quirements of this legislation had profound impacts on land and water management.

Specific federal water quality legislation

Water quality laws, with periodic amendments of gradually increasing specificity, and associated state laws and local ordinances, have provided the guidelines for watershed and water quality protection that the general resource management legislation lacks.

The Federal Water Pollution Control Act (PL 80-845) was originally passed in 1948, but a significant federal presence in water quality control was not initiated until the Federal Water Pollution Control Act Amendments of 1972.[3] The 1972 act (now commonly referred to as the Clear Water Act) optimistically called for the attainment of fishable and swimable waters by 1983 and the elimination of all point source discharges of pollutants into navigable waters by 1985. While the major emphasis of the act was the establishment of effluent standards for point source emissions, section 208 of the act specifically addressed nonpoint source pollution and designated silvicultural and livestock grazing activities as nonpoint sources of pollution. Section 208 required that states adopt an "areawide waste treatment management planning process" that was applicable to "all wastes generated within the area" (33 U.S.C. 1288(b)(1)(A)). The areawide plans were to include "a process to identify ... agriculturally and silviculturally related nonpoint sources of pollution, including runoff from manure disposal areas, and from land used for livestock and crop production," and to set forth "procedures and methods (including land use requirements) to control to the extent feasible such sources" (33 U.S.C. 1288(b)(2)(F)) (see Anderson 1987). The state and local plans were subject to approval by the EPA. Federal land management agencies were subject to all requirements of duly promulgated state water quality law and standards, but only to the same extent as such standards were applied to all nongovernmental entities (33 U.S.C. 1323).

Also of importance to forestry was section 404, which addressed water pollution associated with deposit of dredged and fill material. Unlike the section 208 controls, regulation of dredge and fill operations was primarily a federal function effected by the requirement to obtain a permit from the Army Corps of Engineers for discharge of dredge and fill materials into U.S. waters. The act authorized the EPA to set permit guidelines and veto individual permits (33 U.S.C. 1344).

[3] *Other pre-1972 laws included the Federal Water Pollution Control Act of 1956 (PL 84-660) and its 1961 amendments (PL 87-88), the Water Quality Act of 1965 (PL 89-234), the Clean Water Restoration Act of 1966 (PL 89-753), and the Water Quality Improvement Act of 1970. The pre-1972 acts emphasized point sources and were essentially replaced by the 1972 amendments.*

While focused on wetland protection, section 404 also regulated activities such as bridge and road construction.

Although the EPA recognized the seriousness of nonpoint source pollution early on (for example see EPA 1974, cited by Agee 1975), it initially emphasized the more serious and manageable problems of sewage treatment and industrial emissions. In 1976, some financial assistance for developing 208 plans was awarded to the states, yet implementation of section 208 plans remained a gradual process as states and localities adapted to the new goals and the developing federal-state-local working relationship.

The Clean Water Act of 1977 further amended the water quality legislation by increasing control of toxic pollutants and authorizing a program of grants to help cover the costs to rural landowners of implementing "best management practices" to control nonpoint source pollution. The 1977 amendments also exempted "normal" silvicultural activities, including road construction, from the requirement of obtaining a section 404 permit (33 U.S.C. 1344(f)), while leaving nonpoint source road construction concerns under the perview of 208 plans.

Also in 1977, the EPA formally informed states that they could elect either regulatory or nonregulatory programs for reducing nonpoint source discharges. Nonregulatory plans, adopted by most states, essentially rely on voluntary compliance and educational programs (BMP manuals, seminars, onsite inspections, etc.), sometimes enhanced by cost sharing or tax incentives. Regulatory plans impose mandatory restrictions on land management practices and allow the imposition of penalties for noncompliance. The EPA retained authority not to approve the states' areawide plans unless a state was given at least the authority to require adoption of land management practices, but the possibility of penalties became recognized as an "empty threat" (Goldfarb 1984:188).

The Water Quality Act of 1987 further amended the Clean Water Act, appropriating new funds and establishing in section 319 new requirements for states to develop and implement programs for controlling nonpoint sources of pollution (33 U.S.C. 1329). Section 208 previously required states to identify sources of nonpoint source pollution and to prepare plans to control such pollution, but it did not require that sources be related to specific bodies of water. Thus, section 208 allowed states, if they wished, to maintain only a vague link between cause and effect. The lack of specificity may have hindered plan implementation. Section 319 was intended to encourage implementation by requiring (1) detailed water quality plans that identified water bodies not meeting water quality standards; (2) identification of categories of nonpoint sources or particular nonpoint sources responsible for violation of water quality standards in identified water bodies; and (3) identification of BMP's to control them. Section 319 also detailed the process that the EPA was to use to either approve or disapprove the states' reports and management programs, although section 319 lacked firm criteria for determining whether a proposed management plan was acceptable. States with programs approved by the EPA could receive matching grants to facilitate implementation of the programs.[4]

Federal encouragement of water quality protection was strengthened once more with the Coastal Zone Act Reauthorization Amendments of 1990 (16 U.S.C. 1451 et seq.). These amendments to the Coastal Zone Management Act of 1972 direct the EPA and the National Oceanic and Atmospheric Administration (NOAA) to prepare "guidance for specifying management measures for sources of nonpoint pollution in coastal waters." The amendments direct the coastal states to submit a program for approval by EPA and NOAA within 30 months of publication of the guidance (16 U.S.C. 1455b).

The guidance is to include (1) a description of each "management measure" and the activities or locations for which each measure may be suitable; (2) identification of individual pollutants or categories of pollutants that may be controlled by the measures; and (3) quantitative estimates of the pollution reduction effects and costs of the measures, where "management measure" means an "economically achievable" measure for control of pollutants (16 U.S.C. 1455b).[5] The 1990 Amendments do not clarify what was meant by "economically achievable." According to the CZMA amendments, the state programs are to (1) identify coastal zone boundaries; (2) identify land uses that may cause degradation of coastal waters and management measures necessary to achieve and maintain water quality standards; (3) identify means the state will use to "exert control over" land and water uses; and (4) describe the organizational structure proposed to implement the program (16 U.S.C. 1451).

[4] In 1989, Congress appropriated $40 million for fiscal year 1990, of which $34.8 million was awarded to the states (EPA 1992, table 2). Congress appropriated $51 million for fiscal year 1991.

[5] A 126-page draft for forestry titled "Proposed Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters, Pursuant to Sec. 6217(g) of CZMA Amendments of 1990, Chapter 3: Management Measures for Forestry," was completed on April 27, 1992. The draft discusses road construction, timber harvest, site preparation, and 7 other "measures," and also lists specific "management practices" under each measure. The chapter indicates that while states are required to implement the management measures, they are not required to implement the practices, which are listed for "illustrative purposes only." States are expected to use the individual practices that best suit their specific circumstances. For example, one component of the "timber harvesting" measure is to "locate and construct landings to avoid failure of fill slopes by limiting the slope of the fill and not incorporating woody or organic materials" (p. 60). One of the listed practices for this measure says that "the slope of the landing surface should not exceed 5 percent and should be shaped to promote efficient drainage" (p. 67).

Each state program is to "provide for the implementation ... of management measures ... to protect coastal waters" (16 U.S.C. 1455b). Matching grants are available to states for developing and administering their program. Failure to submit an approvable program may lead to withholding of up to 30% of the grant funds available under both section 306 of the CZMA and section 319 of the CWA. Management of federal lands in or out of a coastal zone that affects the coastal zone waters must conform to the state program.

State nonpoint source pollution control programs

By the mid 1970's when implementation of the nonpoint source pollution provisions of the 1972 Federal Water Pollution Control Act began to take effect, some states with existing programs submitted those programs to meet the new federal requirements. Others developed new approaches, but several states, especially those with relatively few forests or with fewer perceived water quality problems on forestlands, were slow to respond.

Continuing concern about nonpoint source pollution along with the 1987 and 1990 federal legislation have encouraged more proactive state efforts at control. In the past 4 yr, additional states have adopted BMP's for forestlands and many states with programs have increased their efforts to have their BMP's understood and implemented. In addition, some states now provide cost-share funds. Others are establishing penalties for noncompliance with BMP's, especially where that noncompliance results in significant water quality degradation.

State approaches can broadly be categorized as regulatory or voluntary. Regulatory programs impose requirements on land management and allow assessment of fines and other penalties for noncompliance. States with regulatory programs tend to rely on inspection of management activities while the activities are in progress, as well as follow-up inspections, to improve compliance with BMP's and to determine whether penalties are to be assessed. Regulatory states may also require approval of harvest or road construction plans that include water quality protection measures before field work begins. States with voluntary programs emphasize education and training, including onsite inspection where requested. Increasingly, states with voluntary programs are performing formal implementation surveys to judge the success of the voluntary approach.

Four federally funded programs currently provide cost-share funds and technical assistance for forestry activities on forest or agricultural land that may have a positive effect on water quality. The Agricultural Conservation Program, begun in 1936, supports a series of agricultural conservation practices emphasizing water quality and other environmental concerns and includes such practices as tree planting, stand improvement, and animal exclusions in riparian areas. Over 7 million acres have been planted so far, mainly in the southern states. The Conservation Reserve Program, established in 1985 and expected to end in 1995, funds the retiring of highly erodible farm land through establishing permanent cover; over 2.3 million acres have been planted with trees in 41 states, with 92% of the planting occurring in the southern states. (Also, over 20 million acres have been planted in grass.) The Forestry Incentive Program, established in 1974 and slated to end in 1995, funds timber production activities, some of which (e.g., tree planting) may enhance water quality. Over 3.9 million acres have benefitted so far in 49 states, with 70% in the southern states. Finally, the Stewardship Incentive Program, which began disbursing funds in 1992, supports a number of environmental protection activities, including stream bank stabilization, riparian buffer zones, and protection of native vegetation. As of the spring of 1992, about half of the states reported using Stewardship Incentive Program funds. Others were in the process of requesting them. The Agricultural Stabilization and Conservation Service administers the first three of these programs, but forestry aspects of the programs are facilitated by the USDA Forest Service in cooperation with state personnel. The Stewardship Incentive Program is administered by the USDA Forest Service, but the funds are disbursed with the assistance of the Agricultural Stabilization and Conservation Service. In addition to these four cost-share programs, the Federal Income Tax Reforestation Incentive Program provides credits for tree planting.

Summaries of state legislation and programs are provided by NCASI (1983), Cubbage et al. (1987), Guldin (1989, Appendix C), Essig (1991), and Brown et al. (1993). In table 13 and the following paragraphs, we provide a brief summary, as of spring 1992, of state approaches to control nonpoint source pollution from forestlands.

In the Southeast, all states have forestry BMP plans, and two states have grazing management plans, most of which employ voluntary practice guidelines (i.e., BMP's) to be implemented through training and educational programs (see table 13 for the states included in the southeast region). One state (Virginia) offers state-funded cost sharing (for agricultural BMP's that may apply in woodland areas). North Carolina, Florida, and West Virginia require the use of BMP's for certain road construction and silvicultural practices (Lickwar et al. 1990). Across the region, about 24 person-yr were

Table 13.—Number of states with programs and activities to control nonpoint source pollution on forest lands, as of spring 1992.[a]

Region[b]	Total	Silvicultural BMP's[c]			Grazing BMP's[d]	Financial incentives[e]	Implementation monitoring		Effectiveness monitoring (some activity)
		V	R	V/R			Some activity	Formal survey[f]	
Southeast	12	9	2	1	2	1	12	9	6
Northeast	11	4	4	3	1	2	9	3	6
N. Cent. & Great Pl.	8	7	0	0	1	5	3	1	2
Great Plains	6	2	0	0	0	1	4	1	1
Rocky Mountains	6	1	2	1	1	2	3	3	2
Pacific Northwest	3	0	3	0	0	0	3	2	3
Pacific Southwest	4	0	2	0	0	0	2	1	2
U.S.	50	23	13	5	5	11	36	20	22

[a] *This table summarizes a state-by-state table in Brown et al. (1993), which was based on phone interviews with personnel from forestry and/or environmental agencies in each state.*

[b] *Southeast: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, West Virginia. Northeast: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont. North Central and Great Plains: Iowa, Indiana, Illinois, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, Oklahoma, South Dakota, Texas, Wisconsin. Rocky Mountains: Colorado, Idaho, Montana, Nevada, Utah, Wyoming. Northwest: Alaska, Oregon, Washington. Southwest: Arizona, California, New Mexico, Hawaii.*

[c] *V = voluntary program of state approved BMP's; R = regulatory program of state approved BMP's, fines can be assessed for noncompliance; V/R = a combination of voluntary and regulatory approaches.*

[d] *Maine's program is regulatory; the others are voluntary.*

[e] *State-funded cost sharing or tax incentives.*

[f] *Formal periodic post-hoc survey of all or randomly selected sites meeting criteria for selection.*

devoted to nonpoint source pollution control programs in 1987, with a total budget of almost $1 million (table 14). That expenditure has likely increased with the additional effort that many states are allocating to monitoring, as discussed later.

