POLICY FORUM

ECOLOGY

Synthesizing U.S. River Restoration Efforts

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The importance of rivers and streams for fresh water, food, and recreation is well known, yet there is increasing evidence that degradation of running waters is at an all-time high (*1*). More than one-third of the rivers in the United States are listed as impaired or polluted (*2*), and freshwater withdrawals in some regions are so extreme that some major rivers no longer flow to the sea year round (*3*). Extinction rates of freshwater fauna are five times that for terrestrial biota (*4*, *5*). Fortunately, stream and river restoration can lead to species recovery, improved inland and coastal water quality, and new areas for wildlife habitat and recreational activities (*6*–*11*).

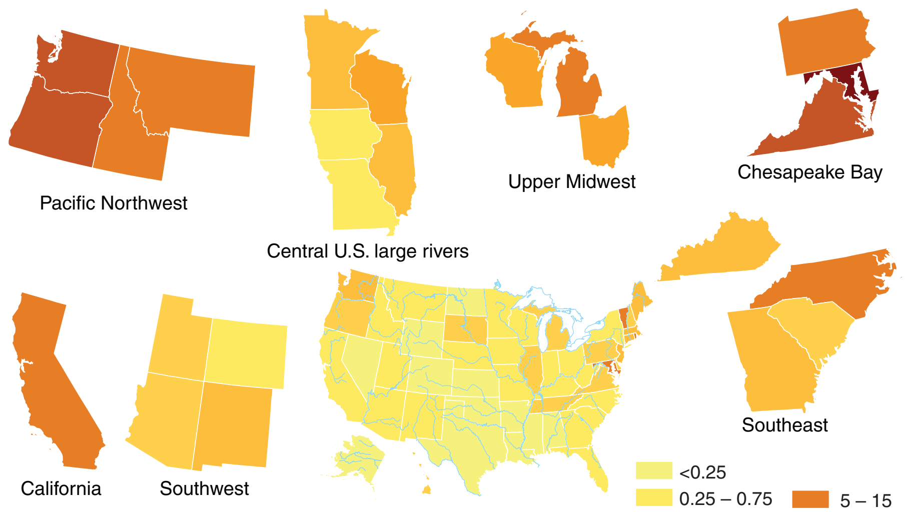
River restoration has become a highly profitable business (*12*, *13*) and will play an increasing role in environmental management and policy decisions (*7*). A few high-profile and large restoration projects such as those on the Kissimmee River (*11*, *14*) and the Grand Canyon (*15*, *16*) are well documented. However, most restoration projects are small scale (implemented on less than 1 km of stream length), and information on their implementation and outcome is not readily accessible. This prompted us to build a database of river restoration across the United States with the goal of determining the common elements of successful projects.

We found that existing restoration databases are highly fragmented and often rely on ad hoc or volunteer data entry. Thus, we developed methods for the unbiased collection and cataloging of river and stream restoration projects. Here, we report a synthesis of information on 37,099 projects in the National River Restoration Science Synthesis (NRRSS) database.

The NRRSS database includes all stream and river restoration projects present in national databases as of July 2004, as well as a large sample of river and stream restoration projects from seven geographic regions (see figure, below) [(*17*) part a]. Because we wanted to document how restoration dollars and efforts were allocated, we did not limit data collection to projects that fit our definition of restoration. No judgments were made of the validity of the terms "stream restoration" or "project." Use of national coverage data sources] (*17*) part b] ensured inclusion of projects from all 50 states. For the seven specific regions, we also collected information on all restoration projects for which we could obtain data, regardless of project size, restoration method, implementer, or perceived success or failure of the project. We identified a priori 13 categories of restoration and classified each project according to its stated goal [see table, page 637 and (*17*) part c].

The number of river restoration projects increased exponentially during the last decade, paralleling the increase in news media and scientific reports [fig. S1 (*17*) part d]. However, restoration efforts varied across geographic regions. Most projects (88%) are from the Pacific Northwest, the Chesapeake Bay watershed, or California (see figure, below). Data from national coverage sources [(*17*) part b] made up <8% of projects in the NRRSS database. Thus, while federal funding supports some tracking efforts, national restoration databases are not tracking the majority of projects and lack information on the regional differences in expenditures and effort found with our approach.

