WATER QUALITY IN FORESTED WATERSHEDS OF THE SOUTHWESTERN UNITED STATES

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ABSTRACT

Water-quality degradation is often constant because information about on- and off-site watershed disturbances and how to reduce their impact is limited. This paper identifies different types of water-quality parameters, their causes and possible sources, and the mandatory or recommended standards for drinking water and aquatic wildlife habitats. Information presented should help develop methods that estimate or forecast the production and movement of diffuse pollutants, determine how to minimize the production of pollutants, and prevent entry of pollutants into streams and other surface water bodies. The paper reviews key models, and various water-quality management activities. The activities can be used independently or together to maintain and restore the quality of degraded surface water at the watershed scale.

INTRODUCTION

According to the new Clean Water Action Plan, jointly developed by nine federal agencies, clean water is the product of a healthy watershed, and water-quality programs, such as nonpoint pollution abatement programs, must be accomplished at the watershed scale (U.S. Environmental Protection Agency 1998). Despite this need, most water-pollution prevention and control programs have been planned and implemented based on political boundaries. Because the flow of water and pollutants does not stop at politically determined boundaries, there is a growing recognition that watershed-management programs that involve water pollution should be comprehensively undertaken within natural watershed boundaries. This practice would help control point and nonpoint pollution sources and protect drinking-water sources and sensitive natural areas.

Watersheds are continuously subjected to a host of natural processes and human activities that impact their health, ecological integrity, and the quality of the water flows. Consequently, proper management of watersheds, especially those in forested areas, is important because watersheds provide water for domestic, agricultural, and recreational uses. Improper watershed management causes undesirable consequences such as flooding, erosion, and ecosystem degradation.

To ensure proper watershed management, federal, tribal, state, and local governments are developing programs and activities to control or stop water-quality degradation and to restore degraded watersheds. For example, the Federal Water Pollution Control Act of 1972 established objectives for the restoration and maintenance of the physical, chemical, and biological integrity of waters in the United States. Section 208 of the Act requires that any water-quality management plan incorporate a process that identifies nonpoint sources (NPS) of water pollution and establishes methods to control the sources, as much as possible. The United States Congress passed the Water Quality Act in 1987, which required states to develop and implement effective programs to control NSP pollution. In 1996, Congress amended the act to protect water at its source. Nonpoint source pollution originates from natural causes, such as surface erosion and the movement of native chemicals, human actions that involve surface disturbances and produce wastes that enter water bodies, and a combination of natural events and human use of land and resources (U.S. Environmental Protection Agency 1980).

Erosion, sediment production, and deposition are the processes that can dramatically change the environment and affect the quality and usefulness of water (Overby and Baker 1995). Other quality parameters that affect the quality and usefulness of water include temperature, pH values, nutrient amount, and other pollutants that enter water bodies on watersheds. We discuss the causes, effects, and standards of these types of the water-quality parameters in this paper and describe erosion and sediment models and other pollutant movement estimation methods. We also suggest appropriate watershed management approaches to protect water quality and restore quality to water sources that are

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degraded. The management methods discussed consider Best Management Practices[1] (BMPs) that relate pollutants to their causes and consider scientific, engineering, ecological, social, cultural, and legal approaches to protect clean water resources and to create reliable restoration mechanisms to water-quality problems.

WATER-QUALITY PROBLEMS AND CAUSES

Landscapes are subject to continuous disturbances that can have serious consequences on water quality. For example, clean water never occurs in rangelands and forested watersheds where grazing occurs (Lee 1980). The levels of impurities in a water body indicate water quality. Water is polluted if the level of impurities impairs the water's suitability for any actual or potential beneficial use. The foreign substances in water determine its characteristics, which can be physical, chemical, or biological. Some disturbances on watersheds, either natural- or human-caused, produce significant changes in the amount and production of water-quality characteristics or parameters.