In contrast to the Southeastern states where voluntary programs prevail, no one program type dominates in the Northeastern states (table 13). Of the 11 states in the region, 4 have regulatory programs, 4 have voluntary programs, and 3 use a combination of the 2 approaches. Of the three states with combinations, two (Massachusetts and New Hampshire) have regulatory programs of BMP's for riparian zones and voluntary programs for non-riparian forestry sites, while New York has a regulatory program for state-owned lands and a voluntary program for private lands. Two northeastern states (Maryland and New Jersey) offer tax incentives for using forest management BMP's, and Maryland has a state-funded cost-sharing program encouraging reforestation.

Nine of the 14 states in the North Central and Great Plains regions now have voluntary programs of state-approved BMP's for forestlands. Many of the states have relatively few forested areas, usually associated with farms and ranches, and thus have felt under less pressure than states in other regions to institute formal forestry BMP programs. Some states have relied on federal regulations where the forests tend to be federally owned. Only Iowa has a program of grazing BMP's, but Kansas is considering formulating them for riparian areas. Illinois has a state-funded cost-sharing program encouraging use of forestry BMP's, and Minnesota has a state-funded program emphasizing protection of riparian areas from livestock damage. In addition, Indiana and Illinois offer tax incentives for use of BMP's in woodland or forest areas. Wisconsin offers both tax incentives and cost sharing for maintenance of woodland through a formal management plan.

Four of the 6 Rocky Mountain states have nonpoint source pollution programs affecting forestlands. Colorado's program is voluntary, while Montana's is regulatory for riparian areas and voluntary elsewhere. Idaho and Nevada have regulatory programs, with Lake Tahoe Basin BMP's being more restrictive than those applying to other parts of Nevada. Two states offer tax incentives—Colorado for tree planting and Idaho for maintenance of forestlands on private property. Only Idaho has so far adopted grazing BMP's.

All three Pacific Northwest states have regulations for controlling of nonpoint sources of pollution from forest practices. In Alaska, a Forest Resources and Practices Act, passed in 1981, requires notification prior to harvesting operations and tries to prevent problems by advising use of BMP's. Alaska's program was strengthened in 1991, and more strict regulation is likely to result. In Washington, Forest Practice Rules and Regulations (pursuant to the 1974 Forest Practice Act) provide standards governing road construction, tree harvest, site preparation, chemical use, and reforestation. Written applications prior to operations are classed into one of five categories, with each category receiving different levels of evaluation. The Oregon Forest Practices Act of 1971 covers road construction, tree harvest, site preparation, chemical use, and reforestation. Practices are regulated on private and state lands.

In the Pacific Southwest, California and New Mexico have regulatory programs; Hawaii relies on strict land use planning requirements rather than BMP's; and Arizona is considering adoption of voluntary silvicultural and grazing BMP's. California's thorough regulatory program involves a combination of legislation, administrative regulation, active enforcement, and licensing of professional foresters and timber operators (Yee 1987). Every timber harvest in California must include a timber

Table 14.—Personnel and budgets for state forestry-related nonpoint source pollution control programs in the Southeast, 1987.[a]

State	Full-year equivalent agency employees		State agency budgets	
	Water quality	Forestry	Water quality	Forestry
Alabama	1.0	0.5	$ 10,000	$10,000
Arkansas	0.0	2.5	0	64,000
Florida	4.7	2.0	211,000	60,000
Georgia	1.0	1.3	0	50,000
Kentucky	0.0	0.5	0	50,000
Louisiana	0.0	0.0	0	0
Mississippi	0.0	0.0	0	0
N. Carolina	1.0	1.5	120,000	40,000
Oklahoma	0.0	1.8	0	80,000
S. Carolina	0.0	0.2	0	5,000
Tennessee	0.0	0.0	0	0
Texas	0.0	0.0	0	0
Virginia	2.0	4.0	85,000	150,000
Total	9.7	14.3	426,000	509,000

[a]*Source: Lickwar et al. (1990).*

harvest plan that is reviewed by an interdisciplinary review process. Once a permit is granted, the Department of Forestry has enforcement responsibilities to ensure compliance with a wide range of regulations (including water protection). This elaborate process was estimated to increase the stumpage cost by about 5-10%. Cooperation between the state and USDA Forest Service has led to an intensive program for maintaining water quality on National Forests, including personnel training, development and refinement of BMP's, a handbook on BMP's, and implementation and monitoring of BMP's in forest operations (Leven et al. 1987).

The Forest Service BMP's are designed to be flexible because water quality problems vary substantially among California's forests. Leven et al. (1987) reported 98 official BMP's grouped in 8 categories from road construction to vegetation management to grazing impacts. The BMP's related to road construction include guidelines on constructing roads of minimum length that conform to the terrain, with well-designed drainage. The rules also require buffer strips along streams, directional falling of trees away from streams, and no physical impact on stream channels (Skaugset 1987). The application of BMP's proceeds in four phases: feasibility, site-specific assessment, application of BMP's, and monitoring. During 5 yr in the early 1980's, about $3.3 million was spent to correct nonpoint source pollution problems resulting from deteriorated watersheds in National Forests in California, but the estimated backlog of rehabilitation projects was $57 million (including $37 million simply for erosion problems).

In addition to state programs, many local ordinances have been passed by counties, townships, and municipalities. Martus et al. (1991) identified 377 local ordinances that regulate forestry activities in the United States, with 72% of them in the Northeastern states. About three-quarters of the ordinances were enacted in the past 10 yr, and nearly half are less than 5 yr old.

Best Management Practices

Whether voluntary or regulatory, state and local programs typically rely on a set of land management practices that land managers are encouraged to follow. These practices are often called best management practices (BMP's), but some states use "acceptable management practices," "forest practice rules," or other terms. As Wilkinson and Anderson (1985:220) report, EPA regulations define BMP's as

> those methods, measures, or practices to prevent or reduce water pollution and include but are not limited to structural and nonstructural controls, and operation and maintenance procedures. BMP's can be applied before, during, and after pollution-producing activities to reduce or eliminate the introduction of pollutants into receiving waters. Economic, institutional, and technical factors shall be considered in developing BMP's (40 C.F.R. 35.1521-(4)(c)(1), 1984).

On forested land, the following BMP's are sometimes used to minimize or prevent nonpoint source pollution from timber harvest: (1) buffer strips along perennial and intermittent streams, where logging is prohibited or limited to selective removal of high-value or undesirable trees; (2) prohibition of skidding over streams, except over approved culverts or bridges, (3) supervision of logging by a qualified forester or engineer; (4) division of timber sales into more easily administered blocks that are harvested one at a time; (5) prohibition of disposal of tops or slash near streams; (6) proper location of haul roads, skid trails, and log landings to avoid soil loss; (7) retirement of skid trails and haul roads after logging; (8) installation of water bars and other erosion control and drainage devices where necessary; (9) seeding and other efforts to maintain vegetative cover; and (10) prohibition of logging during excessively wet periods (Lynch et al. 1985).

Officially designated BMP's for rangeland are less common than those for forests, but more states, in the West, are now taking steps to specify rangeland BMP's. Rangeland BMP's emphasize limiting grazing intensity by controlling (1) livestock numbers, (2) the timing of livestock use, and (3) livestock distribution (with fencing, herding, salt placement, and water development) (Chaney et al. 1990). Implementation of rangeland BMP's often focuses on riparian areas, where the impacts of grazing on water quality are potentially greatest. Other practices aim at improving rangeland vegetation by seeding and at assuring careful brushland management and prescribed burning.

Undoubtedly, BMP's can be designed that will contain the effects of harvest, grazing, and other activities to within acceptable limits. Some careful studies implementating BMP's (e.g., Lynch and Corbett 1990 on Pennsylvania's silvicultural BMP's) have demonstrated the effectiveness of BMP use in protecting water quality. However, the fact that using of a certain set of BMP's is effective in one location does not guarantee that those BMP's will be effective in a different location. The soils and their slopes, weather patterns, and several other factors must be considered in the selection of the most effective site-specific BMP's.

Whitman (1989) suggests that in some conditions, such as areas of steep unstable slopes, BMP's alone are insufficient to control sediment loss to within acceptable limits and that in such conditions the land management planning process should be used on public land to preclude such areas from harvest. His suggestion assumes that BMP's cannot be used directly to exclude some areas from harvest, an assumption that may unnecessarily restrict the purview of the BMP process. BMP's for restricting harvest along stream buffer zones are now common; perhaps the same concept of exclusion could be extended to areas of steep slopes with unstable soils.

Cases where BMP implementation fails to achieve water quality objectives have led to conflict, which sometimes ends up in court. The decision in the so-called *Blue Creek* case involving National Forest land in California was that water quality standards could constitute judicially enforceable constraints on land management. Anderson (1987:605) summarized the Ninth Circuit Court of Appeals' 1986 decision: "Even if all applicable BMP's are followed, a given project or group of projects may be illegal under the CWA [Clean Water Act] if the evidence indicates that the resultant pollution will exceed state standards." However, after the Blue Creek case, the EPA clarified the role of BMP's in nonpoint source pollution control and the relation of BMP's to water quality standards. The EPA (1987) guidelines state in part:

> Once BMP's have been approved by the State, the BMP's become the primary mechanism for meeting water quality standards. Proper installation, operation and maintenance of State approved BMP's are presumed to meet a landowner's or manager's obligation for compliance with applicable water quality standards .... For proposed management actions, BMP's designed and implemented in accordance with a state approved process will normally constitute compliance with the CWA.

The guidelines go on to emphasize the iterative nature of BMP specification (involving implementaiton, monitoring, and subsequent adjustment of BMP guidelines) and the role of standards as a base against which the effectiveness of BMP's are to be measured (Rector 1989). Thus, the difficulty of specifying BMP's to precisely meet standards was acknowledged, the importance of continually upgrading BMP guidelines was highlighted, and the focus of compliance on BMP implementation was reinforced.

Implementation and effectiveness monitoring

Even if BMP's are appropriately specified for the site, they must be implemented. And the effectiveness of their use must be checked to allow reassessment of BMP requirements. Thirty-six of the 50 states reported performing implementation monitoring activities (table 13). States use different procedures for encouraging and checking on compliance (NCASI 1988). Some states, especially those with regulatory programs, rely on visits by state forestry personnel to sites while management practices such as harvest and road construction are in progress. Because ongoing inspection of forest management in progress is expensive, inspectors may only visit the most important sites. Twenty states employ a formal survey of randomly selected recently managed sites (table 13), while others use a less formal inspection of sites or an ad hoc inspection of sites suspected of not being in compliance. Some states include federal lands in their formal surveys, but most leave that to the federal agencies.

Monitoring also occurs where a contract or agreement between the state and a private party requires BMP implementation. This may occur where landowners benefit from financial incentives or where contracts for harvest on state land contain BMP clauses.

The USDA Forest Service now distinguishes between two kinds of monitoring that we group here under effectiveness. First, "effectiveness monitoring" determines whether implemented practices performed as expected. Such monitoring does not necessarily measure water quality. For example, if a practice is designed to reduce sediment delivery to a stream, effectiveness monitoring would inspect on-slope sediment movement. Effectiveness monitoring may use quantitative or qualitative methods. Second, "validation monitoring" determines whether water quality standards are met, and whether water quality prediction models are accurate. Quantitative methods are needed here (Warren Harper, USDA Forest Service, personal communication).

Effectiveness of BMP's implemented on site can basically be checked in two ways: qualitatively by trained professionals during onsite inspection, or by quantitative measurement. Qualitative checking can be accomplished informally or preferably via a formal survey of randomly selected sites, perhaps in the course of a compliance survey. Qualitative checks may miss difficult-to-observe levels of suspended sediment or other constituents that might be found through analyzing water quality samples. Quantitative measurement can include downstream water quality sampling, bedload monitoring, and biological monitoring, as well as on-land monitoring of soil movement. Careful quantitative measurement is preferable to qualitative judgments, but its high cost often limits such measurement to a few carefully selected sites. Twenty-two states reported performing some effectiveness monitoring activities (table 13); five of these employed some quantitative monitoring.

Formal surveys of BMP implementation indicate a range of compliance and effectiveness. Several such studies are summarized here.

1. Florida, which has a largely nonregulatory BMP program (Lickwar et al. 1990), has conducted biannual

compliance checks of selected sites since 1979. Sites selected for investigation were subject to a silvicultural operation (e.g., harvest, site preparation, a regeneration activity) during the previous 2 yr and are located within 300 ft of either a perennial or intermittent stream or lake of at least 10 acres. Eighty-five questions are answered at each site by the county forester, some of which focus on effectiveness of BMP use. The survey concludes with an overall judgment of whether "there was (generally) good compliance with 208 guidelines." In the 1989 survey, 94% of the 128 sites surveyed were judged as generally in compliance (Conner et al. 1989). Overall compliance was 89% in 1987 and 84% in 1985. Additional efforts were recognized as needed to "sensitize equipment operators on the proper use of equipment on more erodible soils" and to improve stabilization of stream crossings (Conner et al. 1989:8).