The most commonly stated goals for river restoration in the United States are (i) to enhance water quality, (ii) to manage riparian zones, (iii) to improve in-stream habitat, (iv) for fish passage, and (v) for bank stabilization (see figure, page 637). Projects with these goals are typically small in scale with median costs of <$45K (see table, page 637). A large proportion of restoration dollars are spent on fewer, more expensive projects aimed at reconnecting floodplains, modifying flows, improving aesthetics or recreation, and reconfiguring river and stream channels (see figure, page 637). Of the projects in our database, 20% had no listed goals; in many cases, descriptions were too limited to determine whether projects were undertaken to restore stream ecosystems or were merely river manipulation projects (e.g., bank stabilization) (*18*).



Project density (no. of projects per 1000 river km) from national coverage databases only versus in-depth regional project record summaries (all data sources) [table S1 (*17*) part h].

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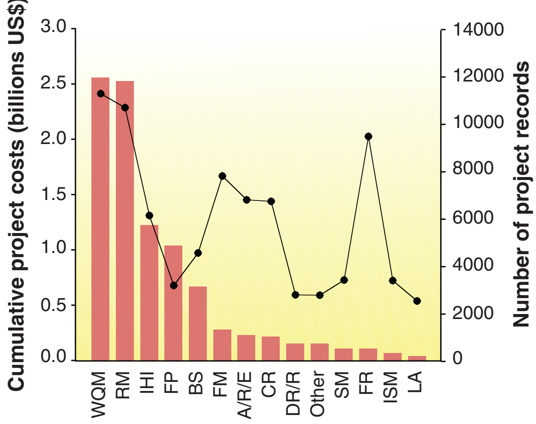
Only 58% of the project records used to populate our database had information on project costs. For this subset, total costs came to $9.1 billion. Most of this was spent after 1990, with $7.5 billion in recorded costs from 1990 to 2003 (from the 58% reporting costs). Applying this cost estimate to the remaining ~40% of projects [(*17*) part e], and taking into account that we captured ~27% of all stream and river restoration projects in the 27 states not within one of our regional nodes [(*17*) part e], at least $14 to $15 billion has been spent on restoration of streams and rivers within the continental United States since 1990, an average of >$1 billion a year. This is probably an underestimate, because data providers reported that the costs listed in project records typically do not include matching or in-kind contributions such as agency labor. In addition, the data sources we accessed did not capture costs for the restoration of the Kissimmee River or the full costs of Glen Canyon, San Francisco Bay, Columbia, and Missouri river restoration efforts, which would add hundreds of millions to billions of dollars (*17*).



Distribution of projects within each restoration goal category. Abbreviations of categories are in table below.

Our analysis confirms what the General Accounting Office (GAO) has suggested in recent reports to the U.S. Congress (*19*, *20*): a comprehensive assessment of restoration progress for the United States, or even for individual regions, is not possible with the "piecemeal" information currently available. We found that only 10% of project records indicated that any form of assessment or monitoring occurred. Most of these ~3700 projects were not designed to evaluate consequences of restoration activities or to disseminate monitoring results.

Monitoring and assessment varied by region: >20% of projects in the Southwest, Southeast, and Central United States had some form of monitoring, whereas only 6% of project records in the Chesapeake Bay watershed indicated that monitoring occurred (see figure, page 636). Projects with higher costs were more likely to be monitored [average costs were $1.5 ± $0.7 million (95% CI), whereas unmonitored project costs were $0.4 ± $0.08 million]. Regions with greater project density tended to have lower average project costs and reported a lower rate of monitoring. Further, differences in regional regulations are likely.

Because most project records were inadequate to extract even the most rudimentary information on project actions and outcomes, it is apparent that many opportunities to learn from successes and failures, and thus to improve future practice, are being lost. The largest and most costly programs have recognized this problem and have enacted solutions (*16*, *19*). Unfortunately, the outcomes of most of the tens of thousands of projects of small-to-modest size are currently not adequately tracked, yet cumulatively, their costs are greater, and their reach is far broader. Much greater effort is needed to gather and disseminate data on restoration methods and outcomes, particularly given the magnitude of costs. It is unrealistic to expect that every restoration project will have extensive monitoring activities, but strategic pre- and postassessments with standardized methods could enable restoration practitioners and managers to understand what types of activity are accomplishing their goals (*21*). Ensuring data compatibility in the tracking of restoration projects and the documentation of results from project evaluations are equally important. To facilitate this effort, the NRRSS database structure and schema are freely available (*22*).