Timber harvesting, grazing, road building, prescribed fire, and silvicultural operations are human-caused disturbances that may result in serious water-quality problems (Rich 1962). Forest roads can contribute 50% to 85% of all the sediment from forested areas to a surface water body. However, the amount of sediment produced from forest roads varies from place to place and is reduced by improving road orientation and inclination, culvert installation, and cable yarding (Rice 1999). Other human-caused activities that can cause water-quality problems include recreation; mining; construction activities; application of fertilizers, insecticides, pesticides, or herbicides; and industrial, domestic, and commercial activities that generate effluents. Some human activities produce changes in vegetation cover and soil characteristics that affect the amount and rate of infiltration. When this happens, erosion and mass wasting (soil movement through slide, slump, debris flow, earth flow, rock fall, gully and rill erosions, and surface sloughing) increase, which affects the physical structure of watersheds.

Natural disturbances include earthquakes, volcanic eruptions, flooding, wildland fires, and mass wasting. These kinds of natural disturbances are sources of many water-quality problems such as sedimentation and chemical contamination of waters. Earthquakes have destabilizing effects on surfaces making them susceptible to erosion and mass wasting. Volcanic eruptions produce high temperatures and bring out subsurface chemicals that contaminate surface waters. Flooding and mass wasting carry earth materials in different forms downstream. Downslope soil mass movements result mainly from gravitational stress, and they occur in the form rapidly moving soil and forest debris (debris avalanches or debris flows) or slowly moving earthflows that can choke water bodies with unneeded sediment and chemical pollutants. Flooding has related effects on water bodies. It erodes surface soils and carries the material downstream where it is deposited along floodplains, slow-moving streambeds and stationary water bodies. The moving and settled sediment is a major water quality problem its suitability for human use and wildlife habitat. The effect of wildfire on water quality is discussed in detail in Neary et al.(2002).

Water erosion (the mechanical detachment by water of mineral soil particles and organic matter from the soil surface and stream channels), sediment movement, and deposition are related processes that affect the physical quality of water in many watersheds. Water erosion is a complex process that varies with time and space within a particular area (Ward and Baker 1984). The variations occur due to temporal and spatial changes in the erosive forces, and other physical and biological factors that influence the amount of erosion from an area. Some specific factors that affect the amount and rate of water erosion include the type of soil; amount and type of vegetation ground and canopy cover; climate, specifically rainfall, temperature, and wind speed; topography, particularly steepness and slope; and land use and management (Zingg 1940, Troendle and Leaf 1980, Ward and Baker 1984).

The sources of chemical pollutants in water can be natural—weathering and dissolution of rocks and soils containing high chemical concentrations, and atmospheric deposition—or human activities such as application of fertilizers, pesticides and herbicides or effluents from industrial, commercial, and mining sites. Sources of physical and biological contaminants can also be natural or human. For example, timber harvesting along stream banks can raise soil and water temperatures to levels that are unsuitable for many aquatic and terrestrial organisms. Human settlements and grazing wildlife and livestock contribute biological pollutants, such as

[1]The practice or combination of practices that are determined (by a state or states, or representative area-wide planning agency, in case two or more states or other conflicting interests are involved) after problem assessment, identification and appropriate participation of all interested parties and clearly articulating their wishes and aspirations, examination of alternative practices, and selecting the most effective and practicable (with respect to criteria that include technological, economic, cultural and institutional considerations) means of preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals.

pathogenic organisms and organic contaminants, to water. Genotyping the sources of the *Escherichia coli* polluting the stream water in Oak Creek Canyon in northern Arizona consisted of raccoons (*Procyon lotor*; 31%), humans (16%), skunks and elks (*Cervus elaphus*; 11% each), beaver (*Castor canadensis*), dogs (*Canis familiaris*), and white-tailed deer (*Odocoileus virginianus*; 6% each) (Arizona Department of Environmental Quality 2001, Poff and Tecle 2002).

WATER-QUALITY PARAMETERS

Individual measurable impurities in water are the water-quality parameters used to assess the suitability of the water for uses such as consumption, swimming, agriculture, and aquatic habitat. Water-quality problems in Southwestern watersheds are either chemical, physical, or biological. As mentioned, the type and level of the pollutants depend directly or indirectly on the sources of the water-quality problem. Many natural and human watershed disturbances produce physical, chemical, and biological water-quality parameters.

Physical Water-Quality Parameters

The two most important physical characteristics that measure the quality of standing or moving water are turbidity and temperature. Another parameter, water color, reflects the type of dissolved organic molecules in the water. However, water color is not important in Southwestern watersheds where little or no organic materials are generated that negatively affect water quality.

