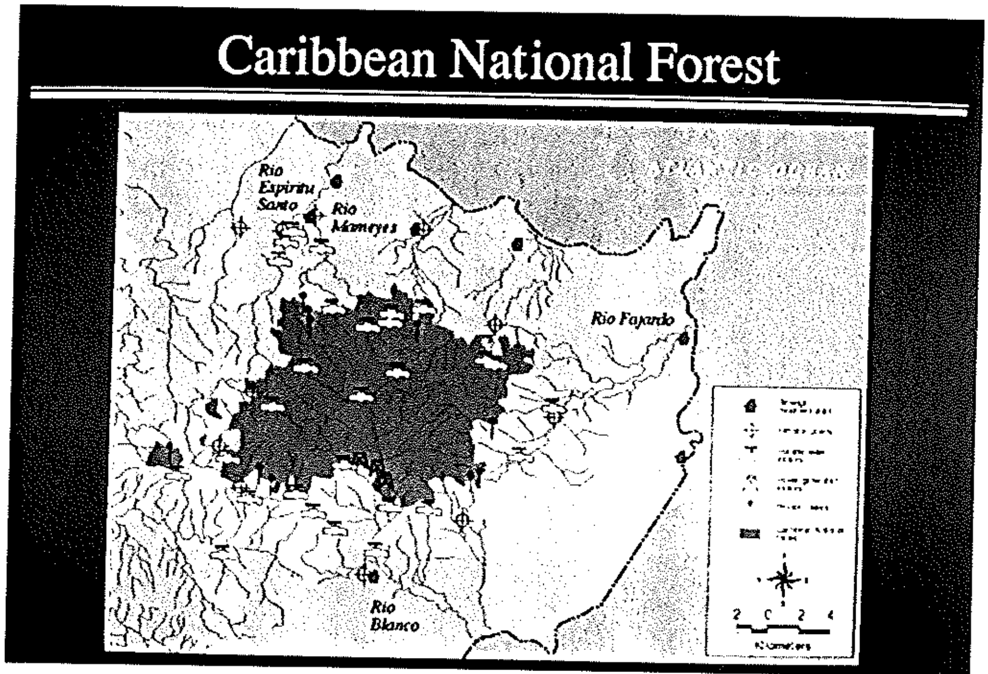

Figure 3—Location of the Caribbean National Forest, Puerto Rico, sites of water withdrawals (i.e., intakes for potable water, power generation, private sewage treatment plants, and filtration plants). Figure from Pringle (2000).

Beyond the Wilderness Watershed

The sheer magnitude and extent of hydrologic alterations in the global landscape are now affecting wilderness through increasingly broad feedback loops. It is ironic that, just as we are now beginning to understand the complexities of human effects on local hydrologic processes within watersheds, wilderness reserves are being threatened by regional and global processes such as overdrawn aquifers, atmospheric deposition, and global climate change.

Just as watersheds are the natural unit of management for surface waters, aquifers are the natural unit of management for groundwaters. Since both groundwater and surface water are integrally connected and aquifers do not always coincide with watersheds, the management of both aquifers and watersheds needs to be coordinated. Management has generally underemphasized groundwater problems (NRC 1999), all-too-often focusing on surface waters, when in fact, the landscape is composed of a diverse and interconnected mosaic of geohydrologic units (Gibert et al. 1994). In some regions of the world, aquifers and aquifer systems still need to be delineated. In other regions, where aquifer systems have been thoroughly mapped, much research is still necessary to fully characterize groundwater quality conditions and groundwater surface water interactions (e.g., Reetz 1998). The situation is also complicated by fragmented management of small portions of aquifers by jurisdictions with different management objectives.