MEDIAN COSTS FOR GOAL CATEGORIES

NRRSS goal category	Median cost	Examples of common restoration activities
Aesthetics/recreation/education (A/R/E)	$63,000	Cleaning (e.g., trash removal)
Bank stabilization (BS)	$42,000	Revegetation, bank grading
Channel reconfiguration (CR)	$120,000	Bank or channel reshaping
Dam removal/retrofit (DR/R)	$98,000	Revegetation
Fish passage (FP)	$30,000	Fish ladders installed
Floodplain reconnection (FR)	$207,000	Bank or channel reshaping
Flow modification (FM)	$198,000	Flow regime enhancement
Instream habitat improvement (IHI)	$20,000	Boulders/woody debris added
Instream species management (ISM)	$77,000	Native species reintroduction
Land acquisition (LA)	$812,000	
Riparian management (RM)	$15,000	Livestock exclusion
Stormwater management (SM)	$180,000	Wetland construction
Water quality management (WQM)	$19,000	Riparian buffer creation/maintenance

Median costs for goal categories.

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22. http://nrrss.nbii.gov

23. The NRRSS is supported by the National Center for Ecological Analysis and Synthesis (NCEAS). The national effort received support from NSF, USGS, the David and Lucille Packard Foundation, Altria, and the U.S. EPA. Individual regional teams received support from the C. S. Mott Foundation, the CRC for Freshwater Ecology, the McKnight Foundation, CalFed, the U.S. Bureau of Reclamation, University of Maryland, and the Maryland DNR. USGS National Biological Information Infrastructure (NBII) provided personnel support; we particularly thank G. Cotter and M. Frame. We thank all data providers (*17*), particularly NWFSC NOAA, M. Ehrhart, S. D. Kunkoski, M. Wiley, and P. Steen; also R. Carlson and K. Ward who provided us with previously synthesized regional databases. Views expressed here do not represent the views of any supporting organization or data provider.

Supporting Online Material
www.sciencemag.org/cgi/content/full/308/5722/636/DC1

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Science **Supporting Online Material**

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Contents

(a) Notes on NRRSS Methodology

We began by compiling data on restoration projects from 18 national coverage databases maintained by federal agencies (**b**), but found that the majority of projects are recorded only at the regional or local level. A large number of municipal, state and regional databases are being developed, but we found few extensive databases (**b**) of river restoration [average no. of project records per data source was 51 ± 26 (95%CI)] (this does not include personal contacts which on average yielded information on six projects). Our working group, with the extensive collaboration of data providers, restoration scientists, managers and practitioners within each of our nodes, has designed and implemented a database to begin addressing this need. The NRRSS metadata and database structure provides a common format to reduce duplication of effort in planned project tracking efforts and is freely available to all interested parties. The NRRSS Summary Database is a mySQL relational database developed on a LINUX platform (**g**). Only open source software was used for the database. The database schema, structure and metadata are available on line (at http://nrrss.nbii.gov) and the raw summary data will be freely available on line by the end of 2005. The database includes all commonly encountered fields in existing regional restoration databases (such as location, costs, implementers, funders) as well as information on project goals, specific project activities, and project monitoring.

What was included: The following key was included in the metadata and used to determine whether a project would be included in the NRRSS database. (DNI, do not include)

Project record is part of a stream restoration specific database or data file — Go to1

-OR-

Project record is part of a database or data file not specific to stream restoration — Go to 4

1.
- a) Project is fundamentally concerned with community education and does NOT include field efforts to improve stream condition — DNI
- b) Project is fundamentally concerned with community education and does include field efforts to improve stream condition — Include / 2

2.
- a) Land acquisition is the only restoration focus of the project — DNI
- b) Land acquisition is a focus of the project, but is specifically performed to improve stream condition — Include / 3

3.
- a) Project is a site or watershed study intended to guide restoration efforts — DNI
- b) Project implemented, regardless of the paucity of information — Include

4.
- a) Project has no statement of intent or activities — DNI
- b) Project contains either a statement of intent or activities — Include / 5

5.
- a) Project record does NOT explicitly state stream restoration as intent — DNI
- b) Project record merely states "stream restoration," even if record contains no additional information — Include / 6

6.
- a) Upland (non-riparian), wetland, estuary, or land acquisition as the only focus/foci of restoration — DNI
- b) Upland (non-riparian), wetland, estuary, or land acquisition as the focus/foci of restoration, but is specifically performed to improve stream condition — Include

The definitions of "project" and "stream restoration" were left up to the data source—no judgments were made of the validity of the term "stream restoration" and there was no standardized size or cost unit for projects.