2. Georgia, another nonregulatory BMP state, recently completed its first large scale compliance survey (Georgia Forestry Commission 1991). The survey focused on BMP's dealing with five types of actions: road construction, harvest, site preparation, reforestation, and fire control. A total of 345 sites where a forestry operation had been completed within the previous 6 months was surveyed. Compliance across all 5 types of BMP's was 86%. Compliance ranged from 69% for road construction BMP's to 96% for reforestation BMP's. Ninety-five percent of the length of stream banks and channels within the survey sites was judged to be "intact and unimpaired." The report concluded that "current BMP's appear to be sufficient in protecting water quality when implemented," but that "it may be necessary to modify some BMP's, be more site specific, and address changes in equipment and technology" (Georgia Forestry Commission 1991:23).

3. In South Carolina, Hook et al. (1991) evaluated BMP compliance on 100 recently logged areas selected on aerial photos to represent a wide range of wetland or riparian site types and a range of harvest area sizes, and to be representative of the state's forestland ownerships and landscape types. The 7 team members from agencies, academia, industry, and a conservation group visited the sites during a 5-month period in 1990. Members recorded their subjective assessments. Nearly all of the sites were on industry or private land, and 61 were on private holdings of less than 1000 acres, or about 400 ha. Overall compliance was 95% on industry land, 86% on private holdings of greater than 1000 acres, and 78% on private holdings of less than 1000 acres. Across all ownerships, compliance varied from about 50% for streamside management zone BMP's along navigable streams to 90% for log deck BMP's. Only 56% of the landowners indicated that they were aware of the voluntary BMP's; lack of awareness was more common for the small forest owners, who were less likely to contract for the services of a professional forester. In another area of South Carolina with 177 harvested sites, Adams (1992) found an overall BMP compliance of 85%, with compliance ranging from 42% for road stream crossing BMP's to 98% for log deck BMP's.

4. The Virginia Department of Forestry attempts to obtain an inspection of all harvested forest areas of five acres or more by either a Department employee or a participating industry or consulting forester. In 1990, based on inspection of over 1000 sites for use of voluntary BMP's, compliance was judged to vary from 84% for skid trails to 98% for site preparation (Virginia Department of Forestry 1991). Compliance with haul road layout, haul road stabilization, landings, and streamside management BMP's was all above 90%.

5. Irland (1985) reported the results of two extensive field surveys of commercially harvested forests in the Northeast. First, in Connecticut a survey conducted in the late 1970s of 2100 ha of harvested forests (in 80 separate sites) revealed that severe gullying developed on 15% of the logged units. Some gullies were as deep as 3 m. Skid trails crossed streams a total of 141 times on the 80 units. Second, a study of 56 harvesting operations in Maine in 1980 found that about 50% of the units showed substantial amounts of erosion or sedimentation. Most of the problems related to inadequate water control on logging roads. The impacts documented in these extensive surveys suggest that operational practices may have greater effects on water quality (particularly sediment loads) than the impacts documented in more intensively studied watersheds.

6. Brynn and Clausen (1991:143) found that compliance with Vermont's timber harvest "acceptable management practices" varied from 0 to 98% depending on the practice at the 78 silvicultural operations they investigated. Postharvest water body sedimentation was above "background levels" at 46% of the sites, but "heavy sedimentation" occurred at only 9% of the sites. The authors suggested that "future research should focus on the impact of timber harvesting operations as conducted under economic constraints rather than unrepresentative research conditions," and they recommended that BMP's "should accurately reflect the economic and technical constraints of ... timber harvesting while adequately protecting water resources from degradation."

7. Texas' first systematic compliance survey investigated recently harvested sites in east Texas (Texas Forest Service 1992). An original sample of 257 sites was selected in a stratified (by county and ownership) quasi-random manner, but time constraints limited onsite inspection to 162 sites. Two foresters jointly visited all sites from mid 1991 to mid 1992, completing a 73-question checklist at each. Overall compliance was rated as good or excellent on two-thirds of the 162 sites and fair on another 22% of the sites. Overall good or

excellent ratings were assigned to 80% of the public land sites, about 73% of the industry and large nonindustrial private sites, and 56% of the small nonindustrial private sites. Compliance was highest where a forester was involved and where the landowner and logger were familiar with BMP's. The most common problems were associated with stream crossings. Based on qualitative assessment, the report concluded that the BMP's were effective in controlling nonpoint source pollution when BMP's were implemented.

8. BMP use is mandatory in Idaho. An interdisciplinary team audited the impacts of forest management on water quality from 40 projects across Idaho (Harvey et al. 1988). Ten projects were selected from each of the following ownerships: National Forests, Idaho Department of Lands areas, forest industry land, and private nonindustrial land. The audit team included people with expertise in fisheries biology, hydrology, road construction, and water quality from the USDA Forest Service, state agencies, and private industry. The team examined whether BMP's were implemented, whether they were effective, and whether any problems were more common on a particular type of land ownership. Compliance with BMP's was high on public and industrial lands, averaging about 95%. Nonindustrial private lands complied with BMP's about 86% of the time. Compliance with BMP's led to no stream sedimentation problems in 99% of the cases, whereas noncompliance led to sedimentation problems in 70% of the cases.

In 1991, the Idaho Department of Lands assessed BMP compliance and effectiveness for 40 timber sales (23 on state land and 17 on private land). Sales were selected by using a variety of criteria and do not represent a random sample. The 40 sales were located within a half-day's drive of an area office, and the private land sales were all in areas draining into "stream segments of concern." Five of the state land sales and eight of the private land sales had some degree of noncompliance resulting in minor water quality impacts. The assessment concluded that "when rules/BMP's are implemented they are effective in minimizing impacts to beneficial uses" (Colla 1992).

9. In Montana, 44 recently harvested sites were surveyed in 1990 by 6-member interdisciplinary teams who rated up to 58 BMP's at each site for compliance and effectiveness (Schultz 1990). The sites were chosen randomly from among a set of sites that met certain criteria, including minimum proximity to a stream and minimum size of harvested area. Two-thirds of the sites were "high hazard" sites, as determined based on slope, erodibility, and riparian proximity. Regarding BMP compliance across all sites, 78% of the BMP applications met all requirements and 14% were only minor departures, with the remaining 8% being major departures. However, for the 9 BMP's most important for protecting water quality, only 53% of the applications met all requirements, 29% were minor departures, and 18% were major departures. Regarding effectiveness across all sites, 80% of the applied practices were rated as providing adequate protection and 11% as potentially causing only minor impacts, with the remaining 8% potentially causing major impacts. However, among the 9 most important BMP's, only 58% of the actual applications were rated as providing adequate protection, with 19% potentially causing minor impacts and 23% potentially causing major impacts.

10. In a 1980 assessment of randomly selected sites in Washington, forest practices were in compliance with established regulations 80% of the time (Sachet et al. 1980). Compliance led to almost no water quality problems, but water quality impacts occurred in about 70% of the noncompliance cases. The most recent survey occurred in 1991, of 191 randomly selected application sites throughout the state where harvest, road construction or maintenance, or chemical use occurred from 1987 to 1991 (TFW Field Implementation Committee 1991). The sites were divided among four evaluators, who were assisted in some cases by other experts. Some of the sites had received visits from state personnel before (31%) or during (18%) the operations. The survey found that while 37% of the applications had differences between what was done and what was stated on the application, only 14% of those (5% of the total) did not meet or surpass the regulations. Only 1% of the applications resulted in damage or potential damage to the public resource.

11. A 1989 assessment of 5,204 operations in Oregon, selected by a priority ranking, found that 97% of the operations were in compliance with state forest practice rules (Oregon Department of Forestry 1990). Of the 190 citations issued for noncompliance, 61 were for failure to notify the state forester and 31 were for violations of written plans, with the remainder dealing with onsite actions such as harvesting and road construction. Other recent assessment efforts in Oregon have dealt with specific issues, such as herbicide use and riparian areas. For example, in 1989 and 1990, water quality samples were taken from 50 herbicide application units in western Oregon. The applied herbicide was not detected in 43 of the samples, and all detected herbicide levels were below research-based monitoring standards (Oregon Department of Forestry 1992).

12. In California, a 4-person multidisciplinary team evaluated compliance with and effectiveness of BMP's on 100 harvest units on nonfederal land selected on a stratified random basis (SWRCB 1987). Implementation of BMP's was variable, but protection measures were generally effective in about 60 of the 100 projects. Where protection was insufficient and resources were placed "at risk," the actual impacts on streams were generally minor, although the impacts at some sites

were moderate to major and a few were judged to be severe. Impacts on streams were generally minor when procedures outlined in timber harvesting plans were followed. The team concluded that "...noncompliance [with forest practice rules] was the single most important impediment to achievement of adequate resource protection" (SWRCB 1987). In 1988, 7,578 onsite inspections by Department of Forestry staff to determine compliance of timber operations with California's forest practice rules found 481 violations (6%), with construction of water-breaks, treatment of slash, watercourse protection, and road maintenance being the most common problems (CDF, 1988). Also, see Knopp et al. (1987) for an examination of the adequacy of BMP's in protecting water quality in the Six Rivers National Forest.

Most states are now performing some sort of compliance survey, and formal surveys of randomly selected sites is the preferred approach. There has been a dramatic increase in the number of states performing formal surveys of BMP compliance. Encouraging results from such surveys are now generally considered to be necessary justification for continuing with voluntary (as opposed to regulatory) nonpoint source pollution control programs. Effectiveness surveys are also becoming more common, with qualitative surveys of randomly selected sites being the most common approach. The obvious trend among the states is toward a more concerted monitoring effort, employing periodic surveys using well-established survey methods.

Overall, it appears that compliance with BMP's is generally high and gradually improving[6] and that water quality is usually within standards where BMP's are implemented. However, cases of noncompliance persist and water quality problems were often associated with such noncompliance, suggesting that continued efforts are needed to ensure BMP implementation. Because the bulk, if not all, of the onsite costs of BMP implementation are borne by the landowner, while the benefits typically accrue to aquatic organisms and downstream water uses, noncompliance may sometimes seem to landowners like an attractive alternative, especially in voluntary states. Thus, compliance and effectiveness monitoring must be an ongoing activity, and instituting a regulatory program must remain a realistic possibility.

Are BMP's the best approach?

The goal of water quality protection programs is to meet standards in the most cost-effective way. BMP's are an administrative approach to reaching this goal. Specifying BMP's to cost effectively reach water quality standards requires an understanding of the complex relations between land disturbance and downstream water quality, as well as of the costs of alternative practices. The complexity arises in part from the difficulty of (1) distinguishing among the individual causes of water quality degradation in a watershed to know the contribution of each area and land practice (a formidable task for "nonpoint" source pollution) and (2) separating natural from management-caused water quality degradation in the context of a variety of weather events. Monitoring of water quality is essential to understand the relations between land disturbance and water quality. By observing the effect over time of precipitation events on water quality downstream of disturbed and undisturbed areas, scientists and land managers can improve their understanding of these relations. This improved understanding can then be used to reassess BMP guidelines so as to more cost effectively reach water quality goals in the future. This iterative process of BMP specification, use, monitoring, and then fine-tuning of BMP specifications for future applications is the key to cost-effective BMP use and effective water quality protection. It relies heavily on gradually improved understanding of the effect of site-specific land management controls on downstream water quality.

Some have called for sufficiently extensive monitoring programs that compliance could be judged directly in terms of meeting water quality standards rather than in terms of applying required BMP's. With achievement of water quality standards as the criterion, landowners would be free to choose the most cost-effective practices on a site-by-site basis to meet prescribed water quality standards for the larger watershed in which the sites are found. However, this idealized approach would only be workable with sufficient water quality monitoring to isolate the specific land area source of the problem and to determine whether the water quality degradation would have happened even in the absence of the land disturbance. Providing such detailed information would require continuous long-term monitoring of both treatment and control sites at many points along the stream network. Applying a comprehensive monitoring program like this over the many areas subject to harvesting and heavy grazing would be very complex and costly. Another problem is that the water quality impacts of land disturbances may not occur until extreme weather conditions develop, which may happen several years after the disturbance. The practical solution has been to (1) prescribe land management practices (i.e., BMP's) that careful studies and professional judgment indicate will control nonpoint source pollution to within standards in most cases, and then (2) to reassess BMP guidelines as new information becomes available. Although the goal of the water quality program is to keep water quality within the standards, the

[6] It should be mentioned that states that have performed formal surveys of BMP implementation may tend to be those that have taken a more proactive stance in explaining the practices to forest managers and operators and in promulgating their use.

immediate objective of the program then becomes the implementation of prescribed BMP's.

Water quality standards are cost effective when they are met accurately, without over- or under-constraining land management. The cost of overconstraining land management is in the waste of resources and consequent loss of income on the part of the landowners. The potential cost of underconstraining land management is in the effect of poor water quality on aquatic organisms and downstream water users.

Common procedures for checking BMP compliance and effectiveness may tend to limit the cost effectiveness with which water quality standards are met. Compliance and effectiveness surveys usually focus on whether or not the goal was met, not on the accuracy with which the goal was met. Exceeding the standard tends to be regarded as a bonus of BMP use, without regard to the cost of implementation. Where BMP implementation is costly and exceedance of the standard is not of comparable value to the cost of exceedance, evaluations of effectiveness of BMP's should measure for over- and underachievement, and future BMP requirements should be adjusted up or down to allow more cost-effective future achievement of the water quality standards.