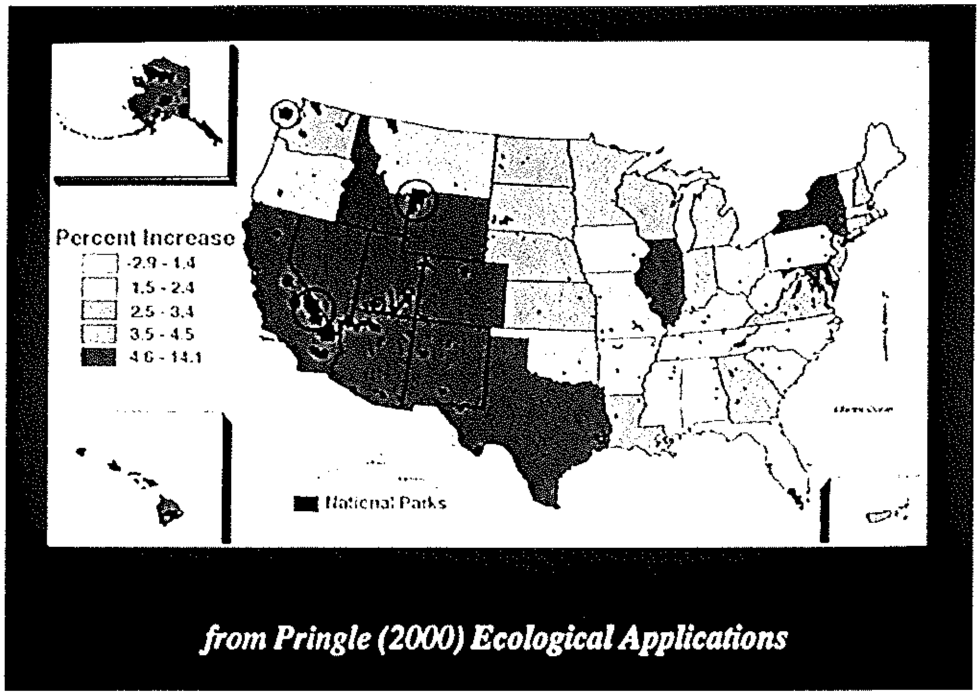

Figure 4—Distribution of national parks in the United States and the projected annual rate of population increase (% per 1,000 population) between 1995 and 2025. Small dots indicate the location of a park that was too small to be drawn to scale. The National Park Service (NPS) manages a network of 368 park units totaling 79 million acres (about 12% of federal land holdings). The United States is participating in water rights adjudications for 50 NPS units in the arid western states. Increasing numbers of water resource conflicts are emerging in the East, and pressure on NPS units are predicted to increase throughout the United States with increasing population growth over the next millennium. (Population data from the U.S. Department of Commerce Bureau of Census [1997]). Figure from Pringle (2000).

The Cumberland Island National Seashore Wilderness Area in coastal Georgia, USA, faces potential water resource problems related to groundwater withdrawals occurring well outside the island's watershed. The island is connected to the mainland by the regional karst aquifer on which the barrier island is perched. Extensive groundwater withdrawals from this regional aquifer have occurred on the mainland, resulting in an approximate 9-meter permanent decline in the potentiometric surface of the aquifer (Johnston et al. 1980, 1981). This is just one example where groundwater withdrawals well outside the boundaries of a wilderness are threatening ecological values protected therein.

Water deficit, defined as the excess of water pumping over recharge from rainfall, has been estimated at 160 billion tons per year on a global basis (Postel 1999). Correspondingly, groundwater depletion and stream dewatering are contributing to loss and alteration of wetland and riparian ecosystems throughout the world, with particularly strong effects on "protected areas" in arid and semiarid regions because surface and groundwater are in high demand for human use by burgeoning human populations (Pringle 2000; Pringle 2001 a, b).