Calibration

Metadata were developed for all database fields to ensure consistency, repeatability, and utility of the data. Calibration of data entry for the database was done initially by the entire working group. All members received the same ten example project files which they entered into the database following the metadata. After this round, the group met to discuss differences in the entries and to modify the metadata to eliminate confusion. All persons responsible for data entry completed three additional rounds of calibration with 10 different projects in each round in which the only field completed was the categorization of stated project goals, objectives, or purposes into the intent categories, the only subjective field in this database. There was some concern during development about the difficulty and inconsistency of inferring intent from project documentation; for this reason, our intent field is only a categorization of the stated goals, objectives, or purposes in the documentation based on the definitions of the intents in the metadata.

Removal of Duplicates

Because the data were obtained from a large variety of sources on a federal, state, and local scale and included funders, designers, implementers, and regulators, duplication of some projects within the database was inevitable. To remove duplicate projects, we sorted the data by location information and looked for projects with the same name and those done on the same stream, in the same area, with the same completion year and the same intents. Because projects may have multiple phases or adjacent, follow-up projects, we only removed projects from the database where they were clearly duplicates.

Validation

Creating a complete database of all stream restoration projects in the country was not a realistic goal. Some data were only available by contacting individual consulting firms for their files, and in some cases government agencies were unwilling or unable to share their data. For these reasons, the goal of NRRSS was to achieve a database that was representative of the goals and geographic variability of stream restoration activities within the seven nodes rather than a comprehensive database.

Validation of the database was done separately for each node. Data were summarized by cost, percent monitored, and intent categories as well as geographically, generally on a county or watershed scale. These summaries, along with a list of data sources used, were submitted to "stream restoration experts" in each node. These were people knowledgeable about stream restoration for a particular portion of the node who had not been involved directly in the overall data gathering for that node. They were asked to assess the completeness of data sources accessed and the representativeness by location and intent category of the NRRSS database for their particular geographic area of expertise. Experts who saw a weakness in the completeness or representativeness of the data were asked to provide suggestions of further data sources or contacts which the working group members then followed up on to complete the database. In some cases, this added only a few projects in a particular location or intent category, while in other cases new, large databases were discovered as a result of the validation process.

(b) List of National Coverage Databases

Environmental Protection Agency (EPA) 5 Star Restoration Challenge grants; EPA Grant Reporting and Tracking System (GRTS) for 319 programs; EPA River Corridor and Wetland Restoration; National Oceanic and Atmospheric Administration (NOAA) Community Based Restoration and Disaster Assistance Restoration Programs; Department of Transportation (DOT) Federal Highway Transportation Enhancement Program; US Fish and Wildlife Service (FWS) FWS Habitat Information Tracking System; FWS National Fish Passage Program; FWS Division of Bird and Habitat Conservation; Army Corps of Engineers (ACOE) 1135; ACOE Aquatic Environmental Projects by the Institute for Water Resources; ACOE Water Resources Development Act projects; Reviews of Non-Corps Restoration Projects (n = 2); National Park Service (NPS) Project Management Information System; Natural Resources Conservation

Service (NRCS) Success Stories; Bureau of Land Management (BLM) Abandoned Mine Land Program, Cleanwater.gov (*federal interagency group*) Watershed Success Stories; Coastal America (*federal interagency group*) Regional Conservation Projects, Federal Interagency Stream Corridor Restoration Working Group

(c) Metadata for Classification of Project Goals/Intents

All metadata and fields available at

http://nrrss.nbii.gov/cgi bin/user_area/sample_input_form.cgi

Select one to many from list of alternatives defined below. Intent should capture only what is stated as a goal/objective/purpose in source documentation.