The cost effectiveness with which BMP's meet water quality standards also depends on how well the BMP's were chosen for a given condition. The more carefully BMP's are tailored to the site-specific conditions, the more likely that they will cost effectively reach their stated goals. Because the professional expertise to carefully select BMP's is costly, BMP's are often specified for large geographical areas (such as counties or multicounty regions), although nonpoint source pollution in specific sites within the larger area may be more inexpensively controlled with one set of BMP's than another. This is not the fault of the BMP approach—rather, it is a matter of how BMP's are specified. The more carefully they are specified for a given site, the more cost effectively the water quality standards will be met, all else equal.

BMP specification must, of course, deal with the complex area of risk. The extent of water quality degradation resulting from land disturbance depends on *when* unusual precipitation events occur. There will be some risk that a severe event could occur soon enough after the land disturbance to cause serious increases in water quality degradation, over and above the background degradation (without the disturbance) that such an event would cause. BMP specification should somehow incorporate an understanding of these risks and reflect a judgment about the level of risk that society is willing to accept.

Costs to the landowner are not the only costs of BMP implementation. Specification of site-specific BMP's by a trained professional, and periodic adjustment of the level of BMP implementation to more accurately attain the water quality goals, can also be costly. These costs should be compared with the costs of overconstraining land management practices to help determine the most efficient level of professional assistance needed in carrying out a BMP program. However, as a general rule, the availability of well-qualified personnel at the field level is probably the most cost-effective approach to meeting water quality standards.

Benefit-cost Comparison of Water Pollution Controls on Forestland

The preceeding discussion of BMP programs focused on the cost effectiveness with which BMP's are specified and implemented to assure that water quality is within water quality standards. That discussion assumes that water quality standards are to be met regardless of the costs. This chapter steps back to compare, to the extent possible given existing literature, the benefits and costs of BMP use. This benefit-cost comparison adopts the perspective of economic efficiency, rather than the more limited perspective of cost effectiveness. Economic efficiency focuses on both benefits and costs. It attempts to do so regardless of to whom the benefits and costs accrue, and regardless of whether the benefits and costs are for goods and services traded in established markets.

The cost of adhering to BMP's may turn a financially profitable timber sale or other operation into a money loosing endeavor, leading to pressure to relax the BMP requirements. However, the effect of BMP constraints on financial returns is not sufficient justification for relaxing BMP specification. It may be that when the true social costs of a sale are tallied, they exceed the benefits, and the sale should not go forward. However, it is also feasible that at some sites the costs of BMP use exceed the benefits of that use. That is, the costs of BMP implementation (increased road construction cost, decreased harvest, etc.) may exceed the cost of the onsite and downstream damage that the BMP's would avert. In this case, it may be reasonable to relax the BMP specifications to the level where the benefits from their use equal their cost.

Section 319 of the Clean Water Act requires the state reports to describe "the process ... for identifying best management practices ... and to reduce, to the maximum extent practicable, the level of pollution ..." (33 U.S.C. 1329(a)(1)(C)). It is not clear what criteria should be used to determine practicability. In particular, should economic considerations enter in determining "practicable" level of control? Because the act also encourages collection and sharing of "information concerning the costs and relative efficiencies of best management practices for reducing nonpoint source pollution" (33 U.S.C. 1285 (l)), there is some suggestion that economic data may be relevant in decisions about BMP specification.

Identification of the physical effects of water quality degradation, and estimation of the social costs of those effects in monetary terms, is a difficult task likely to yield only rough approximations of the true values. Nevertheless, even a rough comparison of such costs of water quality degradation with the costs of avoiding the degradation might provide useful input toward decisions about control efforts. We present a rough comparison here, focusing on erosion, which is the principal water quality effect of silvicultural and related construction activities.[7]

The offsite costs of erosion from various causes have been estimated for specific locations by many authors. Clark et al. (1985) summarized many of these estimates and extended them to the entire area of the 48 conterminous states, and Ribaudo (1986) updated and reorganized these estimates. For sediment and associated categories of nonpoint source pollution, Ribaudo estimated the annual damage cost from erosion of various causes to be from $4.4 billion to $16.1 billion, with a best estimate of $7.6 billion (adjusted to 1985 dollars using the GNP deflator). As the range suggests, the authors recognize the considerable difficulty of estimating such damages. And the difficulties of extrapolation of site specific studies to other areas is an acknowledged problem (Devousges et al. 1992). In any case, the magnitude of total impact is impressive. Damages to recreation and fishing account for about 40% of the total best estimate; damages to water storage and conveyance facilities, ditches and canals, and navigable channels sum to 30%; damages to municipal and industrial users are 17%; and flood-related damages are 13% (table 15).

Ribaudo (1986) disaggregated the table 15 estimates to regions of the United States, and expressed the damage estimate on a per-unit of sediment basis. Regional estimates range from $0.57/Mg for the Northern Plains states to $6.45/Mg for the Northeast states (table 16). Higher costs per Mg were associated with important fishery resources and heavily populated areas. Across all 10 regions, the damage estimate is $1.60/Mg. Erosion source areas for the damage estimates of table 16 included cropland, pasture, rangeland, forests, construction sites, mines, quarries, and stream banks. Neither Clark et al. (1985) nor Ribaudo (1986) specified how much of the total damage is attributable to forests and rangelands. Table 7 lists the average sediment discharges from the different types of land, but costs per Mg are not necessarily proportional to discharge rates. The costs per Mg should be higher for those land types where the sediment is more likely to carry other constituents of water pollution, such as pesticides, salts, and toxics. Such constituents are more likely to be attached to soil leaving farms, mines, and urban areas than to erosion from forests and rangelands.

Ribaudo's estimates of damage per Mg indicate the benefit of reduced erosion and associated contaminants, assuming a linear damage function. The benefit of reduced erosion can be compared with estimates of the costs of controlling erosion on forestlands to allow

[7] For a national benefit-cost comparison focusing on point sources, see Freeman (1982).

Table 15.—Annual offsite damages from erosion for the 48 conterminous states (1985 dollars).[a]

Damage category	Million dollars	Percent of total
Freshwater recreation[b]	2,016	27
Marine sport fishing	591	8
Commercial freshwater fishery	59	1
Commercial marine fishery	378	5
Water storage facilities[c]	1,171	15
Dredging navigable waters	726	10
Flooding[d]	948	13
Drainage ditches and culverts[e]	228	3
Irrigation canals[f]	114	2
Municipal and industrial water use[g]	1,315	17
Irrigated agriculture[h]	30	<1
Total	7,564	100

[a] *Source: Ribaudo (1986), who relied heavily on Clark et al. (1985).*
[b] *Damage to fishing, boating, and swimming.*
[c] *Costs for lost storage capacity (where replacement is infeasible), replacing lost storage capacity, and dredging.*
[d] *Damage from increased flood heights due to channel aggradation; increased flood volumes due to sediment loads, direct sediment damages, and reduced agricultural activity.*
[e] *Based on the cost of keeping them clear.*
[f] *For sediment removal and increased weed control.*
[g] *Based on damages and on the cost of removing sediment and associated contaminants to acceptable levels.*
[h] *Based on costs of salinity.*

Table 16.—Annual offsite damage from soil erosion, by region (1985 dollars).

Region	Damage from all sources (millions of dollars)	Erosion from all sources (millions of Mg)	Damage per Mg (dollars)
Appalachian	566	446	1.27
Corn Belt	991	894	1.11
Delta states	517	216	2.40
Lake states	553	167	3.53
Mountain states	868	925	0.94
Northeast	1099	171	6.45
Northern Plains	351	619	0.57
Pacific	1441	617	2.34
Southeast	343	230	1.48
Southern Plains	837	452	1.85
Total	7564	4736	1.60

Source: Ribaudo (1986).

a rough benefit-cost comparison. Erosion control costs have been estimated in several forest areas, including those of the following five studies. All costs have been adjusted to 1985 dollars using the GNP deflator.

1. Hickman and Jackson (1979) estimated the costs to timber owners of reducing erosion from the roughly 150,000 ha of commercial forest land in Cherokee County in northeast Texas. Costs were in terms of reductions in income resulting from restrictions on site disturbances. Erosion was estimated for the 18 relevant soil types using the universal soil loss equation (USLE), but no attempt was made to determine what portion of the soil loss would be transported to streams. On average, these costs were about $10/Mg for initial reductions and higher thereafter. These costs are over 5 times the Southern Plains states' damage estimate (table 16) of $1.85/Mg. Expressing the cost in terms of units of sediment reaching the stream, rather than in terms of onsite erosion, would increase the estimate of cost per Mg and further weaken the case for the erosion control practices analyzed.

2. Miles (1983) compared the costs of implementing 6 practices (water bars, broad-based dips, buffer strips, culverts, skid trail and landing design, and seeding of roads and landings) on 2 timber sales, a 40 ha area in Minnesota, and a 52 ha area in Michigan.[8] Using the USLE to estimate erosion and sediment loading factors to estimate sediment delivery to the stream, and assuming that the 6 practices would completely avoid the harvest effects, Miles concluded that the cost of the avoided sediment was $69/Mg for the Minnesota site and $39/Mg for the more erodible Michigan site. These costs are considerably above the Lake and Corn Belt states' average damage estimates.

3. Ellefson and Weible (1980) estimated the cost of implementing BMP's during a timber harvest of a 42 ha area in Minnesota. The cost was about $26.50/ha for filter strips, seeding, and improved skid trail design and implementation. Given the Lake states' damage estimate of $3.53/Mg, the BMP's would have to prevent about 7.5 Mg/ha of soil reaching the stream for benefits to match costs.

4. Lickwar et al. (1992) estimated a cost of about $29 ha for implementing currently required BMP's on 22 timber sale areas in 3 southeastern states. Given the Southeast states' damage estimate of $1.48/Mg, the BMP's would have to avoid about 20 Mg/ha of soil reaching the stream.

5. Olsen et al. (1987) estimated costs of implementing proposed Oregon forest practice rules on a representative 541 ha industrial forested watershed in the Oregon Coast Range. The rules would increase restrictions on harvesting and related activities in riparian zones to improve soil stability and protect habitat. The least expensive option they evaluated essentially was incorporated as BMP's that became required by state law in 1987, shortly after the study was completed. Costs of this option were in terms of increased road and harvesting expenses and decreased harvest volume. Depending on the size timber on the site, the cost of implementing these restrictions varied from $250 to $595/ha.[9] Given the Pacific states' damage estimate of $2.34/Mg, the restrictions would have to avoid from 100 to 250 Mg/ha (depending on timber size) of soil reaching the stream if the implementation cost were to be completely covered by offsite water quality benefits.

The simple benefit-cost comparisons are summarized in table 17. The Texas study by Hickman and Jackson (1979) directly estimated onsite costs to timber owners per Mg of avoided erosion. Costs were considerably higher than the offsite benefits. This study evaluated alternative harvest and site preparation practices rather than typical BMP's. It presented results on an average annual basis for the county as a whole; therefore, it is not directly comparable to the other studies, which emphasize BMP's and erosion during and shortly after harvesting activities. The costs estimated by the other studies suggest that, for offsite benefits to equal onsite costs, erosion reaching the stream would have to be from 7.5 Mg/ha (for the Michigan study by Ellefson and Weible 1980) to 20 Mg/ha (for the Southeast areas studied by Lickwar et al. 1992) to 107 Mg/ha or greater for sites with larger timber (for the Oregon study by Olsen et al. 1987). In the studies summaried in the previous chapters, the short-term effects of harvest and related activities on sediment loss ranged from only about 0.05 Mg/ha/yr for some Colorado sites to from 4 to 14 Mg/ha/yr for most of the Southeast sites and 13 Mg/ha/yr for an Idaho site.

These rough benefit-cost comparisons suggest that the cost of avoiding stream sedimentation and associated water quality degradation on forestland often exceeds the offsite benefits of doing so. However, this suggestion must be qualified. The following factors support a more positive view of use of the practices, at least in some areas and to some extent in any given area: (1) The damage estimates are averages over large areas. Some site-specific damages (such as bridge failures) may significantly exceed these averages. (2) The damage estimates do not include effects on the downstream ecosystem (except for the associated impact on fishing value). Economic studies indicate that the public assigns considerable value (called "existence" or "intrinsic" value) to maintaining good water quality (Fisher

[8] *Ellefson and Miles (1985) estimated the cost of these 6 forest practices for 18 timber harvests on 9 National Forests in 5 Midwest states, including the two mentioned here. However, they do not list the sizes of the sale areas, so we could not put their cost estimates on a comparable basis to the other studies.*

[9] *Another, less detailed, Oregon study (Garland 1987) of a similar level of additional riparian zone protection estimated a cost of $1240/ha.*

Table 17.—Comparison of offsite benefits to onsite costs for forest erosion control practices (1985 dollars).