Sediment is the fine, light material, usually higher in clay, silt, and organic matter than the rest of the surface-soil material, which is removed from the soil surface due to erosion, mass wasting, or other mechanisms. Sediment is transported in flowing water in suspension, saltation, or bedload. As a water-quality parameter, sediment is expressed as the concentration of dry weight of sediment per unit volume of water, such as milligrams of sediment per liter of water or nephelometric turbidity units (NTU). Problems from high-sediment loads include siltation of rivers, lakes, and reservoirs, which reduces the usefulness and shortens the lives of water bodies. As sediment covers the bottom of streams and lakes, it destroys algae, which is the basis of aquatic food chain, by grinding action and suffocation (Appelboom et al. 2002).

Suspended sediment is the portion of a river's total transported sediment that floats in the water and does not immediately sink to the bottom. The individual suspended sediment particle sizes are usually <0.5 mm in diameter, which is in the size range that is most harmful to fish and water quality (Reid and Dunne 1984). The amount of sediment moving past the outlet of a particular watershed during a specific interval is the *sediment yield.* Sediment yield depends on the amount of eroded material, the amount and rate of surface water flow, and the condition of the terrain that the surface water travels over.

Turbidity is also measure of the amount of suspended sediment in the water. The optical property of water causes the scattering and absorption of light; light is transmitted in a straight line through pure water (American Public Health Association 1976). Suspended sediment characteristics that affect the optical property of water are particle size, distribution, refractive index, specific weight, and shape factors. Other factors that contribute to the turbidity of water include color, dissolved minerals, air bubbles, and organic matter (Beschta 1980). Water with high turbidity is aesthetically unpleasant, less desirable for recreation, and may contain impurities that are unsuitable for human and animal consumption or aquatic habitats.

Conversely, *bed load*, is that part of fluvial sediment load that moves with or immediately above the streambed by rolling or sliding. Generally, bed load sediment is heavier and larger than suspended sediment. The bed load's immersed weight is supported by a combination of fluid and solid reactive forces exerted at intermittent contacts with the streambed. Hence, bed load transport is part of the interactions between flow dynamics, the sedimentology of the streambed, and the stream channel geometry (Bunte 1996). Some particle characteristics and flow hydraulics allow sediments to move in a jumping or *saltation* mode. Because this mode of movement does not conform to either the suspended or bed load movement, it is an intermediate between the two.

The other major physical water-quality parameter is temperature. Temperature affects the chemical and biological characteristics of water and riparian areas. The solubility of oxygen decreases rapidly with an increase in water temperature (Binkley and Brown 1993). For example, a temperature change from 10 °C to 15 °C decreases oxygen solubility in water about 20% (Golterman et al. 1978), and removal of the tree canopy from over streams usually raises the monthly average stream temperatures by 3 °C to 7 °C or more (Brown 1989, Binkley and Brown 1993). Fish and other aquatic organisms require an optimal range of temperature interval values, therefore, watershed managers should manage vegetation in and around riparian areas to minimize changes in water temperatures from their natural fluctuations. Other physical

effects of forest activities, such as harvesting without leaving buffers along a streamside, include reductions in stream depth, increases in stream width, and sediment deposition along the streambed (Scrivener 1988; Tecle et al. 2001, 2002).

Chemical Water-Quality Parameters

Chemical pollutants generated by activities in watersheds are carried downstream either in a dissolved form or after absorption in sediments suspended in the water. The different chemicals in water are the chemical parameters that describe water quality in surface water. The most important chemicals are nitrate, phosphate, acidity or pH, aluminum, heavy metals, and organic pollutants.

Forest activities significantly affect the concentrations of nitrates, dissolved oxygen, and phosphates in surface water bodies (MacDonald et al. 1991). The primary NPS of phosphorus are commercial fertilizers and animal manure, which are responsible for 90% of the phosphorus in one-third of the rivers and streams studied in the Unites States (Kornecki et al. 1999). The average concentration of nitrates and phosphates from forested watersheds are about 0.23 ppm and 0.006 ppm, respectively, while those from agricultural watersheds are about 3.23 ppm and 0.06 ppm, respectively. Agricultural activities contribute about 9.5 million tons of nutrients annually to surface waters in the United States (Borah and Ashraf 1992). Establishing water-quality management standards helps to reduce the discharge of nitrates and phosphates into water bodies.