Do not infer intent. We have had difficulty, particularly when categorizing longer documents in avoiding this subjectivity. When you are reading a long document (more than a one-paragraph project description), only use sections that explicitly describe objectives/goals/purposes/intents, do not read the full document and then attempt to summarize the purpose yourself.

Some projects will require multiple selections because of overlapping categories (e.g., some dam removals are for fish passage, some dam outlet retrofits are water-quality management). If the project intent is impossible to classify in one of our 13 categories, select other and type in the intent as written in the documentation. If there are sufficient cases falling into a new category, we will add that category to the official database. [categorical]

Bank Stabilization: Practices designed to reduce/eliminate erosion or slumping of bank material into the river channel. This category DOES NOT include stormwater management, see next intent category.

Stormwater Management: Special case of *Flow Modification* that includes the construction and management of structures (ponds, wetlands, and flow regulators) in urban areas to modify the release of storm runoff into waterways from watersheds with elevated imperviousness into waterways. These practices/structures generally aim to reduce peak flow magnitudes and extend flow duration. For the purposes of NRRSS *Stormwater Management* refers to water quantity not quality. Urban sediment, litter and temperature control should be categorized as *Water Quality Management*.

Flow Modification: Practices that alter the timing and delivery of water quantity (DOES NOT include *Stormwater Management*). Typically, but not necessarily, associated with releases from impoundments and constructed flow regulators.

Channel Reconfiguration: Alteration of channel plan form or longitudinal profile and/or day-lighting (converting culverts and pipes to open channels). Includes stream meander restoration and in-channel structures that alter the thalweg of the stream. Note that many instream structures also claim to improve habitat. For NRRSS the intent declared in the source document must be used.

Fish Passage: Removal of barriers to upstream/downstream migration of fishes. Includes the physical removal of barriers and also construction of alternative pathways. Includes migration barriers placed at strategic locations along streams to prevent undesirable species from accessing upstream areas.

Riparian Management: Revegetation of riparian zone and/or removal of exotic species (e.g. weeds, cattle). Excludes localized planting only to stabilize bank areas (see *Bank Stabilization*)**.**

In-Stream Species Management: Practices that directly alter aquatic native species distribution and abundance through the addition (stocking) or translocation of animal and plant species and/or removal of exotics. Excludes physical manipulations of habitat/breeding territory (see *In-stream Habitat Improvement***)**

Dam Removal/Retrofit: Removal of dams and weirs or modifications/retrofits to existing dams to reduce negative ecological impacts. Excludes dam modifications that are simply for improving *Fish Passage*.

Floodplain Reconnection: Practices that increase the flood frequency of floodplain areas and/or promote flux of organisms and material between riverine and floodplain areas.

In-Stream Habitat Improvement: Altering structural complexity to increase habitat availability and diversity for target organisms and provision of breeding habitat and refugia from disturbance and predation. (In some cases habitat improvement may be an action with the intent of *In-Stream Species Management*, in other cases *Habitat Improvement* may be the intent, and might be accomplished through *Channel Reconfiguration*, be very careful to separate action from intent when deciding whether to select this category.

Aesthetics/Recreation/Education: Activities that increase community value: use, appearance, access, safety, knowledge.