The biological integrity of a given wilderness is affected by cumulative alterations of hydrologic connectivity within and outside of its boundaries, from relatively local (e.g., single dam effect), to regional (e.g., cumulative effects of dams, overdrawn aquifers, atmospheric deposition), and global (e.g., climate change) phenomena. The location of a given wilderness in the hydroscape (i.e., juxtaposition with respect to watersheds, regional aquifers, and wind and precipitation patterns) plays a key role in determining how it will be affected by alterations in hydrologic connectivity. Wilderness reserves in biomes, ranging from arid deserts to tropical rainforests, are vulnerable regardless of their size and watershed location. While an old adage of conservation biology is "the larger the reserve the better," the hydrologic connectivity of large reserves must correspondingly be managed on very large scales that often transcend cultural, political, national, and/or international boundaries. There is an increasing need for innovative new strategies to manage hydrologic connectivity across the boundaries of biological reserves as they become remnant natural areas in the human-dominated landscape.

Hydrologic Connectivity and the Future of Wilderness

The U.S. population is expected to increase from 263 million in 1995 to 394 million by 2050 (U.S. Department of Commerce 1997). Population growth will continue to be highest in arid western states where most public lands are located (see Figure 4). Over the next 30 years, the West is projected to grow at nearly twice the national average, while the Northeast and Midwest will grow at one-half the U.S. total rate (Campbell 1996). Water is largely unavailable to meet new demands in many western states as existing watercourses and aquifers have been fully allocated, and the best dam sites have already been developed.

Increasingly, managers of public lands in the United States are stepping forward and fighting for water rights to meet ecological needs. As a result of their efforts, in some cases water is now being diverted from off-stream uses back to public lands because of inadequate water supplies to maintain fish and wildlife. The U.S. National Park Service is participating in water rights adjudications in more than 50 national park system units in just the western states (Pringle 2000). Conflicts between the private sector and state and federal governments over the control of water resources are frequent and widespread. Increased pressure to dam rivers and pump aquifers near public lands, as a result of water shortage coupled with increased human demands, are major threats to the biotic integrity of these areas. The Colorado River in Grand Canyon National Park has been so highly altered by stream regulation associated with an upstream dam that it is considered an exotic ecosystem (Johnson and Carothers 1987).

It is important to develop cooperative partnerships between federal land management agencies and both academic and federal scientists. Such partnerships will play a critical role in developing science-based guidelines to manage hydrologic connections across public land boundaries. One landmark example is the trial flood in the Grand Canyon that was implemented at Glen Canyon Dam by the Interior Department's Bureau of Reclamation, in part as a result of scientific requests. In an attempt to restore some of the pre-dam features of the highly regulated dam, managers increased discharge over the dam by more than fourfold during a weeklong period in March 1996. Never had an intentional flood been released specifically for environmental benefits, and more than 30 scientific projects were designed to examine its effects (Collier et al. 1997).

Effective management of effects of cumulative hydrologic alteration outside public land boundaries not only requires more research, but also incorporation of existing scientific information into management actions. A rich scientific literature exists on hydrologic connections and integrated management at watershed levels that could be more effectively used by public land managers. All too often, however, water resource managers focus on surface waters and, if groundwater resources are recognized, only volume and accessibility receive attention, while water quality and biological characteristics are ignored (NRC 1999). Management and policy must recognize that the flow pathways of surface and groundwater are interconnected along a continuum of geohydrologic units and that the interaction between surface and groundwater influences biological patterns at landscape scales (Pringle and Triska 1999).

The last relatively undisturbed ecosystems in the United States exist on public lands, and they are threatened by mounting human pressures. The development of effective science-based guidelines to manage hydrologic connections across public land boundaries is critical to the long-term stability of these remnant ecosystems. Federal land management agencies are in a transitional phase as they move toward ecosystem management approaches. This provides a window of opportunity for scientists to get involved on a variety of different levels, including research, development of management guidelines, and environmental outreach.

CATHERINE M. PRINGLE is a professor at the Institute of Ecology at the University of Georgia, 306 BioSciences, Athens, Georgia 30602, USA. E-mail: pringle@sparc.ecology.uga.edu.

Pringle's work on hydrologic connectivity was supported by the USDA Forest Service and the National Science Foundation. Special thanks to Alan Watson of the Aldo Leopold Wilderness Research Institute for his editorial help with this paper, which is based on Pringle 1997, 2000, 2001 a, b.