Forest practices can also change the pH, concentration of dissolved oxygen, and specific conductivity in water. Low or high pH water (6.5 to 9.0) and low dissolved oxygen (>5 ppm) are unsuitable for many aquatic organisms. Specific conductivity (EC) is a measure of the amount of salt in the water—the more salts that exist in ionic form, the higher the EC value of the water. The most common EC values in forest streams range from 3 to 15 milliSiemens per meter of water. The objective of forest management is to maintain acceptable levels of pH, a high dissolved oxygen content, and a low EC value to ensure that the water resource is suitable for use.

Biological Water-Quality Parameters

The potential impacts of microbiologically contaminated water to humans are immediate compared with the long-term impacts generally associated with chemical pollutants such nitrogen and phosphorus (Edwards et al. 1997). The most common microbiological pollutants are fecal coliform and fecal streptococcus bacteria. Fecal coliform bacteria originate from humans and other mammals, while most fecal streptococcus is from nonhuman mammals. Because of the distinct sources, the ratio of fecal coliform to fecal streptococci may be used to differentiate between human and animal pollution sources (Binkley and Brown 1993). Both bacteria are valuable pollution indicators in the study of rivers, streams, lakes, and marine systems (Csuros 1994). Because total coliform counts are easy to identify, they are also commonly used to assess possible microbiological contamination of drinking water supplies.

Another biological contaminant of concern is *Giardia lamblia*, which is a human parasite that causes giardiasis. Giardiasis is a waterborne disease of concern in many Western mountain watersheds (Brown 1989) where cases have been traced to streams in watersheds with substantial beaver activity. *Entamoeba histolytica*, which causes amoebic dysentery, and salmonella, which causes salmonellosis, are uncommon in the Southwest. Although waters in the Southwest have almost no contamination from these microorganisms, watershed managers should be vigilant and develop watershed management practices to prevent any contamination of streams from grazing and recreational activities.

WATER-QUALITY STANDARDS

Water-quality standards are threshold values beyond which water is considered aesthetically offensive, hygienically unfit, or economically unsuitable for use (U.S. Environmental Protection Agency 1976, 1986). Researchers have identified different standards for each water-quality parameter and for each use such as consumption, recreation, fisheries, or agriculture (U.S. Environmental Protection Agency 1976, Lee 1980). Adopting different standard values in a particular ecosystem for the same parameter depends on the importance of the water body to different uses, local economic considerations, and the desired degree of safety for human use and aquatic life habitat.

Table 1 shows standard values of water-quality parameters that indicate water suitability for different uses. For example, the acceptable standard for total coliform counts in drinking water is 0 to 1 colony forming units (cfu) per 100 mL, while the common standard for water designated for primary and secondary contact usage human contact use is 200 and 1000 cfu per 100 mL, respectively (Edwards et al. 1997). The table also presents mandatory and recommended standards for drinking water and freshwater aquatic life. The recommended standard for dissolved solids in drinking water in the United States is 500 mg/Kg, and the mandatory standard for turbidity in the same water use is a

Table 1. *Water quality standards for common drinking water supply and freshwater aquatic life (Lee 1980, Hammer and MacKichan 1981, Matthess 1982, Tecle 1991).*