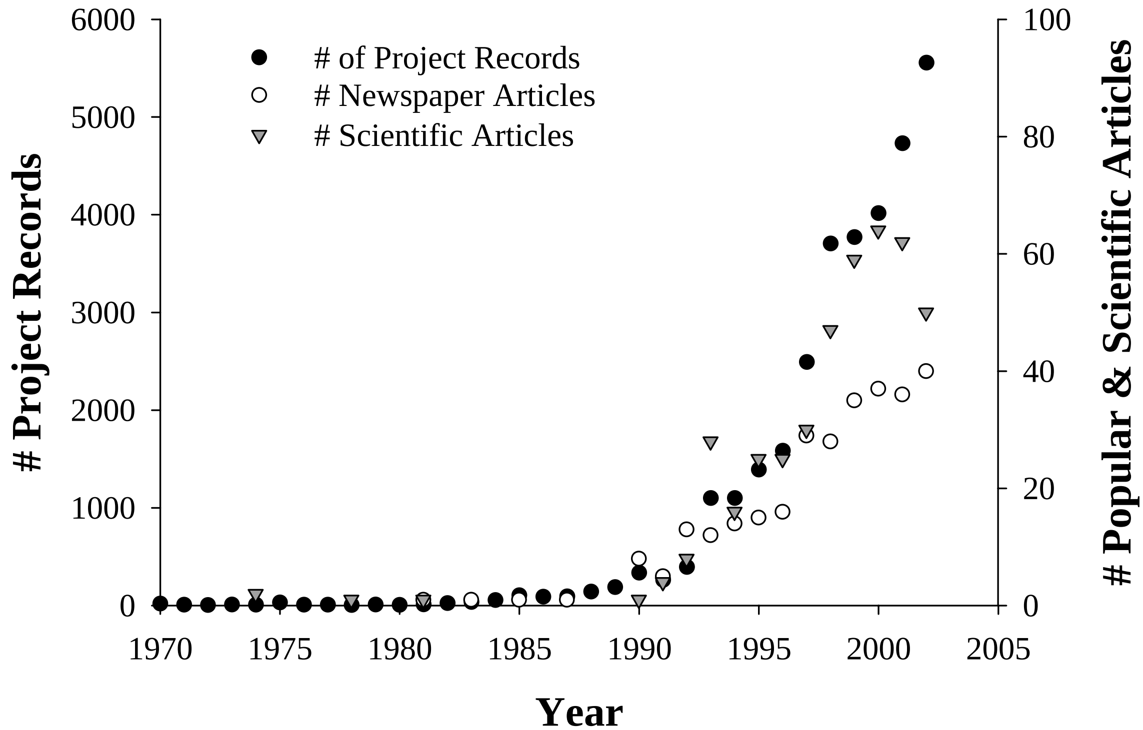
Water-Quality Management: Practices that protect existing water quality or change the chemical composition and/or suspended particulate load. Remediation of acid mine drainage falls into this category as does CSO separation. Excludes urban runoff quantity management (see *Stormwater Management*).

Land Acquisition: Practices that obtain lease/title/easements for stream-side land for the explicit purpose of preservation or removal of impacting agents and/or to facilitate future restoration projects. Note: Simple purchase and preservation to prevent potential future land conversion is insufficient for inclusion in the NRRSS database. NRRSS projects should demonstrate intended or actual cessation of detrimental activities in acquired land or active restoration components.

Other: Specify the project intent that differs from the choices provided. If there is no intent stated you should not select or enter any information in this section. If the intent is the generic "stream restoration" then this section should be left blank [text]

(d) Fig. S1. The number of river restoration projects recorded in NRRSS and citations related to stream restoration.

Fig. S1. The number of river restoration projects recorded in NRRSS is shown alongside the number of newspaper and scientific journal citations related to stream restoration. Newspaper and journal citations were derived from a search for the terms "stream restoration" or "river restoration" in Lexis Nexis Environmental News and ISI Web of Science databases.



(e) Cost Estimates

To estimate costs for the 37,099 project records in our database that occurred between 1990 and 2003 (date of completion, implementation, or permitting fell within this time period), we multiplied the number of records without cost data (n = 13,039) by the average project cost for records that included cost information (n = 19,683; mean project cost $383,547), giving us an estimated $5.0 billion in unrecorded costs. Federal database records accounted for 26.8 ± 10.7 % of the total number of records for each of the 23 states within our study regions. Therefore, we estimate that in-depth data collection in the remaining 27 states would generate between 2605 and 6073 additional projects. Multiplying these numbers by the average project costs for all records ($383,547) within our database generates additional costs of $1.0 to $2.3 billion.

(f) Note on Large Restoration Project Cost

The data sources we accessed did not capture costs for the restoration of the Kissimmee River nor the full costs of Glen Canyon, San Francisco Bay, Columbia, and Missouri river restoration efforts, which would add hundreds of millions to billions of dollars to our cost estimate. Restoration of these large systems involves land acquisition for mitigation, actions aimed at restoring single species under the Endangered Species Act, and experimental management actions. For example, the U.S. Congress has authorized expenditures of over $800 million for land acquisition along the Missouri River (*15, 21*). About 70% of these costs are for programs aimed at understanding whether experimental management actions yield results suitable for implementation as permanent restoration policy. This experimental program also causes a several million-dollar reduction in hydroelectric power revenues each year. It is likely that restoration efforts on large rivers alone will total in the hundreds of millions to billions of dollars in the foreseeable future.