Study	State	Onsite costs ($/ha)	Onsite costs ($/Mg)	Offsite benefit ($/Mg)[a]	Erosion avoided to break even (Mg/ha)
Hickman and Jackson (1979)	TX	na	10+	1.85	na
Miles (1983)	MN	99	69	3.53	283
	MI	101	39	1.11	91
Ellefson and Weible (1980)	MN	26.50	na	3.53	7.5
Lickwar et al. (1991)	AL,GA,FL	29.00	na	1.48	20
Olsen et al. (1987)	OR	250+	na	2.34	107+

na = not available.
[a] *From table 16.*

and Raucher 1984). (3) The damage estimates do not include onsite costs, such as long-term loss of soil productivity.[10] (4) The damage function is not necessarily linear; initial reductions in water pollution may be worth more than the average per-unit reduction. (5) The cost function is not necessarily linear. Hickman and Jackson (1979) and Miller and Everett (1975) found that the marginal cost of reducing soil loss increased as additional erosion was controlled. Initial reductions in erosion will typically be less costly than the average costs listed above.

Conversely, the following concerns reinforce a skeptical view of BMP's on some forest land: (1) The costs listed are onsite costs and do not include the agency costs to inform forest owners about BMP's, to administer a nonpoint source pollution program, and to monitor compliance with BMP's. Lickwar et al. (1990), for example, found that in 1987 the 13 southern states spent about $935,000 on such forestry-related activities (see table 14), and at the time only one state (Florida) was regularly monitoring and enforcing BMP's. Several states indicated that their activities would increase after 1987. (2) Costs per Mg of erosion from forestland are likely to be lower than those for many other types of land because fewer other water quality contaminants are attached to soil from forestland than to soil leaving farms, cities, etc. (3) The damage function is not necessarily linear; initial reductions in water pollution may be worth less than the average per-unit reduction. For example, Ribaudo (1986) suggests that reductions in erosion do not significantly improve fish habitat and recreation quality until the sediment level falls below some threshold.

This benefit-cost comparison is not precise enough for site-specific recommendations about the use of BMP's or for general conclusions about the economic efficiency of BMP implementation. First, the regional average estimates of benefit received from water quality protection are rough at best. Second, the benefit estimates are especially general, each covering a very large geographic area. The variability between regions, in damage per unit of pollution (e.g., Mg of sediment), probably is less than the variability among site-specific locations within regions. Each region may contain specific locations where the benefits exceed the costs and other locations where the reverse is true. However, the benefit-cost comparison does suggest four directions for future consideration of BMP implementation: 1. The BMP's recommended or required for specific locations should reflect the characteristics of the site. Treating large geographical areas as homogeneous units in the selection of BMP's may lead to unwanted water quality degradation at some sites and over-spending at other sites. Implementation of BMP's should focus on those forest areas with the greatest potential benefits. 2. Selection of BMP's should be based on the downstream impacts of water quality degradation as well as the more easily observed onsite disturbances. Across sites, the damage per unit of polluting substance that leaves the treatment site varies widely. 3. At specific sites, initial expenditures on BMP's may be most effective. At some point, the marginal benefit of increasingly more stringent controls falls below the marginal cost of their implementation. In any case, more careful economic comparisons should certainly be performed to better understand the marginal costs and benefits of specific BMP's for various types of land areas and management practices. 4. Better estimates of the costs and benefits of BMP use are needed.

[10] Forest activities that increase sediment movement to streams, such as intensive site preparation after harvesting, can alter forest productivity. Early studies that examined very severe treatments, such as windrowing that removed several inches of topsoil, found significant declines in site productivity that produced substantial costs of reduced future timber yields (Dissmeyer et al. 1987). However, more moderate application of the same types of site preparation (such as windrowing only of slash, with minimal topsoil removal) do not appear to decrease productivity (Allen et al. 1991; L. Morris, University of Georgia, personal communication). In all cases, the reduced productivity came from the movement of soil and nutrients into windrows (typically 150 to 200 Mg/ha of soil moved), rather than from erosion losses from the site (typically less than 5 Mg/ha of soil). Therefore, we expect that erosion does not result in any direct cost of reduced productivity onsite, although high rates of erosion may coincide with poor treatments that do affect site productivity (Dissmeyer 1985).

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Appendix

Table A.1 lists selected characteristics for 43 relatively undisturbed forest and rangeland USGS benchmark stations. The map number listed in the table indicates the location of the station as seen in figure A.1.

Table A.2 lists mean annual values for selected water quality parameters for the benchmark stations listed in table A.1.

Tables A.3 - A.8 summarize the findings for key water quality parameters at experimental watersheds in the 6 regions corresponding to Chapters 3-8.

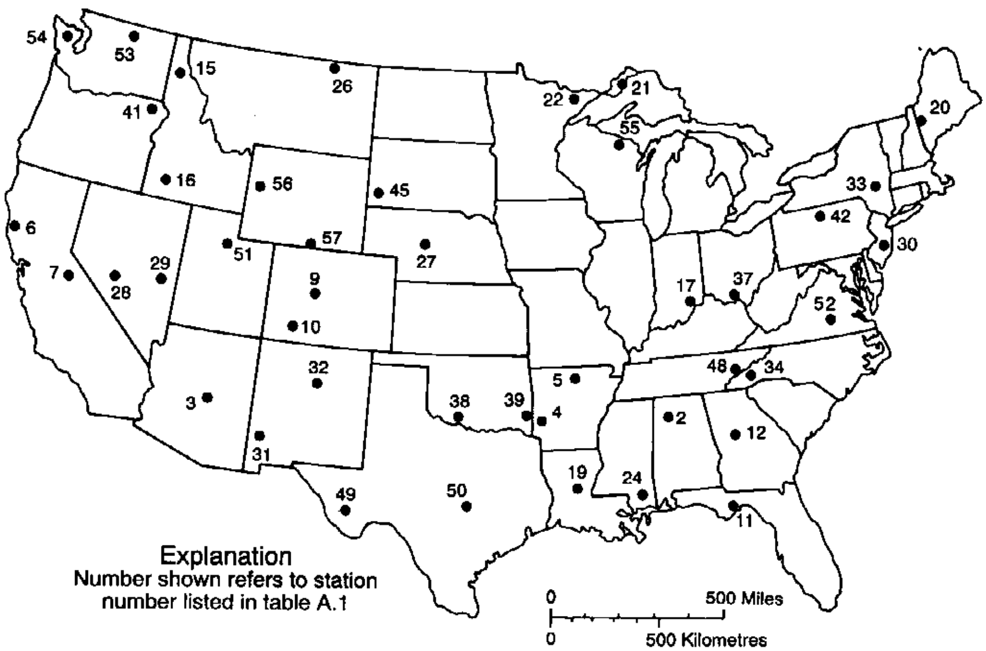

Figure A.1. Locations of hydrologic benchmark stations draining areas largely covered with forest or rangeland vegetation.

Table A.1.—Characteristics of selected hydrologic benchmark stations.[a]

Number	Station name[b]	State	Map number[c]	Drainage (km²)	Flow type[d]	Flow (cm/yr)	Discharge	Precip (m³/sec)	Vegetation (cm/yr)[e]	Influences[f]	Ownership[g]
Southeast											
	Sipsey Fork nr Grayson	AL	2	239	P	66	4.39	132	98% pine and hw	S	NF
	N. Sylamore C nr Fifty Six	AR	5	150	P	48	1.19	114	hw, ug	S	NF
	Cossatot R nr Vandervoort[h]	AR	4	232	P	58	5.58	132	pine & hw, ug	S	NF
	Sopchopp R nr Sopchoppy	FL	11	264	P	64	4.42	142	swamps, pine, oak, ug	S	NF
	Falling C nr Juliette	GA	12	187	P	36	1.50	112	sg pine, hw	S,H	NF
	Big Creek at Pollock	LA	19	132	P	41	1.47	142	sg pine, open land	S,H	NF
	Cypress C nr Janice	MS	24	136	P	51	2.69	152	sg pine, some ag	S,H	M,NF
	Cataloochee C nr Cata.	NC	34	127	P	76	3.14	124	100% hw; ug	R	NP
	Little R above Townsend[h]	TN	48	275	P	91	8.33	147	100% hw, sp, fir	H	NP
	Holiday C nr Andersonville	VA	52	22	P	36	0.20	109	sg hw, sg pine	S	SF
Northeast											
	Wild R at Gilead	ME	20	180	P	86	4.53	112	hw,little conif	S	NF
	McDonalds B Lebanon St Forest	NJ	30	6	P	33	0.03	112	oak, pine,cedar	S	SF
	Esopus C at Shandaken	NY	33	154	P	64	3.79	107	hw, conif	H,R	P
	Young Womans C nr Renovo	PA	42	120	P	43	2.01	97	hw	H	95% public
Midwest											
	S. Hogan C nr Dillsboro	IN	17	99	S	30	1.08	102	pst, some trees nr streams	H	P
	Washington C at Windigo I. Royale	MI	21	34	P	33	0.45	71	hw, sp, fir	R	NP
	Kawishiw R nr Ely	MN	22	655	P	25	6.00	71	pine, lakes	S	NF
	Upper Twin C at McGaw	OH	37	32	P	38	0.34	109	sg hw, some ag	S,F	SF
	Popple R nr Fence	WI	55	360	P	30	3.40	74	95% asp, hw, pine;abd. ag	H,F	P
Great Plains											
	Dismal R nr Thedford	NE	27	2486	P	8	5.38	51	rangeland, few trees	G,F	P
	Blue Beaver C nr Cache	OK	38	64	I	10	0.25	74	native grass, bljack, oak	R	WL,M
	Kiamichi nr Big Cedar	OK	39	104	I	58	2.07	142	pine, hw, grassland	S,H,F	NF
	Castle C ab Dr Res nr Hill Ct	SD	45	215	P	4	0.28	51	90% pine; sp, asp, willow	G,S,F	NF
	S. Fork Rocky C nr Briggs	TX	50	86	I	8	0.37	76	80% gr; 2% ag; oak, willow	H,F,G	P
	Limpia C ab Fort Davis[i]	TX	49	136	I	0.38	0.08	58	cactus, grass, oak, willow	few	?
Rocky Mountains											
	Halfmoon C nr Malta	CO	9	61	P	46	0.74	76	pine, sp, fir, alp.	R	NF
	Vallecito C nr Bayfield	CO	10	187	P	51	3.85	102	sp, aspen, alp	None	W
	Hayden C bl N Fk, nr Hayden	ID	15	57	P	53	0.68	102	sg pine and fir	S	?
	Big Jacks C nr Bruneau (aka Wick)	ID	16	655	I	0.25	0.25	25	Sagebrush and grass	G,B	?
	Rock C blw Horse C nr Int Bndry[h,i]	MT	26	850	I	na	na	na	prairie grasses, sage	few	NG
	S Twin R nr Round Mtn	NV	28	52	P	8	0.14	20	Pinyon, grass, willow	G,M	?
	Steptoe C nr Ely	NV	29	29	P	13	0.17	30	Pinyon and grass	G,R	?
	Red Butte C at Ft. Douglas	UT	51	19	P	25	0.08	64	oak brush, evergreen, asp	few	MW
	Cache C nr Jackson	WY	56	27	P	48	0.34	76	pine, fir, sp, grass, brush	None	?
	Encampment R ab hog pk c nr Enc	WY	57	188	P	43	3.03	76	pine, fir, sp, mead, alp.	R,S	?
Northwest											
	Minam R at Minam	OR	41	622	P	64	12.23	102	pine, fir, larch	None	W
	Andrews C nr Mazama[j]	WA	53	57	P	52	0.94	89	fir, cedar, hemlock, ug	None	PA
	N Fork Quinault R nr Amanda Pk[i]	WA	54	192	P	368	24.50	500	hemlock, fir, sp, cedar, alp	None	NP
Southwest											
	Wet Bottom C nr Childs	AZ	3	94	I	5	0.34	64	chap, pine at high elev	G	W
	Merced R at Happy Isles Br	CA	7	469	P	64	14.75	140	45% bush, fir, pine; alpine	None	NP
	Elder C nr Branscomb	CA	6	17	P	127	0.65	203	dense fir, pines	None	NC
	Mogollon C nr Cliff	NM	31	179	P	9	0.76	33	pine, sp, juniper, willow	None	W
	Rio Moro nr Terrero	NM	32	138	P	18	0.76	61	80% pine, sp, fir, asp; oak	G	W

[a] Sources: (a) Station, name, and drainage area from Hydrologic Benchmark Station List, furnished by Ken Wahl, USGS, Denver 4/5/90; (b) flow type, flow in inches, precipitation, vegetation, and water quality data from Cobb and Biesechker (1971); (c) discharge and precipitation from table 1 of Smith and Alexander (1983). Note: Smith and Alexander took precipitation from Cobb and Biesechker.

[b] U.S. Geological Survey station name.

[c] Except for number 26, these map numbers were used by Cobb and Biesechker.

[d] P=perennial; I=intermittent; S=seasonal.

[e] hw=hardwood; alp=above tree line, sp=spruce, ug=dense undergrowth; sg=second growth.

[f] Influences: B=brush removal; S=silviculture (harvest); H=homes; F=farming; G=grazing; R=recreation; M=mining.

[g] Ownership: W=wilderness; NF=national forest; NP=national park; NC=Nature Conservancy; M=military; IR=Indian reservation; PA=primitive area; MW=municipal watershed; WL=wildlife refuge; SF=state forest; NG=national or provincial grassland; P=private.