Drinking water supply criteria			Freshwater aquatic life criteria	
WQ criterion type	Mandatory standard	Recommended standard	WQ criterion type	Recommended standard
Inorganic chemicals				
Arsenic	0.05		Ammonia	0.02
Barium	1.00		Beryllium	0.011-1.1
Boron	0.01		Calcium	0.75
Cadmium	0.01		Copper	0.20*
Chromium	0.05		Cadmium	0.04-0.12
Chloride		250.00	Chlorine	0.002-0.010
Copper		1.00	Cyanide	0.005
Cyanide`	0.02		Dissolved O_2	>5.00
Fluoride	0.05-2.4[a]		Foaming agents	0.50
Hydrogen sulfide	0.05		Iron	1.00
Iron	0.30		Lead	0.01*
Lead	0.05		pH	6.5-9.0
Manganese		0.05	Mercury	0.005
Mercury	0.002		Nickel	0.01*
Nitrate-N	10.00		Phosphate	0.05
pH		6.5-8.5	Selenium	0.01*
Selenium	0.01		Silver	0.002
Sulfate		250.00	Sodium	2.00
Total dissolved solids		500.00	Sulfide	0.002
Zinc	5.00		Zinc	0.01
Organic chemicals (ppm)				
Endrin	0.0002		Aldrin/diealdrin	0.000003
Lindane	0.004		Chlordane	0.00001
Methoxychlor	0.10		DDT	0.000001
Toxaphene	0.005		Demeton	0.0001
2,4-D	0.10		Endosulfan	0.000003
2,4,5 ST Sivex	0.01		Endrin	0.000004
Trihalomethanes	0.10		Guthion	0.00001
Phenol	0.001		Heptachlo	0.000001
			Lindane	0.0001
			Methoxychlor	0.00003
			Mirex	0.000001
			Parathion	0.00004
			Toxaphene	0.000005
			PCBs	0.000001
Physical characteristics				
Turbidity	1 NTU[b] monthly average			
	5 NTU average for 2 consecutive days			
Odor		3 threshold odor #		
Color		15 color units		
Biological characteristics				
Fecal coliform bacteria		1/0.0264 gal[c]		70/0.264 gal
Fecal streptococcal bacteria	N/A			

*In TL_{50}, median tolerance limit:concentration of test material at which just 50% of the test animals are able to survive under test conditions for a specified period of exposure.
[a]Depending on air temperature
[b]NTU=nepholmetric turbidity test
[c]as monthly mean

monthly average of 1 NTU. Likewise, the mandatory drinking-water standard for nitrate is10 ppm to prevent risks to infants, and for phosphate in freshwater lakes and streams is 0.0001 ppm to prevent eutrophication (the process by which a water body becomes pollution rich in nutrients and deficient in dissolved oxygen) (MacDonald et al. 1991). Maintaining these standards can be a challenge, especially when we consider that in the United States agricultural activities alone annually contribute nearly three billion tons of sediment to streams (Borah and Ashraf 1992).

Besides those listed in the table, standard values for other important parameters, such as temperature and dissolved oxygen, also exist. For example, the lethal temperature for rainbow trout (*Oncorhynchus gairdneri*) is 80 °C (Tiedemann and Higgins 1989). Streams must have a minimum level of dissolved oxygen to be healthy. To avoid suffocation of young fish, dissolved oxygen levels in streams used for spawning should either be a 7-day average of 9.5 ppm or a one-day minimum of 8 ppm (MacDonald et al. 1991). Knowing the standard values for the water-quality parameters is important to:

- Determine water resource conditions;
- Protect clean water supplies;
- Specify the safe use of water;
- Develop and implement restoration programs to improve degraded waters;
- Prevent the use of contaminated waters; and
- Determine the cost and time required to restore degraded water resources.

MODELING WATER-QUALITY PROBLEMS

Researchers have developed and implemented several models to predict soil loss and sediment, nutrient, and pesticide movement from field- and basin-scale watersheds. Tecle (1991) reviewed 19 of the models, and others have since been developed. The universal soil loss equation of Wischmeier and Smith (1978) estimates the total annual amount of erosion from agricultural areas. The modified universal soil loss equation was developed estimate erosion from forested lands (Dissmeyer and Foster 1980, Tecle et al. 1990). Renard et al. (1997) have revised the modified universal soil loss equation to improve its reliability when used for conservation planning. Models used to estimate nonpoint source pollution at the watershed scale are the nonpoint source pollutant and the agricultural runoff management (Donigian and Crawford 1976a, b).

Because of recent advances in hydrology, soil science, erosion mechanics, and computer technology, researchers can integrate different factors into a modeling process and develop complex and physically based erosion estimating and simulating techniques. Physically based models have several advantages over empirical equations. They can:

- Represent the problems and related processes better than other modeling strategies;
- Accurately simulate single-event storms;
- Examine complex problems that have variable spatial and temporal characteristics;
- Analyze erosion, sediment movement, and deposition simultaneously; and
- Consider gully and channel erosion and deposition processes.