(g) Full Description of NRRSS Database Software

LAMP for the National River Restoration Science Synthesis (NRRSS) :
LAMP is an acronym for (Linux, Apache, MySql, Perl/PHP/Python). LAMP is comprised of open source software and as such is non-proprietary. This software is not only highly reliable but is less prone to security problems than some of the proprietary software available.

Linux is the operating system utilized by NRRSS. The two types of Linux that were utilized by NRRSS were first Mandrake Linux and then Suse Linux. Linux is freely distributed and its functionality, adaptability and robustness have made it an excellent alternative to proprietary Microsoft operating systems.

Apache which is also open source software is the web server being used by NRRSS. Apache is currently the number one HTTP server on the Internet. The Apache web server is more widely used than all other web servers combined, accounting for 67% of the web sites on the Internet as of October 2004. Software utilized by NRRSS on this Apache web server was HTML

(HyperText Markup Language), Javascript and CGI (Common Gateway Interface). CGI is the standard for interfacing external applications with information servers, such as HTTP or web servers. One of the external applications employed was Perl (Practical Extraction and Report Language).

MySql was the relational database used by NRRSS and it is the world's most popular open source database with more than 5 million active installations. MySql is a database that provides the following advantages:

- Reliability and performance
- Ease of use and deployment
- Freedom of platform lock-in
- Cross-platform support
- Millions of trained and certified developers.

Perl is the last software component of LAMP used for NRRSS. Perl uses two software packages for the database: Perl DBI (Database Interface) and Perl DBD (Database Drivers) for MySql.

LAMP is a solid and reliable web platform that provides the environment for both the development and deployment of high performance web applications. As a result of LAMP, the NRRSS database can readily be provided to any organization free of charge simply by that organization adopting the use of these open source software tools that are readily available.

(h) Table S1. Regional differences in stream restoration efforts.

Table S1. Regional differences in stream restoration efforts. Number of projects and total cost are shown by state per 1000 km of streams and rivers. Monitoring numbers are percent of projects with some type of monitoring indicated in the project record; however, not all data sources contained monitoring information.

	No. of Projects/ 1000 km	Total Cost/ 1000 km	% Monitoring Indicated
California			
California	11.82	5,953,950.90	22.9
Central US			
Illinois	1.70	747,358.45	15.1
Iowa	0.68	667,966.12	35.9
Minnesota	1.39	1,213,483.03	23.4
Missouri	0.60	2,483,211.41	20.0
Wisconsin	4.69	973,512.71	24.8
Chesapeake Bay			
Maryland	168.12	5,670,841.57	6.3
Pennsylvania	11.16	708,065.45	9.3
Virginia	17.63	657,038.17	2.1
Pacific Northwest			
Idaho	11.32	263,501.75	13.6
Montana	9.12	253,308.73	0.5
Oregon	65.31	2,479,021.90	0.7
Washington	55.17	10,758,253.78	19.6
Southeast			
Georgia	1.11	245,587.47	15.2
Kentucky	2.49	425,690.15	11.2
North Carolina	8.25	7,058,155.31	36.2
South Carolina	0.83	176,758.21	47.5
Southwest			
Arizona	0.96	944,821.01	25.3
Colorado	0.68	1,046,349.40	46.2
New Mexico	1.01	727,113.96	29.4
Utah	0.75	1,053,503.50	17.3
Upper Midwest			
Ohio	3.78	640,720.02	18.1
Michigan	10.22	502,136.69	1.9
Wisconsin	4.69	973,512.71	24.8

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Appendix: Additional Supplemental Information not directly cited in text.

List of all Data Sources

More information on the project available at http://www.nrrss.umd.edu

Table A1. List of types of data sources, the number of each type of source, and the average number of records obtained from each source for the NRRSS database.

Type	Number of Sources	Average Number of Records from Source
Database	73	450
Report	86	11
Webpage	79	4
peer reviewed publication	7	1
Book	9	4
conference proceedings	8	5
personal communication	252	6

Fig. A1. Regional differences in the distribution of types of restoration efforts. To facilitate visual comparison only the top five intent categories for each node are shown in each stacked column. All other "non-dominant" intents are summed as part of the "non-dominant" category.