[h] Station not used by Smith and Alexander (1983).

[i] Station not on Wahl's list.

[j] Station not included in Cobb and Biesechker (1971).

Table A.2.—Mean annual water quality at selected USGS benchmark stations.

Region	State	Map number	Period of record[a]	Temp (°C)	pH	Conduc (mic/cent)	Bicarbon (mg/l)	Diss sol (mg/l)	Diss O (mg/l)	Diss N (mg/l)	SS (mg/l)
Southeast											
	AL	2	65-86	14.33	7.20	84.98	43.23	49.87	10.25	0.21	22.41
	AR	5	66-88	15.03	8.05	265.22	163.62	149.12	9.85	0.12	7.67
	AR	4	67-88	16.70	7.09	73.12	20.00	27.67	9.09	0.20	3.63
	FL	11	64-88	18.50	5.34	73.43	27.90	42.32	7.90	0.23	6.27
	GA	12	64-87	15.55	7.15	117.49	61.78	79.18	9.26	0.24	22.15
	LA	19	64-88	17.96	6.44	39.70	13.56	39.66	8.8	0.44	36.01
	MS	24	66-86	18.14	6.05	24.44	4.02	23.27	8.90	0.42	36.30
	NC	34	67-86	9.46	6.73	15.12	6.31	16.33	10.54	0.33	8.75
	TN	8	64-87	12.23	6.80	18.30	7.71	14.79	11.00	0.42	15.14
	VA	52	67-88	12.75	6.82	37.25	16.06	32.55	10.62	0.46	6.54
Northeast											
	ME	20	64-86	7.68	6.47	24.17	6.65	19.86	11.56	0.14	4.53
	NJ	30	64-88	10.23	4.18	50.20	0.15	18.24	4.56	0.26	3.94
	NY	33	64-86	8.98	6.87	54.34	13.40	30.37	11.68	0.73	7.50
	PA	42	65-87	8.72	6.82	40.54	9.59	26.24	11.49	0.65	5.66
Midwest											
	IN	17	68-85	12.79	8.01	472.98	205.97	282.03	10.88	2.33	60.39
	MI	21	65-88	7.58	7.42	133.20	75.12	86.66	11.07	0.67	6.37
	MN	2	66-87	10.31	7.02	32.44	13.18	23.21	10.03	0.29	2.85
	OH	37	64-88	13.00	6.89	101.02	15.33	64.60	10.43	1.02	29.56
	WI	55	64-87	8.45	7.36	168.38	95.51	98.78	10.34	1.02	5.75
Great Plains											
	NE	27	66-87	11.42	7.70	175.25	101.45	153.50	9.55	1.28	590.60
	OK	38	65-88	14.60	7.28	165.61	67.46	104.05	9.20	0.38	15.31
	OK	39	65-88	15.94	6.87	26.76	8.51	22.80	9.45	0.27	12.29
	SD	45	64-88	6.10	8.26	467.32	296.35	251.78	10.19	0.51	59.65
	TX	50	64-88	18.74	7.82	469.14	267.32	259.91	8.81	2.31	55.72
	TX	49	67-86	19.36	7.44	164.84	69.11	116.00	9.30	1.55	561.00
Rocky Mountains											
	CO	9	64-85	4.37	7.37	96.27	44.03	48.65	8.98	0.57	7.56
	CO	10	63-86	4.08	7.45	73.93	32.37	44.35	9.79	0.47	4.39
	ID	15	85-88	6.70	7.48	64.90	20.00	50.00	11.35		2.31
	ID	16	85-86	6.69	8.18	153.13	55.00	120.00	10.93		226.00
	MT	26	77-87	8.09	8.28	1150.81	315.55	794.70	9.39	2.25	106.07
	NV	29	68-88	6.99	8.31	317.89	197.52	180.19	9.39	0.64	41.78
	NV	28	67-88	6.76	7.93	122.42	66.10	85.22	9.62	0.30	39.64
	UT	51	64-88	7.32	8.15	593.02	278.30	370.98	9.92	.34	199.91
	WY	56	65-86	3.76	8.28	315.50	208.26	178.82	10.55	0.13	28.23
	WY	57	64-88	5.70	7.33	63.43	32.84	44.47	9.36	0.12	6.56
Pacific Northwest											
	WA	54	65-86	6.10	7.27	73.87	32.25	46.18	12.10	0.09	10.24
	WA	53	71-88	2.99	7.58	47.11	28.98	37.44	11.46		1.66
	OR	41	66-87	6.77	7.40	49.11	30.45	46.54	11.60	0.13	11.53
Pacific Southwest											
	AZ	3	68-88	16.34	7.84	260.29	141.76	170.41	8.68	0.20	5.39
	CA	7	68-88	7.00	6.69	22.28	8.55	20.10	10.92	0.13	2.21
	CA	6	68-88	10.79	7.65	111.03	61.86	73.64	10.42	0.46	11.65
	NM	32	64-88	5.57	7.66	101.25	51.93	61.34	9.61	0.10	28.45
	NM	31	67-88	11.23	7.61	109.42	43.94	80.31	9.36	0.16	14.92
mean				10.51	7.27	163.28	75.79	104.33	9.96	0.56	54.29
st dev				4.62	0.79	205.96	87.17	133.58	1.28	0.59	123.95
min				2.99	4.18	15.12	0.15	14.79	4.56	0.09	1.66
max				19.36	8.31	1150.81	315.55	794.70	12.10	2.33	590.60
coef of var				0.44	0.11	1.26	1.15	1.28	0.13	1.04	2.28

[a] *Beginning and ending year of collection of data for this table. The number of months in any one year during which a sample was taken varies across stations and constituents within the range from 0 to 12.*

Table A.3.—Key water quality parameters for small watersheds in the southeastern United States. Level of detail is quite variable, hence the inconsistencies in entries.

Location	Treatment; watershed area (ha); PPT (mm); runoff (mm)	Period	Suspended sediment (mg/L); Turbidity (NTU)	Temperature pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
Coweeta, NC;	Control, WS-2; 12 ha; PPT 1772; Runoff 854	10 yr		pH 3.7	0.003	Ca 0.58 Mg 0.33 Na 1.22 K 0.50 NH_4N 0.002 PO_4P 0.002 SO_4S 0.15 Cl 0.66 TD Si 8.80	Swank and Waide 1988 Swank 1988
	Control WS-27; 39 ha; PPT 2451; Runoff 1737	10 yr		pH 3.5	0.018	Ca 0.36 Mg 0.20 Na 0.48 K 0.23 NH_4N 0.004 PO_4P 0.001 SO_4S 0.38 Cl 0.49	
	White pine, WS-1; 16 ha	10 yr			0.02	Ca 0.651 Mg 0.36 Na 1.06 K 0.52 NH_4N 0.003 PO_4P 0.008 SO_4S 0.14 Cl 0.68 SiO_2 5.42	
	Grass-to-forest succession, WS-6; 9 ha	10 yr			0.67	Ca 0.99 Mg 0.60 Na 1.00 K 0.55 $NH_{4+}N$ 0.005 PO_4P 0.007 $SO_{42-}S$ 0.15 Cl 1.04 SiO_2 6.59	
	Coppice regrowth, WS-7; 59 ha	Calibration			0.00	Ca 0.7-1.35 K 0.0-0.9	
		After treatment			0.01-0.16	Ca 0.75-1.60 K 0.0-0.6	

Table A.3.—Continued

Location	Treatment; watershed area (ha); PPT (mm); runoff (mm)	Period	Suspended sediment (mg/L); Turbidity (NTU)	Temperature pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
	White pine, WS-17; 13 ha	10 yr			0.13	Ca 0.51 Mg 0.23 Na 0.79 K 0.39 NH_4N 0.04 PO_4P 0.002 SO_4S 0.16 Cl 0.53 SiO_2 6.72	
	Coppice regrowth, WS-37; 44 ha				0.18	Ca 0.73 Mg 0.31 Na 0.64 K 0.38 NH_4N 0.004 PO_4P 0.001 SO_4S 0.38 Cl 0.47 SiO_2 4.64	
	Uneven-aged hardwood, WS-40; 20 ha	1 year			0.005	Ca 1.04 Mg 0.40 Na 1.12 K 0.54 NH_4N 0.004 PO_4P 0.003 SO_4S 0.15 Cl 0.61	
	Clearcut + herbicide	First yr		3 °C increases in maximum			Swift and Messer 1971
Great Smoky Mountain National Park	Watersheds at 1500 m; PPT 2500	1 yr	0.3 NTU		4.9	Ca 0.25-1.5 Mg 0.1-0.5 Na 0.75-1.25 K 0.5-1.5 SiO_2 4.3-10.7	Silsbee and Larson 1982
	Watersheds at 500 m; PPT 1400	1 yr	2.5 NTU		0.5		
	< 25% logged	1 yr	0.47 NTU		0.83		
	> 75% logged	1 yr	0.58 NTU		0.36		

Table A.3.—Continued

Location	Treatment; watershed area (ha); PPT (mm); runoff (mm)	Period	Suspended sediment (mg/L); Turbidity (NTU)	Temperature pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
Carteret County NC	Forest (700 h))	1985-1988	12.9 mg/L 20 NTU			Total N 1.1 NH_4N+NO_3N 0.1 Total P 0.07 Biological Oxygen Demand 1.3	Hughes et al. 1989
	Forest (24 ha)	March 1989	<1-10 mg/L 1-19 NTU		0-1.0	NH_4N 0-0.2 PO_4P 0.01-0.06 BOD 0.2-0.9 TC' <2-8	
Walker Branch, TN	Control; 97.5 ha; PPT 1368; Runoff 713	3 yr			0.057	Ca 16 Mg 8.4 Na 0.48 K 0.73 NH_4N 0.022 PO_4P 0.001 TN 0.156	Elwood and Turner 1989
Santee Experimental Forest, SC	Control and prescribe burned	3 yr			0.02	NH_4N 0.03 PO_4P 0.03	Richter et al. 1982
Georgetown County, SC	Control, hardwood forest	2 yr		pH 4.4	0.47	Ca 5.5 Mg 2.7 K 0.80 NH_4N 0.047 SO_4S 10.95 TP <0.01 DO 5.1	Askew and Williams 1986
	Drained	2 yr		pH 4.9	0.94	Ca 10.8 Mg 3.5 K 0.87 NH_4N 0.074 SO_4S 15.6 TP <0.01 DO 5.0	
	Logged	2 yr		pH 5.2	0.11	Ca 7.9 Mg 2.6 K 2.15 NH_4N 0.057 SO_4S 10.08 TP <0.01 DO 5.8	

Table A.3.—Continued

Location	Treatment; watershed area (ha); PPT (mm); runoff (mm)	Period	Suspended sediment (mg/L); Turbidity (NTU)	Temperature pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
	Site prepared	2 yr		pH 5.5	0.20	Ca 6.0 Mg 2.2 K 1.6 NH_4N 0.026 SO_4S 7.91 TP <0.01 DO 5.7	
	Young pine forest	2 yr		pH 5.8	0.05	Ca 5.3 Mg 2.3 K 2.0 NH_4N 0.022 SO_4S 6.21 TP <0.01 DO 5.4	
	Old pine forest	2 yr		pH 5.4	0.48	Ca 5.5 Mg 2.2 K 1.5 NH_4N 0.041 SO_4S 7.48 TP <0.01 DO 6.9	
Bradford County, FL	Control, pine forest; 137 ha; PPT 1400; Runoff 583	3 yr	3 mg/L (annual average)	pH 3.8	0.03	Ca 0.60 Mg 0.73 K 0.14 NH_4N 0.13 PO_4P 0.02 TKN 1.15 TP 0.02	Riekerk 1983
	Harvest, minimum impact; 64 ha; PPT 1400; Runoff 618	2 post-treat yr	4 mg/L	pH 3.6	0.04	Ca 0.20-0.38 Mg 0.77-1.43 K 0.25-0.78 NH_4N 0.06-0.15 PO_4P 0.00-0.03 TKN 1.13-1.45 TP 0.02-0.05	

Table A.3.—Continued

Location	Treatment; watershed area (ha); PPT (mm); runoff (mm)	Period	Suspended sediment (mg/L); Turbidity (NTU)	Temperature pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
	Harvest, maximum impact; 48 ha; PPT 1400; Runoff 656	2 post-treat yr	13 mg/L	pH 4.1	0.05	Ca 0.89-1.69 Mg 0.66-1.71 K 0.45-0.71 NH_4N 0.08-0.09 PO_4P 0.00-0.01 TKN 0.87-1.05 TP 0.01-0.02	
Grant Forest, GA	Control, pine forest, 42.5 ha	6 yr			0.116-0.156	Ca 5.96-6.55 Mg 2.56-2.84 Na 5.55-6.46 K 1.28-2.53 TP 0.23-0.61	Hewlett et al. 1984 Hewlett et al. 1984 Hewlett and Fortson 1982
	Clearcut, 32.5 ha	Calibration, 1 yr			0.043	Ca 3.49 Mg 1.33 Na 5.59 K 2.50 TP 0.23	
		2 yr		11 °C maximum increase in summer; 6 °C maximum decrease in winter	0.027	Ca 2.89 Mg 1.38 Na 4.49 K 1.32 TP 0.32	
	Recovery period	3 yr			0.045	Ca 3.38 Mg 1.43 Na 4.49 K 1.34 TP 0.55	
Natchez Trace State Forest, TN	Controls, pine forests	3 yr	Stormflow 82				McClurkin et al. 1985
	Harvested	1-3 yr post harvest	Stormflow 183				
N Mississippi P. taeda P. elliotti (5 watersheds)	1.49-2.81 ha 135 cm rainfall		Stormflow susp.sed. 49-228		Stormflow 0.01-0.02	Stormflow NH_4N 0.17-0.23 TP 0.024-0.028 COD 20-45 TOC 6-16	Schreiber and Duffy 1982

Table A.3.—Continued

Location	Treatment; watershed area (ha); PPT (mm); runoff (mm)	Period	Suspended sediment (mg/L); Turbidity (NTU)	Temperature pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
Upper coastal plain, MS	Control, hardwood/pine forest	1976 1977	2127 mg/L 393 mg/L				Beasley 1979
	Harvest, chopped	1976 1977	2471 mg/L 670 mg/L				
	Harvest, sheared	1976 1977	2837 mg/L 794 mg/L				
	Harvest, bedded	1976 1977	2808 mg/L 2346 mg/L				

˙TC: Total coliforms (*/100 ml)

Table A.4.—Key water quality parameters for small watersheds in the northeastern U.S. and eastern Canada.