REFERENCES

Benstead, J. P., J. G. March, C. M. Pringle, and F. N. Scatena. 1999. Effects of a low-head dam and water abstraction on migratory tropical stream biota. *Ecological Applications* 9: 656–668.

Campbell, P. R. 1996. Population projections for states by age, sex, race, and Hispanic origin: 1995–2025. Washington, D.C.: Bureau of Census PPL-47.

Collier, M. P., R. H. Webb, and E. D. Andrews. 1997. Experimental flooding in Grand Canyon. *Scientific American* 276 (1): 82–89.

Gibert, J., J. A. Stanford, M. J. Dole-Oliver, and J. V. Ward. 1994. Basic attributes of groundwater ecosystem and prospects for research. In J. Gibert, D. L. Danielopol, and J. A. Stanford, eds. Groundwater Ecology. San Diego, Calif.: Academic Press, pp. 7–40.

Holmquist, J. G., J. M. Schmidt-Gegenbach, and B. B. Yoshioka. 1998. High dams and marine-freshwater linkages: effects on native and introduced fauna in the Caribbean. Conservation Biology 12: 621–630.

Johnson, R. R. and S. W. Carothers. 1987. External threats: the dilemma of resource management on the Colorado River in Grand Canyon National Park, USA. *Environmental Management* 11: 99–107.

Johnston, R. H., R. E. Krause, F. W. Meyer, P. D. Ryder, C. H. Tibbals, and J. D. Hunn. 1980. Estimated potentiometric surface for the Tertiary Limestone Aquifer system, southeastern United States, prior to development. *U.S. Geological Survey Open File Report* 80–406.

Johnston, R. H., H. G. Healy, and L. R. Hayes. 1981. Potentiometric surface for the Tertiary Limestone aquifer system, southeastern United states, May 1980. *U.S. Geological Survey Open File Report* 81–486.

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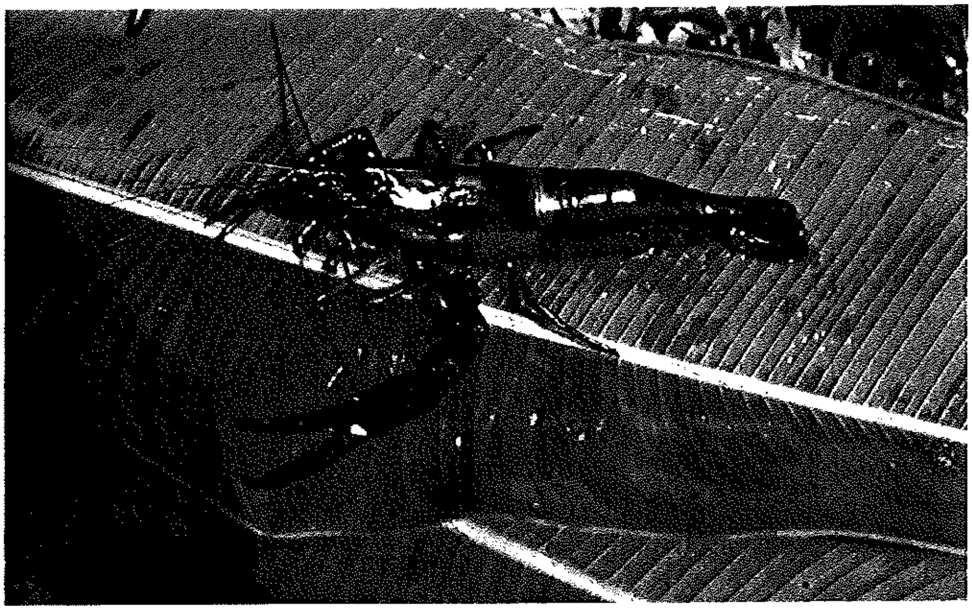

Costa Rican Macrobrachium carcinus. Photo by Catherine Pringle.