Some examples of physically based models that can be used in any watershed are the USDA's water erosion prediction project, which Lane and Nearing developed (1989), a two-dimensional upland soil erosion model, which Johnson et al. (2000) developed, and the spatially integrated model for phosphorus loading and erosion, which Kornecki et al. (1999) developed.

The water erosion prediction project is a process-based model developed for use in soil and water conservation and environmental planning. The model has three versions: the landscape profile or hillslope version, the watershed version, and the grid version (Laflen and Schertz 1990). The hillslope version computes soil loss along a landscape profile like those of the universal soil loss equation. Unlike the universal soil loss equation, the water erosion prediction project model extends the slope through all depositional sections. The watershed version uses hillslope profiles and concentrated flow paths to characterize a watershed within a field-size area. The grid version calculates erosion at all points and along all flow paths (Lane and Nearing 1989).

Researchers developed the two-dimensional upland soil erosion model to simulate the dynamics of upland erosion during single rainstorms. The model is based on the raster-based surface runoff calculations (Johnson et al. 2000). The third example of a physically based model, the spatially integrated model for phosphorus loading and erosion, was developed to predict runoff volume, sediment loss, and phosphorus loading from watersheds (Kornecki et al. 1999). This model simulates the sediment and phosphorus loadings at the cell and field scales. The innovation of skilled hydrologists, soil scientists, engineers, plant scientists, ecologists, and analysts is needed to continue to develop detailed and physically-based models of erosion and sedimentation processes. Physically based models improve our understanding of soil detachment, movement, and deposition, and produce effective soil-erosion and sediment-movement prevention programs. Application of BMPs could then be implemented to resolve water-quality concerns at the watershed scale.

WATER-QUALITY MANAGEMENT APPROACHES

Most of our drinking water comes from healthy watersheds. Such watersheds, located in urban, agricultural, rangeland, and forested areas, are protected and managed to prevent water pollution. Unfortunately, too often water supplies either are already polluted or are seriously threatened. As discussed, natural events and processes, human activities, or a combination of natural and human influences cause water pollution. To protect our water resources and prevent their contamination, state water-quality departments and the U.S. Environmental Protection Agency have adopted the concept of BMPs.

Regulations and amendments exist that require states to adopt BMPs to control water degradation from point and nonpoint pollution sources. The methods that can prevent the production, enrichment, and delivery of NPS pollutants are important to achieve water-quality objectives (Novotny and Chesters 1989). Currently, BMPs are not usually as comprehensively delineated as those in conceptually identified in the definition of BMPs. Additionally, BMPs are not usually adequately implemented to achieve the desired water-quality goals. Further development of BMPs is needed (Clausen and Meals 1989).

BMPs should consider all interested parties and all factors that contribute to the problem and then develop and implement watershed resource management methods. For a lasting solution, such methods must relate pollutants to the:

- Soil properties;
- Hydrologic conditions,
- Land use;
- Pollutants' chemical or biological behavior;
- Causes of the pollution problem;
- Affected ecological components; and
- Stakeholders.

Mathematical models integrate the different factors to abate pollution production and movement (Borah and Ashraf 1992), maintain healthy watersheds, and restore degraded watersheds.

BMPs must incorporate the following activities to ensure the desired quality of surface water supplies.