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
Hubbard Brook, NH	Control (W4-W6) hardwood forest	1965-1968	25 kg/ha/yr stream	0.09 NTU		0.2	Ca 1.27-1.80 Mg 0.35-0.41 Na 0.80-1.13 K 0.18-0.26 NH_4N 0.02-0.09 SO_4S 2.00-2.14 Cl 0.55-0.58 SiO_2 3.8-5.5 Al 0.12-0.33 [W3] DO(%) 30-100	Likens et al. 1970 Hornbeck et al. 1987 Lawrence and Driscoll 1988
	Devegetated (W2)	1965-1966			4 °C increased maximum	0.21	Ca 1.81 Mg 0.37 Na 0.87 K 0.19 NH_4N 0.14 SO_4S 2.27 Cl 0.54 SiO_2 4.1 Al 0.22	
		1966-1967	x4 pre-treatment	0-0.3 NTU	1 °C increased maximum	8.7	Ca 6.45 Mg 1.35 Na 1.51 K 1.92 NH_4N 0.05 SO_4S 1.27 Cl 0.89 SiO_2 5.6 Al 1.5	
		1967-1968	x4 pre-treatment			11.9	Ca 7.55 Mg 1.55 Na 1.54 K 2.96 NH_4N 0.04 SO_4S 1.23 Cl 0.75 SiO_2 5.77 Al 2.0	
	Stripcut	yr 1				1.4 (fig. 4.2)	Ca 2.00 Mg 0.43 Na 1.22 K 0.23 NH_4N 0.028 SO_4S 2.13 Cl 0.57	

Table A.4.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
	Blockcut	yr 1				3.9 (fig. 4.2)	Ca 1.28 Mg 0.41 Na 0.9 K 0.20 NH_4N 0.014 SO_4S 1.84 Cl 0.50	
	Whole-tree harvest	yr 1				3.6 (fig. 4.2)	SO_4S 1.76 Al 0.81	
Nashwaak River, NB	Control, hardwood/ conifer forest	4 yr				0.12		Krause 1982
	Harvested	1-3 yr post harvest				0.6 average; 1.3 maximum		
Various locations, NE	Control and harvested, central hardwoods	2 yrs				0	Ca 1-5 Mg 0.3-1 Na 1.5-2.5 K 0.2-1.2 SO_4S 3-5.2 Cl 1.5-2.5	Martin et al. 1984
	Control and harvested, conifer forests	2 yr				0.1 to 0.5	Ca 1.5-21 Mg 0.5-3 Na 0.5-2.5 K 0-1 SO_4S 1-3 Cl 0.5-2.5	
	Control and harvested, northern hardwoods	2 yr				0.1 to 2.0	Ca 1-7 Mg 0.2-1.5 Na 0.3-1.5 K 0.1-1.0 SO_4S 1-3 Cl 0.1-1.0	
Leading Ridge, PA	Control, mixed hardwood forest	3 yr		1.7 mg/L 2 NTU		0.03	Ca 5.81 Mg 2.28 Na 1.03 K 0.96 SO_4S 2.67	Lynch et al. 1975 Lynch and Corbett 1990 Lynch et al. 1985
	43% of watershed harvested	1-3 yr past harvest		5.9 mg/L 3 NTU		0.08 average; 0.85 maximum	Ca 3.15 Mg 1.49 Na 0.90 K 1.13 SO_4S 1.9	

Table A.4.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
	Devegetated	2 yrs past havest		80 mg/L		2.5	Ca 3.15 Mg 1.76 Na 0.93 K 1.57 SO_4S 1.29	
Quaker Run, PA	Upstream	1985-1986			pH 5	0.13	Ca 2 Mg 2.7 Na 1.1 K 0.6 SiO_2 6.3	Phillips and Stewart 1990
	Downstream	1985-1986			pH 7	0.32	Ca 6.5 Mg 2.0 Na 2.5 K 0.9 SiO_2 6.5	
Fernow Experimental Forest, WV	Control, mixed hardwood forest	3 yr	17 kg/ha/ to stream	2.1 NTU Dis. solids 12.2	14.4 °C pH 6.0	0.2	Ca 0.5-1.5 Mg 0.2-0.5 Na 0.4-0.8 K 0.3-0.7 NH_4N 0-0.5 PO_4P 0.026-0.065 SO_4S 0.67-1.67	Aubertin and Patric 1974
	Harvested	3 yr	49 kg ha^{-1} to stream	3.1 NTU Dis. Solids 11.5	15.6 °C pH 6.0	0.2 average; 1.4 maximum	Ca 0.5-1.5 Mg 0.2-0.5 Na 0.4-1.4 K 0.3-0.7 NH_4N 0-0.5 PO_4P 0-0.029 SO_4S 0.33-1.67	
	Fertilized	3 yr				> 10 for 3 weeks		Edwards et al. 1991

Table A.5.—Key water quality parameters for the North Central and Great Plains regions.

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
Marcell Experimental Forest, MN	Control, aspen forest	2 yr				0.3	Ca 3.0 Mg 1.3 Na 0.8 K 1.5 NH_4N 0.41 PO_4P 0.039 Cl 0.8 TKN 0.85	Verry 1972
	Harvested	2 yr				0.015	Ca 2.7 Mg 1.0 Na 0.7 K 1.5 NH_4N 0.55 PO_4P 0.055 Cl 0.5 TKN 0.8	
Cherokee County, TX	Control, pine forest	Calibration (1980)	340	71 NTU	pH 5.4	0.007	Ca 1.8 Mg 0.7 Na 0.7 K 1.7 NH_4N 0.51 PO_4P 0.0003 TP 0.099	Blackburn et al. 1986 Blackburn and Woods 1990
		First year	33	140 NTU 112 mg/L	pH 5.9	0.002	Ca 1.7 Mg 1.1 Na 1.0 K 2.8 NH_4N 0.036 PO_4P 0.0033 TP 0.077	
		Second year	5	61 NTU 79 mg/L	pH 5.4	0.002	Ca 1.0 Mg 0.8 Na 1.1 K 2.0 NH_4N 0.040 PO_4P 0.0039 TP 0.039	
		Third year	5	38 NTU 31 mg/L	pH 6.6	0.002	Ca 0.7 Mg 1.0 Na 1.2 K 2.0 NH_4N 0.015 PO_4P 0.0013 TP 0.030	

Table A.5.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
		Fourth year	29	54 NTU 213 mg/L	pH 6.4	0.015	Ca 0.7 Mg 1.0 Na 0.8 K 2.1 NH_4N 0.071 PO_4P 0.0042 TP 0.092	
		Fifth year		39 NTU	pH 6.2	0.035	Ca 3.0 Mg 1.1 Na 3.8 K 1.9 NH_4N 0.059 PO_4P 0.0026 TP 0.053	
	Harvested, chopped, burned	Calibration (1980)	85	31 NTU	pH 5.5	0.003	Ca 2.3 Mg 0.9 Na 1.0 K 2.1 NH_4N 0.060 PO_4P 0.0003 TP 0.060	
		First year	25	30 mg/L 59 NTU	pH 6.1	0.021	Ca 2.1 Mg 1.3 Na 1.7 K 5.6 NH_4N 0.043 PO_4P 0.0049 TP 0.053	
		Second year	6	36 mg/L 16 NTU	pH 5.6	0.003	Ca 1.1 Mg 0.8 Na 1.4 K 1.9 NH_4N 0.009 PO_4P 0.0013 TP 0.024	
		Third year	5	12 mg/L 16 NTU	pH 6.5	0.004	Ca 0.8 Mg 1.1 Na 1.7 K 3.0 NH_4N 0.016 PO_4P 0.0007 TP 0.027	

Table A.5.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
		Fourth year	16	28 mg/L 17 NTU	pH 6.5	0.028	Ca 1.7 Mg 1.2 Na 3.0 K 3.3 NH_4N 0.068 PO_4P 0.0042 TP 0.043	
		Fifth year		21 NTU	pH 6.2	0.023	Ca 1.4 Mg 0.9 Na 1.7 K 4.2 NH_4N 0.035 PO_4P 0.0016 TP 0.038	
	Harvested, sheared, windrowed, burned	Calibration	184	79 NTU	pH 5.3	0.003	Ca 2.4 Mg 0.7 Na 0.7 K 3.2 NH_4N 0.067 PO_4P 0.0003 TP 0.068	
		First year	2940	1158 mg/L 153 NTU	pH 6.0	0.046	Ca 0.9 Mg 1.4 Na 1.4 K 4.9 NH_4N 0.058 PO_4P 0.0088 TP 0.219	
		Second year	80	256 mg/L 60 NTU	pH 5.8	0.014	Ca 2.9 Mg 1.1 Na 2.2 K 3.2 NH_4N 0.022 PO_4P 0.0020 TP 0.055	
		Third year	35	113 mg/L 47 NTU	pH 6.5	0.011	Ca 0.8 Mg 0.9 Na 1.4 K 3.0 NH_4N 0.022 PO_4P 0.0003 TP 0.033	

Table A.5.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
		Fourth year	165	489 mg/L 61 NTU	pH 6.3	0.010	Ca 1.4 Mg 1.2 Na 3.2 K 4.5 NH_4N 0.033 PO_4P 0.0020 TP 0.058	
		Fifth year		38 NTU	pH 6.3	0.011	Ca 1.4 Mg 0.9 Na 3.2 K 3.7 NH_4N 0.090 PO_4P 0.0033 TP 0.049	

Table A.6.—Key water quality parameters for the Rocky Mountains.

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
Fraser Experimental Forest, CO	Fool Creek, road construction, partial cutting	1950-1965		< 5 mg/L				Alexander et al. 1985 Stottlemyer 1987 Leaf 1975
		1952-1966	99 to stream					
		1984				0.002	Ca 5.95 Mg 1.03 Na 1.93 K 1.25 NH_4N 0.014 PO_4P 0.0024 SO_4S 0.61 Cl 0.67	
	Control, Lexen Creek	1982-1986				0.006		
		1955-1966	36 to stream					
		1984					Ca 10.64 Mg 1.19 Na 1.01 K 0.51 NH_4N 0.028 SO_4S 0.63	
	Deadhorse Creek, road construction and harvesting	1982-1986				0.06		
		1956-1966	25 to stream					
		1984					Ca 17.64 Mg 2.09 Na 1.59 K 1.09 NH_4N 0.0042 SO_4S 0.83	
Silver Creek, ID	Control, ponderosa pine/ Douglas-fir	1975-1981				0.01		Clayton and Kennedy 1985
	Harvested	1977-1979				0.018 average 0.05 peak		
		1981				0.01		
Priest River, ID	Benton Creek, above cut	1 yr		4.5 mg/L		0.17		Snyder et al. 1975
	In cut unit			6.4 mg/L		1.5		
	Below cut unit			5.0 mg/L		0.2		

Table A.6.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
	Ida Creek, above cut	1 yr		7.1 mg/L		0.15		
	In cut unit			37 mg/L		0.15		
	Below cut unit			12 mg/L		0.15		
	Canyon Creek, above cut	1 yr		3 mg/L		0.015		
	In cut unit			16 mg/L		0.18		
	Below cut unit			4 mg/L		0.015		
Bitterroot National Forest, MT	Spruce Creek, control	Third year post harvest				0.11		Bateridge 1974
	Lodgepole Creek, harvested					0.19		
	Springer Creek, control	First year post harvest				0.17		
	Mink Creek, harvested					0.13		
	Little Mink Creek, control	First year post harvest				0.17		
	Harvested					0.4		
West central Alberta	Control and harvested forests of pine, spruce, aspen	Snowmelt and summer recession flows				0.005 to 0.05		Singh and Kalra 1975
Chicken Creek, UT	Control, aspen					0.008		Johnston 1984
	Harvested					0.025		
Manitou Experimental Forest, CO	Ungrazed and grazed pastures	1 summer		35 to 65 mg/L		0.03-0.07	FC* 200 ungrazed FC 1050 grazed FS** 730 ungrazed FS 1760 grazed	Johnson et al. 1978
S. Fork Poudre River, CO	Ungrazed Little Beaver Creek	2 yr		7 to 25 mg/L			TC*** 37 FC 4 FS 14	Meiman and Kunkle 1967
	Grazed Pennock Creek	2 yr		4 to 21 mg/L			TC 120 FC 68 FS 24	
Nash Fork, WY	Low-use natural area	1 yr					FC 0.2 to 1.2	Skinner et al.
	Grazed, recreational watersheds	1 yr					FC 20 to 30	1974

Table A.6.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
Reynolds Creek, ID	Grazed sagebrush watersheds						FC maximum 2500	Stephenson and Street 1978

*Fecal coliform; **Fecal strepotocci; ***Total coliform colonies/100 mL.