March, J. G., J. P. Benstead, C. M. Pringle, and F. N. Scatena. 1998. Migratory drift of larval freshwater shrimps in two tropical streams, Puerto Rico. *Freshwater Biology* 40: 261–274.

NRC (National Research Council). 1999. New strategies for America's watersheds. Washington, D.C: National Academy Press.

Postel, S. L. 1999. *Pillar of sand: Can the Irrigation Miracle Last?* New York: W.W. Norton.

Pringle, C. M. 1997. Exploring how disturbance is transmitted upstream: going against the flow. *Journal of the North American Benthological Society* 16: 425–438.

Pringle, C. M. 2000. Threats to U.S. public lands from cumulative hydrologic alterations outside of their boundaries. *Ecological Applications* 10: 971–989.

Pringle, C. M. 2001 a. Managing riverine connectivity in complex landscapes to protect "remnant natural areas." Plenary talk. Verhandlungen Internationale Verein. *Limnol* 27 (3): 1149–1164.

Pringle, C. M. 2001 b. Hydrologic connectivity and the management of biological reserves: a global perspective. *Ecological Applications* 11: 981–998.

Pringle, C. M., N. H. Hemphill, W. McDowell, A. Bednarek, and J. March. 1999. Linking species and ecosystems: different biotic assemblages cause interstream differences in organic matter. *Ecology* 80: 1860–1872.

Pringle, C. M. and F. N. Scatena. 1999. Freshwater resource development: case studies from Puerto Rico and Costa Rica. In U. Hatch and M. E. Swisher, eds. Tropical *Managed Ecosystems: The Mesoamerican Experience.* New York: Oxford University Press, pp. 114–121.

Pringle, C. M. and F. J. Triska. 1999. Emergent biological patterns in streams resulting from surface-subsurface water interactions at landscape scales. In J. B. Jones, and P. J. Mulholland, eds. Surface-subsurface interactions in stream ecosystems. New York: Academic Press, pp. 167–193.

Reetz, G. 1998. Water quality in the West. *Report to the Western Water Policy Review Advisory Commission.* Denver, Colo.: U.S. Environmental Protection Agency.

U. S. Department of Commerce. 1997. Demographic state of the nation: 1997. Special Studies Series. Washington, D. C.: Bureau of the Census, pp 23–193.

Ward, J. V., and J. A. Stanford. 1989. The four-dimensional nature of lotic ecosystems. *Journal of the North American Benthological Society* 8: 2–8.

Winter, T. C., J. W. Harvey, O. Lehn Franke, and W. M. Alley. 1998. Groundwater and surface water: a single resource. *Geological Survey Circular (USA) 1139.*

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mocracy between various social groups and nature. The antirestoration arguments, largely articulated by Eric Katz, argue that restoration reflects human hubris and vanity: "There are no limits to our power and ambition to develop, degrade, restore, and manage the natural world. Nature itself—a nature unmodified by human intention, knowledge, technology and power—will lose its value. ... We will create for ourselves a totally artificial world, a world in which the presence of human intentionality is inescapable" (p. 47).

This book came from the 1996 restoration controversy that erupted in Chicago, and the resulting six sessions (26 papers) presented at the International Symposium on Society and Resource Management in 1998. While edited books based on conference presentations often lack focus and contain repetitive passages, the editors have done an excellent job in addressing these potential dangers.

Restoring Nature provides a thought-provoking, challenging, and multidisciplinary analysis of a fascinating issue facing contemporary wilderness and resource managers. The book succeeds because it forces the reader to confront the many difficult questions regarding ecological restoration posed by writers representing different disciplinary and ideological perspectives. Managers of areas from wilderness to urban parks will be increasingly brought into the restoration fray (e.g., the prescribed burning issue), and they would be well advised to consider the wealth of ideas, case studies, practical management techniques, and perspectives offered in this book.

Reviewed by JOHN SHULTIS, *IJW* book review editor. E-mail: shultis@unbc.ca.