- Legislate and consistently implement clear and enforceable federal, state, tribal, and local government regulations and guidelines to mitigate water pollution. Examples of legislative actions against water pollution include issuing ambient standards that establish a threshold of acceptable pollutant levels, establishing performance standards that specify the amount of pollutants can be discharged into the environment, and specifying standards that focus on controlling the process that generates pollutants. For the legislative approach to be successful, identifying and monitoring the pollution sources and enforcing the regulations and guidelines must be effective and efficient.
- Implement economic control of pollutant discharge. Issuing tradable disposal permits (TDPs) and levying product charges and taxes provides economic incentives that help control pollution (Stauffer 1998). TDPs, issued by government entities, entitle a polluter to discharge a unit of pollution during a specific period. The government establishes a target amount for the total acceptable pollution level and issues the appropriate number of permits. This allows dischargers to buy and sell permits among themselves. It also enables environmentalists to purchase permits, and remove them from the market. Product charges are additional taxes on products that pollute. The resulting higher cost encourages producers to develop and implement nonpolluting alternatives, while the government uses the additional funding to further pollution clean-up efforts. Tax incentives, such as a tax exemption or deferral mechanisms, reduce pollution within a specified period, which the polluter determines. Penalty taxes imposed on polluters require compensation for any pollution discharged. However, this approach implies that polluting the environment is acceptable if the polluter can afford to pay a price. Additionally, penalty taxes are not geographically specific and are difficult to enforce, especially when the pollutant is not easily measurable.
- Enlist public pressure and establish education efforts that encourage polluters reduce or prevent pollutant discharge. Educating homeowners about the toxicity of materials used within their homes can foster proper disposal and substitution with safer products. Requiring polluters to reveal information about the amount of pollution being discharged, and its effects on people and the environment, would encourage citizens to demand that their representative enact right-to-know legislation. Right-to-know legislation includes laws to ensure access to public- and private- sector information on environmental issues. Disclosure to workers about toxic substances produced in connection with the materials they handle and labeling of consumer products containing hazardous substances are the results of right-to-know legislation (Stauffer 1998).
- Control pollutant discharges from urban and industrial areas. Rainwater runoff in urban

communities can be reduced through harvest and use, and by directing surface flows into drains before contamination. Water contamination from industrial and commercial facilities can also be minimized through source control and on-site treatment. These methods reduce waste discharge through recycling and internal treatment of wastes, respectively.

- Prevent erosion and mass wasting. Implementing slope stability, which prevents erosion and mass wasting, requires collaboration between forest, rangeland, and agricultural watershed managers, road engineers, environmental groups, and stakeholders to develop an awareness and an ability to recognize when a problem occurs and how to solve it. Collaboration is important because large amounts of pollutants are produced during forest harvesting, livestock grazing, agriculture field preparation, road building and use, and silvicultural treatments.
- Develop and implement techniques that reduce the amount of nutrients and pesticides entering water bodies. Applying the correct type and amount of fertilizers and pesticides during the appropriate season increases their uptake and reduces fertilizer and pesticide runoff.
- Adopt an interactive multi-objective approach to watershed management, which involves recognizing all aspects of a watershed management plan including the interacting watershed components and various stakeholders. This approach holistically integrates the different activities discussed in this paper to maintain and restore water quality at the watershed level.

Effective watershed management accomplishes the above activities at the watershed scale, considers all relevant components, and involves all decision-makers and other interested parties. When different decisionmakers are involved, it is important that communication and understanding prevail to reduce or avoid conflict. The above points are BMPs because their development and implementation achieve the desired quality water and safe environment, and they promote the desired social quality of life.

SUMMARY

Nonpoint source pollution of surface waters is a problem in Southwestern watersheds where the scarcity of water is critical. To determine how to minimize or prevent the problem, this paper explored many aspects of NPS pollution including the causes of water pollution and the different types of water-quality parameters and their specific standards. In addition, we reviewed water-quality models that researchers have used to estimate or simulate the production and movement of the different water-quality parameters. Some models are deterministic, time invariant, and empirically developed, while others are dynamic and physically based. Examples of the first type are the universal soil loss equation, and its modified version, which were developed to estimate the total periodic amount of erosion. An example of the second type is the two-dimensional upland soil erosion model, which is a spatially and temporally varying distributive model to estimate erosion from upland watersheds, sediment movement to stream channels, and sediment routing through a channel to the watershed outlet (Johnson et al. 2000).

Water-quality problems in lakes and streams that drain into watersheds may be due to natural causes, human activities, or the interactions between natural processes and conditions associated with human use of the land and resources. Natural disturbance processes include earth quakes, volcanic eruptions, floods, wildland fires, and mass wasting. Disturbances due to human activities include recreation, livestock grazing, timber harvesting, mining, road building, and industrial and commercial activities. The events can occur incrementally or abruptly due to one or a combination of events that may occur on a watershed simultaneously or sequentially.

Other important requirements for managing water-quality problems are to identify threshold values for acceptable water quality and to estimate the rate and amount of water-quality degradation. Based on such knowledge, managers can determine the appropriate methods to maintain the existing water quality or to restore the degraded water quality. Managers can use the methods independently or integrate them to manage water quality at the watershed scale.

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