Table A.7.—Key water quality parameters for the Pacific Northwest.

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
HJ Andrews Experimental Forest, OR	Control, WS-2			3 mg/L annual average Winter 1966/67 > 10 mg/L 9 days		0.01	PO_4P 0.005-0.01	Fredriksen et al. 1975
	Harvested and burned, WS-1			Winter 1966/67 > 10 mg/L 26 days >1000 mg/L 2 days	Summer maximum increased by 8 °C	0.4 mg/L peak	PO_4P 0.008-0.013	
	Road construction, 25% harvested, WS-3	First 2 road years		15 mg/L				
		Third year		260 mg/L				
		Third year post harvest		2500 mg/L				
	Control, WS-9	Calibration year	(*) Input to channel: SUR 26 DIS 16			0.001	TKN 0.061	Sollins and McCorrison 1981 Sollins et al. 1980
		First year				0.001	TKN 0.064	
		Second year				0.004	TKN 0.072 DOC 1.3	
		Third year	Export from channel:			0.002	TKN 0.072 DOC 2.8 NH_4N 0.014	
		Fourth year	DIS 286 SUS 35 BED 14			0.008	TKN 0.069 DOC 1.3 NH_4N 0.014	
	Clearcut, WS-10	Calibration year	Input to channel: SUR 80 DBS 643 DIS 16 Export from channel: DIS 332 SUS 70 BED 90 DBF 493			0.001	Ca 3.20 Mg 0.834 Na 1.96 K 0.339 TKN 0.047 TP 0.054	
		First year	Input to channel: SUR 199 DBS 1300 DIS 17			0.003	TKN 0.057	
		Second year				0.067	TKN 0.082 DOC 2.7	

Table A.7.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
		Third year	Export from channel: DIS 354 SUS 320 BED 305 DBF 6000			0.033	TKN 0.079 DOC 3.2 NH_4N 0.027	
		Fourth year				0.017	TKN 0.071 DOC 1.3 NH_4N 0.017	
	(W8) Control 21.4 ha	Pre-treatment (2-3 y)		7.94	pH 7.3	0.001	Ca 2.40 Mg 0.64 Na 2.30 K 0.36 TKN 0.046 PO_4P 0.021 $SiO_{2\ 9.03}$	Martin and Harr 1989
		Post-treatment (9 y)		8.2	pH 7.3	0.003	Ca 3.04 Mg 0.57 Na 2.51 K 0.43 TKN 0.039 PO_4P 0.022 SiO_2 12.78	
	(W7) Shelterwood 15.4 ha	Pre-treatment (2-3 y)		2.13	pH 7.3	0.001	Ca 2.70 Mg 0.80 Na 1.76 K 0.41 TKN 0.029 PO_4P 0.022 SiO_2 9.80	
		Post-treatment (9 y)		2.14	pH 7.3	0.006	Ca 3.58 Mg 0.93 Na 2.01 K 0.56 TKN 0.029 PO_4P 0.022 SiO_2 15.15	
	(W6) Clearcut 13.0 ha	Pre-treatment (2-3 y)		4.19	pH 7.3	0.001	Ca 3.05 Mg 0.86 Na 1.80 K 0.29 TKN 0.026 PO_4P 0.016 $SiO_{2\ 10.61}$	

Table A.7.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
		Post-treatment (9 y)		4.24	pH 7.3	0.020	Ca 3.54 Mg 0.89 Na 1.90 K 0.40 TKN 0.034 PO_4P 0.014 SiO_2 13.89	
Middle Fork Santiam River, OR	Above study area	9 year averages		71 mg/L; <30 NTU				Sullivan 1985
	Below study area			50 mg/L; <30 NTU				
Alsea, OR	Control, Flynn Creek	1966-1970		1.5-6.6 mg/L		1.2		Fredriksen et al. 1975, Brown et al. 1973 Brown and Krygier 1970
	25% harvested, Deer Creek	1967-1970, post road/harvest		2.0-16.3 mg/L		1.2		
	100% harvested, Needle Branch	1966-1970, post road/harvest		4.4-15.8 mg/L	2 °C increase winter 8 °C increase summer	0.4		
Coast Range, OR	Control, Siletz Creek	2 yr				0.6	Ca 1.6 Mg 1.0 Na 10.6-11.7 K 0.8	Miller and Newton 1983
	Harvested+Herbicide, Siletz Creek	2 yr				0.6	Ca 1.6 Mg 1.2 Na 11.3-12.2 K 0.8-1.2	
	Control, Drift Creek	2 years				1.5 to 2.0	Ca 2-3.3 Mg 1.9-2.4 Na 12.2-17.3 K 1.2	
	Harvested+Burned+ Herbicide, Drift Creek	2 yr				1.5 to 2.0	Ca 2-3.2 Mg 1.9-2.2 Na 12.4-14.5 K 1.6	
	Control, Brush Creek	2 yr				0.7 to 2.1	Ca 2.8-4.8 Mg 1.7-2.9 Na 11.3-13.3 K 0.8-1.2	
	Harvested+Herbicide, Brush Creek	2 yr				0.7 to 2.1	Ca 2.4-6 Mg 1.7-4.1 Na 8.7-14.7 K 1.6	

Table A.7.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
Bull Run, OR	Control, Fox Creek	1970-1981		0.6-2.4 mg/L		0.010	Ca 0.4-1.3 Mg 0.4-0.7 Na 0.6-1.2 K 0-0.3 TN 0.042 PO_4P <0.003 TP 0.014-0.025 SiO_2 1-3	Fredriksen et al. 1975 Fredriksen and Harr 1988 Harr and Fredriksen 1988
	25% harvested, Fox Creek	1973-1981 post harvest		unchanged		0.08 average 0.28 maximum	Ca 0.5-1.3 Mg 0.4-0.8 Na 0.6-1.2 K 0-0.3 TN 0.038 PO_4P <0.004 TP 0.014-0.028 SiO_2 1-3	
	25% harvested and burned, Fox Creek	1971-1981		unchanged		0.04, declining to 0.01 after 5 years	Ca 0.3-1.2 Mg 0.4-0.7 Na 0.7-1.2 K 0-0.3 TN 0.038 PO_4P <0.003 TP 0.014-0.024 SiO_2 1-3	
Coyote Creek, OR	Control			< 40 mg/L		0.015-0.040	NH_4N 0.005	Fredriksen et al.
	Shelterwood			< 40 mg/L	No change	< 0.015		1975
	Patchcuts			< 40 mg/L	No change	0.015-0.040		Harr et al. 1979
	Clearcut	First year Later years		170 mg/L < 40 mg/L	8 °C maximum increase; after 8 years, 3 C maximum increase	0.1		Adams and Stack 1989
UBC Research Forest, BC	Control	1972-1982			<17 °C pH 6.5-6.8	0.015-0.07	Ca 1.14-2.07 Mg 0.2-0.36 Na 0.64-1.06 K 0.06-0.1 NH_4N 0-0.002 SO_4S 0.47-0.99 SiO_2 2.79-5.51 Cl 0.69-1.05	Feller and Kimmins 1984 Feller 1981
	Clearcut	First year			pH 6.4	0.5	Ca 1.58 Mg 0.36	

Table A.7.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
		Third year			pH 6.5 <21.8 °C	Control levels	Na 1.26 K 0.38 NH_4N 0 SO_4S 0.73 SiO_2 6.75 Cl 1.15 Ca 1.64 Mg 0.26 Na 1.00 K 0.22 NH_4N 0.66 SO_4S 0.51 SiO_2 5.65 Cl 0.66	
	Clearcut, burned	First year Third year			pH 6.5 pH 6.5 <20.3 °C	0.17 Control levels	Ca 2.08 Mg 0.25 Na 0.82 K 0.16 NH_4N 0 SO_4S 0.54 SiO_2 2.95 Cl 0.76 Ca 1.14 Mg 0.29 Na 0.96 K 0.09 NH_4N 0 SO_4S 0.51 SiO_2 5.55 Cl 0.77	
Okanagan Valley, BC	Control	1 yr				0.03 average 0.12 maximum		Hetherington 1976
	Harvested	1 yr				0.03 average 0.4 maximum		
High Ridge Watersheds, OR	Control, mixed conifer forest	Pre-treatment Post-treatment			pH 7.1	0.092 0.162	Ca 3.24 Mg 1.20 Na 1.76 K 0.84 TN 0.11 PO_4P 0.025 Ca 3.42 Mg 1.24	Tiedemann et al. 1988

Table A.7.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
							K 1.04 TN 0.13 PO_4P 0.33	
	Selection harvest	Pre-treatment			pH 6.7	0.003	Ca 2.66 Mg 0.82 Na 1.74 K 0.68 TN 0.06 PO_4P 0.014	
		Post treatment (3 y)				0.006	Ca 2.65 Mg 0.88 K 0.88 TN 0.09 PO_4P 0.013	
	Patch cuts	Pre-treatment			pH 7.0	0.001	Ca 2.04 Mg 0.72 Na 1.58 K 0.59 TN 0.02 PO_4P 0.009	
		Post treatment (3 y)				0.004	Ca 2.16 Mg 0.71 K 0.60 TN 0.06 PO_4P 0.008	
	Clearcut	Pre-treatment			pH 7.1	0.004	Ca 2.46 Mg 0.72 Na 1.65 K 0.68 TN 0.003 PO_4P 0.014	
		Post treatment				0.026	Ca 2.74 Mg 0.86 K 0.78 TN 0.08 PO_4P 0.013	
Hansel Creek, WA	Prior to treatment			3.7 mg/L; 1.0 NTU		0.15		Fowler et al. 1988
	After road construction	First year		178 mg/L; 24 NTU		No increase from roads or harvesting		
		Second year		8.5 mg/L; 1.3 NTU				
		Third year		2.1 mg/L; 1.0 NTU				

Table A.7.—Continued

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
Maybeso Experimental Forest, AK	Harvested	First few years after harvest			0.5 to 2.0 °C maximum increase			Meehan et al. 1969
Southeastern, AK	Control			0.2-310 mg/L; <1 NTU				Stednick et al. 1982
	Harvested, burned			0.2-1290 mg/L; <5 NTU				
Various locations	Nitrogen fertilization					0.2 to 10		Various studies

(*) SUR: Surface erosion, DIS: Dissolved load, SUS: Suspended load, BED: Bedload, DBS: debris slide, DBF: Debris flow

Table A.8.—Key water quality parameters for the Pacific Southwest.

Location	Treatment; water area (ha); PPT (mm); runoff (mm)	Period	Erosion (kg/ha/yr)	Suspended sediment (mg/L); Turbidity (NTU)	Temperature; pH	Nitrate-N (mg/L)	Other chemicals (mg/L)	Reference
Three Bar Watersheds, Arizona	Control, chaparral, WS-D	15 yr 3 yr			pH 7.9-8.1	< 0.3 mg/L Ca 22-27 Mg 6-7 Na 14-17 K 0.34-0.43 SO_4S 2.67-7.01 Cl 4-6.8		Davis 1984, 1987a,b Davis 1989
	Conversion to grassland, WS-B	After first stage 10 years after second stage				2.7 average 9.5 maximum 3.5 to 11.9 average 18.8 maximum		
	Conversion to grassland, WS-F	Post-treatment (10 yr) Post-treatment (prescribed burn) (1 yr)				< 7.4 average	Ca 20 Mg 6 Na 16 K 0.71 SO_4S 4.0 Cl 5.5	
Beaver Creek Watersheds, AZ	Control, ponderosa pine forest	8 yr				0.01		M. Ryan, personal communication
	Heavy thinning	8 yr				0.05		
	Clearcut	8 yr				0.22		
Castle Creek, AZ	Prescribed fire in ponderosa pine	1 yr				< 0.003 mg/L		Gottfried and DeBano 1990
San Dimas Experimental Forest, CA	Grassland, chaparral	2 yr				2.8 mg/L maximum		Riggan et al. 1985
Southern CA	Chaparral	1 yr				1.3 to 19.6		Riggan et al. 1985

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